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Characterization and Mechanisms of Hot Air Drying of Off-Ground Harvested In-Hull
Almonds

By

ZHAOKUN NING
DISSERTATION

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ABSTRACT

In California, off-ground almond harvesting offers significant potential to reduce dust generation, microbial contamination, and insect damage, issues commonly associated with conventional harvesting method. However, freshly off-ground harvested almonds have high moisture content, making them vulnerable to postharvest quality deterioration if not properly dried. The drying process is energy-intensive, which directly impacts profitability. Therefore, the overall goal of this research was to investigate the drying mechanisms of off-ground harvested almonds and develop efficient drying methods to reduce drying time and energy consumption while maintaining product quality and safety. Several important aspects of the drying process of the off-ground harvested almonds, including the initial characteristics of almonds (moisture content distributions, dimensions, chemical compositions, and thermophysical properties), moisture diffusivity, theoretical heat, and moisture transfer modeling, the feasibility of commercial dryer systems, and quality attributes of the dried product, as well as the impact of insect infestation, were investigated.

To investigate insect infestation of almonds, eight almond varieties were collected from 17 orchards across northern and southern California during three consecutive harvesting seasons (2019, 2020, and 2021). A total of 44 samples were analyzed, consisting of 11 off-ground harvested samples collected immediately after shaking and 33 conventionally harvested samples collected at various times during on-ground drying. Results indicated that off-ground harvested almonds were cleaner and had a significantly lower rate of insect infestation ($2.0 \pm 1.7\%$) compared to those from conventional harvest ($4.2 \pm 3.7\%$). Among conventionally harvested samples, those from northern California showed a higher infestation rate ($6.0 \pm 3.4\%$) than those from the southern region ($2.6 \pm 3.4\%$), likely due to the cooler, more humid climate in the north, which favors insect

proliferation. Additionally, the insect damage ratio increased with prolonged on-ground drying. For example, Nonpareil almonds from Nickels and Frank farms had infestation rates ranging from 0.3% to 3.7% and 1.3% to 2.3%, respectively, after drying on the orchard floor for one week. These findings highlight the quality and safety benefits of adopting off-ground harvesting methods for almonds.

Samples were collected at two harvest timings, early harvest (EH) and standard harvest (SH) to comprehensively examine the initial characteristics of off-ground harvested almonds. EH typically begins 3-4 weeks earlier than SH, a timeline traditionally based on regional practices. Key attributes, including moisture content (MC) distributions, dimensions (length, width, and thickness), shapes (sphericity), chemical compositions (dry matter, protein, fat, crude fiber, and carbohydrate), and thermophysical properties (true density, thermal conductivity, and specific heat capacity) of three different almond components (hull, shell, and kernel) were analyzed. Results showed that EH almonds were composed entirely of in-hull almonds, while SH almonds consisted of three fractions: in-hull almonds, in-shell almonds, and loose hulls. The overall average MC for EH almonds was approximately 63% (wet basis), compared to 22% for SH in-hull almonds and 8% for SH in-shell almonds. Specifically, for EH in-hull almonds, the MC values of hull, shell, and kernel were 76.3%, 46.8%, and 28.5%, respectively. In contrast, SH in-hull almonds exhibited lower MC values of 27.1% for hulls, 15.3% for shells, and 13.0% for kernels. In both EH and SH almonds, the hull consistently had the highest MC, followed by the shell and kernel. Regarding dimensions, the average length, width, thickness, and sphericity for EH in-hull almonds were 32.8 mm, 25.2 mm, 24.4 mm, and 83%, respectively, compared to 35.9 mm, 24.1 mm, 24.5 mm, and 77% for SH in-hull almonds. Observations also revealed the presence of air gaps between the hull and the shell and between the shell and the kernel for both EH and SH almonds. Distinct

thermophysical properties were noted among the hull, shell, and kernel, with variations observed between EH and SH almonds. EH hulls and shells exhibited lower true densities but higher thermal conductivities and specific heat capacities than SH samples. A similar trend was observed for the kernels, though the true density was slightly higher in EH almonds. These findings demonstrated the significant differences between EH and SH almonds, which is helpful in designing the drying process for different purposes. Moreover, the results offer valuable data for accurately determining the moisture diffusivity of almonds and identifying essential parameters for model development.

For SH almonds, drying loose hulls results in unnecessary energy consumption, while drying in-hull almonds and in-shell almonds together can lead to over- or under-drying. To address this issue, a dimension- and terminal velocity-based sorting approach was developed to efficiently separate loose hulls while minimizing product loss. The results indicated that in-shell almonds had significantly smaller thicknesses compared to in-hull almonds and loose hulls. Using a cut-off thickness of 21.1 mm, 100% of the in-shell almonds were successfully separated. Additionally, the terminal velocity (TV) range for in-hull almonds was much higher than that of loose hulls. By selecting a critical TV value of 12.2 m/s, the in-hull almonds and loose hulls could be 100% separated. However, some in-hull almonds and loose hulls with smaller thicknesses were misclassified into the in-shell fraction, with misclassification rates of 6.7% and 23.3%, respectively. Despite this, these error rates are relatively low and acceptable for practical applications.

To characterize the intrinsic moisture transfer mechanisms during the drying process, experiments were conducted to determine the effective moisture diffusivities of different almond components during hot air drying of in-hull almonds. Drying experiments were conducted at three air temperatures (45°C, 60°C, and 75°C) with a constant air velocity of 1.4 m/s, using a factorial

experimental design. The process continued until the average moisture content of in-hull almonds reached approximately 9% on a wet basis. Due to natural variations in moisture content, weight, and dimensions of freshly harvested almonds, a single almond could not represent the entire batch. To minimize this variability, 10 almonds with similar weights and dimensions were carefully selected and marked for each drying experiment. At each sampling point, 10 marked almonds were removed from the dryer for dimensional and moisture content measurements. Effective moisture diffusivities were calculated using the slope method derived from the first term of the analytical solution to Fick's second law of diffusion for spherical geometry. A geometry factor was applied to integrate the ellipsoidal dimensions and correlate the intrinsic diffusivity of an ellipsoid to that of an equivalent sphere with a corresponding radius. Non-linear regression analysis in MATLAB software was used to establish mathematical relationships between effective moisture diffusivity and sample moisture content, as well as shrinkage and moisture ratio (MR). Results showed that the drying behavior of the hull and shell followed typical patterns in most food and agricultural materials. However, the kernel differed significantly, with its moisture content beginning to decrease notably after 180 minutes at 60°C and 75°C while remaining relatively unchanged for about 720 minutes at 45°C. In terms of shrinkage, the hull and kernel experienced pronounced dimensional reductions, while the shell displayed minimal shrinkage, with the maximum reduction being 3.1% across all tested temperatures. The length, width, and thickness of the almond components showed different extents of shrinkage. The deformation of almond components was not observed, as the shape (i.e., sphericity) remained relatively unchanged during drying. Additionally, hull splitting was not detected throughout the process. The effective moisture diffusivities of almond components increased with rising air temperatures. Specifically, as the air temperature increased from 45°C to 75°C., the average D_{eff} for the almond hull, shell, and kernel

increased from 9.70×10^{-10} to 2.05×10^{-9} m²/s, 4.71×10^{-10} to 9.24×10^{-10} m²/s, and 5.82×10^{-11} to 1.45×10^{-10} m²/s, respectively. Polynomial equations were developed to correlate D_{eff} with moisture content, which effectively captured the dynamic variations in D_{eff} during in-hull almond drying, with adjusted R-squared (R_{adj}^2) values greater than 0.973 for the hull, 0.926 for the shell, and 0.978 for the kernel. The findings provided critical insights into the non-isotropic shrinkage of almond components, the absence of hull splitting or deformation during drying, and established mathematical relationships linking effective moisture diffusivity with moisture content. This information is essential for the development of a comprehensive theoretical heat and moisture transfer model for in-hull almonds.

To further study the heat and moisture transfer mechanisms and visualize the spatial moisture and temperature profiles within in-hull almonds during drying, a single in-hull almond was modeled. The model identified the presence of air gaps between the hull and shell and between the shell and kernel, with thickness ranging from 0.1 to 0.25 mm. For simplification, a uniform average air gap thickness of 0.2 mm was used. The in-hull almond was represented as an ellipsoid with five distinct layers: the hull, the air gap between the hull and shell, the shell, the air gap between the shell and kernel, and the kernel. In addition to validated assumptions of non-isotropic shrinkage, negligible shell shrinkage, and absence of deformation or hull splitting, the model incorporated multiphase moisture transfer (involving liquid water and water vapor), variable moisture diffusivity, and a non-equilibrium approach to phase change between liquid water and water vapor. Conservation equations for liquid water, water vapor, and energy were derived from Fick's second law of diffusion and Fourier's law. A local evaporation/condensation rate term was integrated into the energy balance equation to capture the thermal effects of moisture evaporation more accurately. Three scenarios were modeled for comparative analysis: Scenario 1 (nsh_CD)

assumed a constant moisture diffusivity coefficient and no shrinkage; Scenario 2 (nsh_VD) considered moisture-dependent diffusivity without shrinkage; and Scenario 3 (sh_VD) included both moisture-dependent diffusivity and shrinkage effects. This comparative approach allowed for a comprehensive evaluation of how shrinkage and variable moisture diffusivity influence the drying kinetics of in-hull almonds. The governing partial differential equations were solved using the finite element method in COMSOL Multiphysics software. The “Transport of Dilute Species” module was employed to simulate liquid water and water vapor transfer, while the “Heat Transfer in Solids” module handled heat transfer simulations. The “moving mesh” feature, based on the Arbitrary Lagrangian-Eulerian (ALE) method, was used to account for hull and kernel shrinkage during drying. Results showed that all three models demonstrated good agreement with experimental data, achieving R_{adj}^2 values greater than 0.942 for temperature predictions and 0.946 for moisture content predictions. Of the three, the sh_VD model showed the closest alignment with experimental moisture content data, with R_{adj}^2 values of 0.966, 0.990, and 0.974 at drying air temperatures of 45°C, 60°C, and 75°C, respectively. For final overall moisture content predictions, the nsh_CD model produced large deviations of 17.4%, 7.4%, and 17.4% at 45°C, 60°C, and 75°C, respectively, whereas the sh_VD model yielded errors of 5.6%, 0.6%, and 0.2%. A sensitivity analysis was also conducted to evaluate the impact of the evaporation rate constant (K) on the model performance. Results indicated that the evaporation rate constant had less impact on the temperature profile compared to its effect on the moisture profile. Using different K values for the hull, shell, and kernel, improved the accuracy of the model predictions compared to using a uniform K value, which is commonly used in existing literature. The spatial moisture profile results revealed that moisture loss primarily occurred from the hull surface, leading to relatively low surface moisture levels, while higher moisture concentrations persisted within the almond

kernel. This discrepancy suggested that the drying process may appear complete when observing only the hull surface, but elevated moisture content within the kernel could still pose a risk of microbial growth and spoilage. The developed model successfully visualized spatial temperature and moisture profiles within the in-hull almond during drying, providing a valuable tool for estimating optimal drying time and optimizing and designing of drying process.

To evaluate the feasibility of using commercial dryers for drying off-ground harvested almonds and address knowledge gaps in both drying techniques and product quality assessment, three types of commercial dryers: tunnel dryers, stadium dryers, and trailer dryers, were tested under different drying conditions. Tunnel drying was conducted using six tunnels to dry the independence almond variety under three conditions: ambient air drying starting during the daytime, ambient air drying starting at nighttime, and hot air drying at 46°C. The air velocity for all three conditions was 1 m/s. Stadium drying used four bins (three assigned to Monterey and one to Fritz) with an air temperature of 35°C and an air velocity of 0.7 m/s. Trailer drying was conducted using four trailers to dry Monterey almonds under two conditions (two trailers per condition) at 43°C and 54°C, with an air velocity of 1.2 m/s. The quality attributes of the dried product were evaluated based on the incidence of kernel cavities, concealed damage, whiteness index, and oil quality (peroxide value and free fatty acids). For energy use and cost, the utility use of each drying test, consisting of electricity use for the blowers and natural gas or propane used for the burners, was calculated using the numbers obtained from the drying facilities. The dryer performance indicators assessed were drying rate, throughput, specific energy consumption (SEC), specific moisture extraction rate (SMER), and coefficient of performance (COP). Results showed that all tested dryers were capable of drying off-ground harvested almonds in a short period without compromising product quality. Final moisture content distributions of almonds varied widely across dryers: 3.6-31.1% for

Independence almonds after tunnel drying, 3.2-9.7% for Monterey almonds after stadium drying, 3.2-16.6% for Fritz almonds after stadium drying, and 1.6-11.9% for Monterey almonds after trailer drying. Across all conditions, the dried almonds showed no cavities, concealed damage, or notable color changes in the kernels. Only almonds dried using trailer dryers exhibited higher peroxide values (1.33-1.83 meq/kg oil) and free fatty acid levels (0.26-0.31%). However, these values remained well below the industry standards of 5 meq/kg oil for peroxide values and 1.5% for free fatty acid levels. Energy use and costs varied based on the initial moisture content, dryer type, and drying conditions. Among the evaluated dryers, trailer dryers presented superior performance with higher SMER (0.34-0.83 kg/MJ) and COP (4.5-9.6) and lower energy costs (¢0.52-¢1.34/lb of dried product). Besides, trailer dryers were also preferred due to their ease of temperature control and larger drying capacity.

In summary, this research comprehensively characterized various aspects of hot air drying for off-ground harvested almonds using experimental and modeling approaches. The findings provide valuable insights into the drying behavior of almonds, spanning from bench-scale studies to commercial-scale applications. The improved understanding of heat and moisture transfer mechanisms can inform the optimization and design of efficient drying processes in future investigations.

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1 CHAPTER 1 INTRODUCTION

1.1 Background

Almond (*Prunus dulcis* (Mill). D.A. Webb) is a stone fruit characterized by an outer fibrous layer or hull (mesocarp), along with the endocarp. The endocarp, commonly referred to as the shell, encapsulates the seed or kernel, which is the primary commercial component of the fruit. The seed is enclosed by two layers known as integuments, which eventually form the seedcoat, also called the skin or pellicle (Crisosto & Crisosto, 2020; Hawker & Buttrose, 1980). Figure 1.1 shows these different components.

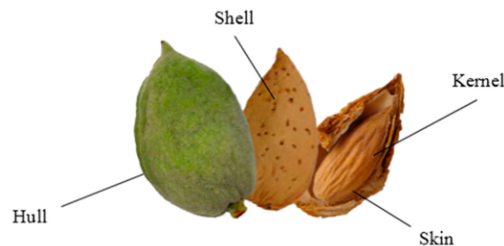


Figure 1.1 The components of almond fruit (Prgomet et al., 2017)

Almond kernels are one of the most prevalent tree nuts in terms of their unique flavor, crunchy structure, nutritional value, and health benefits. They are rich in proteins and lipids, primarily oleic acid (omega-9), linoleic acid (omega-6), and palmitic acid (Hernandez, 2016; Sathe, 1992). Hyson et al. (2002) found that almond consumption could cause a reduction in plasma cholesterol and LDL. In addition, almond kernels have a low sodium content and a high potassium content, making them useful in low-sodium diets (Richardson et al., 2009). They can be consumed as raw almonds and roasted almonds or used as a component of savory and sweet food.

Almond is an important economic crop in California. The Mediterranean climate of California, with its mild, wet winters and hot, dry summers, proved to be an ideal environment for the cultivation of almond trees in the Central Valley. Today, nearly 100% of the U.S. almonds are

produced in California. Moreover, in 2021, the California almond industry achieved a remarkable milestone, producing over 3 billion pounds of almonds for the first time in its history (ABC, 2021). The total output reflected an astonishing 21.8% surge from the previous year and an overall increase of 37% over the past two years. The almond production in California accounted for 80% of the world supply (Figure 1.2). More than \$ 5.03 billion was generated for the state's economy (USDA-NASS, 2022).

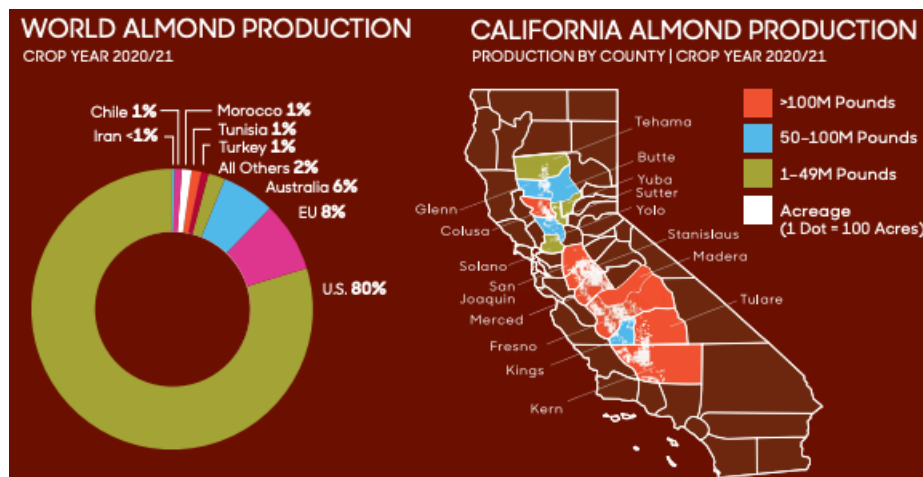


Figure 1.2 The 2021 almond production of the world and California (ABC, 2021)

Almond harvesting usually starts in early August and lasts through October, depending on almond cultivars and maturity. The onset of almond nut maturity is indicated by two distinct processes. The first process is hull dehiscence, where the hull splits along the suture line, gradually detaches from the shell, and starts to dry out (Connell et al., 1989; Crisosto & Crisosto, 2020; Micke, 1996). The second process is the abscission layer that forms between the nut and the peduncle, and it usually happens around the same time as hull dehiscence (Crisosto & Crisosto, 2020). Flint (2002) showed the harvested almonds could be categorized into six visual stages based on the hull split development, as shown in Figure 1.3.

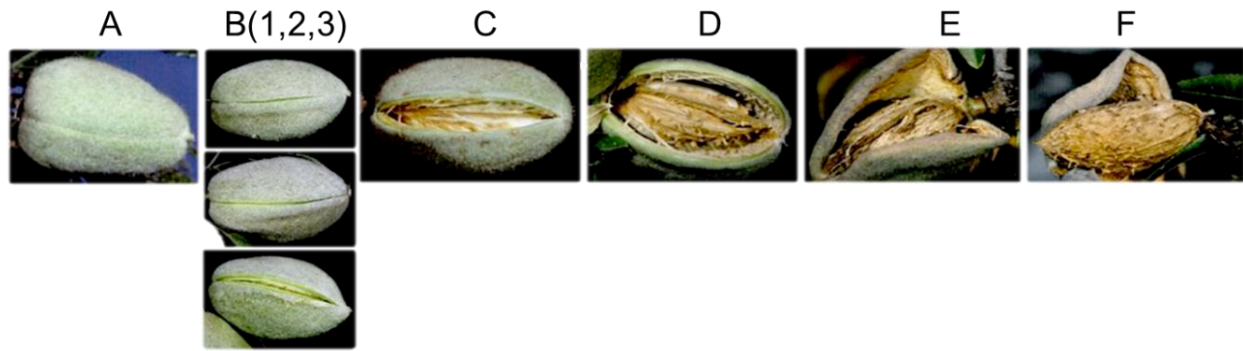


Figure 1.3 Hull split categories (Flint, 2002)

The harvesting of almonds is considered ready when 100% of the hulls have started to dehisce. Conventional harvest typically includes four main steps, tree shaking, on-ground drying, sweeping, and picking up (Figure 1.4). Once the almonds are matured, they are shaken to the orchard floor by utilizing a piece of equipment, which clamps to the tree trunk and applies a vibrational force. The on-ground natural drying usually takes 1 to 2 weeks for the early harvested almonds, 4 to 7 days for the late-harvested almonds, where drying may have progressed while fruits remained in the trees, or even a prolonged period of time when the rainfall occurs during harvest (Micke, 1996; Venkitasamy et al., 2018). The actual number of days is determined based on the resulting moisture content of the kernels and outer hulls. The target water activity for stored almonds is below 0.65 (approximately moisture content of 6%) (Kader, 2013), and the maximum hull moisture of 12% ensures efficient hulling (Thompson et al., 1996). Next, the dried almonds around the trees are swept into windrows by a mechanical sweeper and then picked up from the windrows by machines into trailers and transported to a site for stockpiling and fumigation or, most commonly, directly to a huller/sheller facility (Micke, 1996).



Figure 1.4 Conventional harvest of almonds. Clockwise from top left: shaking, on-ground drying, sweeping, and picking. (photos from Almond Board of California)

However, the current harvesting method of almonds is associated with three primary concerns, including dust generation, microbial contamination from soil, and insect damage. Dust production is predominantly observed during the final two steps of the harvesting process, as depicted in Figure 1.4, leading to significant particulate matter pollution that spans a wide area and poses health risks to millions of people. Furthermore, this dust carries contaminants, subsequently spreading them to the harvested almonds (ABC, 2021; Faulkner & Capareda, 2012). In addition, almonds come into direct contact with the ground and become thoroughly mixed with the top layer of orchard soil during the windrowing and picking-up processes (Harris & Ferguson, 2013). Moreover, a significant concern arises when certain almonds prematurely detach from trees, become wet with irrigation water, and undergo repeated mixing. The presence of free moisture on these almonds creates a favorable environment for bacterial (e.g., *Salmonella*) and fungal (such as *Aspergillus flavus* and *Aspergillus parasiticus*) growth, resulting in the production of aflatoxin (Harris & Ferguson, 2013; Pier & Richard, 1992). Studies have shown that *Salmonella Enteritidis* PT 30 can proliferate in wet almond hull and shell slurries (Uesugi et al., 2006), wetted hulls

(Danyluk et al., 2008), and wetted dusts (Du et al., 2010). Disturbingly, between 2001 and 2017, nine *Salmonella* outbreaks in the United States were directly linked to the consumption of raw almonds (Palumbo et al., 2017).

The harvested almonds remain in the orchard for extended periods, making them vulnerable to insect infestation. The prominent insect pest affecting almonds in California is the navel orangeworm (NOM), scientifically known as *Amyelois transitella* (Walker). Between 1980 and 1983, the losses incurred by almond growers and processors due to navel orangeworm damage amounted to over \$97 million (Rice et al., 1996). The extent of damage inflicted by navel orangeworm can range from barely noticeable pinhole entries to complete destruction of the nutmeat. Female moths deposit their eggs either within or on the surface of almonds, as well as in proximity to fruits on twigs or fruit stems. Depending on the environmental temperature, the eggs hatch within a span of 4 to 23 days. Subsequently, the navel orangeworm larvae burrow into the kernel to feed on the nutmeat, leaving behind frass and webbing, thereby contaminating the kernels, as shown in Figure 1.5.



Figure 1.5 Insect damage of almonds (photographed by the author)

Furthermore, during oviposition, the adult moths can introduce *Aspergillus* spp. fungus, which serves as an additional source of aflatoxins (Campbell et al., 2003; Harris & Ferguson, 2013). Almond orchards in California have witnessed navel orangeworm damage rates as high as 30% (Higbee & Siegel, 2009). Such damage directly impacts the marketability of the almond kernels, resulting in significant negative economic repercussions for almond producers (Campbell et al., 2003; Phillips et al., 1980).

1.2 Significance

Consequently, in response to the problems associated with the conventional harvest method, the Almond Board of California (ABC) and the almond industry have actively pursued the development of alternative harvesting technologies. Among these approaches, the off-ground/shake-catch harvesting method (illustrated in Figure 1.6) has emerged as a particularly promising solution. However, it is worth noting that the almonds harvested using this novel method exhibit higher moisture content, necessitating prompt drying to facilitate efficient handling of the large volume of the almonds while ensuring both quality and safety. To address this requirement, artificial dryers are employed, enabling earlier harvesting to mitigate the risks associated with mold growth, insect damage, and adverse weather conditions. Furthermore, the adoption of early harvesting practices has been recognized as a strategy for promoting sustainable irrigation, pest control, and disease management within almond cultivation (Smith et al., 2022).



Figure 1.6 Off-ground harvesting machine and freshly harvested almonds

The drying process plays a pivotal role in agricultural processing, requiring substantial energy consumption and directly influencing overall profitability (Taskin et al., 2024). In recent years, many advanced drying technologies have been applied to dehydrate almonds, including radio frequency heating (Gao et al., 2010), infrared heating (Venkitasamy et al., 2018), vacuum (Safari et al., 2016), and ultrasound pre-treatment (Kaveh et al., 2018) to reduce the drying time and improve product quality. However, it is rare to find the applications of these technologies for industrial purposes, which could be due to high equipment cost, operational complexity, and scale-up challenges (Radoiu, 2020; Siddique et al., 2022; Zeng et al., 2022). Deep bed drying with hot air heating is still the industry's most widely applied drying method due to its advantages in large processing capacity and relatively low operating cost (Chen et al., 2020).

Additionally, improper drying can trigger reactions that lead to nutritional degradation, reduced enzyme activity, chemical changes, and the proliferation of microbial growth (Qu et al., 2016). Kaveh et al. (2018) pointed out that the high temperature drying (70°C) caused a color change ($\Delta E=17.96$) of almond kernel compared to the drying at 40°C. Rogel-Castillo et al. (2017)

reported that drying air temperatures above 75°C produced many almonds with concealed damage (CD, a brown discoloration of nutmeat), as shown in Figure 1.7, and the drying air temperature below 65°C could decrease CD occurrence by 40%. Coates (2018) showed that a high drying rate could lead to kernel cavities for almonds with high moisture content.

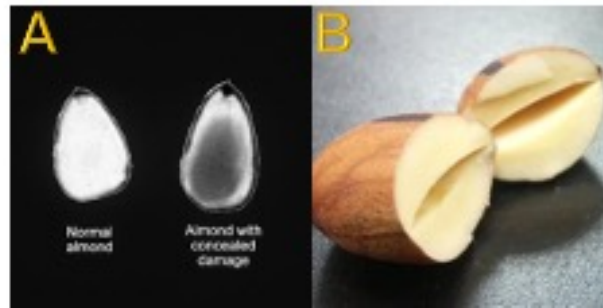


Figure 1.7 Damaged almonds: (A) concealed damage and (B) kernel cavity

To date, while drying kinetics have been extensively studied for other agricultural products and simpler systems, including single-layer or homogeneous structures, the drying kinetics of almonds with a multi-layer structure comprising hull, shell, and kernel remain largely unexplored. Each layer has unique chemical and physical properties, making the drying process more complex and less understood. Therefore, there is an urgent need to investigate the drying and quality characteristics of off-ground harvested almonds to address this gap and develop an efficient drying method for the almond industry.

2 CHAPTER 2 GOAL AND OBJECTIVES

The goal of this work is to study the drying behavior and quality attributes of off-ground harvested almonds under hot air drying and to develop a mathematical model for optimizing the drying conditions, improving almond quality, and minimizing energy consumption. The specific objectives are:

1. Evaluate the extent of insect damage in off-ground harvested almonds compared to those conventionally harvested.
2. Determine the physical, chemical, and thermal properties of almond components (hull, shell, and kernel) as influenced by harvest timing.
3. Characterize the dynamics of hull split and shrinkage in almond components during drying at different temperatures.
4. Determine the effective moisture diffusivity of almond components during hot air drying under different temperatures and moisture contents.
5. Develop a theoretical model for heat and moisture transfer in in-hull almonds, incorporating shrinkage effects during hot air drying.
6. Assess the feasibility, energy efficiency, and product quality of using existing commercial dryers for drying off-ground harvested almonds.

3 CHAPTER 3 LITERATURE REVIEW

3.1 Physiological Characteristics, Physical Properties, and Chemical Composition of Almonds

3.1.1 Structure

The almond (*Prunus dulcis* (Mill). D.A. Webb) is a stone fruit characterized by an outer fibrous layer or hull (mesocarp), along with the endocarp. The endocarp, commonly referred to as the shell, encapsulates the seed or kernel, which is the primary commercial component of the fruit. The seed is enclosed by two layers known as integuments, which eventually form the seedcoat, also called the skin or pellicle (Crisosto & Crisosto, 2020; Hawker & Buttrose, 1980). Figure 1.1 shows the different components of almond fruit.

3.1.2 Almond cultivar

There are more than 24 different varieties of almonds produced in California (ABC, 2022). The almond varieties are classified into categories based on characteristics such as size and shape, shell hardness, kernel shape, and flavor. The three primary varieties, namely Nonpareil, California, and Mission, account for more than 90% of total almond production, with Nonpareil being the dominant variety, making up 40% of the annual production. Nonpareil is a paper-shell or soft-shell variety known for its attractive kernel, medium size, uniform shape, smooth surface, and light-colored skin. Due to its high market demand, Nonpareil almonds receive a premium price. California-type varieties feature a wide range of kernel shapes and sizes, with wrinkled surface and brown skin. Varieties like Monterey and Carmel are particularly suited for the slicing process or slivering process due to their large kernel sizes. Mission-type varieties have small, short, and plump kernels with wrinkled surfaces and dark brown skin. The appearance of several almond varieties is shown in Figure 3.1.

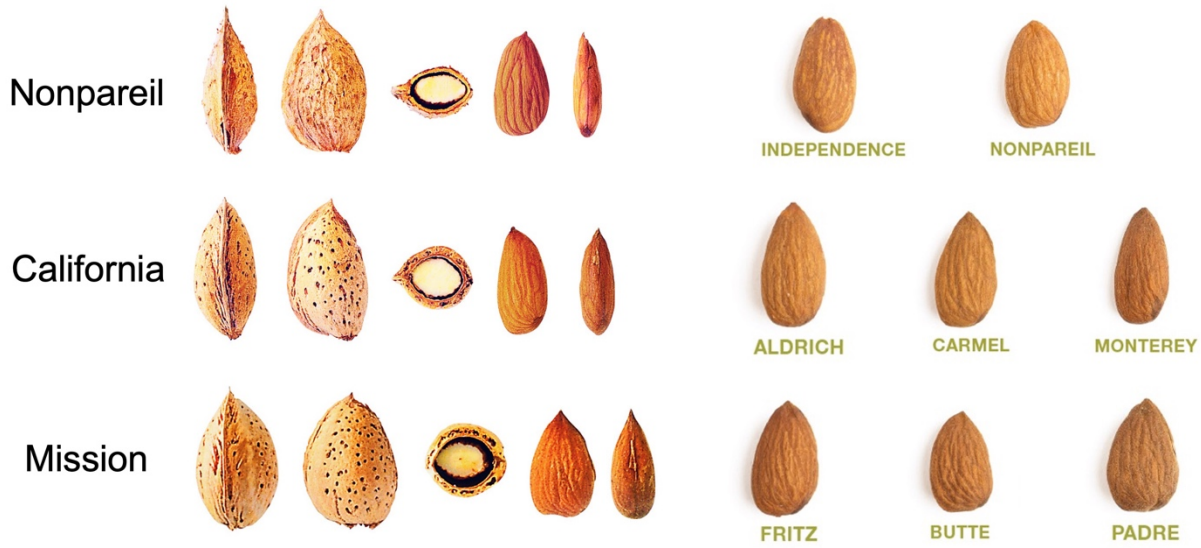


Figure 3.1 Three major classifications of almond production in California (ABC, 2022)

3.1.3 Shape and dimensions

The physical characteristics of almonds, including their shape and size, are crucial engineering parameters that significantly influence various aspects of its processing and utilization. Accurate measurement and control of these parameters are essential for effective sorting, sizing, processing operations, as well as determining drying rates and times, predicting transport properties, and optimizing handling procedures (Chen et al., 2021; Ercisli et al., 2012; Gastón et al., 2002; Kang & Delwiche, 2000; Mahmoodi et al., 2011; Van Eck et al., 1998; Wycislo et al., 2008).

The axial dimensions of the in-hull almond (almond with hull and shell), in-shell almond (almond with shell), and almond kernel are usually measured as: Length (L), Width (W), and Thickness (T) as shown in Figure 3.2. The geometric mean diameter (d_g), sphericity (ϕ), and volume (V) are defined with Equations 3.1, 3.2 and 3.3 (Mohsenin, 1968):

$$d_g = (LWT)^{1/3} \quad (3.1)$$

$$\phi = \frac{d_g}{L} \times 100\% \quad (3.2)$$

$$V = \pi d_g^3 / 6 \quad (3.3)$$

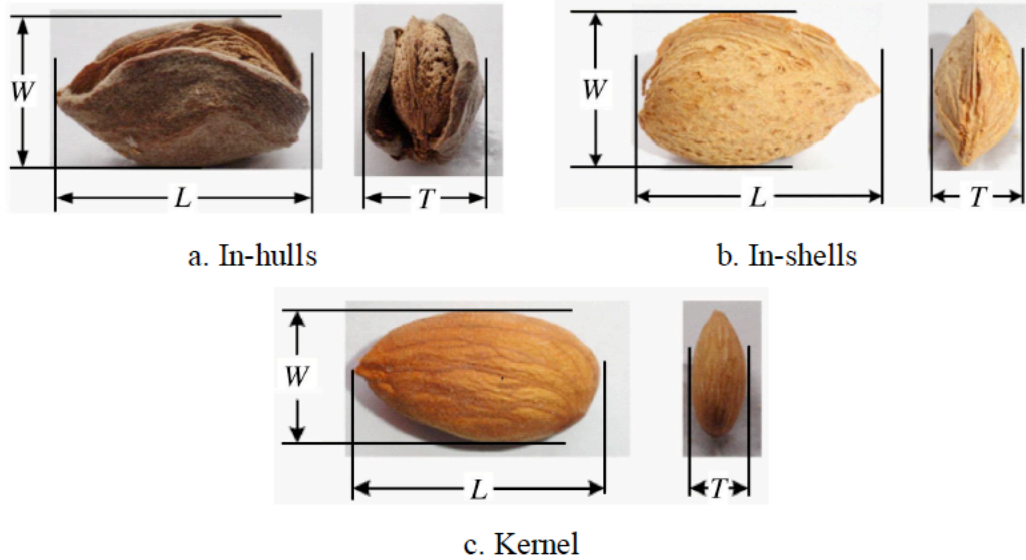


Figure 3.2 Engineering dimensions of almond (Dingke & Fielke, 2014)

The engineering dimensions of some common almond varieties are shown in Table 3.1.

Table 3.1 Mean and standard errors of dimensions of in-hull almond, in-shell almond, and kernel

Variety	Almond type	L (mm)	W (mm)	T (mm)	d_g (mm)	$\emptyset$ (%)	Reference
<i>Nonpareil</i>	In-hull	34.65	22.04	22.31	-	-	Dingke and Fielke (2014)
		± 2.84	± 2.23	± 4.77	-	-	
	In-shell	31.38	19.78	13.40	-	-	
		± 2.74	± 2.03	± 1.26	-	-	
	Kernel	24.16	12.97	8.64	-	-	
		± 1.51	± 0.71	± 0.57	-	-	
<i>Sangi</i>	In-hull	32.40	19.08	13.42	20.20	62.96	Mirzabe et al. (2013)
		± 4.99	± 2.23	± 1.33	± 2.09	± 5.35	
	Kernel	22.61	11.71	6.12	11.68	52.14	
		± 2.99	± 1.60	± 0.87	± 1.02	± 4.90	
<i>Picantili</i>	In-shell	31.26	19.26	11.51	18.95	60.45	Altuntas et al. (2010)
		± 1.62	± 1.7	± 2.18	± 2.64	± 3.83	
	Kernel	25.78	13.43	7.29	13.57	52.72	
		± 0.62	± 0.35	± 0.08	± 0.72	± 1.88	

<i>Drake</i>	In-shell	27.09	18.53	13.38	18.76	69.36	Aydin (2003)
		± 0.67	± 0.43	± 0.35	± 1.09	± 4.27	
	Kernel	20.09	11.24	8.15	12.20	60.83	
		± 0.53	± 0.23	± 0.14	± 0.52	± 1.66	
<i>Tasbadem</i>	In-hull	25.49	17.03	12.12	18.13	69.59	
		± 0.12	± 0.1	± 0.08	± 0.24	± 1.75	
	Kernel	21.19	11.34	6.38	11.42	55.17	
		± 0.08	± 0.83	± 0.07	± 0.15	± 1.23	
<i>Fransis</i>	In-shell	33.35	21.00	14.28	21.53	64.76	Mahmoodi et al. (2011)
		± 4.4	± 2.75	± 1.04	± 2.36	± 2.2	
	Kernel	25.52	13.13	7.87	13.78	54.28	
		± 3.49	± 2.22	± 0.41	± 1.43	± 2.83	
<i>Mamaei</i>	In-shell	36.27	22.01	15.19	22.94	63.19	
		± 3.87	± 2.90	± 2.48	± 2.84	± 2.43	
	Kernel	25.89	12.67	7.80	13.64	52.71	
		± 3.13	± 1.70	± 1.64	± 1.93	± 3.94	
<i>Rabei</i>	In-shell	37.82	16.73	14.53	21.95	57.99	Chen et al. (2021)
		± 3.94	± 2.25	± 2.12	± 2.66	± 2.59	
	Kernel	27.37	13.41	9.01	14.85	54.18	
		± 2.63	± 1.44	± 1.87	± 1.83	± 2.46	
<i>Monterey</i>	In-hull	38.3	24.8	23.2	-	-	
		± 3.2	± 2.3	± 2.0	-	-	
	In-shell	38.0	22.2	17.4	-	-	
		± 3.0	± 1.5	± 1.4	-	-	
	Kernel	24.9	13.7	8.3	-	-	
		± 3.3	± 1.8	± 0.7	-	-	
<i>Fritz</i>	In-hull	35.9	24.1	24.5	-	-	
		± 2.7	± 2.5	± 2.5	-	-	
	In-shell	32.5	20.3	17.2	-	-	
		± 2.7	± 1.6	± 1.3	-	-	

Kernel	21.9	12.5	8.6	-	-
	±1.7	±1.1	±1.2		

3.1.4 Moisture content and distribution of almonds

Understanding the moisture distribution in freshly harvested almonds is critical for developing effective drying methodologies. The moisture content (MC) of almonds significantly affects their physical, mechanical, aerodynamic, and thermal properties, as well as their overall quality. An optimum hull moisture range of 8% to 12% is necessary for efficient hulling (Thompson et al., 1996). Moreover, a target water activity level below 0.65 (approximately 6% moisture) is recommended for stored almond kernels (Kader, 2013). Maintaining this water activity level is essential to prevent the growth of bacterial and fungal microorganisms, including the toxigenic fungi *Aspergillus flavus* and *Aspergillus parasiticus*, which are known to produce aflatoxin, a carcinogenic compound (Harris & Ferguson, 2013).

The moisture content (MC) of individual almonds at the time of harvest exhibits significant variation. Fruit drying begins on the tree once hull split occurs in the almonds. Almonds with widely opened hulls in the upper tree canopy tend to be significantly drier compared to those in the lower interior canopy (Crisosto & Crisosto, 2020). A method for qualitatively identifying the stages of hull split was developed by Flint (2002), featuring six visual stages, as shown in Figure 1.3. Additionally, MCs of almonds may vary depending on the harvest time during the season. Almonds harvested earlier typically exhibit higher MCs (Kazantzis et al., 2003).

Moreira and Bakker-Arkema (1989) determined the initial moisture content of Nonpareil almonds and their components. For in-hull almonds, the MCs of the hull, shell, and kernel were approximately 25%, 16.4%, and 8.7% (wet basis), respectively, with the hull containing the highest moisture content. Additionally, Chen et al. (2021) identified a strong correlation between the overall MC of almonds and the MC of the kernel. Linear regression models were developed to

predict kernel moisture (MC_{kernel}) as a dependent factor based on the overall MC of in-hull almond or in-shell almond for the Nonpareil, Monterey, and Fritz varieties tested (Table 3.2).

Table 3.2 Correlation between the MCs of overall almonds and corresponding kernel MCs

Variety	Fraction	Regression equation	R_{adj}^2	RMSE
Nonpareil	In-hull	$MC_{kernel} = 1.146 \times MC_{in-hull} - 0.020$	0.902	0.00467
	In-shell	$MC_{kernel} = 0.527 \times MC_{in-shell} - 0.019$	0.932	0.01194
Monterey	In-hull	$MC_{kernel} = 1.408 \times MC_{in-hull} - 0.038$	0.985	0.00647
	In-shell	$MC_{kernel} = 0.687 \times MC_{in-shell} - 0.012$	0.912	0.01624
Fritz	In-hull	$MC_{kernel} = 1.295 \times MC_{in-hull} - 0.040$	0.895	0.00806
	In-shell	$MC_{kernel} = 0.948 \times MC_{in-shell} - 0.070$	0.796	0.03660

3.1.5 True density, bulk density, and porosity

The densities of almonds, including true density and bulk density, are critical for determining the capacity of dehydration systems, aerated storage facilities, and transportation equipment. The true density (ρ_t) is the ratio of the mass sample to its volume, excluding pores, and it can be measured using the liquid displacement method. Toluene (C_7H_8) is often used in replacement of water because almonds absorb it to a lesser extent (Ö ğ, 1998; Sitkei, 1987). To prevent toluene penetration during volume measurements, the sample can be coated with a thin layer of paraffin wax (melting point: 58-62°C), and the volume of the wax film is considered negligible (Giri & Prasad, 2006).

The bulk density (ρ_b) refers to the ratio of the mass sample to its total volume when almonds are stacked in bulk, and it is determined using the method introduced by Aydin (2003). According to Mohsenin (1986), the porosity (ε) can be calculated using both bulk density and true density:

$$\varepsilon = \left(1 - \frac{\rho_b}{\rho_t}\right) \quad (3.4)$$

Bulk density, true density, and porosity of almonds are closely correlated with moisture content. Aydin (2003) reported a negative correlation between bulk density and moisture content of almonds, while true density and porosity showed a positive correlation as moisture content increased. For almonds with moisture content ranging from 2.77% to 24.97% (d.b.), bulk density decreased from 655 to 525 kg/m³, while true density increased from 1,015 to 1,115 kg/m³, and porosity increased from 35.53 to 53.21%. Similar changes were observed in almond kernels, where bulk density decreased from 595 to 475 kg/m³, true density increased from 900 to 995 kg/m³, and porosity increased from 34.24 to 50.29%. These findings are consistent with the results obtained by Mirzabe et al. (2013). With increasing moisture content in almonds from 4.03 to 28.13% (w.b.), bulk density decreased from 629.81 to 499.53 kg/m³, while true density and porosity increased from 1025.12 to 1149.7 kg/m³ and from 38.56 to 56.55%, respectively. For kernels with moisture content ranging from 4.2 to 29.64%, bulk density decreased from 585.35 to 462.34 kg/m³, and true density and porosity increased from 939.63 to 1077.43 kg/m³ and from 37.70 to 57.09%, respectively.

Dingke and Fielke (2014) reported true densities of the hull and shell to be around 802.06 kg/m³ and 458.23 kg/m³ at moisture contents of 16.6% and 8.8% (dry basis), respectively. Additionally, the true density of in-sealed-shell almonds was found to be 1.4% lower than that of in-opened-shell almonds, suggesting that sealed shells are impermeable to air and that there is a space between the kernel and shell. In a study by Rasouli et al. (2010), the true density of the in-shell almonds ranged from 790 to 1260 kg/m³ at kernel moisture contents from 1% to 6% (w.b.). The corresponding bulk density and porosity for in-shell almonds ranged from 280 to 480 kg/m³ and 48 to 75%.

3.1.6 Thermophysical properties

The knowledge of thermal-physical properties of almonds (hull, shell, and kernel), including specific heat, thermal conductivity, and thermal diffusivity, is essential for developing efficient processes and equipment for drying and handling almonds. While many experimental studies have focused on determining the thermal properties of various food and agricultural materials, such as cumin seed (Singh & Goswami, 2000), sheanut kernel (Aviara & Haque, 2001), minor millet grains and flours (Subramanian & Viswanathan, 2003), pistachio nuts (Kouchakzadeh & Tavakoli, 2009; Razavi & Taghizadeh, 2007), and cashew kernel (Bart-Plange et al., 2012), there are limited studies specifically reporting the thermal properties of almonds. This gap highlights the need for further research to optimize almond drying and handling processes based on their unique thermal characteristics.

Additionally, the thermal properties of agricultural products are influenced by factors such as particle size, moisture content, and temperature. Aremu and Nwannewuihe (2011) showed that the specific heat of ground fresh sheanut kernel increased with increase in moisture content and varied with temperature for different particle sizes. Notably, the effect of moisture content was greater than both particle size and temperature. Similarly, Bart-Plange et al. (2012) demonstrated a positive linear correlation among specific heat, thermal conductivity, and thermal diffusivity in cashew kernels with moisture content ranging from 5.0 to 9.0% (w.b.). For pistachio nuts, the specific heat ranged from 0.419 to 2.930 kJ/kg·K as MC varied from 5 to 25% (w.b.) (Razavi & Taghizadeh, 2007). The thermal conductivity of pistachio nuts ranged from 0.1 to 0.2 W/m·K with moisture content between 5 and 40% (w.b.), while bulk thermal conductivity ranged from 0.029 to 0.037 W/m·K with MC between 9 and 27% (w.b.) (Hsu et al., 1991). The specific heat of cashew kernels ranged from 1.586 to 1.756 kJ/kg·K with MC ranging from 5 to 9% (w.b.), and the

corresponding thermal conductivity ranged from 0.2103 to 0.2296 W/m·K (Bart-Plange et al., 2012). However, limited information is available in the literature regarding the thermal properties of almonds.

The specific heat of agricultural products and foods is commonly measured using the method of mixture with a calorimeter (Aviara & Haque, 2001; Jangi et al., 2011; Razavi & Taghizadeh, 2007; Singh & Goswami, 2000). According to the principle of calorimetry, i.e., the heat loss by the hot body equals the heat gain by the cold body, the specific heat of the sample can be calculated using the following equation. The detailed procedures for the calculation are in accordance with Aviara and Haque (2001):

$$c_{p,i} = \frac{(m_c c_{p,c} + m_w c_{p,w}) \times (T_e - T_0)}{m_{s,i} \times (T_s - T_e)} \quad (3.5)$$

where $c_{p,i}$ is the specific heat (J/kg·K) (i = sample); m_c is the mass of calorimeter (kg); $c_{p,c}$ is the specific heat of the calorimeter (J/kg·K); m_w is the mass of water (kg); $c_{p,w}$ is the specific heat of water (J/kg·K); T_0 is the initial temperature of calorimeter with water (K); T_e is the equilibrium temperature of mixture (K); $m_{s,i}$ is the mass of sample (kg); T_s is the initial temperature of sample (K).

Thermal conductivity can be measured using the line heat source technique (Sweat & Haugh, 1974). The thermal conductivity (k) is calculated using the following equation:

$$k = \frac{Q \ln(t_2/t_1)}{4\pi(T_2 - T_1)} \quad (3.6)$$

where $Q = VI/L$ is the power consumed by the probe heater (W/m); V is the voltage (V); I is the current (A); t is the time (s); T is the temperature (°C).

The thermal diffusivity (α) can be determined using the experimentally obtained values of specific heat (c_p), thermal conductivity (k), and density (ρ) as follows (Bart-Plange et al., 2012):

$$\alpha = \frac{k}{\rho c_p} \quad (3.7)$$

In addition to direct measurement, the thermal properties of different food constituents can be predicted using a temperature-dependent mathematical models with the major mass fractions determined (Choi 1986; Mason et al. 2016), as shown in Table 3.3. These models take into account the major constituents of the food, including moisture content, carbohydrates, total lipids, proteins, and ash. This method allows for the estimation of thermal properties such as specific heat, thermal conductivity, and density based on the composition of the product.

Table 3.3 Characterization of almond physical properties

Physical properties	Prediction model	Remark
Density (kg/m ³)	$\rho = \frac{(1 - \varepsilon)}{\sum (x_i / \rho_i)}$	ε : porosity of food material; -40°C to 150°C ρ_i : density of food component
Specific heat (kJ/kg·K)	$c = \sum c_i x_i$	x_i : mass fraction of food component c_i : specific heat of food component
Thermal conductivity (W/m·K)	$k = \frac{1}{\sum (x_i^v / k_i)}$	x_i^v : volume fraction of food component k_i : thermal conductivity of food component

3.1.7 Chemical composition

The chemical composition of almond components varies significantly. Almond hulls are a rich source of water-soluble, fermentable sugars and fiber (Holtman et al., 2015; Wang et al., 2021). In Nonpareil hulls, sugar contents ranged from 21.2 to 37.3% (Holtman et al., 2015), while Prime hulls and California-type hulls have lower sugar contents of 18.14% and 15.19%, respectively (Wang et al., 2021). The differences in sugar content can be attributed to varying almond varieties and extraction methods. Almond shells are composed mainly of highly porous, hygroscopic fibrous material consisting of 38.5% cellulose, 28.8% hemicellulose, and 29.5% lignin (Li et al.,

2018). Almond kernels contain 16-22% proteins and 54-56% lipids, primarily oleic and linoleic acids, accounting for more than 90% of the total lipid content (Sathe, 1992). Due to the high content of unsaturated fatty acids, almond kernels are prone to rancidification when exposed to heat and oxygen during thermal processing and storage (Buransompob et al., 2003; Sathe et al., 2008; Venkatachalam & Sathe, 2006).

3.2 Almond Production, Harvest, and Post-harvest Practice

3.2.1 History and production

Almond belongs to the genus *Prunus* and is classified into sweet almonds (*Prunus dulcis* (Mill) D.A. Webb) and bitter almonds (*Prunus amygdalus*). The cultivated almond tree grown today can be traced back to wild species that thrived in the deserts and foothills of Central and South-west Asia. People selected and cultivated the specimens with sweet almond, and their popularity spread throughout the ancient world as early as 4000 BC. Since then, almonds have been under cultivation for more than 4000 years, and they were grown extensively along the Mediterranean coastline from Turkey to Tunisia from around 450 BC (Crisosto & Crisosto, 2020; Kader, 2013).

The arrival of almonds in California dates back to the establishment of the Spanish California missions in the late 1700s. However, it was not until the 1850s that the large-scale commercial industry began to take shape, thanks to the selection of local seedlings from varieties originally from the Languedoc region of southern France (Micke, 1996). The Mediterranean climate of California, with its mild, wet winters and hot, dry summers, proved to be an ideal environment for cultivating almond trees in the Central Valley. Today, nearly 100% of the U.S. almonds are produced in California.

Almond is an important economic crop in California. In 2021, the California almond industry achieved a remarkable milestone, producing over 3 billion pounds of almonds for the first time in

its history (ABC, 2021). The total output reflected an astonishing 21.8% surge from the previous year and an overall increase of 37% over the past two years. Almond production in California accounted for 80% of the world supply (Figure 1.2). More than \$ 5.03 billion was created to the state's economy (USDA-NASS, 2022).

3.2.2 Conventional and off-ground harvesting

Almond harvesting typically begins in early August and continues through October, depending on the almond cultivars and maturity. Almond maturity is marked by two distinct processes. The first process is hull dehiscence, where the hull splits along the suture line, gradually detaches from the shell, and starts to dry out (Connell et al., 1989; Crisosto & Crisosto, 2020; Micke, 1996). The second process is the formation of an abscission layer between the nut and the peduncle, which typically occurs around the same time as hull dehiscence (Crisosto & Crisosto, 2020). Harvesting is considered ready when 100% of the hulls have begun dehiscing.

Conventional almond harvest involves four main steps: shaking, on-ground drying, sweeping, and picking up (Figure 1.4). Once the almonds are mature, they are shaken from the tree onto the orchard floor using equipment that clamps onto the tree and applies vibrational force. The on-ground natural drying usually takes 1 to 2 weeks for early-harvested almonds and 4 to 7 days for late-harvested almonds, where drying may have progressed while the fruits remained in the trees. Prolonged drying periods may occur if rainfall occurs during harvest (Micke, 1996; Venkitasamy et al., 2018). The target water activity for stored almonds is below 0.65, which corresponds to a moisture content of about 6% (Kader, 2013), and the hull moisture should not exceed 12% to ensure efficient hulling (Thompson et al., 1996). Next, the dried almonds around the trees are swept into windrows by a mechanical sweeper and then picked up from the windrows by machines

into trailers and transported to a site for stockpiling or, most commonly, directly to a huller/sheller facility (Micke, 1996).

The current almond harvesting method is associated with three primary concerns: dust generation, microbial contamination from soil, and insect damage. Dust production is predominantly observed during the final two steps of the harvesting process, sweeping and picking up, as shown in Figure 3.6. This creates a considerable amount of particulate matter pollution that affects a wide area, posing health risks to millions of people (ABC, 2021; Faulkner & Capareda, 2012). Furthermore, this dust can carry contaminants, which may be transferred to the harvested almonds.

Microbial contamination is another major issue, as almonds come into direct contact with the ground during the windrowing and picking-up processes, becoming mixed with the top layer of orchard soil (Harris & Ferguson, 2013). This problem is exacerbated when almonds prematurely detach from trees, become wet from irrigation water, and undergo repeated mixing. Free moisture on these almonds creates an ideal environment for the growth of bacteria, such as *Salmonella*, and fungi, including *Aspergillus flavus* and *Aspergillus parasiticus*, which produce harmful aflatoxins (Harris & Ferguson, 2013; Pier & Richard, 1992).

Studies have shown that *Salmonella Enteritidis* PT 30 can thrive in wet almond hull and shell slurries (Uesugi et al., 2006), wetted hulls (Danyluk et al., 2008), and wetted dust (Du et al., 2010). Between 2001 and 2017, nine outbreaks of *Salmonella* in the United States were directly linked to the consumption of raw almonds (Palumbo et al., 2017), raising serious food safety concerns within the almond industry.

Insect infestation can cause significant damage to almonds, affecting both their quality and quantity. Harvested almonds often remain in orchards for extended periods, making them

susceptible to insect attacks. The most prominent insect pest affecting almonds in California is the navel orangeworm (NOW), scientifically known as *Amyelois transitella* (Walker). Between 1980 and 1983, almond growers and processors suffered losses exceeding \$97 million due to NOW damage (Rice et al., 1996). The damage caused by NOW ranges from minor pinhole entries to complete destruction of the nutmeat. Female moths lay eggs either within or on the surface of almonds or on nearby twigs and fruit stems. Depending on environmental temperature, the eggs hatch within 4 to 23 days, after which the larvae burrow into the kernel, feeding on the nutmeat and contaminating it with frass and webbing.

Additionally, during oviposition, adult moths can introduce *Aspergillus* spp. fungus, which is a known source of aflatoxins (Campbell et al., 2003; Harris & Ferguson, 2013). In California, navel orangeworm damage rates in almond orchards have been reported to be as high as 30% (Higbee & Siegel, 2009). This damage severely impacts the quality and marketability of almond kernels, leading to significant economic losses for almond producers (Campbell et al., 2003; Phillips et al., 1980).

Consequently, in response to these problems associated with the conventional harvest method, the Almond Board of California (ABC) and the almond industry have actively pursued alternative harvesting technologies. Among these, the off-ground/shake-catch harvesting method (illustrated in Figure 1.6) has shown significant promise. However, almonds harvested using this novel approach tend to have higher moisture content, necessitating immediate drying to ensure efficient handling and to maintain both quality and safety standards. Artificial dryers are employed to address this need, allowing for earlier harvests that reduce the risks of mold growth, insect damage, and weather-related losses.

In addition to reducing these risks, the adoption of early harvesting practices offers other benefits, including improved sustainability in irrigation practices, more effective pest control, and enhanced disease management within almond cultivation (Smith et al., 2022). By mitigating the issues associated with traditional harvesting methods, this approach contributes to more sustainable and efficient almond production.

3.2.3 Post-harvest practices

Postharvest operations for almonds involve several key steps, including precleaning, drying, hulling, shelling, stockpiling, and chemical fumigation treatment. These activities depend on factors such as the condition of the almonds, weather, costs, and equipment availability (Thompson et al., 1996). After the initial harvest, almonds undergo precleaning through a system of multiple devices such as aspirators, rotating or vibrating screens, destoners, and gravity tables. This system effectively removes extraneous materials like leaves, sticks, stones, soil, sand, and other fine or heavy substances.

Almonds with high moisture content may require drying before hulling, as hull moistures above 12% can hinder the efficiency of hullers and shellers, while even moisture levels exceeding 8% can impair certain equipment (Thompson et al., 1996). During peak harvest periods, when handling large volumes of almonds, stockpiling may be necessary. A well-managed stockpiling system allows for rapid movement of almonds from the orchard, minimizing losses from pests and adverse weather conditions (Thompson et al., 1996).

Hulling and shelling operations follow to meet the demand for both in-shell and shelled almonds. During the hulling process, five distinct fractions are produced: loose hulls, unhulled nuts with hulls, hulled nuts with hulls, shelled nuts with hull pieces, and fine shell pieces. An air separator is used to separate the hull pieces from the in-shell nuts. Following this, a cracker roll

with two counter-rotating steel cylinders is employed to crack the shells and extract the almond meats.

3.3 Principle and Method of Food Product Drying

Drying is a critical unit operation in the food industry, essential for reducing the moisture content and water activity of food products. This process is key to extending shelf life, reducing microbial spoilage and chemical reactions, enhancing product stability, lowering shipping weights and associated costs, and minimizing packaging requirements (Fortes & Okos, 1980; Göğüş & Maskan, 1998; McLaughlin & Magee, 1998; Rossello et al., 1992; Simal et al., 1996; Srikiatden & Roberts, 2007). Drying operations represent a significant portion of energy consumption in various process industries (Keey, 1980). Therefore, understanding the mechanisms of internal moisture transfer is crucial for optimizing product quality and improving process efficiency and economics.

3.3.1 Material hygroscopic, porous, and shrinkage characteristics

Drying is a complex process that involves the simultaneous transfer of heat and moisture, with specific mechanisms determined by the material's physical structure and chemical composition (Rossello et al., 1992). As illustrated in Figure 3.3, a typical drying procedure comprises multiple stages: internal moisture diffusion towards the external surface, convective transfer of water vapor into the surrounding air, conductive heat transfer within the material, and convective heat transfer from hot air to the surface of the food product (Maroulis et al., 1995). The concentration gradient drives internal moisture diffusion, and the specific flow mechanism, either liquid or vapor diffusion, depends on the food material's characteristics.

For non-porous or low-porosity foods such as rough rice grains, potatoes, corn, and dense pasta, liquid diffusion is often the dominant mechanism of internal moisture transfer during drying (Aguerre et al., 1982; Doymaz & Pala, 2003; Ece & Cihan, 1993; Waananen & Okos, 1996). In

contrast, several researchers have identified vapor diffusion as the primary mechanism for moisture transfer during drying (Chirife, 1983; Karel & Lund, 2003; Van Arsdel, 1947) for porous materials. Additionally, in hygroscopic porous materials, capillary flow has been recognized as a key mode of water transport within the material (Berger & Pei, 1973; Luikov, 1964; Philip & De Vries, 1957; Whitaker, 1977).

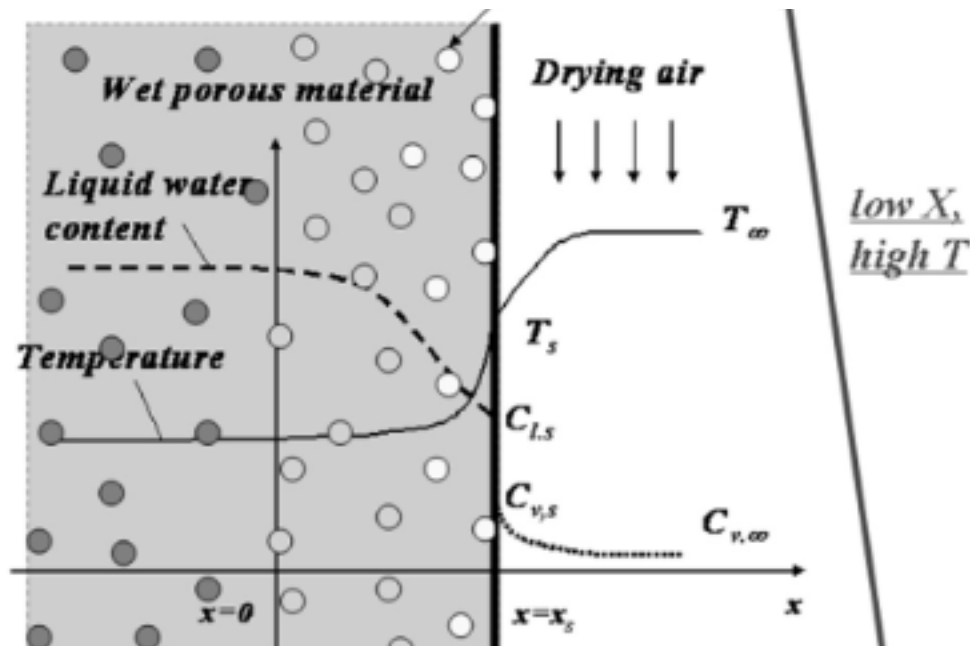


Figure 3.3 Schematic diagram of heat and moisture transfer during food drying (Chen, 2007)

Materials can be categorized based on their water-binding characteristics into non-hygroscopic and hygroscopic classes. Non-hygroscopic materials contain no bound water, meaning the partial pressure of water within the material equals the vapor pressure of free water. In contrast, hygroscopic materials contain bound water, resulting in a lower vapor pressure than that of free water (Geankoplis, 1993). However, there are exceptions; for instance, a hygroscopic material with an initial equilibrium moisture content exceeding atmospheric saturation will have a vapor pressure equal to that of pure water, behaving similarly to a non-hygroscopic material (Karel & Lund, 2003). The relationship between moisture content and partial pressure, influenced by

temperature, is typically represented through sorption isotherms (Karel & Lund, 2003; Rizvi, 2014).

The transport properties of food materials are strongly influenced by their porous structure. Porosity refers to the proportion of free space within a material relative to its total volume (Karathanos et al., 1996). Materials with low porosity have fewer interconnected pores, which increases resistance to airflow (Srikiatden & Roberts, 2007). Srikiatden and Roberts (2007) classified porous structures into three categories: low porosity (below 0.25), intermediate porosity (between 0.25 and 0.4), and high porosity (above 0.4). As drying progresses, bulk porosity typically increases, which significantly impacts moisture transfer properties transfer (Krokida & Maroulis, 1997; Lozano et al., 1983; Zogzas et al., 1994).

During drying, many hygroscopic materials undergo volume shrinkage, which can alter the mechanisms of moisture or vapor migration within the material. Shrinkage is generally proportional to the change in moisture content (Karathanos et al., 1996; Lozano et al., 1983; Sjöholm & Gekas, 1995; Zogzas et al., 1994). The extent of shrinkage in porous materials is influenced by internal vapor pressure during drying (Khraisheh et al., 1997). Moreover, shrinkage affects the physical properties of food materials, such as density and porosity, though the degree of change depends on the specific material (Wang & Brennan, 1995). Christenson et al. (1989) found that porous foods generally exhibit less shrinkage compared to non-porous foods, likely due to the higher initial moisture content commonly found in non-porous materials.

3.3.2 Mechanisms of moisture transfer

The typical drying process of food can be divided into two main stages: the constant rate period and the falling rate period (Karel & Lund, 2003; Rizvi, 2014). During the constant rate period, unbound moisture on the surface of the food is removed via evaporation, with internal moisture

transfer maintaining a saturated surface. As a result, the evaporation rate remains constant. At this stage, the drying rate is primarily governed by external conditions, such as temperature, relative humidity (RH), air velocity, the surface area exposed to the drying media, and heat and mass transfer coefficients (Chirife, 1983; Griskey, 2005).

The falling rate period begins once the surface of the food is no longer saturated, which occurs when the material reaches its critical moisture content (Chirife, 1983; Rizvi, 2014). The critical moisture content varies based on material thickness and external drying conditions (Srikiatden & Roberts, 2007). For many fruits and vegetables, such as tapioca (Chirife & Cachero, 1970), sugar beet root (Vaccarezza et al., 1974), and avocado (Alzamora & Chirife, 1980), the critical moisture content is close to the initial moisture content, indicating little to no constant rate period. Most drying of biological products occurs during the falling rate period (Chirife, 1971; Saravacos & Charm, 1962; Vaccarezza et al., 1974).

In the falling rate period, the drying rate is controlled by internal moisture diffusion (Sherwood, 1931). The drying rate decreases as internal resistance to moisture transfer increases and the heat flux into the material diminishes (Karel & Lund, 2003; Rizvi, 2014; Srikiatden & Roberts, 2007). The interior temperature of the material remains close to the wet-bulb temperature, and the heat flux from the air to the surface decreases due to the reduced temperature gradient (Geankoplis, 1993). In highly porous materials, or in cases where significant porosity develops during drying, mass transfer occurs primarily in the vapor phase, with evaporation happening within the material (Rizvi, 2014). Heat must then conduct through both the dry solid and the low-conductivity pore regions, further slowing the drying rate. At this stage, removing the final 10% of moisture often takes as long as removing the initial 90% (Chirife, 1983; Jason, 1958; Karel & Lund, 2003; Vaccarezza et al., 1974). Drying ceases when the vapor pressure of the material equals the partial

vapor pressure of the surrounding air and the moisture content reaches equilibrium, known as the equilibrium moisture content (EMC).

3.3.3 Drying methods of almond

As discussed in Section 3.1, the maturity levels of harvested almonds can vary, resulting in different initial moisture contents (MCs). During typical drying processes, achieving uniform final MCs for all almonds is challenging. Almonds with higher MCs that are insufficiently dried can pose food safety risks and reduce shelf life. Conversely, intentionally prolonging the drying time to ensure lower MCs can lead to over-drying, causing deterioration in oil quality and unnecessary energy consumption. Therefore, it is critical to consider drying conditions that account for the varying MCs of almonds to achieve optimal drying outcomes.

To the best of my knowledge, research on almond drying methods remains limited, possibly due to the prevalent practice of natural sun-drying in orchards, as mentioned in Section 3.2.2. However, with the increasing adoption of off-ground harvest methods in the almond industry, there is an urgent need to investigate almond drying characteristics and explore viable mechanical drying methods suitable for large-scale production. Consequently, further investigation is required to expand the knowledge base and develop efficient almond drying techniques.

Several studies have explored almond drying using various methods and equipment. Coates (2018a) conducted experiments in a lab-scale dehydrator with controlled temperature and humidity while Kaveh et al. (2018) using a convection dryer with ultrasound pretreatment. Moreira and Bakker-Arkema (1989) employed a thin-layer tray dryer, Chen, Abd El Gebreil, et al. (2020) used a pilot-scale column dryer with heated air, and Venkitasamy et al. (2018) investigated a sequential infrared and hot air dryer (SIRHA). Additionally, Mayanja et al. (2021) examined the drying performance of almonds using a stockpile heated and ambient air dryer (SHAD). These studies

demonstrated the significant influence of factors such as drying temperature, air velocity, stack depth, and initial almond moisture content on the drying process.

The Sequential Infrared and Hot Air (SIRHA) dryer, developed by Venkitasamy et al. (2017), is shown in Figure 3.4. This system uses an electric heater with heating coils and a blower positioned at the top to draw ambient air. The blower's impeller speed controls airflow, set at 2 m³/min during experiments. The heated air's temperature is regulated between 60°C and 70°C using an air temperature controller. To ensure uniform airflow distribution, the air passes through a perforated screen acting as a plenum. The SIRHA dryer also includes three quartz IR emitters placed 30 cm apart. Venkitasamy et al. (2018) observed that using SIRHA drying conditions—infrared drying at 70°C for 1 hour followed by hot air drying at 70°C, reduced drying time by 40% compared to hot air drying alone for almonds. Additionally, this technology showed a decontamination effect on almonds inoculated with *Enterococcus faecium*, resulting in average reductions of 4.69, 1.82, and 1.52 log CFU/nut on hulls, shells, and kernels, respectively. Despite the time and energy-saving benefits of the IR-based technology for almond drying, scaling up to handle large quantities of almonds remains a challenge and requires further development.

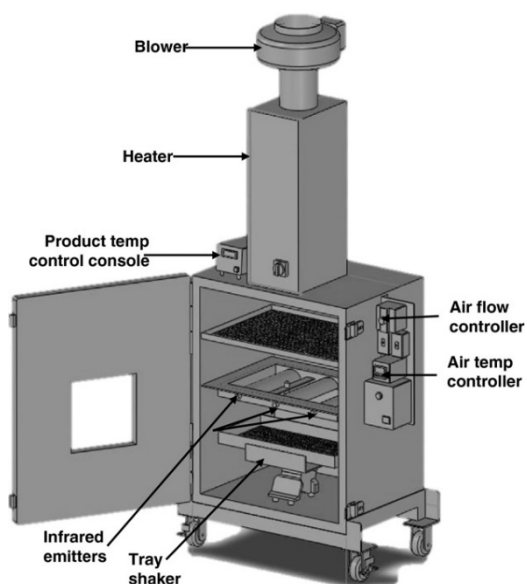


Figure 3.4 Schematic diagram of the SIRHA dryer (Venkitasamy et al., 2017)

Figure 3.5 illustrates the dehydrator developed by Coates (2018a), which features precise control of temperature and humidity, ranging from 10°C to 80°C and 5% to 95% relative humidity (RH), respectively. In the experimental setup, almonds were manually sorted into five forms: in-hull almond, in-shell almond, hull, shell, and kernel. Each form, weighing between 150 and 200 grams, was placed in separate mesh trays and subjected to hot air drying at temperatures between 30°C and 50°C, 30% relative humidity, and an air velocity of 3 m/s.

Drying times varied significantly among the different almond components. The hull and kernel exhibited longer drying durations compared to the shell, taking approximately 40 to 80 hours and 30 to 80 hours, respectively, while the shell took only 5 to 20 hours to reach equilibrium moisture content (EMC). Both in-hull and in-shell almonds required 60 to 140 hours to reach EMC. The in-hull almonds, composed of the hull with higher moisture content, experienced an extended constant rate drying period, followed by a prolonged falling rate period due to strongly bound water in the kernel. In contrast, in-shell almonds demonstrated rapid moisture release from the shell, followed by a gradual release from the kernel, which took a substantial amount of time to reach its EMC, indicating strong water binding.

However, it is important to note that this study may not fully represent the actual drying characteristics of the hull, shell, and kernel, as these components were separated from the whole fruit and dried independently. As a result, investigating the drying behaviors of individual components during in-hull or in-shell almond drying is valuable to better understand the overall process. Additionally, assessing the potential shrinkage of each component during drying is crucial, as it could influence the drying kinetics and the final product quality.

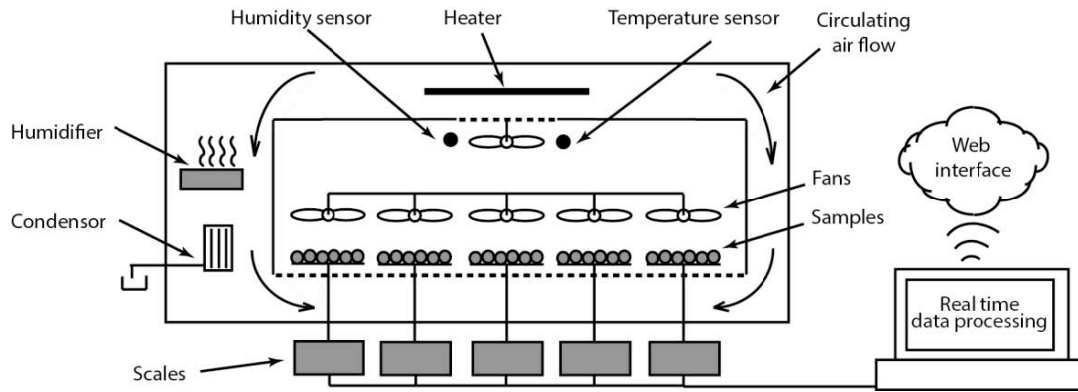


Figure 3.5 Schematic of dehydrator (Coates, 2018a)

Figure 3.6 illustrates the Stockpile Heated and Ambient Air Dryer (SHAD) developed by Mayanja et al. (2021). In this setup, almonds were placed directly onto the A-frame from a conveyor cart, forming a bottom layer with a stockpile height of approximately 0.30 meters. This process was repeated to create middle and top layers, reaching partial stockpile heights of 1.22 meters and 2.13 meters, respectively. The SHAD dryer accommodated a total of 4,155 kg of almonds, which were dehydrated from an initial kernel moisture content of 12.6% (d.b.) to a final moisture content of 6.04% over an 11-day period.

The drying process successfully maintained the quality of the dried almonds. The energy performance indicators for the SHAD system revealed a specific moisture extraction rate (SMER) of 0.64 kg/kWh, a moisture extraction rate (MER) of 1.02 kg/h, a coefficient of performance (COP) of 1.33, and a drying cost of \$11.65 per ton. When compared to other commercial dryers, the SMER and MER values were within acceptable ranges; however, the COP was relatively low, indicating potential inefficiencies in the system. Specifically, these inefficiencies were attributed to the challenges in achieving the desired drying temperature and the non-uniform air distribution within the stockpile.

sorting freshly harvested almonds into moisture-specific groups for separate drying could be a more effective approach to improve drying uniformity, product quality, and energy efficiency.

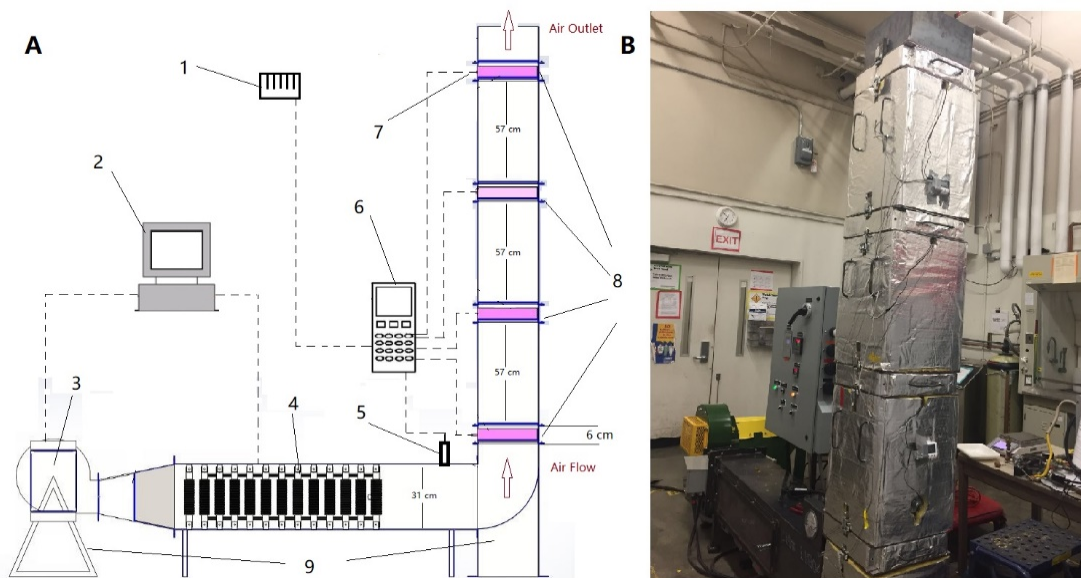


Figure 3.7 Schematic diagram (A) and photo of the column dryer (B) (Chen, Abd El Gebreil, et al., 2020)

3.4 Mathematical Modeling of Food Product Drying

Mathematical modeling serves as a valuable tool for investigating the drying kinetics of food materials, enabling the assessment of the impact of operating conditions as well as inherent physical and structural parameters on the drying behavior of foods. These mathematical models can be broadly categorized into three main types based on their underlying principles and development approaches: empirical models, semi-empirical models, and analytical models. Each type offers unique advantages and considerations, allowing for a comprehensive understanding of the drying process and facilitating the optimization of drying operations in the food processing industry.

3.4.1 Empirical model

Empirical models are derived from thin-layer drying experiments, and they are typically fitted to experimental drying data using regression analysis techniques. These models are advantageous due to their simplicity, ease of computation, and broad applicability to a wide range of food materials (Doymaz & Kocayigit, 2011; Zhang et al., 2016). Table 3.4 provides an overview of some commonly employed empirical models in food drying.

Table 3.4 Empirical thin layer drying models

Model	Equation
Lewis	$MR = \exp(-kt)$
Page	$MR = \exp(-kt^n)$
Logarithmic	$MR = a \cdot \exp(-kt) + c$
Two-term model	$MR = a \cdot \exp(-k_1 t) + b \cdot \exp(-k_2 t)$
Wang and Singh	$MR = 1 + at + bt^2$
Henderson and Pabis	$MR = a \cdot \exp(-kt)$

where MR is moisture ratio; a, b, c are drying coefficients; k is drying constants in the models.

Numerous studies have been conducted to develop mathematical models for different tree nuts, such as pistachios (Kashaninejad et al., 2007), hazelnuts (Ceylan & Aktaş, 2008; Özdemir & Devres, 1999), cashew nuts (Asiru et al., 2013), and walnuts (Hassan-Beygi et al., 2009). These models have demonstrated remarkable accuracy in characterizing the drying behavior of these nuts. During the empirical modeling process, multiple models are concurrently compared, and the optimal model is selected based on the evaluation criteria of chi-squared (χ^2), root mean square error (RMSE), and the coefficient of determination (R^2). The equations for calculating the χ^2 , RMSE, and R^2 are shown as follows:

$$\chi^2 = \frac{\sum_{i=1}^n (MR_{exp,i} - MR_{pre,i})^2}{n-z} \quad (3.8)$$

$$RMSE = \sqrt{\frac{1}{n} \sum_1^n (MR_{pre,i} - MR_{exp,i})^2} \quad (3.9)$$

$$R^2 = 1 - \frac{\sum_1^n (MR_{pre,i} - MR_{exp,i})^2}{\sum_1^n (MR_{pre,i} - MR_{exp,i})^2} \quad (3.10)$$

where n is the number of observations; z is the number of constants/coefficients; $MR_{pre,i}$ is the predicted MR values; $MR_{exp,i}$ is the experimental MR values.

It is important to note that the applicability of these models is limited to the specific experimental operating conditions employed, including drying temperature, air velocity, material thickness, initial moisture content, and relative humidity (Erbay & Icier, 2010; Panchariya et al., 2002). Furthermore, these models often neglect the influence of material geometry restrictions, and the regression parameters obtained from these models may not possess substantial physical significance.

3.4.2 Analytical model

Analytical modeling of the drying process typically involves the utilization of fundamental equations, including Fick's second law of diffusion and the heat diffusion equation, to characterize the heat and mass transfer mechanisms. The general equations in Cartesian coordinates for heat and mass transfer are presented below:

Heat Transfer:

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left(k_z \frac{\partial T}{\partial z} \right) + \dot{q} = \rho c_p \frac{\partial T}{\partial t} \quad (3.11)$$

where k_x , k_y , k_z are the thermal conductivities associated with conduction in the x, y, z-directions, respectively (W/m·k). In an isotropic material, the thermal conductivity is direction independent, i.e., $k_x = k_y = k_z = k$; $\dot{q}$ represents the energy generation rate per unit volume of the medium (W/m³).

This term is positive when thermal energy is produced within the material from other forms of energy, such as chemical, electrical, or nuclear energy, and negative when thermal energy is

consumed. The expression, $\rho c_p \frac{\partial T}{\partial t}$ denotes the energy storage term, indicating the rate of thermal energy accumulation or depletion within the material. The simplified version of Equation 3.11 for 1-dimension slab geometry with no energy generation is shown below:

$$\frac{\partial}{\partial x} \left(k \frac{\partial T}{\partial x} \right) = \rho c_p \frac{\partial T}{\partial t} \quad (3.12)$$

Mass transfer:

$$\frac{\partial}{\partial x} \left(D_{AB} \frac{\partial C_A}{\partial x} \right) + \frac{\partial}{\partial y} \left(D_{AB} \frac{\partial C_A}{\partial y} \right) + \frac{\partial}{\partial z} \left(D_{AB} \frac{\partial C_A}{\partial z} \right) + \dot{N}_A = \frac{\partial C_A}{\partial t} \quad (3.13)$$

where D_{AB} represents the binary diffusion coefficient or mass diffusivity (m^2/s); $\dot{N}_A$ is the rate of change of the mole concentration of species A per unit volume of the mixture ($\text{mole}/\text{m}^3 \cdot \text{s}$).

Similarly, the simplified version of Equation 3.13 is shown below:

$$\frac{\partial}{\partial x} \left(D_{AB} \frac{\partial C_A}{\partial x} \right) = \frac{\partial C_A}{\partial t} \quad (3.14)$$

The constants k , ρ , c_p , D_{AB} are known values which normally can be obtained from literature or measurements.

To address the heat and mass equations, defining an initial condition, two boundary conditions, and making certain critical assumptions is necessary. In reported drying studies, taking a spherical shape food product as an example, several critical assumptions are usually made:

- 1) Uniform initial moisture distribution throughout the food product.
- 2) Mass transfer is symmetric at the center of the sphere.
- 3) The surface moisture content of the food product instantaneously reaches equilibrium with that of drying media.
- 4) Resistance to mass transfer at the surface is negligible compared to the internal resistance of the food product.
- 5) Mass transfer is by diffusion only.

6) Diffusivity is constant, and shrinkage is negligible.

The appropriate initial and boundary conditions are as follows:

$$t = 0; M = M_0, 0 < r < r_s \quad (3.15)$$

$$t > 0; \left. \frac{\partial M}{\partial r} \right|_{r=0} = 0 \quad (3.16)$$

$$t > 0; M = M_e, r = r_s \quad (3.17)$$

The solution to Equation 3.14, considering the aforementioned condition, can be expressed as follows (Crank, 1979):

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp \left(-\frac{n^2 \pi^2 D_{eff} t}{r_s^2} \right) \quad (3.18)$$

where M is the MC (kg water/kg wet mass); MR is the moisture ratio; r_s is the sphere radius (m); D_{eff} is the effective diffusion coefficient (m²/s); t is the time (s).

In the case of long drying times, typically with a moisture ratio (MR) below 0.6, Equation 3.18 can be simplified to the first term, which exhibits reliable predictability. The first term of the solution, presented in both its original form and logarithmic form, is provided below (Brennan, 1994; Senadeera et al., 2003):

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{6}{\pi^2} \exp \left(-\frac{\pi^2 D_{eff} t}{r_s^2} \right) \quad (3.19)$$

$$\ln(MR) = \ln \left(\frac{6}{\pi^2} \right) - \frac{\pi^2 D_{eff} t}{r_s^2} \quad (3.20)$$

The slope (α) and D_{eff} can be determined as follows:

$$\alpha = \frac{\pi^2 D_{eff} t}{r_s^2} \quad (3.21)$$

To improve the accuracy of mathematical modeling, it is crucial to account for the influence of temperature and moisture content on moisture diffusivity (Chen, Venkitasamy, et al., 2020). Moisture diffusivity plays a key role in determining the moisture removal rate during drying, and

its dependence on temperature and moisture content can significantly affect the drying kinetics. Incorporating this variability ensures a more accurate prediction of the drying process under different operating conditions.

Additionally, it is important to acknowledge that effective moisture diffusivity varies depending on the type of diffusion process involved. As De Vries (1958) and Hii et al. (2023) pointed out, diffusion can be categorized into liquid diffusion and vapor diffusion, each with distinct mechanisms and implications for the drying behavior of food materials. For instance, liquid diffusion occurs when moisture is in the liquid phase within the material, typically dominating during the initial drying stages. In contrast, vapor diffusion becomes more significant as the moisture content decreases and the material structure becomes more porous, leading to moisture migration in the vapor phase.

Figure 3.8 visually illustrates these two diffusion processes, emphasizing how the transition from liquid to vapor diffusion occurs as drying progresses. By considering these variations in diffusivity and the underlying diffusion mechanisms, mathematical models can better capture the complex nature of moisture transport in food materials, leading to more reliable predictions of drying performance under diverse conditions.

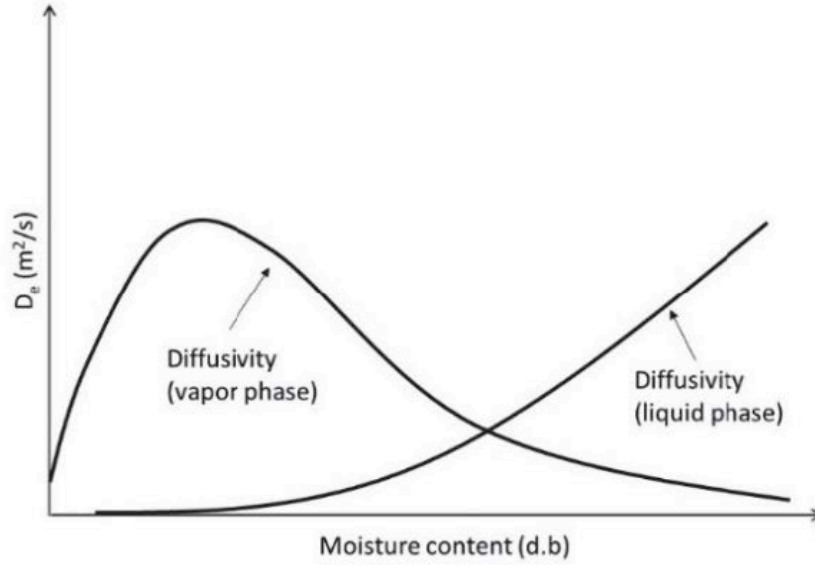


Figure 3.8 Variation in liquid and vapor phase diffusivities (De Vries, 1958)

For practical purposes, the convective boundary equations presented below are frequently employed to solve the heat and mass transfer equations.

Boundary condition for mass transfer:

$$-D_{eff} \frac{\partial M}{\partial x} = h_m(M - M_e) \quad (3.22)$$

Boundary condition for heat transfer:

$$-k \frac{\partial T}{\partial x} = h_t(T - T_s) \quad (3.23)$$

where h_m is the mass transfer coefficient (m/s); h_t is the heat transfer coefficient (W/m²·K); M_e is the equilibrium moisture content (kg water/kg wet mass); T_s is the surrounding temperature (K).

The coefficients, h_m and h_t can be determined using established correlations such as Sherwood and Nusselt number correlations, which depend on the product's geometry and the conditions air flow conditions (Putranto & Chen, 2015; Whitaker, 1972).

To ensure precise simulation and prediction, Chen and Xie (1997) developed a mechanistic model for drying using a reaction engineering approach (REA). This model recognizes drying as

a competitive process involving evaporation and condensation reactions. In this context, the drying process is governed by a zero-order evaporation reaction and a first-order condensation reaction, which collectively describe the dynamics of moisture removal and phase change during drying. The REA model is represented by the following equation:

$$m_s \frac{dX}{dt} = -h_m A \left(\exp \left(\frac{-\Delta E_v}{RT_s} \right) \rho_{v,sat}(T_s) - \rho_{v,b} \right) \quad (3.24)$$

where X is the average moisture content (kg water/kg dry solid); m_s is the mass of dry solid (kg); A is the surface area of materials being dried (m^2); T_s is the surface temperature of sample (K); ΔE_v is the activation energy (J/mol); $\rho_{v,sat}$ is the saturated water vapor concentration (kg/m^3); $\rho_{v,b}$ is the concentration of water vapor in the drying media (kg/m^3).

By utilizing Equation 3.24, the experimental determination of the activation energy (ΔE_v) becomes feasible once the drying data is obtained:

$$\Delta E_v = -RT_s \ln \left(\frac{-m_s \frac{dX}{dt} \frac{1}{h_m A} + \rho_{v,b}}{\rho_{v,sat}(T_s)} \right) \quad (3.25)$$

3.4.3 Semi-empirical model

The Fickian-type drying model, which assumes negligible external resistance to mass transfer, may not be suitable for food materials that exhibit significant resistance during the drying process. In response to this limitation, semi-empirical models offer a balanced approach between theoretical rigor and practical implementation (Fortes & Okos, 1980). Dincer and Dost (1995); (1996) developed and validated an analytical model based on the Biot number to better describe the mass transfer dynamics in solid objects of various geometries. This model accounts for both internal and external resistance to moisture transfer and introduces two critical drying parameters: the drying coefficient (S) and the lag factor (J_1). These parameters represent the moisture diffusion capacity within the material and the resistance to moisture transfer, respectively.

The moisture ratio (MR), as shown in Equation 3.26, is represented by an exponential function of drying time (t), incorporating the regression parameters S and J_1 . In this model, it was assumed that the solid object and the drying fluid possess constant thermophysical properties and that the influence of heat transfer on mass transfer was negligible. Specifically, the moisture diffusivity was presumed to occur radially within the solid cylinder and sphere and in the thickness direction within the slab.

$$MR = J_1 \exp(-St) \quad (3.26)$$

By determining J_1 values, the dimensionless Biot number (B_i) can be obtained from Equation 3.27:

$$\text{For infinite slab object: } J_1 = \exp\left(\frac{0.2533 \times B_i}{1.3 + B_i}\right) \quad (3.27)$$

Then, moisture diffusivity can be calculated by using Equation 3.28:

$$D = \frac{S \times L^2}{\mu_1^2} \quad (3.28)$$

where D is the moisture diffusivity (m^2/s); L is the half thickness of slab (m); μ_1 is the root of the transcendental characteristics equation (dimensionless). To facilitate practical drying applications, a simplified expression was derived to compute μ_1 based on the Biot number for infinite slab geometry:

$$\text{For } B_i > 100; \mu_1 = \frac{\pi}{2} \quad (3.29)$$

$$\text{For } 0 < B_i < 100; \mu_1 = \tan^{-1}(0.640443B_i + 0.380397) \quad (3.30)$$

Next, the moisture transfer coefficient can be determined using Equation 3.31:

$$h_m = \frac{B_i \times D}{L} \quad (3.31)$$

The analytical model has been successfully applied to simulate the drying processes of various food materials, providing accurate predictions of moisture transfer. For instance, Mcminn et al.

(2003) applied the model to potato samples in slab and cylindrical forms, demonstrating its ability to handle different geometries. Similarly, Corzo et al. (2008) utilized the model for drying mango slices, and Sadeghi et al. (2013) applied it to lemon slices. In each case, the model's predictions closely matched experimental results, confirming its reliability and efficiency as a tool for simulating drying processes.

3.4.4 Modeling of drying with food product shrinkage

Simultaneous with moisture transport, shrinkage often occurs during the drying process of food materials (Wang & Brennan, 1995). Shrinkage significantly impacts the quality of the dried product, affecting characteristics such as shape, volume, texture, and rehydration capability. These changes include volume loss, increased hardness, surface cracking, and reduced rehydration capacity (Akiyama & Hayakawa, 2000; Fortes & Okos, 1980; Jayaraman et al., 1990; Mayor & Sereno, 2004; Mcminn & Magee, 1997; Mensah et al., 1984). In addition, shrinkage alters moisture removal rates, diffusion coefficients, and physical properties like density and porosity, affecting the accuracy of moisture and temperature profiles predicted by drying models (Khraisheh et al., 1997; Mayor & Sereno, 2004).

Several researchers have emphasized the importance of accounting for shrinkage in drying models to improve the precision of drying process representations (Balaban, 1990; Chen & Johnson, 1969; Mulet et al., 1987; Park, 1998; Simal et al., 1998). Two common approaches exist for modeling shrinkage during the drying of food materials: fundamental and empirical models.

The fundamental model incorporates mechanical laws to account for material stresses and deformations occurring during drying (Srikiatden & Roberts, 2007). However, developing such models requires a detailed investigation of the structure, mechanical properties, and elasticity of the food material, as well as the effects of varying moisture content and temperature (Ratti, 1994).

This approach can be costly and computationally intensive, making it less practical for many applications (Adrover et al., 2019; Srikiatden & Roberts, 2007).

As a practical alternative, empirical models based on experimental data offer a more feasible approach to studying food shrinkage. In past studies, various empirical relationships between volumetric shrinkage and moisture content have been proposed for different food materials, summarized in Table 3.5. For instance, Suzuki et al. (1976) proposed three models to predict volumetric shrinkage coefficients: the uniform drying model, the core drying model, and the semi-core drying model.

Uniform drying model: Assumes that shrinkage volume equals the volume of water loss. This model can be applied using either initial moisture content and bulk density data or equilibrium moisture content and bulk density data.

Core drying model: Suitable for materials with an inner core and outer shell, where the densities of the core and shell correspond to initial and equilibrium values, respectively.

Semi-core drying model: Applies when the dried shell layer has a density that is a weighted average between initial and equilibrium densities.

Table 3.5 Common shrinkage models

Equations	Material	Reference
$\frac{V}{V_0} = \frac{X+0.8}{X_0+0.8}$	Vegetables	Kilpatrick et al. (1955)
$\frac{V}{V_0} = 1 - \alpha \frac{\rho_0(X_0 - X_m)}{\rho_w(1 + X_0)}$	Soybean	Irigoyen et al. (2014)
$\frac{V}{V_0} = 1 - 0.276(X_0 - X)$	Cocoa bean	Adrover and Brasiello (2020)
Uniform drying model:		
(1) $\frac{V}{V_0} = \frac{X+a}{X_0+a}; a = X_e \left(\frac{1}{\rho_e} - 1 \right) + \frac{1}{\rho_e}$	Carrot, potato, sweet	Suzuki et al. (1976)
(2) $\frac{V}{V_0} = bx + c; b = \frac{\rho_0}{X_0+1}; c = 1 + a - \rho_0$	potato, radish	

Core drying model:

$$\frac{V}{V_0} = dX + 1; d = \frac{1-e}{X_0-X_e}; e = \frac{(X_e+1)\rho_0}{(X_0+1)\rho_e}$$

Semi-core drying model:

$$\frac{V}{V_0} = fX + g;$$

$$f = \frac{1-e}{X_0-X_e-h(eX_0-X_e+e-1)};$$

$$g = \frac{eX_0-X_e-h(eX_0-X_e+e-1)}{X_0-X_e-h(eX_0-X_e+e-1)};$$

$$h = \frac{\rho_e-(1-X)\rho_e}{\rho_0}$$

Model including porosity

$$\frac{V}{V_0} = \frac{1}{1-\varepsilon} \left(1 + \frac{\rho_0(X-X_0)}{\rho_w(1+X_0)} - \varepsilon_0 \right)$$

Apple,

potato,

carrot, squid

Mayor and Sereno (2004);

Perez and Calvelo (1984)

Moreover, for food materials exhibiting negligible or uniform porosity development during drying, linear models are often sufficient to describe the relationship between shrinkage and moisture content. These models have been successfully applied to a variety of food products (Lozano et al., 1980; Misra & Young, 1980; Ratti, 1994; Vagenes & Marinos-Kouris, 1991). In such cases, shrinkage is directly proportional to moisture loss, simplifying the modeling process.

However, for food materials that experience significant porosity increases during the later stages of drying, linear models may not adequately capture the complex behavior of shrinkage. In these instances, non-linear models are more appropriate. The exponential model (Mayor & Sereno, 2004; Mulet et al., 1997) and the quadratic model (Mayor & Sereno, 2004) offer improved accuracy in fitting the experimental data, particularly when porosity development intensifies towards the end of drying. These non-linear models can better represent the changes in material structure and the rate of shrinkage, providing a more precise depiction of the drying behavior for porous materials.

To formulate the governing equations for heat and mass transfer considering the effect of shrinkage, it is possible to analogize shrinkage as convective flow, where the material surface contracts inward at a certain velocity toward the center of the sample (Jomaa & Puiggali, 1991). Therefore, the one-dimensional moisture diffusion can be expressed as follows:

$$\frac{\partial M}{\partial t} + u \frac{\partial M}{\partial x} = D_{eff} \frac{\partial^2 M}{\partial x^2} \quad (3.32)$$

The shrinkage is assumed to exhibit a linear distribution of shrinkage velocity and the velocity of shrinkage can be mathematically expressed as proposed by Qing (1997):

$$u(x) = u(b) \frac{x}{b} \quad (3.33)$$

The velocity at the surface is:

$$u(b) = \frac{b-b_0}{\Delta t} \quad (3.34)$$

where b is half the thickness of the thin slab.

Adrover and Brasiello (2020) introduced a moving-boundary model that incorporates the local shrinkage by considering the pointwise shrinkage velocity as follows:

$$\frac{\partial c_w}{\partial t} + \nabla(c_w v) = \nabla(D_w \nabla c_w) \quad (3.35)$$

where c_w is the concentration of water (kg/m^3); v is the shrinkage velocity (m/s); $\nabla(c_w v)$ is the convective term arising from the local shrinkage.

To determine the shrinkage velocity, it is assumed that the shrinkage velocity is proportionate to the diffusive flux (Adrover & Brasiello, 2020; Karim & Hawlader, 2005):

$$v = -\alpha(c_w) D_w \nabla c_w / \rho_w \quad (3.36)$$

where $\alpha(c_w)$ is the shrinkage factor depending on the water concentration. In this study, the shrinkage factor is regarded as constant throughout the drying process as proposed by Adrover and

Brasiello (2020), i.e., $\alpha(c_w) = \alpha_0$. The relationship between volume reduction and moisture content can be expressed linearly as follows:

$$\left(1 - \frac{V_d}{V_0}\right) = \alpha_0 \phi_0 \left(1 - \frac{X_d}{X_0}\right) \quad (3.37)$$

where V_0 and V_d are the volume of the initial and dry sample (m^3), respectively; X_0 and X_d are the initial and the dry moisture content, respectively; ϕ_0 is the initial volume fraction of water inside the sample and can be estimated as follows:

$$\phi_0 = \frac{M_0}{\rho_w V_0} \frac{X_0}{1 + X_0} \quad (3.38)$$

where M_0 is the initial mass of the sample (kg); ρ_w is the water density (kg/m^3).

To date, there have been no theoretical investigations reported on the simulation of almond drying, taking into account its heterogeneous nature consisting of almond hull, shell, and kernel. When addressing material discontinuity, traditional methods such as analytical solutions and finite difference methods (FDM) prove inadequate in solving the governing differential equations, as highlighted by Chen, Venkitasamy, et al. (2020); Prakash (2011). Alternatively, the finite element method (FEM) emerges as a more suitable approach for handling material discontinuity and addressing two or three-dimensional problems. FEM has proven successful in simulating the drying process of various food materials, including rice components (Lu & Siebenmorgen, 1992; Sarker et al., 1994; Yang et al., 2002), macadamia nuts (Pankaew et al., 2016), and walnuts (Chen, Venkitasamy, et al., 2020) under hot air drying conditions. However, no studies have reported on the drying simulation of in-hull almonds using convective drying and FEM techniques.

Furthermore, it is widely recognized that a physically accurate model, closely resembling the actual geometry of the material, is crucial for obtaining precise moisture and temperature profiles and reliable estimates of moisture and thermal diffusivities. Previous studies have predominantly considered almonds as spherical shapes (Coates, 2018a; Kaveh et al., 2018; Mirzabe et al., 2013),

enabling the derivation of analytical solutions to the diffusion equation. Prakash and Pan (2012) noted that adopting a simpler shape may deviate from the true almond shape and introduce prediction errors. In reality, almonds exhibit an ellipsoidal geometry characterized by the dimensions of major (2a), intermediate (2b), and minor axes (2c) (Mohsenin, 1986). Therefore, an ellipsoidal model is more suitable for simulating the drying process of almonds.

Li et al. (2004) proposed the utilization of a geometry factor (E), which incorporates the dimensions of the ellipsoid, to establish a relationship between the intrinsic diffusivity of an ellipsoid and the equivalent diffusivity of a sphere with the corresponding equivalent radius (r_e).

The equations presented are as follows:

$$D_{sphere} = ED_{ellipsoid} \quad (3.39)$$

$$E = \frac{1}{3} \left(\frac{1}{(a/r_e)^2} + \frac{1}{(b/r_e)^2} + \frac{1}{(c/r_e)^2} \right) \quad (3.40)$$

$$r_e = (abc)^{1/3} \quad (3.41)$$

The numerical outcomes obtained through the implementation of the ellipsoidal model exhibit excellent agreement with the experimental data for corn, wheat, and rice, as reported in previous studies (Gastón et al., 2002; Hendrickx et al., 1986; Igathinathane & Chattopadhyay, 1999; Li et al., 2004; Tolaba et al., 1989).

3.5 Quality Attributes and Quality Preservation Methods for Foods

Food products, whether raw, processed, or formulated, are exposed to various environmental conditions, including pressure, temperature, humidity, oxygen, and light. These factors initiate mechanisms that lead to food deterioration, which can be classified as physical, chemical, or biological, and are the primary contributors to reduced food quality and safety.

3.5.1 Physical changes

Physical damage to food often results from improper handling during harvesting, processing, and distribution (Singh, 1994). Bruising fruits and vegetables can lead to rot, while dried snack foods can be crushed during distribution, compromising their quality. In high-humidity environments, dried foods may absorb moisture, leading to undesired sogginess (Singh, 1994). Additionally, temperature fluctuations can cause frozen food to develop an undesirable sandy texture. High-temperature drying can result in shrinkage, surface hardening, or cracking in food products (Akiyama & Hayakawa, 2000; Fortes & Okos, 1980; Mayor & Sereno, 2004; Mensah et al., 1984).

3.5.2 Chemical changes

Key chemical changes during food processing and storage are linked to enzymatic action, oxidative reactions, and non-enzymatic browning (Singh, 1994). These changes can lead to unpleasant odors, off-flavors, visual degradation, nutrient loss, and reduced shelf life. Such reactions involve internal food components and are influenced by external factors such as temperature, oxygen levels, water activity, and pH.

Enzymatic browning occurs when polyphenol oxidase (PPO) interacts with cell components in the presence of oxygen, a process that can accelerate at ambient temperatures. This browning is especially prevalent in bruised or cut fruits and vegetables, including apples, bananas, and potatoes (Sapers & Miller, 1995; Singh, 1994). Blanching is an effective technique for deactivating PPO activity (McEvily et al., 1992). Notably, enzymes such as lipoxygenase can still impact food quality, even at sub-freezing temperatures, if they are not denatured during blanching (Rahman, 2007; Singh, 1994).

Oxidative deterioration is a significant concern, particularly in lipid-containing foods such as tree nuts. Unsaturated fatty acids are prone to rancidity when exposed to oxygen during storage. The rate of lipid oxidation is affected by multiple factors, including temperature and water activity (Singh, 1994). Nelson and Labuza (1992) found that lipid oxidation rates are highest at very low water activity and within the water activity range of 0.4 to 0.7, as shown in Figure 3.9.

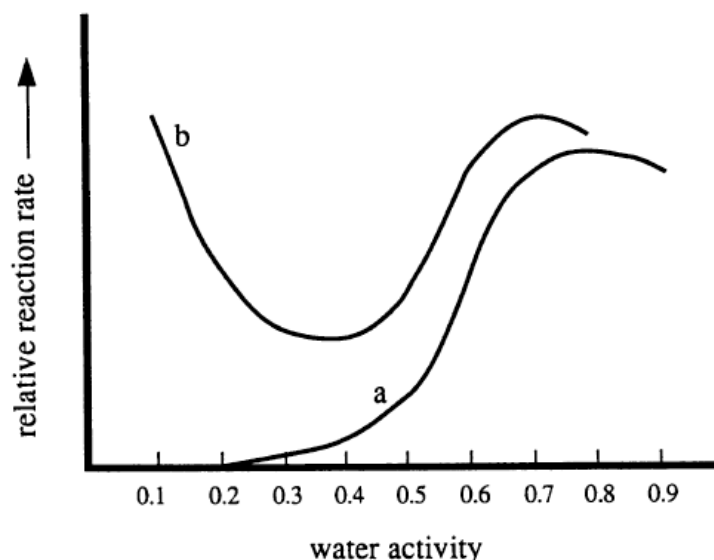


Figure 3.9 Relative rates of nonenzymatic browning (a) and lipid oxidation (b) as a function of water activity

Non-enzymatic browning, also known as the Maillard reaction, is a major contributor to quality deterioration and the loss of nutritive value in food (Singh, 1994). This reaction is accelerated by heat and involves the interaction between free amine groups in proteins or peptides and carbonyl groups in sugars or carbohydrates (Lee & Shibamoto, 2002). The effects of this process include a reduction in protein solubility, darkening of dried products, the development of bitter flavors, and the formation of various chemical compounds, some of which may be toxic (Shibamoto, 1989; Singh, 1994). Factors such as temperature, water activity, and pH significantly influence the

Maillard reaction. The relationship between water activity and the reaction rate is shown in Figure 3.9.

Figure 3.10 illustrates a common quality issue in almonds, known as concealed damage (CD), which manifests as brown discoloration in the nutmeat only after exposure to moderate heat treatments, such as roasting. Research has shown that high-temperature and moisture treatments can significantly increase the occurrence of concealed damage in almonds (Pearson, 1999; Rogel-Castillo et al., 2015).



Figure 3.10 Undamaged almond and almond with CD (Pearson, 1999)

3.5.3 Biological changes

Microbial growth in food leads to spoilage, often resulting in undesirable sensory changes and, in some cases, the production of harmful toxins (Singh, 1994). Before harvest, fruits and vegetables have natural defense mechanisms against microbial attacks, but once harvested, they become more vulnerable to microbial proliferation. Pathogenic microorganisms such as *Salmonella* species, *Escherichia coli*, *Aspergillus flavus*, *Clostridium botulinum*, and *Staphylococcus aureus* may be present. Figure 3.11 illustrates the growth rates of molds, yeasts, and bacteria as a function of water activity. Water activity levels between 0.6 and 0.7 for most foods represent a critical threshold below which microorganisms cannot grow. As water activity

increases, the risk of foodborne illness rises accordingly (Bonazzi & Dumoulin, 2011; Rahman, 2007).

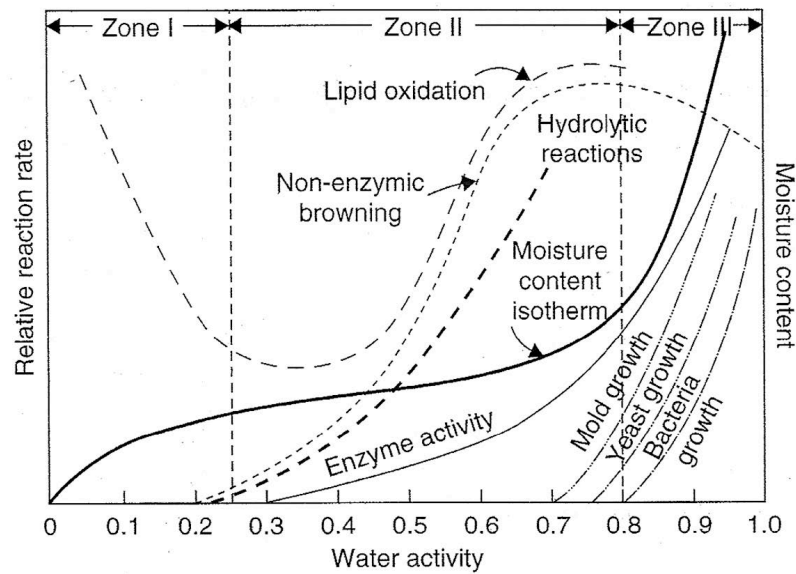


Figure 3.11 Relative water activity stability map (Labuza, 1970)

Various strategies are commonly used to minimize or inhibit microbial growth in food. These include adjusting environmental temperature, lowering it to slow microbial growth or raising it to kill microbes. Controlling environmental gases, such as reducing oxygen levels or increasing carbon dioxide concentration, also effectively inhibits microbial growth. Additionally, acidification can suppress microbial activity, while fermentation processes, which lower pH, further inhibit microbial proliferation (Man & Jones, 1994).

4 CHAPTER 4 INITIAL CHARACTERISTICS OF OFF-GROUND HARVESTED ALMONDS AT EARLY AND STANDARD HARVESTING

4.1 Introduction

Almond (*Prunus dulcis* (Miller) D.A. Webb) are among the most popular tree nuts globally, known for their unique flavor, crunchy structure, nutritional value, and numerous health benefits. They are consumed in various forms, including raw and roasted almonds or as an ingredient in savory and sweet food. California is the world's leading producer of almonds, accounting for over 80% of the global supply (ABC, 2021; USDA-NASS, 2022). Almond orchards in California are distributed across the north, central, and south counties of the Central Valley (Yada et al., 2013).

Almond harvesting is a crucial step that significantly affects product quality and safety. The conventional method of harvesting includes four main steps: shaking, on-ground drying, sweeping, and picking up. During this process, mature almonds are shaken onto the orchard floor using equipment that applies vibrational force to the tree trunk. The almonds are then dried naturally on the ground for 1 to 2 weeks for early-harvested almonds and 4 to 7 days for late-harvested almonds. In some cases, drying time is prolonged by rainfall during harvest (Micke, 1996; Venkitasamy et al., 2018). After drying, almonds are swept into windrows by a mechanical sweeper, picked up by machines, and transported for stockpiling or directly to a huller/sheller facility (Micke, 1996).

However, conventional harvesting presents three main concerns: dust generation, soil contamination, and insect damage. Dust generated during sweeping and pickup procedures creates significant particulate pollution, posing health risks over a wide area. Moreover, almonds remain on the ground for extended periods, increasing their exposure to soil-borne microbes and other contaminants. A particular risk arises when almonds prematurely detach from trees, become wet due to irrigation or rain, and remain on the ground. The moisture creates a favorable environment

for bacterial growth (e.g., *Salmonella*) and fungal contamination (e.g., *Aspergillus flavus* and *Aspergillus parasiticus*), which can lead to aflatoxin production (Harris & Ferguson, 2013; Pier & Richard, 1992). Studies have shown that *Salmonella Enteritidis* PT 30 can proliferate in wetted almond hulls and shell slurries (Danyluk et al., 2008; Du et al., 2010; Uesugi et al., 2006). Between 2001 and 2017, nine outbreaks of *Salmonella* in the United States were linked to raw almonds (Palumbo et al., 2017).

Additionally, almonds left in the orchard for extended periods are susceptible to insect infestation. A key pest is the navel orangeworm (*Amyelois transitella*), which can cause extensive damage to almonds, ranging from minor pinhole entries to complete destruction of the kernel (Kader, 2013; Kim & Schatzki, 2001). The adult moth can also introduce *Aspergillus* spp. Fungus during egg-laying, further increasing the risk of aflatoxin contamination (Campbell et al., 2003; Harris & Ferguson, 2013). Navel orangeworm damage rates in California orchards have been reported as high as 30%, significantly impacting almonds' marketability and economic value (Campbell et al., 2003; Higbee & Siegel, 2009; Phillips et al., 1980).

In response to these challenges, the Almond Board of California (ABC) and the almond industry have explored alternative harvesting methods. One promising approach is off-ground and shake-catch harvesting, which minimizes ground contact and reduces the risks associated with conventional methods. However, almonds harvested using this technique typically have higher moisture content, requiring prompt artificial drying to ensure efficient handling and maintain product quality (Chen, Abd El Gebreil, et al., 2020). Early harvesting not only reduces risks such as mold growth, insect damage, and adverse weather but also supports sustainable practices in irrigation, pest control, and disease management (Smith et al., 2022).

Hull split and abscission layer formation signal almond maturity, making them key indicators for harvest timing. Flint (2002) developed a qualitative method to identify different stages of hull split, depicted in Figure 1.3. The standard harvest usually begins when hull dehiscence is fully developed, which corresponds to stages E or F, and the hull and kernel are essentially dry on the tree (Connell et al., 1989; Crisosto & Crisosto, 2020). Early harvest, which occurs 3 to 4 weeks earlier, can mitigate insect damage and improve product quality without affecting yield (Connell et al., 1989; Kazantzis et al., 2003).

Significant differences in dimensions, shapes, and colors are observed between early and standard harvested almonds. Understanding these initial characteristics is essential for designing efficient processing units, such as drying and sorting systems. Moreover, this knowledge is critical for modeling moisture transport during drying, as it necessitates the determination of specific thermophysical parameters (Cunha et al., 2021).

Despite the importance of these factors, limited data exist on the properties of almond components (hull, shell, kernel), including density, thermal conductivity, and specific heat. Furthermore, the distribution of moisture at harvest is crucial, as moisture content impacts the physical, mechanical, and thermal properties of almonds, as well as their quality (Aviara & Haque, 2001; Kaleemullah & Gunasekar, 2002; Kashaninejad et al., 2006; Liang, 1977; Liang et al., 1984; Mohsenin, 1970; Nelson & Labuza, 1994; Olaniyan & Oje, 2002; Rajabipour et al., 2001; Razavi & Taghizadeh, 2007; Tang et al., 1982; Toğrul & Arslan, 2007). Maintaining a moisture content of around 6% ensures stored almonds' safety and shelf life by inhibiting microbial growth (Kader, 2013).

4.2 Specific Objectives

This study aims to address existing research gaps by investigating off-ground harvested almonds' characteristics, examining insect damage, and identifying critical parameters for drying process simulation. The specific objectives of this research include: (1) Evaluate the insect damage in almonds harvested using off-ground and conventional methods; (2) Determine the initial moisture content distribution of whole almonds and their components (hulls, shells, and kernels) at both early and standard harvest times; (3) Determine the physical, chemical, and thermal properties of different almond components. (4) Investigate the aerodynamic properties of in-hull almonds, in-shell almonds, and loose hulls, and develop an effective sorting method for off-ground harvested almonds.

4.3 Materials and Methods

4.3.1 Sample collection

Samples from off-ground harvested almonds were collected immediately after being shaken from the trees at two harvest stages: early harvest (EH) and standard harvest (SH). EH involves removing almonds approximately 3-4 weeks before SH, a timeline traditionally based on regional practices. Samples of the Fritz variety were collected from the Nickels Soil Lab in Arbuckle, CA, to assess the initial characteristics of off-ground harvested almonds during the 2022 season.

For the insect damage studies, various almond varieties were gathered from multiple orchards and regions over three consecutive harvest seasons (2019, 2020, and 2021), as shown in Figure 4.1. Detailed descriptions of the experimental procedures are provided in the corresponding subsections.

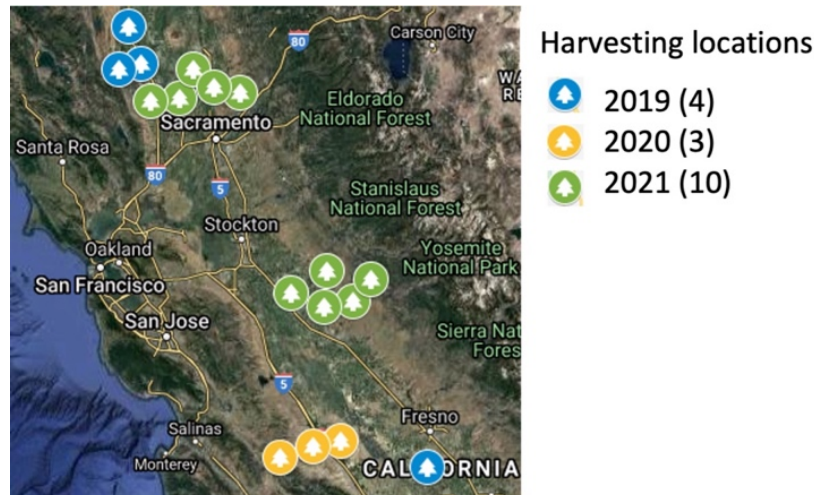


Figure 4.1 Harvesting locations and number of orchards during three consecutive harvesting seasons

4.3.2 Almond insect damage evaluation

Seventeen orchards located across northern and southern California were selected to evaluate the initial insect damage and development in on-ground dried almonds. A total of 44 samples were analyzed, consisting of 11 off-ground harvested samples collected immediately after shaking and 33 conventionally harvested samples dried on the ground at various times. Each sample was evaluated for insect damage in triplicate. Detailed sampling information is provided in Table 4.1.

The insect damage assessment was conducted through visual inspection and quantified as a percentage. For each evaluation, 100 whole almonds were cracked open to observe different types of insect damage, including pinholes (small boreholes caused by the navel orangeworm), feeding damage (removal of nut surface in distinct chunks), and gross damage (presence of insect parts, frass, or webbing) (Kim & Schatzki, 2001).

Table 4.1 Summarized harvest information of almond samples used for insect damage evaluation

Farm	Region	Variety	Harvest date	Collect date- 1	Collect date- 2	Collect date- 3
Campos Brother	S	Independence	8/15/19	n/a	n/a	8/25/19
Emerald	N	Monterey	9/23/19	n/a	n/a	10/3/19
Emerald	N	Fritz	9/23/19	n/a	n/a	10/3/19
Nickels Soil Lab	N	Nonpareil	9/8/19	n/a	n/a	9/19/19
Bakers	S	Nonpareil	8/6/20	n/a	n/a	8/16/20
Bakers	S	Wood Colony	8/26/20	n/a	n/a	9/5/20
Bakers	S	Monterey	9/23/20	n/a	n/a	10/3/20
Frank N	N	Nonpareil	8/8/21	8/9/21	8/11/21	8/14/21
Nickels Soil Lab	N	Kochi	8/7/21	8/9/21	8/11/21	8/14/21
Nickels Soil Lab	N	Nonpareil	8/7/21	8/9/21	8/11/21	8/14/21
Nickels Soil Lab	N	Fritz	9/14/21	9/14/21	9/17/21	9/22/21
Cutter	N	Nonpareil	8/11/21	8/11/21	8/14/21	8/18/21
Warnerville	S	Monterey	9/3/21	9/3/21	9/7/21	9/9/21
312	S	Aldrich	9/8/21	9/9/21	9/13/21	n/a
312	S	Sonora	9/8/21	9/9/21	9/13/21	n/a
321	S	Aldrich	9/9/21	9/9/21	9/13/21	n/a
321	S	Sonora	9/9/21	9/9/21	9/13/21	n/a

Note: S and N mean the south and north regions of California, respectively.

4.3.3 Determination of initial moisture content distribution

Thirty pieces of almonds were used to determine the overall moisture content on a wet basis of whole almonds and individual almond components, using the standard oven method at 105°C for 24 hours. The hulls, shells, and kernels were separated and weighed in aluminum dishes, and

their MC was calculated based on their initial (wet) and final (dry) weights. The overall MC of the whole almond was determined using the following equation:

$$MC = \frac{(W_{hi}-W_{hd})+(W_{si}-W_{sd})+(W_{ki}-W_{kd})}{W_{hi}+W_{si}+W_{ki}} \times 100\% \quad (4.1)$$

where W_{hi} , W_{si} , and W_{ki} were the initial weights (wet) of the hulls, shells, and kernels (g), respectively; W_{hd} , W_{sd} , and W_{kd} were the final weights (dry) of the hulls, shells, and kernels (g), respectively.

4.3.4 Determination of initial weight ratio and bulk density

Harvested almonds may consist of three fractions: in-hull almonds, in-shell almonds, and loose hulls, depending on the harvest time. The weight ratio of each fraction using the following equation:

$$WR_i = \frac{W_i}{W_t} \quad (4.2)$$

where i represents the fraction (in-hull almonds, in-shell almonds, and loose hulls); W_i is the weight of the specific fraction, and W_t is the total sample weight.

The bulk density (ρ_b) is defined as the ratio of the mass of the sample to its total volume when stacked in bulk. It was determined using the method introduced by Aydin (2003) and calculated using the following equation:

$$\rho_b = \frac{W_{component}}{V} \quad (4.3)$$

where $W_{component}$ is the mass of the component and V is the volume.

4.3.5 Determination of three axial dimension and shape

Thirty almonds from each fraction (in-hull, in-shell, and kernel) were measured for their axial dimensions, including length (L), width (W), and thickness (T), using a digital caliper with an accuracy of 0.01 mm (KR_001, KRAFTLER), as shown in Figure 4.2Fig.

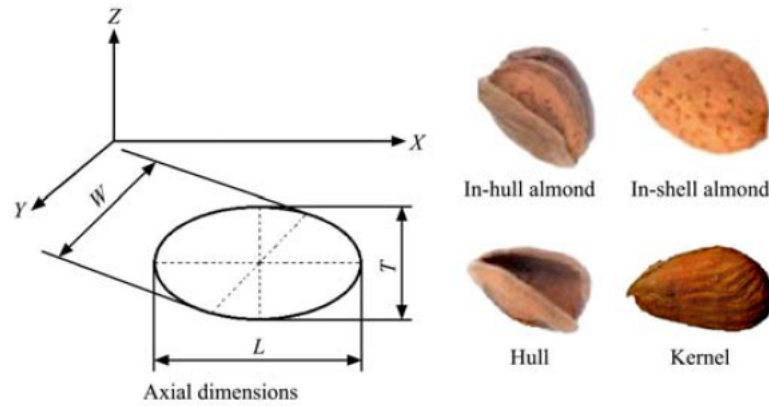


Figure 4.2 Axial dimensions and different fractions of off-ground harvested almonds

Using the measured dimensions, the geometric mean diameter (d_g), sphericity (ϕ), and volume (V) were calculated as follows (Mohsenin, 1986):

$$d_g = (LWT)^{1/3} \quad (4.4)$$

$$\phi = \frac{d_g}{L} \times 100 \quad (4.5)$$

$$V = \pi d_g^3 / 6 \quad (4.6)$$

4.3.6 Determination of chemical composition

Thirty almonds were separated into hulls, shells, and kernels and then ground using a Kitchen Food Chopper (Model KFC3516, Benton Harbor, MI). The ground samples were sent to Denele Analytical Lab in Woodland, CA, for proximate analysis. Table 4.2 summarizes the methods and instruments used to measure protein, fat, carbohydrate, crude fiber, and ash contents.

Table 4.2 Determination of major chemical compositions of different almond components

Composition	Method/Equipment	Reference
Dry matter	Oven drying at 105°C until constant weight	Method B-1.10 Gavlak et al. (2003)
Ash	Dry ashing/Muffle furnace	Method B-4.10 Gavlak et al. (2003)

Protein	Automated combustion/Velp Dumas NDA 702 (VELP Scientific Inc., Babylon, NY)	Method B-2.20 Gavlak et al. (2003)
Fat	High temperature solvent extraction/Ankom-XT10 fat extractor (Ankom Technology Crop., Macedon, NY)	(AOCS- Am 5-04)
Crude fiber	Filer Bag Technique A2000/ANKOM (Ankom Technology Crop., Macedon, NY)	(AOCS- Ba 6a-05)
Carbohydrate	Water extraction of sugar and analyzed by HPLC (Shimadzu Scientific Instruments) equipped with a Biorad Aminex HP-87P column and a refractive index detector (RID)	Holtman et al. (2015)

4.3.7 Determination of thermal properties

Using the chemical composition data, the thermal property (k_i), density (ρ_i), and specific heat (c_i) of different food constituents were predicted through temperature-dependent models developed by Choi (1986), as detailed in Table 4.3. All calculations were based on an ambient temperature of 20°C.

Murakami and Okos (1989) proposed parallel and perpendicular models to estimate the upper and lower bounds of thermal conductivity for food components. These models were applied to determine the thermal conductivity of almond components as follows:

The parallel model:

$$k = \sum x_i^v k_i \quad (4.7)$$

The perpendicular model:

$$k = 1 / \sum (x_i^v / k_i) \quad (4.8)$$

$$x_i^v = \frac{x_i / \rho_i}{\sum (x_i / \rho_i)} \quad (4.9)$$

where k_i is the thermal conductivity of the food constituents; x_i is the mass fraction of the food constituent; ρ_i is the density of the food constituents; x_i^v was the volume fraction of constituent i .

The density of almond components was calculated using the following equation:

$$\rho = \frac{1}{\sum x_i/\rho_i} \quad (4.10)$$

The specific heat of almond components was calculated as:

$$c = \sum c_i x_i \quad (4.11)$$

where c_i is the specific heat of the food constituents.

Table 4.3 Temperature-dependent thermal property models of food constituents

Thermal property	Food constituents	Thermal property model at temperatures ranging from -40°C to 150°C
Thermal conductivity k (W/m · K)	Moisture	$k = 5.7109 \times 10^{-1} + 1.7625 \times 10^{-3}T - 6.7036 \times 10^{-6}T^2$
	Protein	$k = 1.7881 \times 10^{-1} + 1.1958 \times 10^{-3}T - 2.7178 \times 10^{-6}T^2$
	Fat	$k = 1.8071 \times 10^{-1} - 2.7604 \times 10^{-4}T - 1.7749 \times 10^{-7}T^2$
	Carbohydrate	$k = 2.0141 \times 10^{-1} + 1.3874 \times 10^{-3}T - 4.3312 \times 10^{-6}T^2$
	Fiber	$k = 1.8331 \times 10^{-1} + 1.2497 \times 10^{-3}T - 3.1683 \times 10^{-6}T^2$
	Ash	$k = 3.2962 \times 10^{-1} + 1.4011 \times 10^{-3}T - 2.9069 \times 10^{-6}T^2$
Density ρ (kg/m ³)	Moisture	$\rho = 9.9718 \times 10^2 + 3.1439 \times 10^{-3}T - 3.7574 \times 10^{-3}T^2$
	Protein	$\rho = 1.3299 \times 10^3 - 5.184 \times 10^{-1}T$
	Fat	$\rho = 9.2559 \times 10^2 - 4.1757 \times 10^{-1}T$
	Carbohydrate	$\rho = 1.5991 \times 10^3 - 3.1046 \times 10^{-1}T$
	Fiber	$\rho = 1.3115 \times 10^3 - 3.6589 \times 10^{-1}T$
	Ash	$\rho = 2.4238 \times 10^3 - 2.8063 \times 10^{-1}T$
Specific heat c_p (kJ/kg · K)	Moisture	$c_p = 4.1289 - 9.0864 \times 10^{-5}T + 5.4731 \times 10^{-6}T^2$
	Protein	$c_p = 2.0082 + 1.2089 \times 10^{-3}T - 1.3129 \times 10^{-6}T^2$
	Fat	$c_p = 1.9842 + 1.4733 \times 10^{-3}T - 4.8008 \times 10^{-6}T^2$
	Carbohydrate	$c_p = 1.5488 + 1.9625 \times 10^{-3}T - 5.9399 \times 10^{-6}T^2$
	Fiber	$c_p = 1.8459 + 1.8306 \times 10^{-3}T - 4.6509 \times 10^{-6}T^2$
	Ash	$c_p = 1.0926 + 1.8896 \times 10^{-3}T - 3.6817 \times 10^{-6}T^2$

4.3.8 Determination of terminal velocity

The terminal velocity of individual almonds was determined using a cylindrical column based on the experimental procedure outlined by Khir et al. (2014). The experimental setup, shown in Figure 4.3, consisted of a custom-designed vertical transparent plastic column with 1 m in height and 0.2 m in diameter. A centrifugal blower (Dayton Electric Mfg. Co.) generated the upward airflow, with its speed controlled by a speed amplifier (Dayton Electric Mfg. Co.). An air straightener was integrated into the system to ensure uniform airflow. A perforated screen, positioned 0.5 m above the column's base, supported the almond samples.

The air velocity at which each almond became suspended was measured using a hot-wire anemometer (HHF-SD1, Omega, USA) with an accuracy of 0.1 m/s. Each almond was placed individually on the perforated screen, and the terminal velocity was recorded as the point at which the upward airflow caused the almond to be dislodged from the screen. Three replicate measurements were performed for each almond.

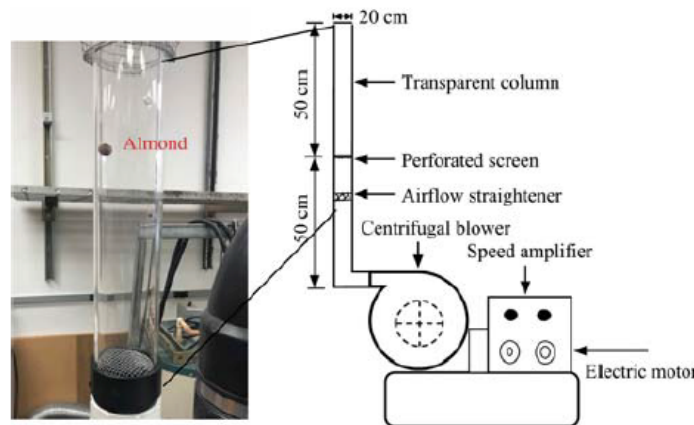


Figure 4.3 Schematic diagram and photo of terminal velocity measurement device (Khir et al., 2014)

4.3.9 Statistical analysis

The results were analyzed using RStudio (version 2021, PBC, Boston, MA), Prism (version 9.4.0, GraphPad Software, LLC), and MATLAB (version R2020b, The MathWorks, Inc).

Statistical significance and multiple comparisons were evaluated using one-way analysis of variance (ANOVA) at a significant level of $\alpha = 0.05$, followed by Tukey's Honestly Significant Difference (HSD) post hoc test.

4.4 Results and Discussion

4.4.1 Insect damage of almond

Figure 4.4 illustrates the insect development change (IDC) in almonds during the conventional harvest. IDC varied across farms and almond varieties, with Fritz almonds from Nickels farm and Nonpareil almonds from Cutter farm exhibiting the highest values, reaching 10.3% and 10.7%, respectively. Nonpareil almonds from Nickels and Frank farms showed an increasing IDC trend, ranging from 0.3% to 3.7% and 1.3% to 2.3%, respectively, after drying on the orchard floor for about one week. In contrast, other varieties and farms displayed lower IDC values, around 1.0%. These results highlight the greater susceptibility of Nonpareil and Fritz almonds to insect infestation, emphasizing the need for enhanced pest management practices at Frank, Cutter, and Nickels farms.

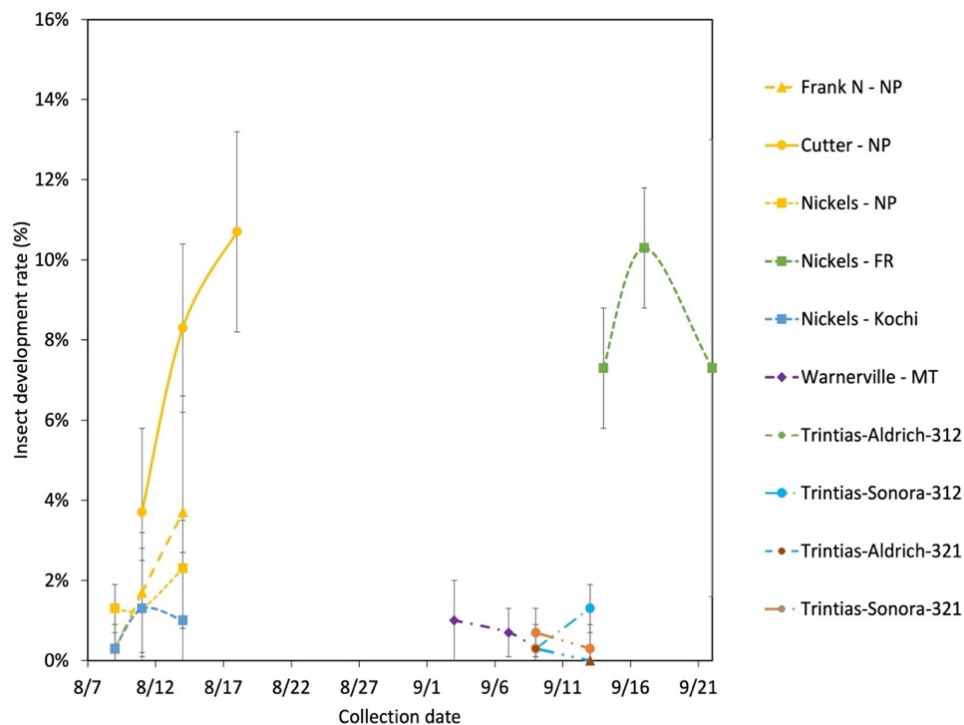


Figure 4.4 Insect damage changes in conventionally harvested on-ground dried almonds

The data presented in Figure 4.5 compares the insect damage ratio of off-ground harvested almonds to conventionally harvested almonds. Off-ground harvested almonds had a significantly lower insect damage ratio ($2.0 \pm 1.7\%$) compared to conventionally harvested almonds ($4.2 \pm 3.7\%$). Regionally, conventionally harvested almonds from the northern region displayed a higher insect damage ratio ($6.0 \pm 3.4\%$) than those from the southern region ($2.6 \pm 3.4\%$). The higher insect damage in the northern region may be due to its cooler, more humid climate, which favors insect proliferation. However, no clear trend was observed regarding the year of harvest and insect damage ratio.

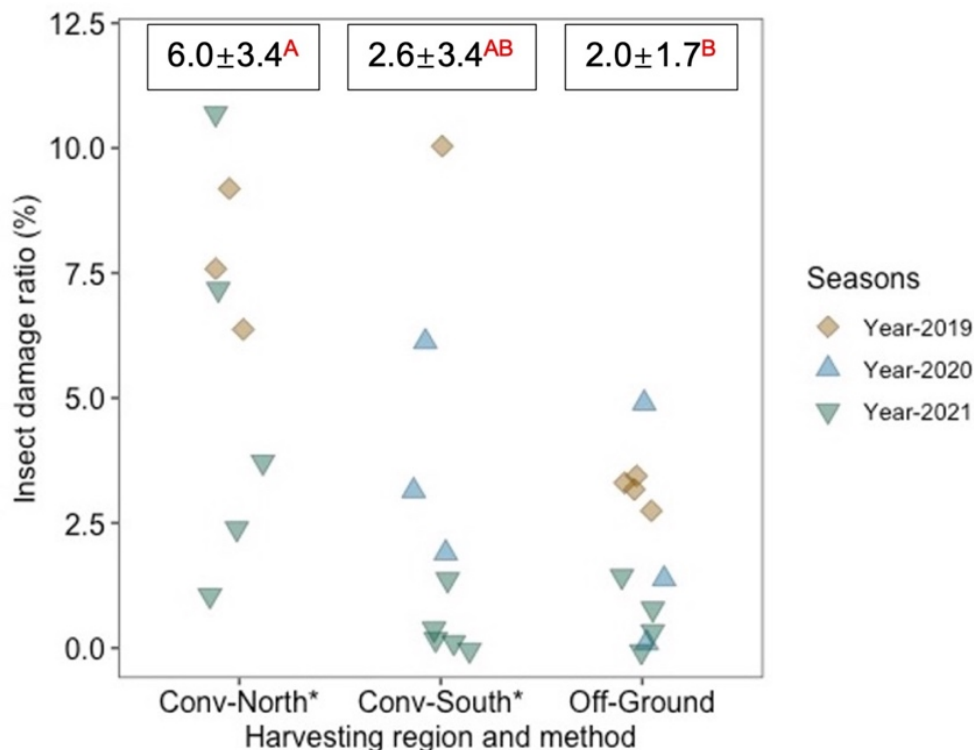


Figure 4.5 Insect damage ratios of conventionally harvested almonds from north and south regions and off-ground harvested almonds during three consecutive harvesting seasons. Note: Values followed by the same capital letter are not significantly different at $P < 0.05$

4.4.2 Distribution of initial moisture content

Figure 4.6 illustrates the initial moisture content (MC) distribution of almonds harvested at early harvest (EH) and standard harvest (SH). The results reveal that EH almonds consisted solely of in-hull almonds, whereas SH almonds comprised three fractions: in-hull almonds, in-shell almonds, and loose hulls (not shown in the figure). Overall, almonds harvested at EH had a significantly higher moisture content than those harvested at SH. The average overall MC of EH almonds was approximately 63% (wet basis), while for SH, the in-hull almonds had an average MC of about 22%, and the in-shell almonds averaged 8%.

For EH in-hull almonds, the respective MC values for hulls, shells, and kernels were 76.3%, 46.8%, and 28.5%. In comparison, SH in-hull almonds exhibited MC values of 27.1% for hulls,

15.3% for shells, and 13.0% for kernels. The hulls displayed the highest MC in both EH and SH almonds, followed by the shells and kernels.

A clear difference in MC between SH in-hull and in-shell almonds was also observed. In-hull almonds had a wider and higher range of moisture, with overall MC varying from 11.7% to 44.4%, compared to in-shell almonds, which ranged from 5.4% to 14.6%. Kernel MC for in-hull and in-shell almonds ranged from 3.6% to 32.5% and 3.4% to 15.8%, respectively.

The coexistence of both high-moisture in-hull almonds and low-moisture in-shell almonds in SH can pose challenges during the drying process. High-moisture in-hull almonds may be under-dried, raising food safety concerns, while low-moisture in-shell almonds risk being over-dried, leading to diminished product quality and increased energy consumption. Thus, the development of an effective sorting procedure for almonds harvested at SH is critical to ensure optimal drying outcomes.

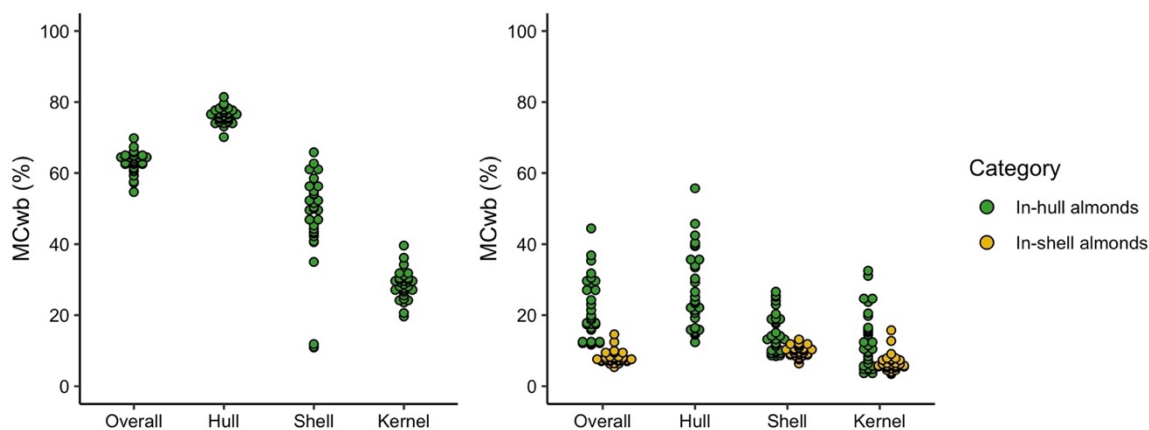


Figure 4.6 Initial MC distribution of early harvested (left) and standard harvested (right) almonds

4.4.3 Correlation between the whole almond MC and kernel MC

Estimating the moisture content (MC) of almond kernels based on the overall MC of whole almonds is crucial for determining optimal drying conditions. Figure 4.7 illustrates the relationship between the overall MC of in-shell and in-hull almonds and the corresponding kernel MC for

almonds from early harvest (EH) and standard harvest (SH). Regression analysis was used to determine the correlations between the overall MC of in-hull and in-shell almonds and their corresponding kernel MC, with the results presented in Table 4.4.

The analysis showed that SH in-shell almonds exhibited a relatively strong linear correlation ($R^2_{adj}=0.8955$) between the overall almond MC and kernel MC, followed by in-hull almonds ($R^2_{adj}=0.7423$). In contrast, no clear correlation was observed for EH almonds. This discrepancy may be attributed to the fact that most EH almonds were either in unsplit or minimally split conditions (stages C and D, as shown in Figure 1.3), where the moisture in the hull begins to decrease while the kernel moisture remains largely unchanged. These findings align with Coates (2018), who indicated that moisture does not move uniformly through the almond fruit, as the kernel only begins to lose moisture after the shell and hull have undergone significant moisture loss.

Therefore, the regression models are useful for predicting the kernel moisture based on overall almond moisture for almonds from SH but not for EH almonds due to the uneven moisture distribution at the early stages of hull split.

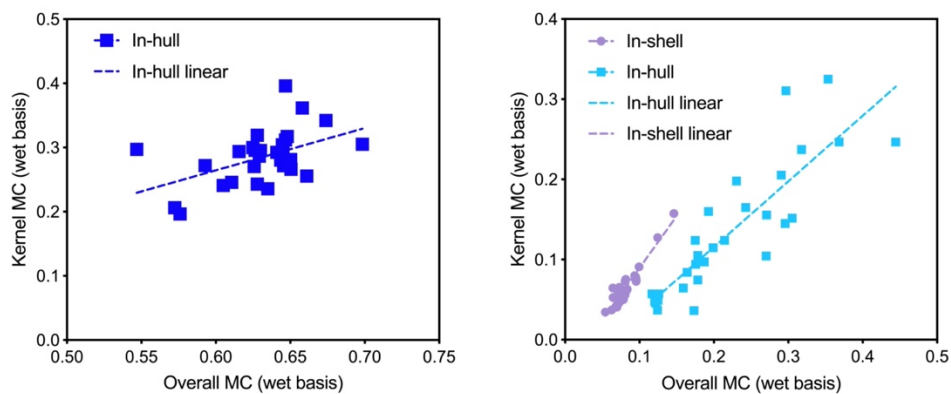


Figure 4.7 Correlation between the overall MC of in-hull and in-shell almonds and corresponding kernel MC (Left side: almonds from EH; Right side: almonds from SH)

Table 4.4 Correlation between MC of whole almonds and their corresponding kernels for both in-hull and in-shell almonds at early and standard harvest

Harvest timing	Fraction	Regression equation	R_{adj}^2	RMSE
EH	In-hull	$MC_{kernel} = 0.6586 \times MC_{in-hull} - 0.131$	0.2102	0.03678
SH	In-hull	$MC_{kernel} = 0.8182 \times MC_{in-hull} - 0.048$	0.7423	0.04126
	In-shell	$MC_{kernel} = 1.295 \times MC_{in-hull} - 0.040$	0.8955	0.00806

4.4.4 Characteristics of size and shape

Table 4.5 summarizes the dimensions, sphericity, geometric mean diameter, unit mass, volume, bulk density, and initial weight ratio of different almond components for both early harvest (EH) and standard harvest (SH). For EH in-hull almonds, the mean values for length, width, thickness, sphericity, hull mass, and bulk density were 32.8 mm, 25.2 mm, 24.4 mm, 83%, 5.0 g, and 0.41 g/cm³, respectively. The corresponding values for SH in-hull almonds were 35.9 mm, 24.1 mm, 24.5 mm, 77%, 3.3 g, and 0.39 g/cm³. The moisture content (MC) results from the previous section revealed a decrease in MC from EH to SH, which correlates with the observed decrease in bulk density. This trend aligns with findings for other agricultural products, such as pistachio nut (Razavi & Taghizadeh, 2007), terebinth fruits (Aydın & Özcan, 2002), pumpkin seeds (Joshi et al., 1993), cumin seed (Singh & Goswami, 1996).

However, a negative linear relationship between bulk density and moisture content was also reported by various researchers (Aydın, 2003; Bart-Plange & Baryeh, 2003; Carman, 1996; Deshpande et al., 1993; Mirzabe et al., 2013). These discrepancies could stem from differences in cell structure and how the material's volume and mass change as moisture content increases (Razavi et al., 2007; Singh & Goswami, 1996).

Significant differences were found between EH and SH in-hull almonds, with EH in-hull almonds exhibiting greater hull mass, unit mass, and sphericity but shorter lengths than SH

almonds. When comparing these results with values from Aydin (2003) and Mirzabe et al. (2013), both EH and SH almonds showed greater dimensions and dimensional properties (geometric mean diameter, sphericity, and volume). Furthermore, both EH and SH almonds had more spherical shapes, making them easier to roll on a surface compared to conventionally harvested almonds, which have a sphericity range of 52.1% to 76.5% (Abalone et al., 2004; Aydin, 2003; Mahmoodi et al., 2011; Mirzabe et al., 2013; Muir et al., 2001). This increased sphericity is critical for the design of handling equipment such as hoppers and dehullers for off-ground harvested almonds.

From a drying model perspective, the sphericity of in-hull almonds is not as high compared to in-shell walnuts (92% on average) and kernels (82% on average), as noted by Chen, Venkitasamy, et al. (2020). Previous studies have generally assumed that almonds are spherical (Coates, 2018a; Kaveh et al., 2018; Mirzabe et al., 2013), which could lead to oversimplification in analytical solutions to diffusion equations. Based on the current research, it is more accurate to assume that the geometry of in-hull almonds and their components is ellipsoidal when modeling the drying process.

Table 4.5 Size and shape characteristics of different types of almonds

Almond type	Property	Early harvest (EH)	Standard harvest (SH)
In-hull almond	Length (mm)	32.8 ± 1.2^b	35.9 ± 2.7^a
	Width	25.2 ± 0.9	24.1 ± 2.5
	Thickness	24.4 ± 1.1	24.5 ± 2.5
	d_g (mm)	27.2 ± 0.9	27.6 ± 1.9
	ϕ (%)	83.0 ± 2.2^a	77.0 ± 3.3^b
	Hull mass (g)	5.0 ± 0.7^a	3.3 ± 0.8^b
	Volume (cm ³)	10.6 ± 1.0	11.2 ± 2.3
	Bulk density (g/cm ³)	0.41 ± 0.01	0.39 ± 0.02
	Initial weight ratio (%)	100.0 ± 0.0^a	51.0 ± 6.0^b

In-shell almond	Unit mass (g)	7.5 ± 1.1^a	5.8 ± 1.2^b
	Length (mm)	27.0 ± 0.9^b	32.5 ± 2.7^a
	Width	17.6 ± 0.9^b	20.3 ± 1.6^a
	Thickness	15.5 ± 0.8^b	17.2 ± 1.3^a
	d_g (mm)	19.5 ± 0.7^b	22.4 ± 1.5^a
	$\emptyset$ (%)	72.2 ± 2.2^a	69.2 ± 2.4^b
	Shell mass (g)	1.1 ± 0.3	1.2 ± 0.3
	Volume (cm ³)	3.9 ± 0.4^b	6.0 ± 1.4^a
	Bulk density (g/cm ³)	n/a	0.34 ± 0.01
	Initial weight ratio (%)	n/a	11.0 ± 5.0
	Unit mass (g)	2.5 ± 0.5	2.5 ± 0.6
	Length (mm)	21.1 ± 0.9	21.9 ± 1.7
Kernel	Width	13.0 ± 0.6	12.5 ± 1.1
	Thickness	11.0 ± 0.5^a	8.6 ± 1.2^b
	d_g (mm)	14.5 ± 0.6	13.3 ± 1.1
	$\emptyset$ (%)	68.4 ± 1.8^a	60.6 ± 3.9^b
	Unit mass (g)	1.4 ± 0.2	1.3 ± 0.3
	Volume (cm ³)	1.6 ± 0.2	1.2 ± 0.3
	Length (mm)	n/a	36.3 ± 3.0
Loose hull	Width	n/a	22.7 ± 6.1
	Thickness	n/a	28.3 ± 7.9
	Bulk density (g/cm ³)	n/a	0.26 ± 0.02
	Initial weight ratio (%)	n/a	38.0 ± 6.0

Note: Values followed by the different lower-case letters in each column are significantly different at $p < 0.05$. Values without letters are not significantly different. n/a: not applicable.

This section compares the size and shape characteristics of in-shell almonds and kernels from early harvest (EH) and standard harvest (SH). For in-shell almonds, SH almonds exhibited significantly greater length, width, thickness, geometric mean diameter, and volume but lower

sphericity compared to EH almonds. The mean values for EH in-shell almonds were 27.0 mm in length, 17.6 mm in width, 15.5 mm in thickness, 19.5 mm in geometric mean diameter, 3.9 cm³ in volume, and 72.2% sphericity. In contrast, SH in-shell almonds had values of 32.5 mm in length, 20.3 mm in width, 17.2 mm in thickness, 6.0 cm³ in volume, and 69.2% sphericity.

These changes in dimensions are likely due to a surface hardening process of the shell during the transition from EH to SH. Observations showed that shells from EH almonds were wetter and softer than SH almonds, which displayed a harder surface (Figure 4.8 a-b). Additionally, the hull and shell remained adhered to one another for EH almonds while they were separated in SH almonds (Figure 4.8 c-d).



Figure 4.8 EH almond (a, c) and SH almond (b, d)

In the case of kernels, no significant differences in most dimensional parameters were noted between EH and SH almonds, except thickness and sphericity. Kernels from EH almonds exhibited significantly greater thickness (11.0 mm) and sphericity (68.4%) than those from SH almonds, which had values of 8.6 mm and 60.6%, respectively.

4.4.5 Chemical composition of almonds

Table 4.6 presents the major chemical composition of almond components during early harvest (EH) and standard harvest (SH). The measured data were compared with historical literature, though data on almond shells were not available. Yada et al. (2013) highlighted the natural variability in almond kernel composition across varieties through multi-year, multi-region studies of seven major almond varieties grown in California. In this study, the major chemical composition of Fritz almonds generally aligned with the literature. As expected, almond kernels had higher lipid content, more sugar in almond hulls, and a higher fiber content in almond shells.

From EH to SH, the crude fat content of almond kernels increased from 40.1% to 45.9%, the sugar content in almond hulls rose from 19.8% to 34.6%, and the fiber content in almond shells ranged from 46.0% to 47.6%. Additionally, the ash content in almond hulls and fiber content in kernels was slightly higher than reported in the literature.

Across all almond components, a clear increase in sugar content was observed from EH to SH. The sugar content rose from 19.8% to 34.6% in hulls, 4.6% to 5.1% in shells, and 20.0% to 22.4% in kernels.. The increasing sugar content in kernels is consistent with findings by Kazantzis et al. (2003), who reported that early-harvested ‘Ferragnes’ almonds had lower sugar content (17.4%) compared to late-harvested almonds (27.3%), with kernel moisture contents of 29.6% (wet basis) and 6.3% (wet basis), respectively. These results suggest that sugar content steadily increases as almonds mature closer to harvest time.

Table 4.6 Major chemical composition (on a DM basis) of Fritz and data reported in the literature

Item	EH- Hull	SH- Hull	Literature ¹	EH- Shell	SH- Shell	Literature ²	EH- Kernel	SH- Kernel	Literature ³
Crude protein	6.9	8.6	2.2-10.3	6.1	6.2	n/a	27.8	23.7	19.1-25.6

Crude fat	1.7	1.4	1.6-3.6	1.5	0.5	n/a	40.1	45.9	46.2-57.7
Sugar	19.8	34.6	14.1-56.9	4.6	5.1	n/a	20.0	22.4	17.4-27.3
Crude fiber	10.2	6.0	10.6-15.1	46.0	47.6	n/a	16.3	14.5	11.0-13.1
Ash	13.0	16.3	5.0-12.0	4.9	3.4	n/a	2.9	2.6	2.4-3.6

1 = DePeters et al. (2020); 2 = Not available; 3 = Kazantzis et al. (2003); Rizwan et al. (2022); Yada et al. (2013)

4.4.6 Thermal properties of different almond components

The thermal properties of various almond components are presented in Table 4.7. The results indicate that the hulls in early harvested (EH) almonds exhibited lower true density but higher thermal conductivity and specific heat than those in standard harvested (SH) almonds. A similar trend was observed for the shells. The mean values for true density, thermal conductivity, and specific heat were 1.165 g/cm³, 0.553 W/m·K, and 3.419 kJ/kg·K for EH hulls, and 1.593 g/cm³, 0.414 W/m·K, and 2.178 kJ/kg·K for SH hulls, respectively. The corresponding values for shells were 1.278 g/cm³, 0.459 W/m·K, and 2.904 kJ/kg·K for EH almonds, and 1.778 g/cm³, 0.316 W/m·K, and 1.699 kJ/kg·K for SH almonds. These findings are consistent with previous research on agricultural materials like cumin seeds (Singh & Goswami, 2000), pistachios (Hsu et al., 1991), and sheanut kernels (Aviara & Haque, 2001), where thermal conductivity and specific heat increased linearly with moisture content, while true density increased as moisture content decreased. Similar trends were observed for apples, bananas, carrots, potatoes, garlic, and onions (Boukouvalas et al., 2006; Krokida et al., 2000; Krokida & Maroulis, 1997; Wang & Brennan, 1995; Zogzas et al., 1994).

For almond kernels, the mean values for true density, thermal conductivity, and specific heat were 1.062 g/cm³, 0.305 W/m·K, and 2.742 kJ/kg·K for EH almonds, and 1.054 g/cm³, 0.226 W/m·K, and 2.279 kJ/kg·K for SH almonds, respectively. Notably, there was a slight decrease in kernel density as moisture content decreased, deviating from the typical trend. This may be attributed to the significant presence of other chemical constituents in the kernels, such as fat, sugar, and protein, which can influence the density in addition to moisture content.

Table 4.7 Thermal properties of different almond components of Fritz almond

Thermal property	EH- Hull	SH- Hull	EH- Shell	SH- Shell	EH- Kernel	SH- Kernel
ρ	1.165	1.593	1.278	1.778	1.062	1.054
(g/cm ³)	1.139-1.247	1.349-2.068	1.219-1.463	1.647-1.963	1.056-1.077	1.039-1.059
k (W/m·K)	0.553	0.414	0.459	0.316	0.305	0.226
	0.532-0.574	0.332-0.496	0.455-0.463	0.223-0.408	0.233-0.377	0.187-0.264
c_p (kJ/kg·K)	3.419	2.178	2.904	1.699	2.742	2.279
	3.142-3.515	1.429-2.765	2.359-3.113	1.403-1.943	2.441-2.859	2.138-2.734

4.4.7 Assessment of sorting efficiency in almond harvest

The primary goal of sorting is to efficiently remove loose hulls while minimizing product loss. Additionally, in-shell and in-hull almonds should be effectively separated, as their moisture contents (MCs) differ significantly, allowing for separate drying. The results showed that the range of terminal velocity (TV) for in-hull almonds was much higher than that of loose hulls, with minimal overlap (Figure 4.9). This suggests that the separation of in-hull almonds and loose hulls could be achieved based on their TV differences. By selecting a critical TV value of 12.2 m/s, the in-hull almonds and loose hulls could be 100% separated (Figure 4.10). However, the TV range of in-shell almonds overlapped more with the other two fractions, indicating that using TV as the

primary sorting method may not be effective, as large portions of in-shell almonds could be misclassified.

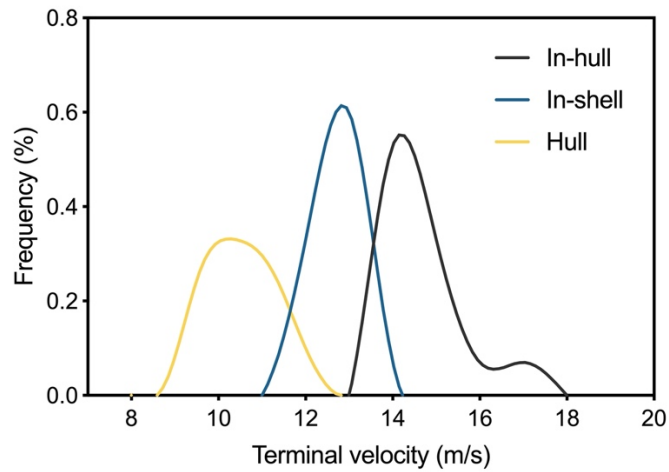


Figure 4.9 Terminal velocities of different fractions of freshly harvested almonds at SH

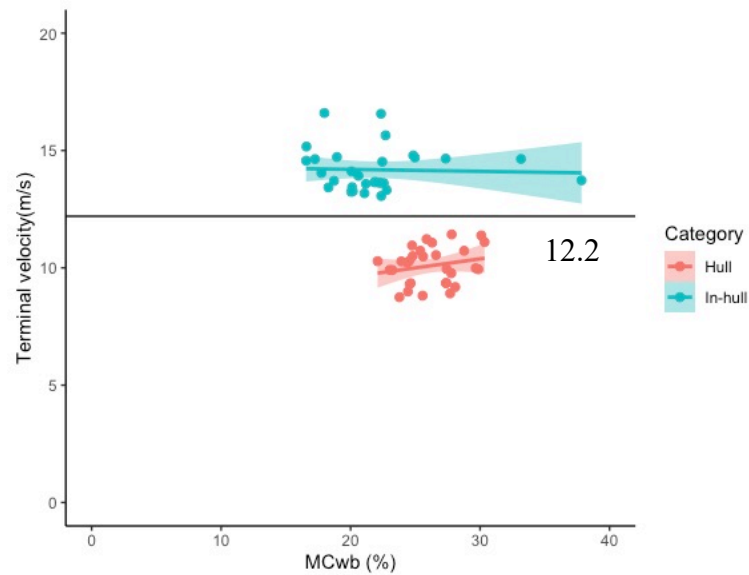


Figure 4.10 Distributions of terminal velocity of in-hull almonds and loose hulls against moisture content, with the critical value (black line) of terminal velocity

As discussed in Section 4.4.4, the axial dimensions (length, width, and thickness) of in-hull almonds were larger than those of in-shell almonds, while the size of loose hulls was similar to in-hull almonds. Thickness (T) was the smallest dimension, and in-shell almonds had significantly smaller thickness ($p < 0.05$) than both loose hulls and in-hull almonds. Therefore, thickness could

be used as a cut-off size for separating in-shell almonds from the other two fractions. The sorting potential based on dimensional characteristics is shown in Figure 4.11. The thickness of in-shell almonds had a relatively narrow distribution range, and a cut-off size of 21.1 mm would allow for 100% separation of in-shell almonds. However, some in-hull almonds and loose hulls with smaller thicknesses would be mixed into the in-shell fraction.

To assess sorting accuracy, misclassification percentages were determined. The results showed that 6.7% of in-hull almonds and 23.3% of loose hulls would be misclassified into the in-shell almonds. These percentages are relatively small and acceptable. Thus, thickness-based size sorting can be applied as the first step to separate in-shell almonds, followed by TV sorting to separate in-hull almonds and loose hulls.

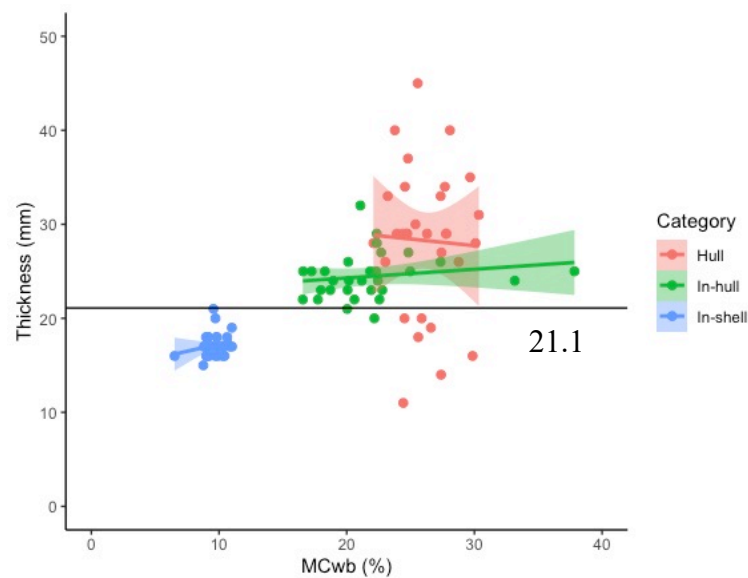


Figure 4.11 Sorting potential based on dimensional characteristics

4.5 Conclusions

Off-ground harvested almonds exhibited a significantly lower percentage of insect infestation compared to conventionally harvested almonds. Freshly harvested almonds were observed in varying stages of maturity, leading to three fractions, namely in-hull almonds, in-shell almonds,

and loose hulls for SH (standard harvest) and one fraction (in-hull almonds) for EH (early harvest). The overall moisture content of almonds was considerably higher for EH almonds compared to SH almonds, although SH almonds exhibited a broader range of moisture levels. Notably, in-hull almonds and loose hulls had substantially higher moisture content than in-shell almonds at SH, emphasizing the need for fraction sorting prior to drying.

A two-step sorting approach was developed. In the first step, a cut-off size of 21.1 mm was found to effectively sort in-shell almonds with 100% accuracy. In the second step, in-hull almonds were successfully separated from loose hulls using a terminal velocity threshold of 12.2 m/s. After sorting, the moisture content variation among the in-shell and in-hull almonds was reduced compared to the unsorted almond mixture.

The dimensional, chemical, and thermal properties of almonds from both EH and SH were determined. The thermal conductivity of EH almond hulls, shells, and kernels ranged from 0.532 to 0.574 W/m·K, 0.455 to 0.463 W/m·K, and 0.233 to 0.377 W/m·K, respectively. For SH almonds, these values ranged from 0.332 to 0.496 W/m·K, 0.223 to 0.408 W/m·K, and 0.187 to 0.264 W/m·K, respectively. Similarly, the specific heat of EH almond components ranged from 3.142 to 3.515 kJ/kg·K, 2.359 to 3.113 kJ/kg·K, and 2.441 to 2.859 kJ/kg·K for hulls, shells, and kernels, respectively, while SH almonds had specific heat values of 1.429 to 2.765 kJ/kg·K, 1.403 to 1.943 kJ/kg·K, and 2.138 to 2.734 kJ/kg·K.

The detailed understanding of almond properties from this study will facilitate future research on mathematical modeling of the drying process. Furthermore, the findings provide valuable insights into the development of efficient sorting and drying methods for off-ground harvested almonds, ultimately enhancing processing efficiency, product quality, and safety.

5 CHAPTER 5 EFFECTIVE MOISTURE DIFFUSIVITY AND EVOLUTION OF SHRINKAGE IN IN-HULL ALMONDS DURING HOT AIR DRYING

5.1 Introduction

Almonds harvested using the off-ground method, particularly at early stages, tend to have high moisture content. To ensure the quality and safety of the final product, rapid drying of off-ground harvested almonds is essential. The drying process is dynamic, involving significant heat and moisture transfer. Understanding the drying kinetics during hot air drying is therefore crucial for developing efficient drying methods.

Effective moisture diffusivity is a key parameter in characterizing moisture transfer mechanisms during drying (Karathanos et al., 1990). Fick's law of diffusion is commonly used to relate moisture diffusivity to the drying rate. Many studies have applied the Fickian diffusion model to estimate average effective moisture diffusivity in various foodstuffs, often using the slope method and assuming constant diffusivity throughout the drying process (Akhijani et al., 2016; Babalis & Belessiotis, 2004; Kayran & Doymaz, 2017; Rafiee et al., 2010). Additionally, the effect of drying temperature on moisture diffusivity is often described using an Arrhenius-type relationship (Akhijani et al., 2016; Kumar et al., 2017).

Research shows that moisture content and temperature significantly influence moisture diffusivity in biological and food materials (Azzouz et al., 2002; Bal et al., 2010; Çağlar et al., 2009; Chen, 2007; Hassini et al., 2007; Karim & Hawlader, 2005; Thuwapanichayanan et al., 2011). As a result, average diffusivity values may not adequately capture the true dynamics of moisture diffusion during drying, especially at lower moisture levels (Md Imran Hossen Khan et al., 2017; Raghavan et al., 1995). In several foods, moisture diffusivity has been shown to vary with moisture content, following exponential (Hsu, 1983), power-law (Coumans & Luyben, 1988),

or gamma functions (Villalobos, 1986). Dak and Pareek (2014) also identified a third-order polynomial relationship for microwave-vacuum drying of pomegranate arils. The variability of moisture diffusivity is complex and system-specific, depending on the interaction between food polymers and water (Karathanos et al., 1990). However, limited research has focused on moisture-dependent diffusivity in almonds under varying drying conditions.

Additionally, most physical models treat almonds as spherical objects (Coates, 2018b; Kaveh et al., 2018; Mirzabe et al., 2013). In reality, almonds are ellipsoidal with distinct major, intermediate, and minor axes (Mohsenin, 1986). Accurately modeling this geometry is critical to determine moisture diffusivity and reduce predictive errors (Li et al., 2004; Prakash & Pan, 2012). Almonds also have a multi-layer structure comprising a hull, shell, and kernel, each with unique chemical and physical properties (Aydin, 2003; Crisosto et al., 2020; Hawker & Buttrose, 1980; Holtman et al., 2015; Li et al., 2018; Moreira & Bakker-Arkema, 1989; Prgomet et al., 2017; Sathe, 1992; Wang et al., 2021). To date, no studies have simultaneously reported effective moisture diffusivity for the hull, shell, and kernel during in-hull almond drying.

Shrinkage, often neglected in drying models, can also impact the prediction of moisture content profiles, as many foodstuffs experience volume reduction with water loss. This shrinkage can affect moisture and vapor migration (Hatamipour & Mowla, 2002; Khraisheh et al., 1997; Mayor & Sereno, 2004; Suzuki et al., 1976). Therefore, investigating the shrinkage of different almond components during in-hull drying under various conditions is critical. The insights gained will help develop more accurate theoretical models for almond drying.

5.2 Specific Objectives

The research presented in this chapter was designed to determine the effective moisture diffusivities of the almond hull, shell, and kernel during in-hull almond drying using hot air. It

aimed to establish mathematical correlations between effective moisture diffusivity and the moisture content (MC) of the samples. Additionally, the study sought to investigate the shrinkage behavior of these three almond components throughout the drying process, providing critical insights for the development of a comprehensive drying model in the subsequent chapter. The findings are expected to significantly enhance the understanding of moisture diffusion dynamics in almond drying.

5.3 Materials and Methods

5.3.1 Sample preparation

Almonds of the 'Fritz' variety, freshly harvested off-ground, were collected from the Nickels Soil Lab in Arbuckle, California, during the 2022 harvest season for this study. To prevent moisture loss under ambient conditions, the samples were stored in sealed bags. Given the natural variation in moisture content, weight, and dimensions of freshly harvested almonds, a single almond could not represent the entire batch. Therefore, to minimize variability in initial weight and moisture content, almonds with comparable weights and dimensions were carefully selected for the drying experiments.

It was assumed that almonds from the same batch shared a consistent average moisture content and component weight ratio. Prior to testing, each almond was marked, and its weight and dimensions were recorded to track moisture content (MC) and dimensional changes throughout the drying process. Moisture content was determined by dehydrating the samples in an electric oven at 105°C for 24 hours. The almond hulls, shells, and kernels were then separated and weighed in aluminum dishes, and their MC was calculated based on the initial and final dry weights. The overall MC of the almond was calculated using the following equation:

$$MC = \frac{(W_{hi}-W_{hd})+(W_{si}-W_{sd})+(W_{ki}-W_{kd})}{W_{hi}+W_{si}+W_{ki}} \times 100\% \quad (5.1)$$

where W_{hi} , W_{si} , and W_{ki} were the initial weights (wet) of the hulls, shells, and kernels (g), respectively; W_{hd} , W_{sd} , and W_{kd} were the final weights (dry) of the hulls, shells, and kernels (g), respectively.

5.3.2 Drying experiment

5.3.2.1 Hot air dryer

A laboratory-scale hot air (HA) dryer, with dimensions of 450 mm in length, 350 mm in width, and 350 mm in height, developed by Chen, Venkitasamy, et al. (2020), was used for the HA drying experiments. The design and operational setup of the dryer are depicted in Figure 5.1 A and 5.1 B. The dryer was equipped with a commercial resistance heating element and an electrical fan (Avantco Instrument CFD 10, CA, USA), allowing for precise temperature control within the system.

Sample temperatures were continuously monitored using fast-response hypodermic T-type thermocouples (Omega, Sa1XL-T-120, USA). Weight measurements of the samples were taken both manually and automatically. For automated measurements, two S-beam load cell sensors with a capacity of 4,000 g and an accuracy of 2 g (Meacon automation, Hangzhou, China) were employed. These sensors continuously recorded the weight data, which was displayed on a touch-screen terminal (NT8071iE, Weinview, China). Before the drying tests, the dryer was preheated for 30 minutes to ensure temperature stabilization at the desired conditions.

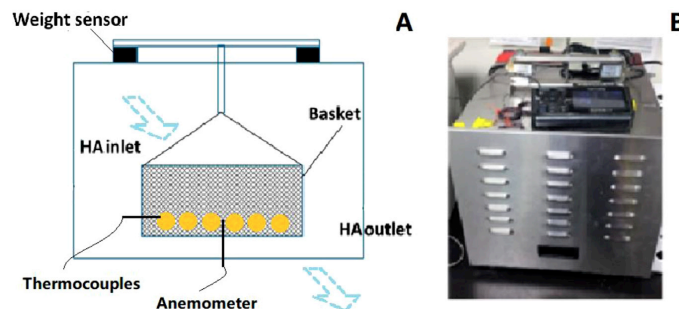


Figure 5.1 Laboratory-scale HA dryer: (A) Schematic diagram and (B) Digital photo

5.3.2.2 *Drying test*

To investigate the moisture diffusion characteristics during almond drying, freshly harvested in-hull almonds were placed in a single layer on the sample trays. Drying experiments were conducted at hot air temperatures of 45°C, 60°C, and 75°C, with an air velocity of 1.4 m/s, following a factorial experimental design. The process continued until the average moisture content of the in-hull almonds reached approximately 9% on a wet basis.

The drying air temperature was continuously monitored using a logged T-type thermocouple, while air velocity was measured with a hot wire anemometer (HHF-SD1, Omega, USA), with an accuracy of ± 0.1 m/s. The relative humidity (RH) values corresponding to the drying air temperatures were recorded as 13.1%, 4.4%, and 3.5%, respectively.

To track the sample temperatures, a T-type thermocouple was inserted into the center of the kernel through a pre-drilled hole in the in-hull almond. Additional thermocouples were attached to the surfaces of the almond shell and hull. Experiments were conducted under stable laboratory conditions, with an ambient temperature of 25.1°C and an RH of 36.3%. All tests were replicated two times to ensure accuracy.

5.3.2.3 *Sampling method*

At each sampling point, 10 marked almonds were removed from the dryer for dimension and moisture content measurements. The axial dimensions of the in-hull almond, including length, width, and thickness, were measured using a digital caliper (KR_001, KRAFTLER) with an accuracy of ± 0.01 mm. After removing the hull and shell, the dimensions of the in-shell almonds and kernels were measured separately. For MC determination, the hull, shell, and kernel of each

almond were separated, weighed individually, and recorded. Each data point represented the average of the 10 sampled almonds, ensuring consistency and accuracy in the measurements.

5.3.3 Determination of the effective moisture diffusivity

The drying curve and rate were derived from the drying experiments, with the drying rate (DR) calculated using the following equation (Abhijit & Gupta, 2003):

$$DR = \frac{M_0 - M_t}{t} \quad (5.2)$$

where, M_0 is the initial moisture content of the sample (kg water/kg dry matter); M_t is the moisture content at time t (kg water/kg dry matter); t is the drying time at different sampling points (min).

The moisture ratio (MR) of the samples was calculated using the following equation:

$$MR = \frac{M_t - M_e}{M_0 - M_e} = \frac{M_t}{M_0} \quad (5.3)$$

where M_e is the equilibrium moisture content (kg water/kg dry matter). Since the surrounding air in the drying chamber was assumed to be completely dry, the value of M_e was considered negligible (Diamante & Munro, 1993; Rani & Tripathy, 2020; Shi et al., 2008), and therefore M_e was assumed to be zero in this study.

Moisture transfer within heterogeneous media is often analyzed using Fick's second law, which is adapted for homogeneous materials. This law, reflecting the heterogeneity of the material through its effective moisture diffusivity, is widely used to model internal moisture transfer, particularly during the falling rate period of drying in biological products. The effective moisture diffusivities of the hull, shell, and kernel in in-hull almonds were determined using Fick's second law of diffusion, expressed as follows:

$$\frac{\partial M}{\partial t} = D_{eff} \nabla^2 M \quad (5.4)$$

Crank (1979) provided the analytical solution to the diffusion equation (Eq. 5.4) for spherical geometry as follows:

$$MR = \frac{6}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{n^2} \exp\left(\frac{-n^2 \pi^2 D_{eff} t}{R^2}\right) \quad (5.5)$$

where R is the radius of the material.

The Eq. 5.5 is often used to estimate the effective moisture diffusivity for long drying times, typically when the moisture ratio (MR) falls below 0.6 (Koua et al., 2019; Onwude et al., 2016; Senadeera et al., 2003):

$$MR = \frac{6}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} t}{R^2}\right) \quad (5.6)$$

Eq. 5.6 can be expressed in a logarithmic form as:

$$\ln(MR) = \ln\left(\frac{6}{\pi^2}\right) - \frac{\pi^2 D_{eff} t}{R^2} \quad (5.7)$$

The effective moisture diffusivity can be determined by plotting $\ln(MR)$ against time, where the slope of the line is used to calculate D_{eff} using the following equation:

$$D_{eff} = k \frac{R^2}{\pi^2} \quad (5.8)$$

where k is the slope of the line.

In previous research, almonds have often been modeled as either spherical (Chilka & Ranade, 2018; Coates, 2018b) or parallelepiped shapes (Ruiz-Beviá et al., 1999; Taitano et al., 2012). However, such simplifications may lead to predictive inaccuracies due to deviations from the almond's actual form (Prakash & Pan, 2012). Almonds are accurately described by an ellipsoidal geometry, defined by their major (2a), intermediate (2b), and minor axes (2c) (Mohsenin, 1986). Consequently, an ellipsoidal model is better suited for simulating the drying kinetics of almonds.

Li et al. (2004) introduced a geometry factor (E) to integrate ellipsoidal dimensions and correlate the intrinsic diffusivity of an ellipsoid to that of an equivalent sphere with a corresponding radius (r_e). The equations are as follows:

$$D_{sphere} = E \times D_{ellipsoid} \quad (5.9)$$

$$E = \frac{1}{3} \left(\frac{1}{(a/r_e)^2} + \frac{1}{(b/r_e)^2} + \frac{1}{(c/r_e)^2} \right) \quad (5.10)$$

$$r_e = (abc)^{1/3} \quad (5.11)$$

Implementing the ellipsoidal model has produced numerical results that closely match experimental data for agricultural products such as corn, wheat, and rice (Gastón et al., 2002; Hendrickx et al., 1986; Igathinathane & Chattopadhyay, 1999; Li et al., 2004; Tolaba et al., 1989).

The average effective moisture diffusivity (D_{ave}) was calculated as the arithmetic mean of all diffusivity values at different MCs, as shown in the following equation (Shi et al., 2008; Singh & Gupta, 2007):

$$D_{ave} = \sum_1^n \frac{D_{eff}}{n} \quad (5.12)$$

To establish a mathematical relationship between effective moisture diffusivity and the sample's MC, regression analysis techniques were applied. The dependency of effective moisture diffusivity on sample MC was represented by a polynomial equation, as shown in Eq. 5.13. Temporal averages of the temperature profiles for the almond hull, shell, and kernel were derived from stable segments of the recorded data. The relationship between average moisture diffusivity and drying air temperature was characterized by the Arrhenius equation (Eq. 5.14):

$$D_{eff} = AM^3 + BM^2 + CM + D \quad (5.13)$$

$$D_{ave} = D_0 e^{-\left(\frac{E_a}{RT}\right)} \quad (5.14)$$

where A, B, C, D are the regression coefficients. D_0 is the pre-exponential factor (m^2/s); T is the absolute temperature (K); R is the universal gas constant ($8.314 \text{ kJ/mol}\cdot\text{K}$); E_a is the activation energy (kJ/mol).

5.3.4 Shrinkage study

For calculating effective moisture diffusivity without accounting for shrinkage, the equivalent radius (r) was assumed to remain constant ($r = r_0$). For shrinkage-inclusive calculations, however, the equivalent radius was treated as a time-dependent variable ($r = r(t)$), derived from the drying experiments. As detailed in Section 5.3.2.3, 10 marked almonds were periodically removed from the dryer to measure their dimensions. The averaged dimensional data were used to develop mathematical models correlating shrinkage with the moisture ratio (MR).

Linear, quadratic, and cubic models, shown in Equations 5.15-17, were fitted to the data using non-linear regression analysis in MATLAB (version R2020b, The MathWorks, Inc.). Additionally, dimensional data from the various sampling points were statistically analyzed using Prism (version 9.4.0, GraphPad Software, LLC). A one-way analysis of variance (ANOVA) was performed to identify significant differences at a significant level of $\alpha = 0.05$, with post-hoc comparisons made using Tukey's Honestly Significant Difference (HSD) test.

$$\text{Linear model:} \quad S_i = a + b \times (MR) \quad (5.15)$$

$$\text{Quadratic model:} \quad S_i = a + b \times (MR) + c \times (MR)^2 \quad (5.16)$$

$$\text{Cubic model:} \quad S_i = a + b \times (MR) + c \times (MR)^2 + d \times (MR)^3 \quad (5.17)$$

where S_i represents the shrinkage parameter (length, width, thickness, and volume); a, b, c, and d are the equation constants.

5.3.5 Statistical analysis

The fitted models for effective moisture diffusivity and shrinkage of almonds during hot air drying were evaluated using the coefficient of determination (R^2), adjusted R-squared (R_{adj}^2), and root mean square error (RMSE). The formulas for these statistical metrics are given below:

$$R^2 = \frac{n \sum_{i=1}^n S_{exp,i} S_{pre,i} - \sum_{i=1}^n S_{exp,i} \sum_{i=1}^n S_{pre,i}}{\sqrt{(n \sum_{i=1}^n S_{pre,i}^2 - (\sum_{i=1}^n S_{pre,i})^2)(n \sum_{i=1}^n S_{exp,i}^2 - (\sum_{i=1}^n S_{exp,i})^2)}} \quad (5.18)$$

$$R_{adj}^2 = 1 - \frac{(1-R^2)(n-1)}{n-p-1} \quad (5.19)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (S_{exp,i} - S_{pre,i})^2}{n}} \quad (5.20)$$

where n is the number of observations; p is the number of independent variables; $S_{exp,i}$ and $S_{pre,i}$ are the i th experimental and predicted parameters, respectively. The regression parameters were selected to minimize the RMSE and maximize R^2 and R_{adj}^2 .

5.4 Results and Discussion

5.4.1 Drying kinetics

The drying kinetics of the almond hull, shell, and kernel during in-hull almond drying at hot air temperatures of 45°C, 60°C, and 75°C are depicted in Figure 5.2-5.4(A), along with their corresponding drying rate curves in Figure 5.2-5.4(B). Consistent with the typical drying behavior observed in most food and agricultural materials (Pakowski & Adamski, 2007; Srikiatden & Roberts, 2006), the moisture content of both the almond hull and shell progressively decreased over time. Higher air temperatures resulted in a marked reduction in drying time, with steeper drying curves, particularly during the initial drying phase ($t < 180$ min). The hull exhibited significantly higher drying rates than the shell; however, as the drying process advanced, the hull and shell rates converged across different temperatures.

According to drying theory, during the early stages of drying, the drying rate is primarily limited by the rate of heat transfer, especially when moisture evaporation occurs at the material surface, in this case, the almond hull. As drying progresses, the evaporation front moves inward, leading to a decrease in the drying rate as the vapor must pass through an increasingly thick layer of dried material (Brennan, 1994).

The drying behavior of the almond kernel differed significantly from that of the hull and shells. Kernel moisture content began to decrease notably after 180 minutes at air temperatures of 60°C and 75°C. In contrast, at 45°C, kernel moisture remained relatively unchanged until approximately 720 minutes (Figure 5.4A). This suggests that 45°C was insufficient for effectively drying almond kernels within in-hull almonds. Additionally, drying at 60°C achieved higher rates and required less time to reach a similar MC in the kernel compared to 75°C, indicating greater efficiency at the moderate temperature. The lower drying rate observed at 75°C could be attributed to the intensified case-hardening effect, which may have formed a barrier, hindering moisture removal from the kernel. This phenomenon is supported by studies on potato samples, where case-hardening was observed as a result of a thin and extremely dry layer forming on the outside of the material. This layer exhibited different transport and mechanical properties compared to the core, impeding internal moisture migration and reducing the overall drying rate (Gulati & Datta, 2015).

At elevated temperatures, the surface of the hull tends to dry rapidly, potentially leading to stiffening, which can hinder subsequent drying (Gulati & Datta, 2015). This rapid surface drying, characterized by steep moisture gradients, can result in the formation of a crust. Such phenomena have been experimentally confirmed in the drying of gels, as demonstrated through MRI analyses (Schrader & Litchfield, 1992). From a diffusion perspective, Achanta et al. (1997) emphasized that this surface region experiences reduced capillary diffusivity and flux, forming a barrier that

impedes the outward migration of internal moisture. Due to this low capillary diffusivity, moisture within the hull is forced to exit the system primarily as water vapor through internal evaporation processes.

The extent of case hardening is influenced by the temperature of exposure, and its effect on reducing the drying rate has been reported in various studies on agricultural and food products, including green bell pepper slices (Sigge et al., 1998), banana slices (Demirel & Turhan, 2003), chicken meat (Matashige & Akahoshi, 2002), shark fillets (Mujaffar & Sankat, 2005), and papaya and garlic (Fernando et al., 2008).

Figure 5.2-5.4(B) examine the moisture loss rate and indicate that the drying of the hull, shell, and kernel occurred predominantly during the falling-rate period. These findings align with observations from earlier studies Alzamora and Chirife (1980); Chirife (1971); Chirife and Cachero (1970); Saravacos and Charm (1962); Vaccarezza et al. (1974), which suggest that the drying of biological products typically takes place during the falling-rate phase. Therefore, in this study, Eq. 5.5 was applicable for determining the effective moisture diffusivities for the almond hull, shell, and kernel under the tested drying conditions.

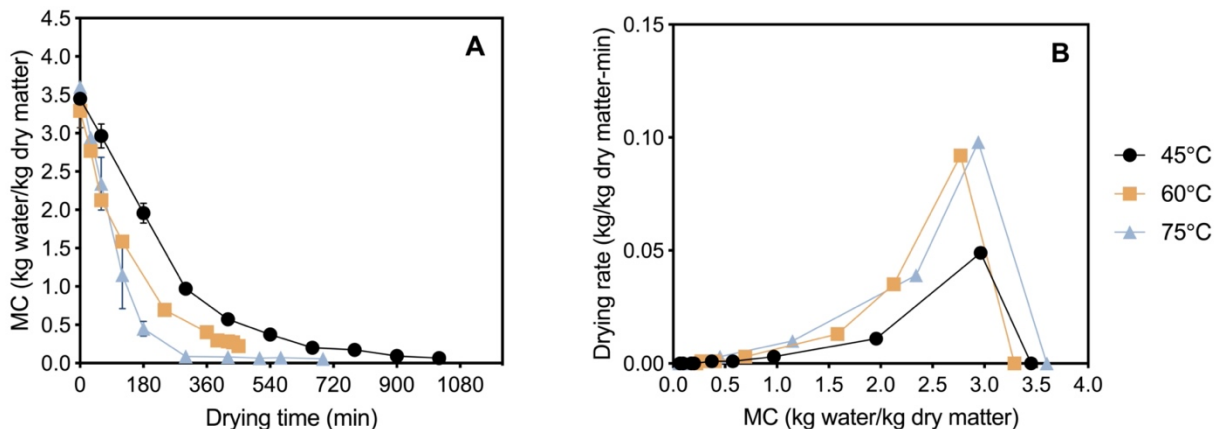


Figure 5.2 Drying curves (A) and rate curves (B) of the almond hull under in-hull almond drying at hot air temperatures of 45°C, 60°C, and 75°C

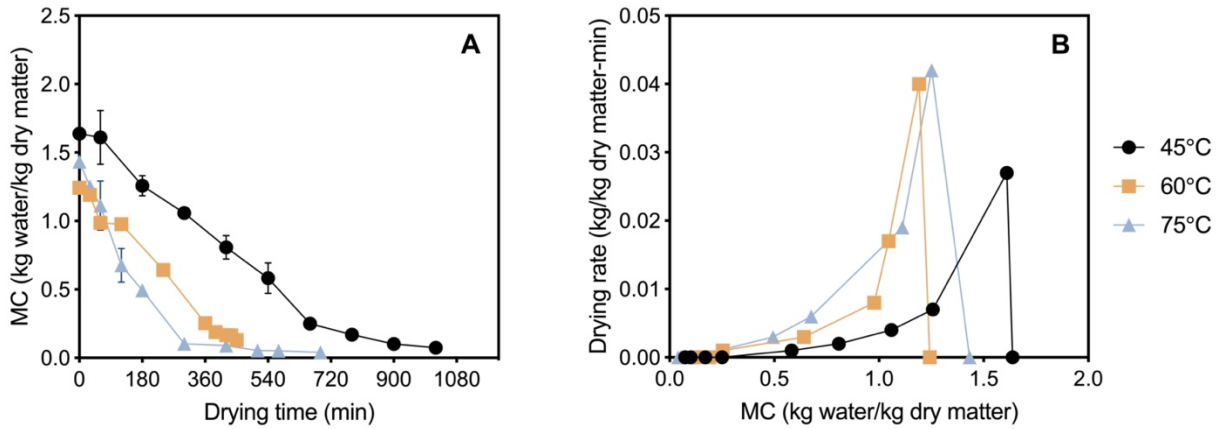


Figure 5.3 Drying curves (A) and rate curves (B) of the almond shell under in-hull almond drying at hot air temperatures of 45°C, 60°C, and 75°C

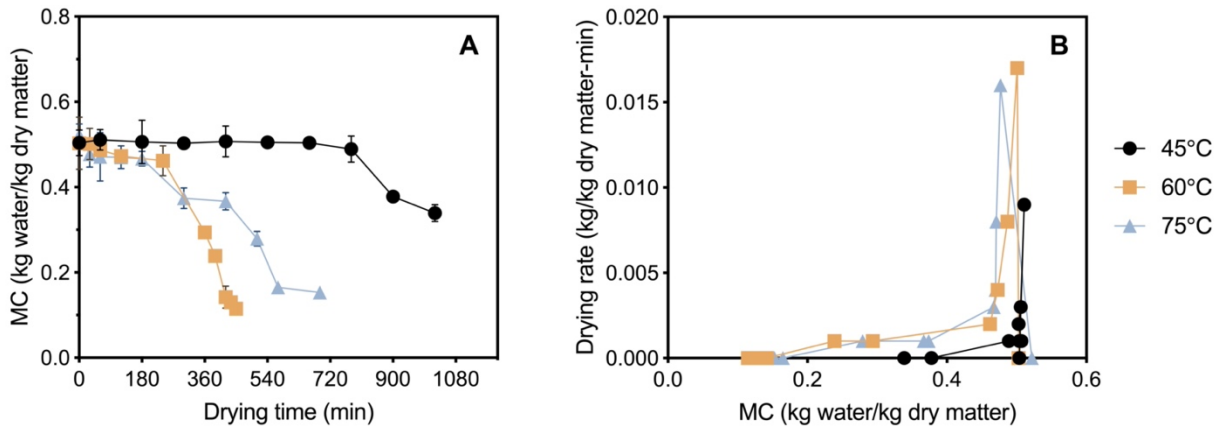


Figure 5.4 Drying curves (A) and rate curves (B) of the almond kernel under in-hull almond drying at hot air temperatures of 45°C, 60°C, and 75°C

5.4.2 Dimension change during drying

Table 5.1-5.3 present the size and shape changes of in-hull almonds, in-shell almonds, and kernels throughout the drying process at 45°C, 60°C, and 75°C. Overall, dimensional reductions were most pronounced in the in-hull almonds, followed by kernels and in-shell almonds. For instance, at 45°C, in-hull almonds exhibited average shrinkage of 1.7 mm in length, 1.0 mm in width, 1.1 mm in thickness, and 1.2 mm in geometric mean diameter, as shown in Table 5.1. These changes represented reductions of 5.2%, 4.3%, 4.6%, and 4.7%, respectively. For kernels, the

average reductions were 0.86 mm in length, 0.68 mm in width, 0.86 mm in thickness, and 0.76 mm in geometric mean diameter, corresponding to respective decreases of 4.1%, 5.3%, 8.0%, and 5.3%. In contrast, in-shell almonds displayed smaller dimensional decreases, with mean reductions of 0.34 mm in length, 0.23 mm in width, 0.15 mm in thickness, and 0.23 mm in geometric mean diameter, equating to decreases of 1.2%, 1.3%, 1.0%, and 1.2%, respectively.

A similar pattern of dimensional shrinkage was observed during drying at 60°C and 75°C, but with more pronounced changes. At 60°C, in-hull almonds experienced an average reduction of 2.46 mm in length, 1.62 mm in width, 1.47 mm in thickness, and 1.81 mm in geometric mean diameter, as shown in Table 5.2. These reductions corresponded to 7.3%, 6.5%, 6.1%, and 6.6%, respectively. For kernels dried at 60°C, significant dimensional changes were observed: an average reduction of 1.94 mm in length, 1.02 mm in width, 1.84 mm in thickness, and 1.65 mm in geometric mean diameter, with corresponding decreases of 8.9%, 7.9%, 17.0%, and 11.4%. Notably, the greatest shrinkage occurred along the thickness axis, suggesting that moisture migration during drying primarily occurred along this dimension. This finding is consistent with the observations of Joardder, Brown, et al. (2015), who highlighted the influence of intracellular water transport and cell wall water on material shrinkage during food processing.

Regarding the timing of significant dimensional changes, the data indicated that during drying at 60°C, kernel shrinkage first became apparent in the thickness, followed sequentially by width and length. Specifically, significant shrinkage was observed at 360 minutes for thickness, 390 minutes for width, and 435 minutes for length, with the total drying time for the kernel at this temperature being 450 minutes. This sequential shrinkage pattern was even more pronounced during drying at 75°C, where the thickness was the only dimension that underwent a significant change, highlighting its higher susceptibility to rapid moisture loss than the other dimensions.

These findings emphasize the importance of understanding moisture diffusion dynamics along different axes during the drying process, particularly in optimizing drying conditions for almond kernels.

During the drying process at 45°C, 60°C, and 75°C, changes in sphericity for in-hull almonds were minimal, with average differences of 0.4%, 0.6%, and 0.8%, respectively. For in-shell almonds and kernels, these changes were 0%, 0.7%, and 0.7% for in-shell almonds, and 1.8%, 1.8%, and 4.1% for kernels, respectively. The negligible variation in sphericity suggests a lack of significant deformation under the applied drying conditions, which is an important consideration for drying modeling. Zambra et al. (2022) emphasized that shrinking deformation is a crucial factor for accurately modeling heat and mass transport. Additionally, in-shell almond dimensions exhibited minimal shrinkage, with the largest reduction being just 3.1% across all tested temperatures (Table 5.1-5.3). This dimensional stability in in-shell almonds was likely due to their sturdy cell wall structure, predominantly composed of cellulose (38.5%), hemicellulose (28.8%), and lignin (29.5%) (Li et al., 2018). Cellulose microfibrils and lignin are key elements in maintaining cell wall rigidity and structural integrity (Hoson & Wakabayashi, 2015). Consequently, in this study, shell shrinkage was considered negligible and thus excluded from the mathematical models developed to correlate shrinkage with moisture ratio in the subsequent Section 5.4.3.

Table 5.1 Characteristics of dimensional property of almond during drying process at 45°C

Almond type	Dimensional property	Initial	Final	Mean Diff.	Reduction (%)	Significance	p value
IH almond	L (mm)	32.21	30.54	1.7	5.2%	*	0.031
	W (mm)	24.25	23.21	1.0	4.3%	ns	0.579
	T (mm)	23.48	22.41	1.1	4.6%	ns	0.591

	dg (mm)	26.37	25.14	1.2	4.7%	ns	0.378
	Ø (%)	81.9%	82.3%	-0.4%	-0.5%	ns	>0.999
IS almond	L (mm)	27.58	27.24	0.34	1.2%	ns	0.877
	W (mm)	17.46	17.23	0.23	1.3%	ns	0.993
	T (mm)	14.80	14.65	0.15	1.0%	ns	0.987
	dg (mm)	19.24	19.02	0.23	1.2%	ns	>0.999
	Ø (%)	69.8%	69.8%	0.0%	0.0%	ns	>0.999
Kernel	L (mm)	21.10	20.24	0.86	4.1%	ns	0.390
	W (mm)	12.89	12.21	0.68	5.3%	ns	0.770
	T (mm)	10.78	9.92	0.86	8.0%	ns	0.423
	dg (mm)	14.27	13.51	0.76	5.3%	ns	0.725
	Ø (%)	68.3%	66.5%	1.8%	2.6%	ns	>0.999

Note: * means there is a significance

Table 5.2 Characteristics of dimensional property of almond during drying process at 60°C

Almond type	Dimensional property	Initial	Final	Mean Diff.	Reduction (%)	Significance	p value
IH almond	L (mm)	33.55	31.09	2.46	7.3%	**	0.007
	W (mm)	24.92	23.3	1.62	6.5%	ns	0.312
	T (mm)	24.24	22.77	1.47	6.1%	ns	0.373
	dg (mm)	27.26	25.46	1.81	6.6%	*	0.041
	Ø (%)	81.3%	81.9%	-0.6%	-0.8%	ns	>0.999
IS almond	L (mm)	28.03	27.17	0.86	3.1%	ns	0.060
	W (mm)	17.63	17.37	0.26	1.5%	ns	>0.999
	T (mm)	15.09	14.84	0.25	1.7%	ns	0.688
	dg (mm)	19.54	19.13	0.40	2.1%	ns	0.848
	Ø (%)	69.7%	70.4%	-0.7%	-1.0%	ns	>0.999
Kernel	L (mm)	21.81	19.87	1.94	8.9%	****	<0.0001
	W (mm)	12.95	11.93	1.02	7.9%	**	0.003
	T (mm)	10.80	8.96	1.84	17.0%	****	<0.0001

dg (mm)	14.50	12.86	1.65	11.4%	****	<0.0001
Ø (%)	66.5%	64.7%	1.8%	2.7%	ns	>0.999

Table 5.3 Characteristics of dimensional property of almond during drying process at 75°C

Almond type	Dimensional property	Initial	Final	Mean Diff.	Reduction (%)	Significance	p value
IH almond	L (mm)	32.71	30.71	2.00	6.1%	*	0.031
	W (mm)	24.71	22.96	1.75	7.1%	**	0.006
	T (mm)	23.36	21.65	1.71	7.3%	**	0.008
	dg (mm)	26.63	24.81	1.82	6.8%	*	0.041
	Ø (%)	81.4%	80.8%	0.6%	0.8%	ns	>0.999
IS almond	L (mm)	26.52	25.72	0.80	3.0%	ns	0.995
	W (mm)	18.08	17.81	0.27	1.5%	ns	>0.999
	T (mm)	15.08	14.80	0.28	1.9%	ns	0.618
	dg (mm)	19.34	18.93	0.41	2.1%	ns	0.998
	Ø (%)	72.9%	73.6%	-0.7%	-0.9%	ns	>0.999
Kernel	L (mm)	20.73	20.27	0.46	2.2%	ns	0.618
	W (mm)	12.76	12.02	0.74	5.8%	ns	0.073
	T (mm)	10.74	9.06	1.68	15.6%	****	<0.0001
	dg (mm)	14.16	13.02	1.14	8.1%	***	<0.0001
	Ø (%)	68.3%	64.2%	4.1%	6.0%	ns	>0.999

5.4.3 Shrinkage kinetics

Figure 5.5 visually depicts the shrinkage phenomenon observed in in-hull almonds during drying at 60°C. Notably, hull splitting, which typically occurs when almonds partially dry on the tree during conventional harvesting, was not observed in this hot air drying process. The exact cause for the absence of hull splitting remains unclear at this time. However, this observation is

critical and must be considered as a key assumption in developing a theoretical drying model for in-hull almonds. Incorporating this detail into future modeling efforts will help ensure more accurate predictions of drying behavior.

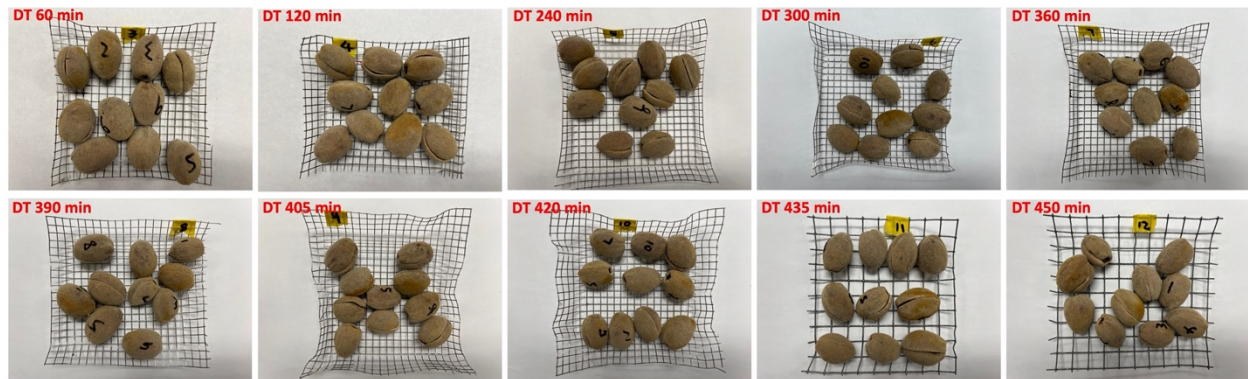


Figure 5.5 Pictorial representation of in-hull almonds showing the occurrence of shrinkage throughout the drying period at an air temperature of 60°C

Figure 5.6-5.7 illustrate the evolution of dimensional shrinkage in length, width, and thickness for almond hulls and kernels at a drying temperature of 45°C, 60°C, and 75°C, while Figure 5.8 shows the corresponding volume shrinkage. The shrinkage kinetics appeared to be primarily governed by internal moisture transfer rates and the specific process conditions. At the initial drying period, shrinkage was minimal, likely because free water in the intercellular spaces evaporated, a process that has a negligible effect on material shrinkage (Joardder, Brown, et al., 2015; Md Imran H Khan, Chandan Kumar, et al., 2017; Md Imran H Khan, R Mark Wellard, et al., 2017).

After this initial phase, significant shrinkage became evident as intracellular water migrated through ruptured cell membranes, leading to dimensional and volumetric reductions (Joardder, Karim, et al., 2015; Md Imran H Khan, R Mark Wellard, et al., 2017). Notably, shrinkage occurred when the moisture ratio ranged between 0.2 and 0.6 for almond hulls and between 0.6 and 0.8 for almond kernels. During this period, most intracellular water is transferred to intercellular spaces

and then evaporated into the environment. In the final stages of drying, all three dimensions of the in-hull almonds showed a steep decline, despite minimal changes in moisture content, whereas kernel dimensions began to stabilize. This suggests the potential collapse of cell structures, with a more pronounced collapse in the almond hull, which could be due to its higher porosity (Aydin, 2003).

The graphs in Figure 5.6-5.8 also reveal the significant effect of temperature on shrinkage kinetics. Shrinkage increased in a nonlinear fashion as moisture content decreased. However, at higher drying temperatures, the relationship between shrinkage and moisture ratio became more linear, especially for changes in the thickness and volume of the hull and kernel at 60°C and 75°C.

Polynomial models, including linear, quadratic, and cubic, were applied to the experimental data to better understand the relationships between shrinkage and moisture content in almond hulls and kernels during drying at different temperatures. Table 5.4-5.6 provide details of the model constants and the statistical analysis of the fitted models for length, width, thickness, and volume. The analyses showed that cubic models provided higher R^2 values and lower RMSE values compared to linear models for dimensional shrinkage, while quadratic models were sufficient to describe volume shrinkage. These results demonstrate the superior predictive accuracy of cubic and quadratic models over linear models in defining the relationship between shrinkage and decreasing moisture ratio for the hull and kernel during in-hull almond drying across different temperatures.

These findings align with research by Ponkham et al. (2012), Rani and Tripathy (2020), Mayor and Sereno (2004), and Yingjie et al. (2019) on drying processes for pineapple rings, apples, carrots, potatoes, and peanut shells. In contrast, linear relationships were observed in the hot air drying of potato slabs, carrot slabs, and pumpkin (Aprajeeta et al., 2015; Madiouli et al., 2012;

Mayor et al., 2011). This suggests that the specific nature of the product and drying conditions greatly influence the appropriate model for accurately predicting shrinkage behavior.

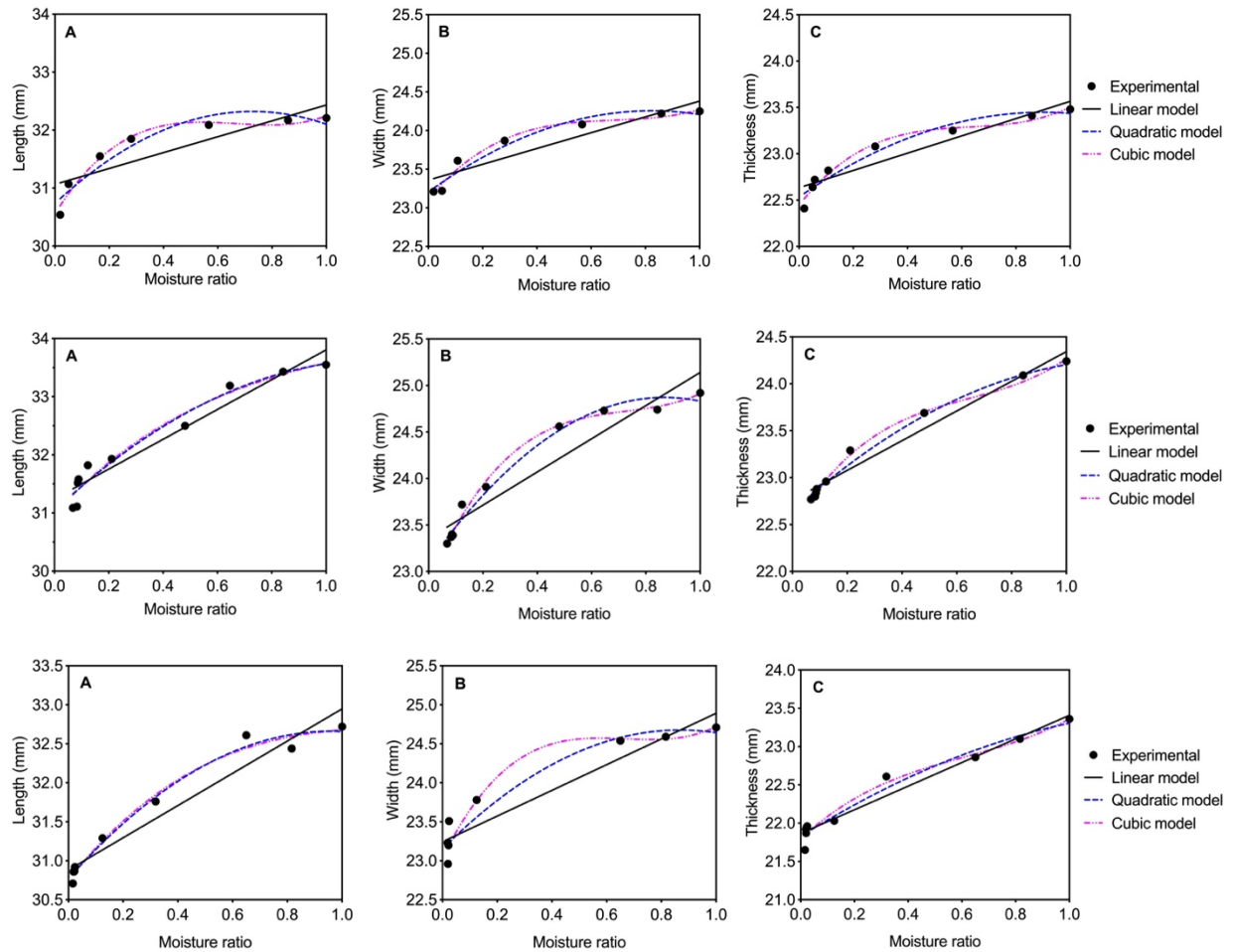


Figure 5.6 Evolution of shrinkages in length (A), width (B), and thickness (C) of the almond hull during the in-hull almond drying at hot air temperatures of 45°C (top three), 60°C (middle three), and 75°C (bottom three)

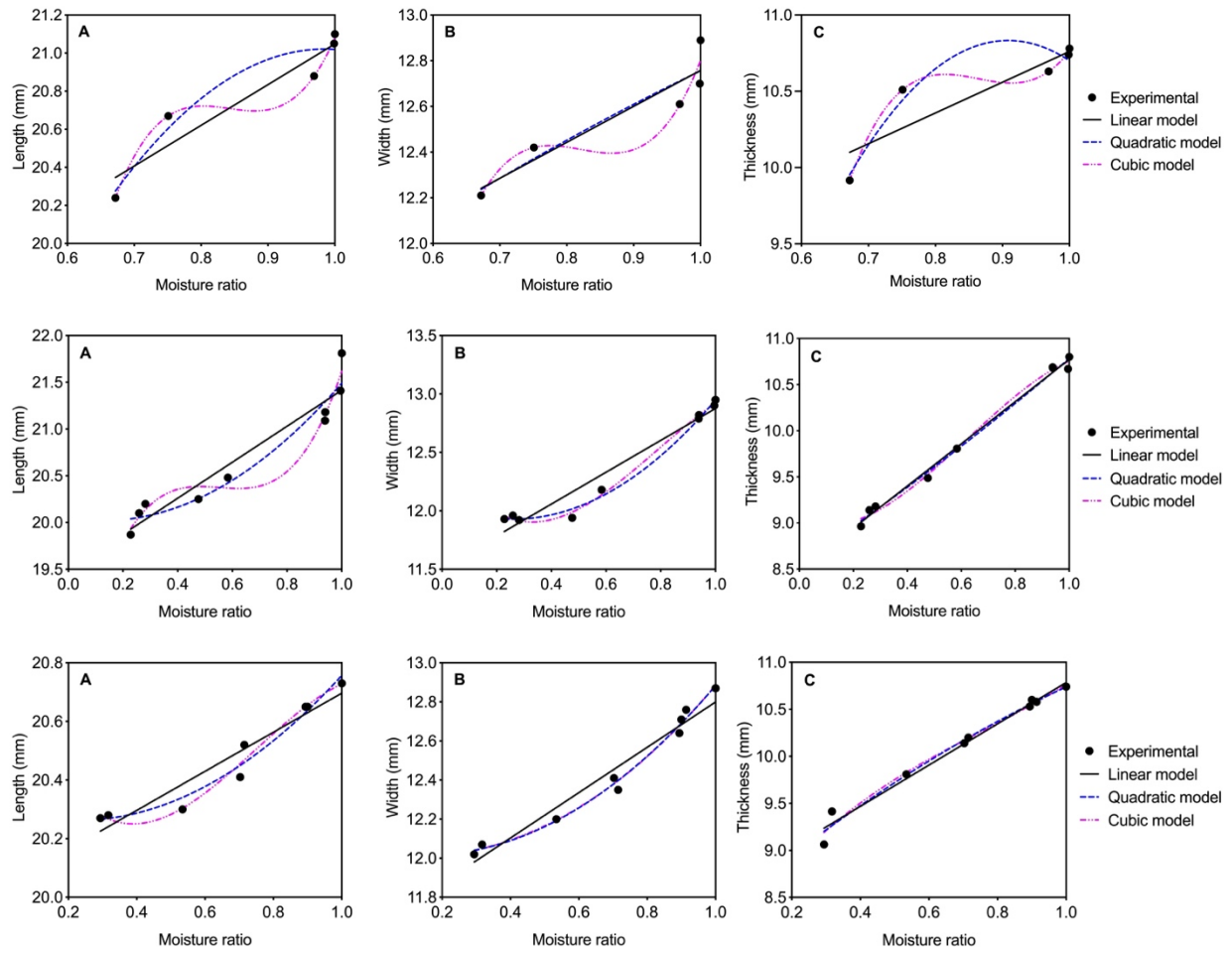


Figure 5.7 Evolution of shrinkages in length (A), width (B), and thickness (C) of almond kernel during the in-hull almond drying at hot air temperatures of 45°C (top three), 60°C (middle three), and 75°C (bottom three)

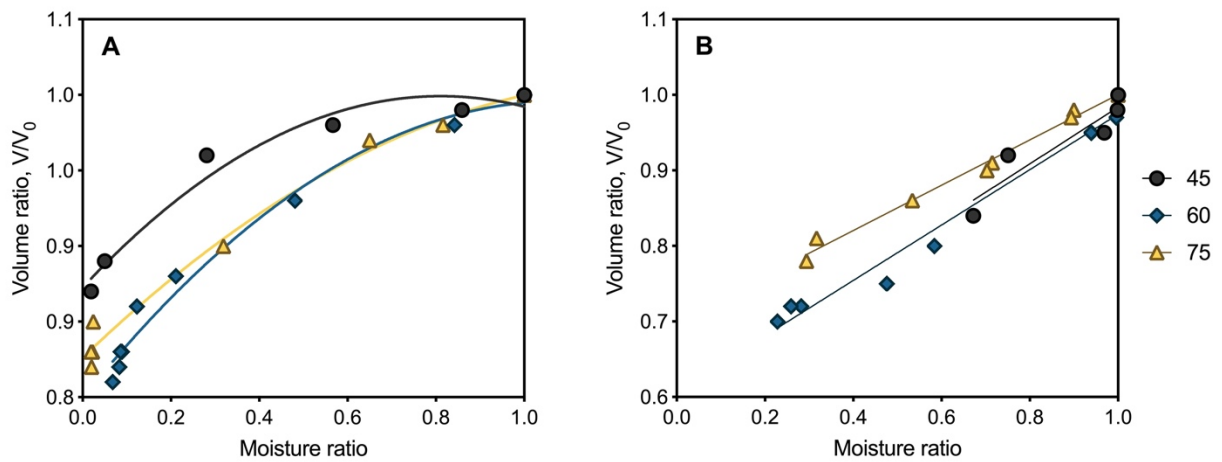


Figure 5.8 Evolution of shrinkages in volume ratio for almond hull (A) and kernel (B) during the in-hull almond drying at different hot air temperatures

Table 5.4 Estimated values of equation constants and statistical errors of models fitted to shrinkage dimensions of almond hull at hot air temperature of 45°C

Shrinkage dimension		Equation constants				R ²	RMSE
	Model	a	b	c	d		
Almond hull							
Length	Linear	31.07	1.37			0.728	0.330
	Quadratic	30.74	4.36	-2.99		0.923	0.175
	Cubic	30.55	7.60	-11.86	5.95	0.975	0.101
Width	Linear	23.36	1.02			0.854	0.169
	Quadratic	23.20	2.56	-1.55		0.959	0.090
	Cubic	23.12	4.15	-5.86	2.86	0.980	0.063
Thickness	Linear	22.63	0.93			0.888	0.130
	Quadratic	22.53	2.03	-1.13		0.952	0.085
	Cubic	22.45	3.71	-5.66	3.01	0.978	0.057
Volume	Linear	0.89	0.12			0.842	0.022
	Quadratic	0.87	0.31	-0.19		0.967	0.009
Kernel		a	b	c	d		
Length	Linear	18.91	2.14			0.901	0.110
	Quadratic	13.63	15.02	-7.63		0.934	0.090
	Cubic	-46.49	240.50	-286.30	113.40	0.998	0.015
Width	Linear	11.18	1.57			0.874	0.093
	Quadratic	10.84	2.41	-0.50		0.874	0.093
	Cubic	-34.16	171.20	-209.10	84.88	0.939	0.065
Thickness	Linear	8.75	2.01			0.793	0.160
	Quadratic	-2.14	28.56	-15.72		0.930	0.093
	Cubic	-64.57	262.70	-305.10	117.80	0.999	0.012

Volume	Linear	0.61	0.38		0.868	0.023
	Quadratic	-0.36	2.73	-1.39	0.902	0.019

Table 5.5 Estimated values of equation constants and statistical errors of models fitted to shrinkage dimensions of almond hull at hot air temperature of 60°C

Shrinkage dimension	Model	Equation constants				R ²	RMSE
		a	b	c	d		
Almond hull							
Length	Linear	31.24	2.56			0.939	0.232
	Quadratic	31.04	4.34	-1.81		0.961	0.185
	Cubic	30.99	5.00	-3.38	0.98	0.961	0.184
Width	Linear	23.36	1.78			0.909	0.200
	Quadratic	23.10	4.09	-2.35		0.984	0.085
	Cubic	22.88	6.86	-8.93	4.10	0.994	0.051
Thickness	Linear	22.76	1.58			0.966	0.105
	Quadratic	22.64	2.62	-1.06		0.987	0.066
	Cubic	22.47	4.81	-6.26	3.24	0.996	0.038
Volume	Linear	0.82	0.19			0.952	0.015
	Quadratic	0.80	0.36	-0.17		0.980	0.010
Kernel		a	b	c	d		
Length	Linear	19.49	1.93			0.918	0.194
	Quadratic	20.05	-0.48	1.92		0.942	0.163
	Cubic	17.96	13.55	-24.90	15.01	0.970	0.118
Width	Linear	11.51	1.36			0.948	0.108
	Quadratic	12.05	-0.96	1.86		0.993	0.039
	Cubic	12.50	-3.95	7.56	-3.19	0.996	0.031
Thickness	Linear	8.49	2.29			0.994	0.062
	Quadratic	8.56	1.96	0.26		0.994	0.060

	Cubic	9.02	-1.13	6.17	-3.31	0.995	0.055
Volume	Linear	0.61	0.37			0.979	0.018
	Quadratic	0.69	0.003	0.29		0.995	0.009

Table 5.6 Estimated values of equation constants and statistical errors of models fitted to shrinkage dimensions of almond hull at hot air temperature of 75°C

Shrinkage dimension	Model	Equation constants				R ²	RMSE
Almond hull		a	b	c	d		
Length	Linear	30.88	2.07			0.942	0.194
	Quadratic	30.77	3.94	-2.05		0.986	0.096
	Cubic	30.76	4.38	-3.28	0.82	0.987	0.094
Width	Linear	23.24	1.65			0.915	0.209
	Quadratic	23.15	3.50	-2.02		0.960	0.143
	Cubic	23.04	7.15	-10.94	5.47	0.980	0.103
Thickness	Linear	21.87	1.54			0.959	0.121
	Quadratic	21.83	2.20	-0.72		0.969	0.106
	Cubic	21.79	3.31	-3.81	2.07	0.975	0.095
Volume	Linear	0.83	0.18			0.971	0.013
	Quadratic	0.83	0.28	-0.11		0.987	0.009
Kernel		a	b	c	d		
Length	Linear	20.03	0.67			0.914	0.055
	Quadratic	20.30	-0.37	0.82		0.966	0.034
	Cubic	20.86	-3.55	6.15	-2.73	0.979	0.027
Width	Linear	11.64	1.16			0.954	0.067
	Quadratic	12.05	-0.37	1.21		0.990	0.032
	Cubic	12.00	-0.10	0.75	0.24	0.990	0.032
Thickness	Linear	8.59	2.19			0.980	0.082

Volume	Quadratic	8.37	3.05	-0.67		0.983	0.076
	Cubic	7.94	5.49	-4.77	2.11	0.984	0.074
	Linear	0.70	0.30			0.988	0.009
	Quadratic	0.72	0.22	0.06		0.990	0.008

5.4.4 Effective moisture diffusivity

Figure 5.9 presents the mean variation of the effective diffusion coefficients (D_{eff}) with moisture content for the almond hull, shell, and kernel at the three studied air temperatures. The effective moisture diffusivity increased gradually as the moisture content decreased, reaching a maximum at moisture content of around 0.45 (kg/kg dry matter) for the almond hull at 75°C, 0.69 (kg/kg dry matter) at 60°C, 0.97 (kg/kg dry matter) at 45°C. Towards the end of the drying process, as the moisture content became low, this trend reversed, with the diffusion coefficient starting to decline. This reversal was thought to be a consequence of moisture depletion in the hull, leading to an exhaustion of the mass transport mechanism. Such a pattern of diffusivity change, correlating with vapor diffusion as a function of moisture content, has been previously described by De Vries (1958); Luikov (2012); Zambra et al. (2022). Similar trends were also observed in the drying of the shell and kernel, as depicted in Figure 5.9 (B) and (C).

The effective diffusion coefficient (D_{eff}) for the almond hull was consistently higher than that of the shell and kernel under the tested conditions. This observation aligns with the findings of Chen (2007), who reported that elevated material moisture content and temperature typically enhance moisture diffusion, leading to higher D_{eff} values in food materials. Analyzing Figure 5.2-5.4 shows that the moisture content of the hull remained consistently higher than that of the shell and kernel throughout most of the drying process. Moreover, thermal energy, delivered by convective heat, permeated inward into the almond via conduction, causing the hull to heat up more quickly than the shell and kernel, thereby maintaining a higher temperature during drying.

Nevertheless, as drying advanced, the disparities in MC and temperature between the hull, shell, and kernel diminished, which was reflected by the convergence of D_{eff} values, as depicted in Figure 5.9.

Table 5.7 shows the average effective moisture diffusivities for almond hull, shell, and kernel at different drying temperatures. With the increase in drying temperature 45°C to 75°C, the D_{eff} for the almond hull ranged between $9.70 \times 10^{-10} \text{ m}^2/\text{s}$ and $2.05 \times 10^{-9} \text{ m}^2/\text{s}$. For the shell and kernel, the respective diffusivity ranges were 4.71×10^{-10} to $9.24 \times 10^{-10} \text{ m}^2/\text{s}$ and 5.82×10^{-11} to $3.75 \times 10^{-10} \text{ m}^2/\text{s}$. These values were in line with those reported for other tree nuts: pistachio nuts (5.4×10^{-11} to $9.3 \times 10^{-10} \text{ m}^2/\text{s}$) over the temperature range of 25°C to 70°C (Kashaninejad et al., 2007), macadamia shell (1.93×10^{-10} to $2.46 \times 10^{-10} \text{ m}^2/\text{s}$) and macadamia kernel (6.49×10^{-10} to $1.15 \times 10^{-9} \text{ m}^2/\text{s}$) over the temperature range of 40°C to 60°C (Pankaew et al., 2016), and apricot (1 to $3 \times 10^{-11} \text{ m}^2/\text{s}$) at 50°C to 80°C (Halouat & Labuza, 1987), as well as the values of most fruits and vegetables with over 80% in the region of 10^{-10} to $10^{-8} \text{ m}^2/\text{s}$ (Onwude et al., 2016). To the best of the author's knowledge, this is the first study to simultaneously determine the effective moisture diffusivities of the almond hull, shell, and kernel during in-hull almond drying with hot air heating.

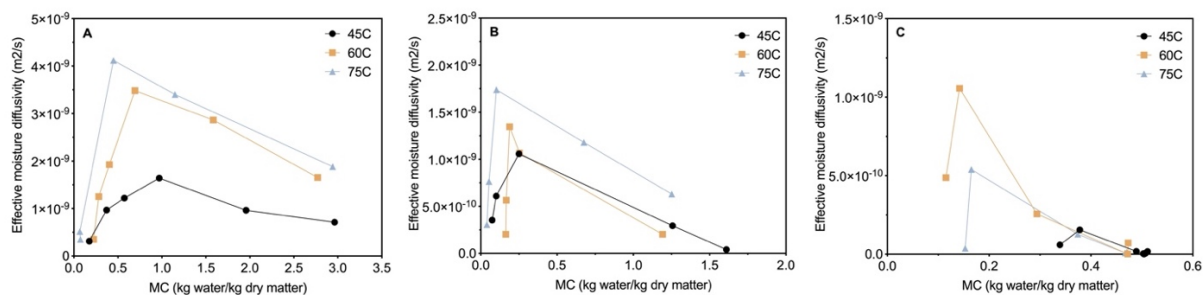


Figure 5.9 Variation in effective moisture diffusivity of (A) almond hull, (B) almond shell, and (C) almond kernel with moisture content under hot air drying at different temperatures (45, 60, and 75°C)

5.4.5 Model development for effective moisture diffusivity

The non-linear regression approach was used to develop the models of the effective moisture diffusivity for the almond hull, shell, and kernel throughout the hot air drying process, and the results are shown in Table 5.7. The regression model, as expressed by Eq. 5.14, successfully captured the dynamic changes of effective moisture diffusivity during in-hull almond drying. The adjusted R-squared (R_{adj}^2) values exceeded 0.973, 0.926, and 0.978 for the hull, shell, and kernel, respectively, indicating a high degree of model accuracy.

Table 5.7 Regression coefficients for moisture diffusivity model at different drying temperatures

Hull		Regression coefficients				R_{adj}^2	RMSE
T (°C)	$D_{eff,ave}$ (m ² /s)	A	B	C	D		
45	9.70×10^{-10}	5.3×10^{-10}	-2.9×10^{-9}	4.3×10^{-9}	-3.4×10^{-10}	0.973	7.35×10^{-11}
60	1.92×10^{-9}	2.0×10^{-9}	-1.0×10^{-8}	1.4×10^{-8}	-2.2×10^{-9}	0.973	1.85×10^{-10}
75	2.05×10^{-9}	3.5×10^{-9}	-1.6×10^{-8}	1.7×10^{-8}	-6.8×10^{-10}	0.989	1.81×10^{-10}
Shell		A	B	C	D		
45	4.71×10^{-10}	2.5×10^{-9}	-7.8×10^{-9}	6.1×10^{-9}	2.3×10^{-9}	0.944	9.14×10^{-11}
60	6.77×10^{-10}	5.2×10^{-7}	-8.4×10^{-7}	2.9×10^{-7}	-2.7×10^{-8}	0.926	1.40×10^{-10}
75	9.24×10^{-10}	3.1×10^{-8}	-6.2×10^{-8}	3.1×10^{-8}	-7.4×10^{-10}	0.931	1.46×10^{-10}
Kernel		A	B	C	D		
45	5.82×10^{-11}	1.9×10^{-7}	-2.6×10^{-7}	1.1×10^{-7}	-1.6×10^{-8}	0.987	5.74×10^{-12}
60	3.75×10^{-10}	4.5×10^{-7}	-3.9×10^{-7}	1.0×10^{-7}	-6.5×10^{-9}	0.995	3.06×10^{-11}
75	1.45×10^{-10}	6.3×10^{-7}	-6.3×10^{-7}	1.9×10^{-7}	-1.7×10^{-8}	0.978	3.36×10^{-11}

Table 5.8 enumerates the measured average sample temperatures for almond hull, shell, and kernel throughout the drying process under various conditions. These temperatures were

incorporated into Eq. 5.13 to study the temperature dependence of the average effective moisture diffusivity ($D_{\text{eff,ave}}$). This relationship was graphically analyzed by plotting the natural logarithm of $D_{\text{eff,ave}}$ against the reciprocal of the absolute drying temperature ($1/T$), as illustrated in Figure 5.10. The apparent activation energy (E_a) for each component was deduced from the slopes of these plots, yielding values of 24.29 kJ/mol for the hull, 20.89 kJ/mol for the shell, and 32.25 kJ/mol for the kernel. The higher E_a of the kernel suggested its effective moisture diffusivity was more susceptible to changes in drying temperature compared to that of the hull and shell.

Table 5.8 Average temperature, pre-exponential factor, and activation energy of different almond components

Almond component	Drying temperature (°C)	Temperature (°C)	D_0 (m ² /s)	E_a (kJ/mol)
Hull	45	42.5 ± 0.2	1.09×10^{-5}	24.29
	60	58.2 ± 0.3		
	75	71.3 ± 0.4		
Shell	45	41.9 ± 1.0	1.36×10^{-6}	20.89
	60	57.7 ± 0.2		
	75	70.9 ± 0.4		
Kernel	45	42.4 ± 0.6	1.92×10^{-5}	32.25
	60	57.0 ± 0.8		
	75	70.2 ± 0.7		

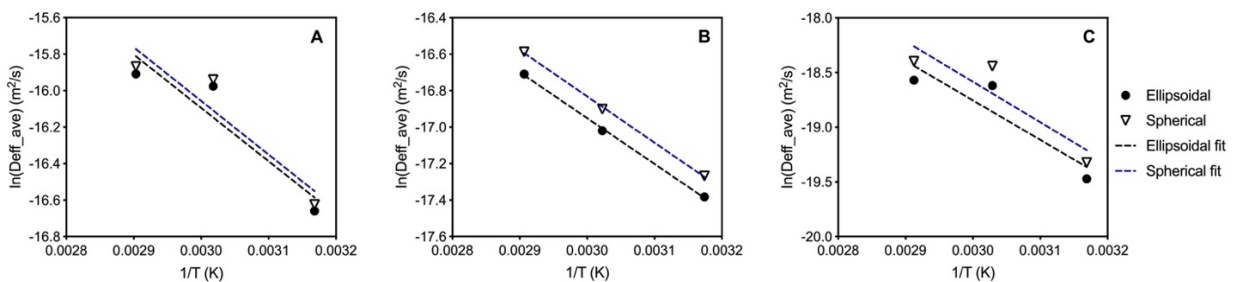


Figure 5.10 Influence of drying temperature on the average effective moisture diffusivities of almond hull, shell, and kernel

5.4.6 Shrinkage and shape effects on D_{eff}

The differential impact of shrinkage and shape on the average effective moisture diffusivity (D_{eff}) for almond hull, shell, and kernel is summarized in Table 5.9. Relative differences were calculated by comparing the D_{eff} values D_3 and D_4 , D_2 and D_4 , D_1 and D_4 , which correspond to the shape effect, shrinkage effect, and the combined effect of shrinkage and shape, respectively. It was observed that D_{eff} values, when accounting for shrinkage, were consistently lower than those calculated without considering shrinkage. For instance, the relative difference between the average D_{eff} values D_2 and D_4 varied from 1.7% to 8.8% for the hull, 0.7% to 3.8% for the shell, and 13.6% to 20.3% for the kernel. These variations suggested that shrinkage exerted a more pronounced influence on the kernel, followed by the hull and shell, confirming the observed drying and shrinkage data trends.

The analysis revealed that the effective moisture diffusivities (D_{eff}) assumed for a spherical shape were higher than those for an ellipsoidal shape. The relative differences between the D_{eff} values D_3 and D_4 ranged from 3.5% to 4.0% for the hull, 10.8% to 11.5% for the shell, and 13.6% to 16.9% for the kernel. This pronounced relative difference between the shell and kernel can be attributed to their intrinsically elliptical geometries. Correspondingly, the sphericity of the shell and kernel was relatively lower, at 69.8% and 68.3%, respectively, when compared to that of the hull at 81.9%. This suggests that the natural elliptical shape of the shell and kernel contributed significantly to the observed discrepancies in D_{eff} values.

When comparing the effective diffusivity D_1 and D_4 , the relative difference may represent the potential maximum error that could arise in modeling the moisture profile if neither shrinkage nor

shape effects were considered. The most significant relative difference was observed in drying the kernel at 60°C, reaching up to 31.6%.

Consequently, these findings emphasize the importance of incorporating both shrinkage and the actual shape of almonds in drying models to enhance the accuracy of moisture and temperature profiles. The omission of these factors can significantly impact moisture removal rates, diffusion coefficients, and the physical properties of the drying material (Khraisheh et al., 1997; Mayor & Sereno, 2004). Numerous researchers have underlined the critical role of shrinkage consideration in drying models for accurately capturing drying kinetics (Balaban, 1990; Chen & Johnson, 1969; Mulet et al., 1987; Park, 1998; Simal et al., 1998).

Table 5.9 The comparison of average D_{eff} of almond hull, shell, and kernel with and without considering shrinkage and shape effects

Almond component	HA (°C)	D_{eff} without shrinkage		D_{eff} with shrinkage		Relative Diff.		
		Sphericity	Ellipsoid	Sphericity	Ellipsoid	D ₃ vs. D ₄	D ₂ vs. D ₄	D ₁ vs. D ₄
		D ₁	D ₂	D ₃	D ₄			
Hull	45	1.02E-09	9.86E-10	1.00E-09	9.70E-10	3.5%	1.7%	5.1%
	60	2.19E-09	2.11E-09	1.99E-09	1.92E-09	3.6%	8.8%	12.4%
	75	2.21E-09	2.14E-09	2.14E-09	2.05E-09	4.0%	3.8%	6.9%
Shell	45	5.19E-10	4.67E-10	5.28E-10	4.71E-10	10.8%	-0.7%	9.3%
	60	7.87E-10	6.97E-10	7.62E-10	6.77E-10	11.2%	3.0%	14.0%
	75	1.06E-09	9.56E-10	1.04E-09	9.24E-10	11.5%	3.4%	12.6%
Kernel	45	3.52E-11	3.04E-11	3.46E-11	2.99E-11	13.6%	1.5%	15.1%
	60	5.48E-10	4.70E-10	4.51E-10	3.75E-10	16.9%	20.3%	31.6%
	75	1.95E-10	1.71E-10	1.74E-10	1.45E-10	16.6%	15.0%	25.8%

5.5 Conclusions

This study investigated the drying characteristics of the almond hull, shell, and kernel under the in-hull almond drying. While the hull and shell exhibited typical drying patterns for most food and agricultural materials, the kernel responded differently at varying temperatures. Specifically, 45°C was insufficient for rapidly and effectively drying almond kernels to the desired moisture content within in-hull almonds in this study, likely due to the absence of hull splitting, which impeded moisture removal, compounded by the low-temperature effect. In contrast, drying at 60°C was more effective than at 75°C, potentially due to case-hardening on the hull's surface, which occurred during high-temperature drying and restricted moisture transfer.

Effective moisture diffusivities in almonds were found to increase as moisture content decreased, reaching a maximum and then starting to decrease towards the end of the drying process. Polynomial equations were developed to model the relationship between effective moisture diffusivity and sample moisture content. These equations, reflecting variable moisture diffusivity coefficients, are expected to enhance the accuracy of future drying models.

The study observed minimal deformation regarding size and shape changes, with shrinkage primarily occurring in the thickness dimension. Accounting for the actual shape and shrinkage effects, the maximum relative difference in effective moisture diffusivity reached up to 31.6% during kernel drying at 60°C. Consequently, integrating shrinkage as a function of moisture content into drying models and considering the almond's elliptical shape is crucial for a realistic theoretical modeling approach.

These insights contributed to the understanding of the moisture diffusion characteristics and evolution of shrinkage and deformation in different almond components during hot air drying. The findings will be used in the next chapter to develop a theoretical drying model for a single in-hull almond.

6 CHAPTER 6 MODELING OF HEAT AND MOISTURE TRANSFER DURING CONVECTIVE DRYING OF IN-HULL ALMONDS CONSIDERING NON- ISOTROPIC SHRINKAGE AND VARIABLE MOISTURE DIFFUSIVITY

6.1 Introduction

In Chapter 5, the effective moisture diffusivities of the almond hull, shell, and kernel during hot air drying were determined and modeled as a function of the sample moisture content. A detailed examination of the in-hull almond structure revealed the presence of air gaps between the hull and shell, as well as between the shell and kernel. These air gaps introduce complexities in the mechanisms of multiphase moisture transfer during drying, potentially involving processes such as evaporation, condensation, water vapor diffusion, and liquid water diffusion. Furthermore, varying degrees of shrinkage in the hull, shell, and kernel were observed, which likely influenced moisture transfer within the in-hull almond during the drying process. Despite these findings, the drying mechanism of in-hull almonds remains insufficiently studied.

Mathematical modeling is a valuable tool for investigating the drying kinetics of food materials, allowing researchers to assess the effects of both operating conditions and the inherent physical and structural parameters on drying behaviors. These models can be broadly classified into three categories based on their principles and development approaches: empirical models, semi-empirical models, and analytical models, each offering distinct advantages and considerations. Empirical models, for example, are advantageous due to their simplicity and broad applicability across various food materials (Doymaz & Kocayigit, 2011; Prakash, 2011; Zhang et al., 2016). However, their applicability is often limited to the specific experimental conditions under which they were developed (Erbay & Icier, 2010; Panchariya et al., 2002). Additionally,

these models tend to neglect the effects of material geometry constraints, and the regression parameters derived from them may lack substantial physical significance.

In contrast, analytical modeling of the drying process typically employs fundamental equations, such as Fick's second law of diffusion and the heat diffusion equation, to characterize heat and mass transfer mechanisms. These models provide the capability to visualize internal spatial temperature and moisture profiles and are particularly suited to incorporating factors such as shrinkage and variable moisture diffusivity. For example, Chen et al. (2022) developed an analytical model that accounts for variable moisture diffusivity and heterogeneous systems for in-shell walnuts during hot air drying. Similarly, Rani and Tripathy (2020) created a 3D model to analyze moisture migration during the drying of pineapple rings, incorporating variable moisture diffusivity, mass transfer coefficients, and both radial and longitudinal shrinkage. To the best of the author's knowledge, no analytical models have yet been reported for drying simulations of in-hull almonds, which are considered a heterogeneous system

Furthermore, distinguishing between liquid water and water vapor transport may enhance the accuracy of internal moisture profile estimates, as suggested by Litchfield and Okos (1992). Water transport models have been developed for processes such as bread baking (Ousegui et al., 2010; Zhang & Datta, 2006) and pasta drying (Mercier et al., 2014). In modeling food materials undergoing water evaporation during drying, a non-equilibrium approach has been proposed by several researchers Chen et al. (2022); Gulati et al. (2015); Halder et al. (2011); Kar and Chen (2011); Mercier et al. (2014); Ousegui et al. (2010); Rakesh and Datta (2011). In this approach, the water evaporation rate is proportional to the difference between the actual vapor density and the equilibrium vapor density.

In most previous studies, almonds have been modeled as spherical (Coates, 2018a; Kaveh et al., 2018; Mirzabe et al., 2013). However, as Prakash and Pan (2012) noted, using simplified shapes may deviate from the true geometry and lead to prediction errors. In this study, the in-hull almond was instead modeled as an ellipsoid with three distinct components: hull, shell, and kernel, along with the air gaps between the hull and shell and the shell and kernel. The simultaneous heat, liquid water, and water vapor transfers during in-hull almond drying were simulated using a non-equilibrium approach. The model also incorporated non-isotropic shrinkage and variable moisture diffusivity across almond components.

6.2 Specific Objectives

The specific objectives of this study are: 1) to determine the initial characteristics of in-hull almonds, including dimensions, initial moisture content, and water activity; 2) to develop a simultaneous heat and moisture transfer model for a single in-hull almond during hot air drying, incorporating non-equilibrium multiphase moisture transfer, shrinkage, and variable moisture diffusivity; and 3) to validate the model through single-layer drying experiments at three different temperatures: 45°C, 60°C, and 75°C.

6.3 Materials and Methods

6.3.1 Initial characteristics

6.3.1.1 Dimensions and shape

Freshly harvested off-ground almonds of the Fritz variety were collected from the Nickels Soil Lab in Arbuckle, California, during the 2022 harvest season for use in this study. The axial dimensions of in-hull almonds, in-shell almonds, and almond kernels, including length (L), width (W), and thickness (T), as well as the thickness (δ) of the hull and shell, were measured following

the methods described in Chapters 4 and 5. The geometric mean diameter (d_g) and sphericity (ϕ) of the three almond types were then calculated and summarized in Table 6.1.

Table 6.1 Summary of axial dimensions and shape characteristics

Almond type	L (mm)	W (mm)	T (mm)	δ (mm)	d_g (mm)	ϕ (%)
In-hull	32.8 ± 1.2 (29.8 - 35.0)	25.2 ± 0.9 (23.3 - 27.3)	24.4 ± 1.1 (22.2 - 26.7)	2.9 ± 0.2 (2.6 - 3.1)	27.2 ± 0.9 (25.7 - 28.8)	83.0 ± 2.2 (79.0 - 88.4)
In-shell	27.0 ± 0.9 (24.4 - 28.7)	17.6 ± 0.9 (15.7 - 19.7)	15.5 ± 0.8 (14.0 - 17.0)	2.7 ± 0.2 (2.3 - 3.1)	19.5 ± 0.7 (18.3 - 21.1)	72.2 ± 2.2 (68.1 - 76.2)
Kernel	21.1 ± 0.9 (18.6 - 22.6)	13.0 ± 0.6 (11.8 - 14.1)	11.0 ± 0.5 (10.0 - 12.3)	- -	14.5 ± 0.6 (13.4 - 15.7)	68.4 ± 1.8 (65.1 - 72.6)

6.3.1.2 Initial moisture content (IMC) and water activity (a_w)

The procedures for determining the moisture content and water activity of the three almond components are illustrated in Figure 6.1. Almonds were manually separated into hull, shell, and kernel components, which were then ground using a Kitchen Food Chopper (Model KFC3516, Benton Harbor, MI). From each of the three components, a small representative sample (approximately 7 g) was taken for measurements of IMC and a_w . Moisture content was measured using the standard oven method (105°C for 24 hours), while water activity was determined with an AquaLab water activity meter (Model CX-2, Decagon Devices, Inc., with ± 0.0003 accuracy), as depicted in Figure 6.1. For the overall water activity (a_w) of the in-hull almond, the sample was prepared by mixing the three almond components. The overall moisture content of the in-hull almond was calculated using Eq. 4.1 in Chapter 4. All measurements were performed in triplicate, and the results are presented in Table 6.2.

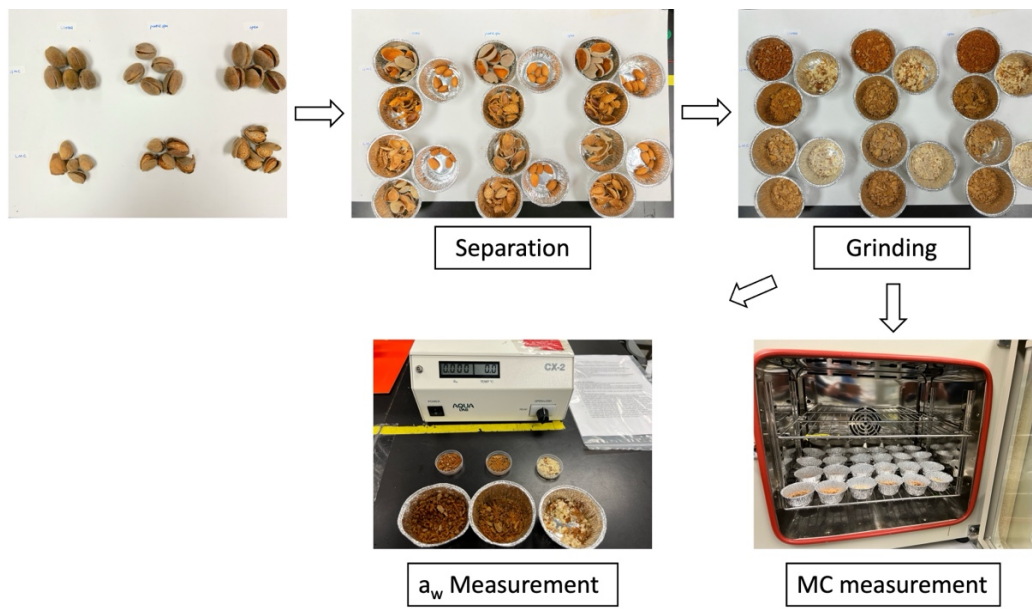


Figure 6.1 Flow diagram for the determination of IMC And a_w

Table 6.2 IMC (wet basis) and water activity of three different almond components

Measurement	Hull	Shell	Kernel	Overall
a_w	0.980 ± 0.003	0.971 ± 0.000	0.963 ± 0.002	0.975 ± 0.002
	(0.978 - 0.982)	-	(0.961 - 0.964)	(0.973 - 0.976)
IMC	$77.8\% \pm 1.7\%$	$59.9\% \pm 3.7\%$	$33.9\% \pm 3.8\%$	$66.2\% \pm 1.9\%$
	(73.0% - 79.9%)	(52.7% - 68.6%)	(27.9% - 45.8%)	(61.9% - 70.8%)

6.3.2 Drying experiment

Freshly harvested, off-ground in-hull almonds were used for the drying experiments. Approximately 500 g of almonds were spread in a single layer on a sample tray, and the drying tests were conducted at three different temperature levels (45°C, 60°C, and 75°C) with an air velocity of 1.4 m/s. The target final moisture content (MC) of the whole almonds was around 9% (wet basis). The drying air temperature was continuously monitored using a logged T-type thermocouple, and air velocity was measured with a hot wire anemometer (HHF-SD1, Omega, USA) with an accuracy of 0.1 m/s. The relative humidity (RH) corresponding to the drying air temperatures was recorded at 17.5%, 4.4%, and 3.5%, respectively. To continuously monitor

sample temperatures, one T-type thermocouple was inserted into the center of the kernel through a pre-drilled hole in the in-hull almond, while two additional thermocouples were affixed to the surfaces of the shell and hull using thermal conductive tape, as illustrated in Figure 6.2. The drying tests were carried out under laboratory conditions with an ambient temperature of 25.1°C and RH of 36.3%, with all tests replicated two times for accuracy.

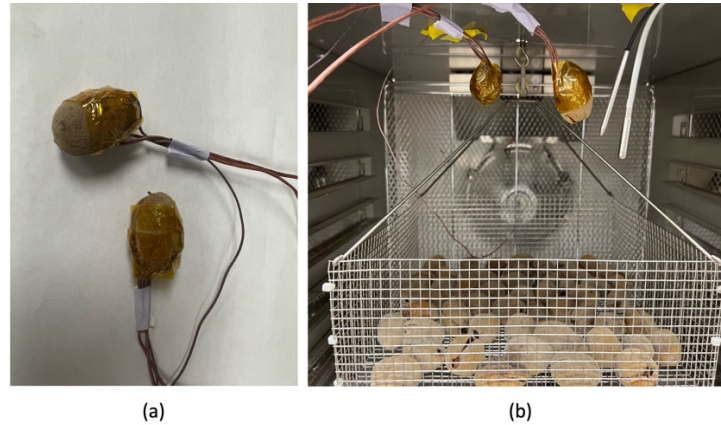


Figure 6.2 (a) Almond temperature measurement setup. (b) Drying chamber setup

6.3.3 Geometric model

The structure of the fresh in-hull almond and its simplified geometry is illustrated in Figure 6.3. The in-hull almond is a multi-domain system, consisting of the hull, shell, kernel, and air gaps between the hull and shell, as well as the shell and kernel. The thickness of these air gaps is relatively small, ranging from 0.1 to 0.25 mm, and for modeling purposes, a uniform average thickness of 0.2 mm was assumed. Due to the low sphericity of the almond, it was modelled as an ellipsoid. Figure 6.3B presents the simplified geometry of the in-hull almond, showing five distinct layers. Figure 6.3C depicts the 3-D meshed model representing one-eighth of a single in-hull almond. The model was defined using the mean values of the three axial dimensions as well as the hull and shell thicknesses.

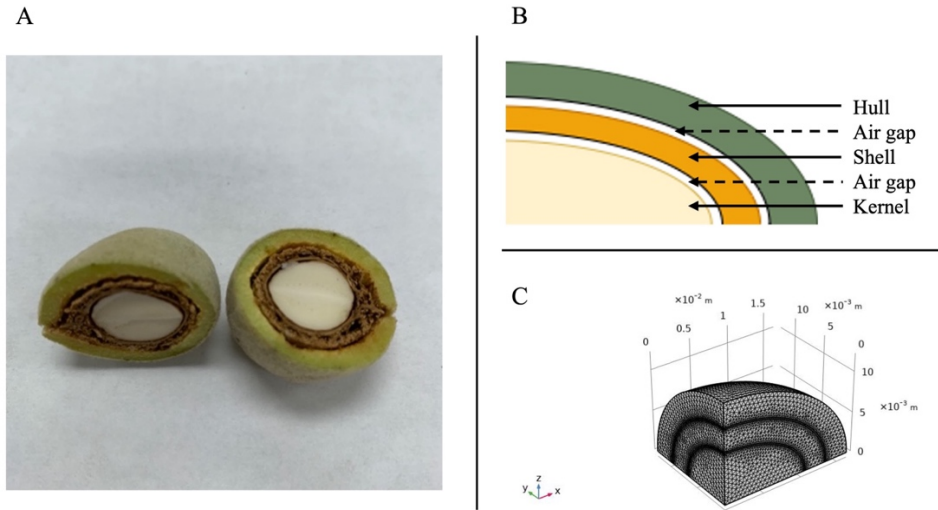


Figure 6.3 (A) Longitudinal cross-section of a single in-hull almond. (B) Simplified geometry of in-hull almond. (C) 3-D meshed model of one-eighth of a single in-hull almond

6.3.4 Model development

6.3.4.1 System definition

The model was developed to simulate the hot air drying of a single in-hull almond under constant temperature and air velocity conditions. Each of the three almond components, hull, shell, and kernel, was treated as a porous medium consisting of three phases: solid (dry matter), liquid water, and gas (a mixture of water vapor and air). Liquid water and water vapor were considered the two transportable phases within each component.

6.3.4.2 Assumptions

For simplification and improved predictability, the following assumptions were made:

- The drying air was uniformly distributed throughout the dryer, and the almond surface was uniformly heated
- Each almond component was assumed to be isotropic and homogenous.
- Initial moisture contents were uniform within each almond component.
- Water in the vapor phase was exchanged between the almond and the drying chamber.

- e. The temperature and relative humidity of the air in the drying chamber remained constant.
- f. Only water vapor diffused within the air gap.
- g. There was no airflow in the air gap.
- h. Shrinkage occurred in the almond hull and kernel during the drying process. Due to the rigidity of the almond shell and prior results showing a relatively small size reduction (less than 3.1%), shell shrinkage was neglected.
- i. Hull splitting was not considered in the model, as justified by the shrinkage kinetics studied in the previous chapter.
- j. Deformation of the material was not considered in the model, as it was verified in the previous chapter that the shape (degree of sphericity) of the almond remained unchanged during the drying process.
- k. No chemical reactions occurred during the drying process.
- l. Water vapor and air in the system followed the ideal gas law.
- m. Pressures developed due to evaporation were assumed to be insignificant, keeping the system at atmospheric conditions.

6.3.4.3 *Governing equations*

To develop the heat and mass transfer equations, a control volume of the drying material was considered, accounting for the space-time evolution of liquid water and water vapor concentrations, as well as the temperature within the almond. The conservation of mass and energy equations for the control volume (CV) can be expressed as:

$$(\text{Moisture/Energy gained in CV} - \text{Moisture/Energy out of CV}) + \text{Generation} = \text{Storage} \quad (6.1)$$

Since no chemical reactions occur during drying, the generation term is zero. Mass conservation equations were formulated for the different phases present in the in-hull almond

system. These include the liquid water phase within the almond components (hull, shell, and kernel) and the gas phase within the almond components and the air gaps. To account for the effects of liquid water and water vapor transfer during the drying process, two separate mass balance equations were established, one for liquid water and one for water vapor. These equations were linked by a local evaporation/condensation rate term $\dot{I}$, which was also incorporated into the energy balance equation to represent the thermal effects of moisture evaporation more accurately.

The conservation equations for moisture and energy were derived from Fick's second law of diffusion and Fourier's law, respectively, and are given as follows:

$$\frac{\partial c_{wi}}{\partial t} = \nabla(D_{wi}\nabla c_{wi}) - \dot{I}_i \quad (6.2)$$

$$\frac{\partial c_{vi}}{\partial t} = \nabla(D_{vi}\nabla c_{vi}) + \dot{I}_i \quad (6.3)$$

$$\rho_i c_{pi} \frac{\partial T_i}{\partial t} = \nabla(k_i \nabla T_i) - \dot{I}_i \Delta H_v \quad (6.4)$$

where $i = h, s, k$ represents the hull, shell, and kernel, respectively; c_w and c_v denote the concentrations of liquid water and water vapor (kg/m^3), respectively; D_w and D_v are the effective diffusivities for liquid water and water vapor (m^2/s), respectively; $\dot{I}$ is the internal evaporation/condensation rate ($\text{kg/m}^3\cdot\text{s}$), which is typically defined as positive during local evaporation; ρ represents the density of the almond components (kg/m^3); c_p is the specific heat capacity of the sample ($\text{J/kg}\cdot\text{K}$); k denotes the thermal conductivity of the sample ($\text{W/m}\cdot\text{K}$); ΔH_v is the latent heat of moisture evaporation (J/kg); The term $\dot{I}\Delta H_v$ accounts for the latent heat associated with internal moisture evaporation.

Transport of water vapor in the air gap was given by:

$$\frac{\partial c_a}{\partial t} = D_{bin} \nabla^2 c_a \quad (6.5)$$

where D_{bin} is the vapor diffusivity in air (m^2/s).

The evaporation/condensation rate term, $\dot{I}$ can be obtained using the non-equilibrium approach, leading to an explicit formulation (Gulati et al., 2015; Ousegui et al., 2010). This rate is proportional to the difference between the actual vapor density and the equilibrium vapor density, expressed as:

$$\dot{I} = K_i(\rho_{v,eq} - \rho_v)\varphi_{vi} \quad (6.6)$$

where K is an evaporation rate constant (1/s). Since K strongly depends on the system operating conditions and is difficult to determine through analytical or empirical expressions, a parameter estimation method described by (Halder et al., 2007a) and (Ousegui et al., 2010) was used for its estimation. φ_{vi} represents the saturation fraction of the surface area covered by water vapor; ρ_v is the vapor density at any location inside the material (kg/m³), and $\rho_{v,eq}$ is the equilibrium water vapor density, which can be obtained from the moisture sorption isotherm of the material and the ideal gas law (Gulati et al., 2015; Mercier et al., 2014):

$$\rho_{v,eq} = a_{wi}\rho_{v,sat} \quad (6.7)$$

$$\rho_{v,sat} = \frac{P_{v,sat}}{R_v T_i} \quad (6.8)$$

where a_w is the water activity; R_v is the water vapor gas constant (J/kg·K); T_i is the almond sample temperature (K); $\rho_{v,sat}$ is the saturation vapor density (kg/m³); $P_{v,sat}$ is the saturation vapor pressure (Pa), which can be calculated at the sample temperature (T_i) using the Clausius-Clapeyron equation, as shown below:

$$P_{v,sat} = P_{ref} \exp \left(\frac{\Delta H_v}{R_v} * \left(\frac{1}{T_{ref}} - \frac{1}{T_i} \right) \right) \quad (6.9)$$

where P_{ref} is the vapor pressure (Pa) at a reference temperature (T_{ref}).

Water activity (a_w) is a function of moisture concentration and temperature, but for almond components, experimental moisture isotherms are not available in the literature. In this study, the

water vapor inside the air gap is assumed to be in instantaneous equilibrium with the solid surfaces (i.e., kernel surface, shell surface, and inner hull surface). Therefore, water activity (a_w) is derived based on estimated relative humidity at the interface (RH_s) using the reaction engineering approach (REA), as described by Chen (2008); Kar and Chen (2011); Putranto and Chen (2013).

The relative humidity at the interface (RH_s) can be determined using the following equation:

$$RH_s = \exp \left(-\frac{\Delta E_v}{RT_i} \right) \quad (6.10)$$

where R is the universal gas constant (J/mol·K); ΔE_v is the apparent activation energy for the REA model (J/mol), which can be determined experimentally using the following equation (Putranto & Chen, 2013):

$$\Delta E_v = -RT_i \ln \left(\frac{-m_s \frac{dX_i}{dt} \frac{1}{h_m A} + \rho_{v,b}}{\rho_{v,sat}} \right) \quad (6.11)$$

where m_s is the dried mass of sample (kg); X is the sample moisture content (kg water/kg dry mass); $\frac{dX}{dt}$ represents the drying rate (kg/kg·s), which can be determined from one drying experiment; A is the surface area of the in-hull almond, in-shell almond, and almond kernel (m²), respectively, which was calculated using dimensional data from Table 6.1; $\rho_{v,b}$ is the vapor density in the drying medium (kg/m³), which can be determined using psychrometric methods.

The relationships between RH_s and the average moisture content of the almond hull, shell, and kernel at three different drying temperatures were estimated using polynomial regression models, which were fitted via the method of least squares and implemented in MATLAB software (version R2020b, The MathWorks, Inc.). The resulting polynomial equations and fitted curves for each component at 45°C, 60°C, and 75°C are presented below:

For hull component:

$$\text{at } 45^\circ\text{C: } y = -0.007x^4 + 0.0549x^3 - 0.138x^2 + 0.1573x + 0.2016, \quad R^2 = 0.9998 \quad (6.12)$$

$$\text{at } 60^{\circ}\text{C: } y = -0.0012x^4 + 0.0153x^3 - 0.0567x^2 + 0.0974x + 0.0598, \quad R^2 = 0.9978 \quad (6.13)$$

$$\text{at } 75^{\circ}\text{C: } y = -0.0062x^4 + 0.057x^3 - 0.1599x^2 + 0.1712x + 0.0469, \quad R^2 = 0.997 \quad (6.14)$$

For shell component:

$$\text{at } 45^{\circ}\text{C: } y = -0.1717x^4 + 0.7363x^3 - 0.9718x^2 + 0.4895x + 0.2754, \quad R^2 = 0.9991 \quad (6.15)$$

$$\text{at } 60^{\circ}\text{C: } y = 0.0192x^4 + 0.3116x^3 - 0.6004x^2 + 0.332x + 0.1294, \quad R^2 = 0.9968 \quad (6.16)$$

$$\text{at } 75^{\circ}\text{C: } y = -0.1232x^4 + 0.846x^3 - 1.3795x^2 + 0.79x + 0.0714, \quad R^2 = 0.9705 \quad (6.17)$$

For kernel component:

$$\text{at } 45^{\circ}\text{C: } y = -613.79x^4 + 1131.5x^3 - 760.03x^2 + 221.99x - 23.556, \quad R^2 = 0.994 \quad (6.18)$$

$$\text{at } 60^{\circ}\text{C: } y = 85.473x^4 - 87.719x^3 + 30.767x^2 - 4.5042x + 0.4799, \quad R^2 = 0.9988 \quad (6.19)$$

$$\text{at } 75^{\circ}\text{C: } y = 247.24x^4 - 300.94x^3 + 131.75x^2 - 24.339x + 1.7222, \quad R^2 = 0.9889 \quad (6.20)$$

These equations demonstrate that RH_s fluctuated significantly as moisture content decreased for the kernel component, compared to the hull and shell. This phenomenon may be attributed to temperature fluctuations caused by the evaporative cooling effect near the surfaces. Additionally, each almond component likely dries at different rates, resulting in variations in moisture release dynamics. A similar phenomenon was also observed by Lertworasirikul and Tipsuwan (2008) in their study of semi-finished cassava crackers during the hot air drying process in a tray dryer. These findings highlight the complexity of moisture transfer and evaporative processes in multi-layered food materials like in-hull almonds.

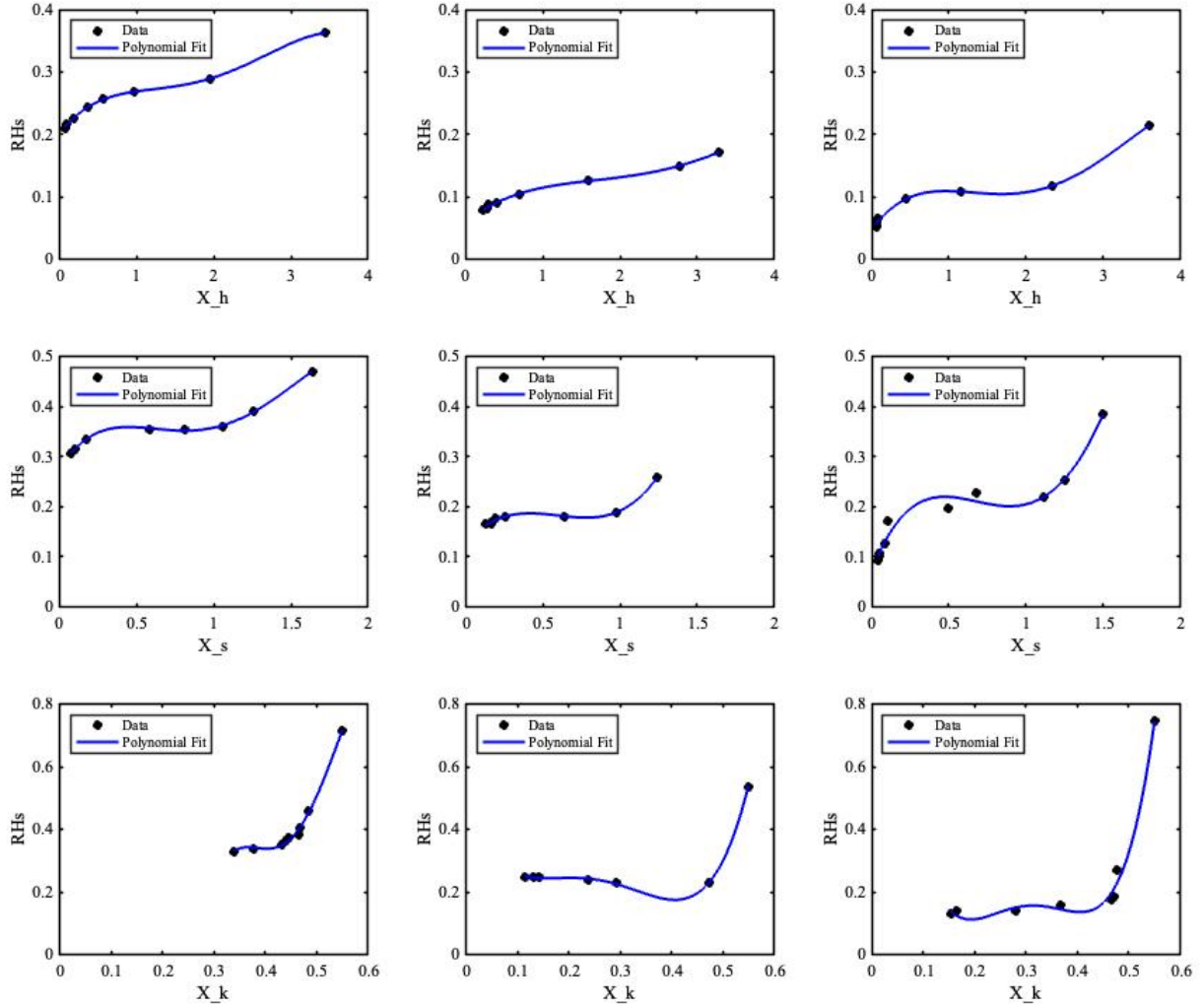


Figure 6.4 The fitted curve between RH_s and average moisture content (d.b.) of almond hull (X_h), shell (X_s), and kernel (X_k) components for drying air temperatures of 45°C (left), 60°C (middle), and 75°C (right)

6.3.4.4 Initial conditions

The initial conditions required to solve the governing equations were based on the hypothesis of uniform concentration and temperature within each almond component at the beginning of the drying process:

$$c_{wi} = c_{wi,0}, c_{vi} = c_{vi,0}, T_i = T_0 \quad (i = h, s, k) \quad \text{for } (t=0) \quad (6.21)$$

The concentrations were determined using the following equations (Gulati et al., 2015; Mercier et al., 2014; Ousegui et al., 2010):

$$c_{wi} = \rho_w \varphi_{wi} = \frac{m_{wi}}{V_i} \quad (6.22)$$

$$c_{vi} = \rho_v \varphi_{vi} \quad (6.23)$$

$$\varphi_{vi} = \varepsilon_i - \varphi_{wi} \quad (6.24)$$

$$\rho_v = \rho_g \omega_{vi} \quad (6.25)$$

where ρ_w is the density of water (kg/m³); φ_{wi} and φ_{vi} are the fractions of surface area covered by liquid water and water vapor, respectively; m_{wi} is the mass of water (kg); V_i is the volume (m³); ε_i is the porosity; ρ_g is the density of gas (kg/m³); Initially, the gas phase in each almond component was assumed to be saturated with vapor, allowing for the calculation of the initial mass fraction (ω_{vi}), using the Clausius-Clapeyron equation and Dalton's law (Gulati et al., 2015). For small gaps, the initial vapor concentration ($c_{a,0}$) can be approximated as the average of the vapor concentrations at the respective surfaces. Therefore, the initial conditions for the governing equations were as follows:

$$c_{wh0} = 670.56 \text{ kg/m}^3 \quad (6.26)$$

$$c_{ws0} = 318.75 \text{ kg/m}^3 \quad (6.27)$$

$$c_{wk0} = 213.95 \text{ kg/m}^3 \quad (6.28)$$

$$\omega_{vho} = 0.0173 \quad (6.29)$$

$$\omega_{vso} = 0.0171 \quad (6.30)$$

$$\omega_{vko} = 0.017 \quad (6.31)$$

$$c_{vho} = 2.24\text{e-}5 \text{ kg/m}^3 \quad (6.32)$$

$$c_{vso} = 5.10\text{e-}3 \text{ kg/m}^3 \quad (6.33)$$

$$c_{vko} = 5.33\text{e-}3 \text{ kg/m}^3 \quad (6.34)$$

$$c_{a0} = 2.56\text{e-}3 \text{ kg/m}^3, \text{ at the air gap between hull and shell} \quad (6.35)$$

$$c_{a0} = 5.21\text{e-}3 \text{ kg/m}^3, \text{ at the air gap between shell and kernel} \quad (6.36)$$

$$a_{wh,0} = 0.980 \quad (6.37)$$

$$a_{ws,0} = 0.971 \quad (6.38)$$

$$a_{wk,0} = 0.963 \quad (6.39)$$

$$T_0 = 23.7^\circ\text{C} \quad (6.40)$$

6.3.4.5 Boundary and interface conditions

During the drying process, hot air heating led to convective heat and moisture transfers at the outer surface of the hull, which was taken as the system boundary. Heat was transported inward through thermal conduction, while moisture diffused outward. Liquid water at the surface of the hull, shell, and kernel could evaporate into the air gap, and only water vapor could pass through the air gap.

At the outer surface of the almond hull:

$$-D_{w,h} \frac{dc_w}{dn|_{x_b}} = -h_m \varphi_{wh} (\rho_{v,s} - \rho_{v,b}) \quad (6.41)$$

$$-D_{v,h} \frac{dc_v}{dn|_{x_b}} = -h_m \varphi_{vh} (\rho_{v,s} - \rho_{v,b}) \quad (6.42)$$

$$-k_h \frac{dT}{dn|_{x_b}} = h_t (T_b - T) - h_m \varphi_{wh} (\rho_{v,s} - \rho_{v,b}) \cdot \Delta H_v(T) \quad (6.43)$$

where n is the outward-pointing normal unit vector; $D_{w,h}$ and $D_{v,h}$ are the effective diffusivities of liquid water and water vapor in the hull (m^2/s), respectively; $\rho_{v,s}$ is the surface water vapor density (kg/m^3); $\rho_{v,b}$ is the water vapor density in the drying air (kg/m^3); h_m is the mass transfer coefficient (m/s); h_t is the heat transfer coefficient ($\text{W}/\text{m}^2\cdot\text{K}$); k_h is the thermal conductivity of the hull ($\text{W}/\text{m}\cdot\text{K}$). T_b is the drying air temperature (K).

At the hull – air gap interface:

$$-D_{w,h} \frac{dc_w}{dn} = -h_{ma} \varphi_{wh} (\rho_{v,s} - \rho_v) \quad (6.44)$$

$$-D_{v,h} \frac{dc_v}{dn} = -D_{v,a} \frac{dc_v}{dn} + h_{ma} \varphi_{wh} (\rho_{v,s} - \rho_v) \quad (6.45)$$

$$-k_h \frac{dT}{dn} = -k_a \frac{dT}{dn} - h_{ma} \varphi_{wh} (\rho_{v,s} - \rho_v) \cdot \Delta H_v(T) \quad (6.46)$$

where h_{ma} is the moisture transfer coefficient in the air gap (m/s); $D_{v,a}$ is the water vapor diffusivity of air (m²/s); k_a is the thermal conductivity of air (W/m·K).

At the air gap (between hull and shell) – shell interface:

$$-D_{w,s} \frac{dc_w}{dn} = -h_{ma} \varphi_{ws} (\rho_{v,s} - \rho_v) \quad (6.47)$$

$$-D_{v,s} \frac{dc_v}{dn} = -D_{v,a} \frac{dc_v}{dn} + h_{ma} \varphi_{ws} (\rho_{v,s} - \rho_v) \quad (6.48)$$

$$-k_s \frac{dT}{dn} = -k_a \frac{dT}{dn} - h_{ma} \varphi_{ws} (\rho_{v,s} - \rho_v) \cdot \Delta H_v(T) \quad (6.49)$$

where $D_{v,s}$ is the water vapor diffusivity of the shell (m²/s); k_s is the thermal conductivity of the shell (W/m·K).

At the shell – air gap (between shell and kernel) interface:

$$-D_{w,s} \frac{dc_w}{dn} = -h_{ma} \varphi_{ws} (\rho_{v,s} - \rho_v) \quad (6.50)$$

$$-D_{v,s} \frac{dc_v}{dn} = -D_{v,a} \frac{dc_v}{dn} + h_{ma} \varphi_{ws} (\rho_{v,s} - \rho_v) \quad (6.51)$$

$$-k_s \frac{dT}{dn} = -k_a \frac{dT}{dn} - h_{ma} \varphi_{ws} (\rho_{v,s} - \rho_v) \cdot \Delta H_v(T) \quad (6.52)$$

At the air gap – kernel interface:

$$-D_{w,k} \frac{dc_w}{dn} = -h_{ma} \varphi_{wk} (\rho_{v,k} - \rho_v) \quad (6.53)$$

$$-D_{v,k} \frac{dc_v}{dn} = -D_{v,a} \frac{dc_v}{dn} + h_{ma} \varphi_{wk} (\rho_{v,k} - \rho_v) \quad (6.54)$$

$$-k_k \frac{dT}{dn} = -k_a \frac{dT}{dn} - h_{ma} \varphi_{wk} (\rho_{v,k} - \rho_v) \cdot \Delta H_v(T) \quad (6.55)$$

where $D_{v,k}$ is the water vapor diffusivity of the kernel (m^2/s); k_k is the thermal conductivity of the kernel ($\text{W}/\text{m}\cdot\text{K}$).

At the center of the almond kernel:

$$\frac{dc_w}{dn} = 0, \frac{dc_v}{dn} = 0, \frac{dT}{dn} = 0 \quad (6.56)$$

6.3.4.6 Determination of model input parameters

- Effective moisture diffusivity, vapor diffusivity, and thermal property

In Chapter 5, the effective liquid moisture diffusivities (D_{eff}) were determined for the almond hull, shell, and kernel during in-hull almond drying experiments at three different drying air temperatures. Both constant and variable effective moisture diffusivities were used in this study.

The effective vapor diffusivity was calculated using the method of Slattery and Bird (1958):

$$D_{vi} = D_{v0} \frac{\varepsilon}{\tau} \quad (6.57)$$

where D_{v0} is the water vapor diffusivity (m^2/s), which depends on the vapor temperature. For food and biological materials, D_{v0} can be expressed as (Gimmi et al., 1993):

$$D_{v0} = 2.09 \times 10^5 + 2.137 \times 10^{-7}(T - 273.15) \quad (6.58)$$

The tortuosity (τ) in food materials is generally related to porosity and can be expressed using the Bruggeman relation (Pisani, 2011):

$$\tau = \varepsilon^{-0.5} \quad (6.59)$$

The thermal conductivity and specific heat capacity of the three almond components were estimated using their chemical composition data and temperature-dependent models developed by Choi (1986), as detailed in Chapter 4.

- Moisture and heat transfer coefficients

The heat and moisture transfer coefficients during hot air drying were determined based on the properties of the drying air. These transport coefficients were calculated using established Sherwood and Nusselt number correlations for flow over a single sphere (Whitaker, 1972).

$$Sh = \frac{h_m d}{D_{AB}} \quad (6.60)$$

$$Sh = 2 + (0.4Re^{0.5} + 0.06Re^{0.67})Sc^{0.4} \times \left(\frac{\mu}{\mu_s}\right)^{0.25} \quad (6.61)$$

$$Re = \frac{Vd}{\nu} \quad (6.62)$$

$$Sc = \frac{\nu}{D_{AB}} \quad (6.63)$$

where, Re is the Reynolds number; Sc is the Schmidt number; V is the air velocity (m/s); d is the geometric mean diameter ($d = \sqrt[3]{length * width * thickness}$) (m); ν is the kinematic viscosity of air (m^2/s); D_{AB} is the binary diffusivity coefficient of water vapor in air; μ and μ_s represent the viscosities of air evaluated at the mean bulk temperature and the mean surface temperature ($kg/s \cdot m$), respectively. D_{AB} was calculated using the equation proposed by Marrero and Mason (1972):

$$D_{H_2O-Air} = 1.87 \times 10^{-10} \frac{T^{2.072}}{P}, 280K < T < 450K \quad (6.64)$$

where P is the total pressure (atm); T is the temperature (K).

Similarly, due to the analogy between heat and mass transfer, the heat transfer coefficient was determined using the Nusselt number:

$$Nu = \frac{hd}{k} \quad (6.65)$$

$$Nu = 2 + (0.4Re^{0.5} + 0.06Re^{0.67})Pr^{0.4} \times \left(\frac{\mu}{\mu_s}\right)^{0.25} \quad (6.66)$$

$$Pr = \frac{\nu}{\alpha} \quad (6.67)$$

where Pr is the Prandtl number; α is the thermal diffusivity of air (m^2/s).

6.3.4.7 Shrinkage velocity

As delineated in Chapter 5, Section 5.3.2.3, 10 marked almonds were periodically removed from the dryer to measure their dimensions. The averaged dimensional data were then applied to mathematical models to establish a relationship between shrinkage (S_i) and moisture ratio (MR). Linear, quadratic, and cubic models, as expressed in Equations 5.14-16, were fitted using non-linear regression analysis in MATLAB (version R2020b, The MathWorks, Inc.)

The shrinkage phenomena were incorporated into the finite element modeling by introducing shrinkage velocity as an input parameter via the moving mesh module in COMSOL. Shrinkage velocity (SV) was calculated using the distance and time relationship as shown below:

$$SV = \frac{S_i}{t} \quad (6.68)$$

where S_i represents the shrinkage parameter (m) in the length, width, and thickness directions; SV is the shrinkage velocity (m/s); t is time (s).

The thermal properties (k_a , c_{pa} , ρ_a) of the air in the air gaps between the hull and shell and between the shell and kernel were derived from Bergman (2011). These properties were used to develop interpolation functions of temperature, which were then incorporated into the model. The input parameters are shown in Table 6.3.

Table 6.3 Input parameters for the model

Parameter	Symbol	Value	Units	Source
Porosity				
Hull	ε_h	0.673	n/a	Dingke and Fielke (2014)
Shell	ε_s	0.572	n/a	Dingke and Fielke (2014)
Kernel	ε_k	0.481	n/a	Dingke and Fielke (2014)

True density				
Hull	ρ_h	1165	kg/m ³	Determined
Shell	ρ_s	1278	kg/m ³	Determined
Kernel	ρ_k	1062	kg/m ³	Determined
Density of air	$\rho_a(T)$	Interpolation	kg/m ³	Bergman (2011)
Density of water vapor	ρ_v	Ideal gas	kg/m ³	Determined
Density of water	ρ_w	998	kg/m ³	
Thermal conductivity				
Hull	k_h	0.553	W/m·K	Determined
Shell	k_s	0.459	W/m·K	Determined
Kernel	k_k	0.305	W/m·K	Determined
Air	$k_a(T)$	Interpolation	W/m·K	Bergman (2011)
Specific heat				
Hull	c_{ph}	3419	J/kg·K	Determined
Shell	c_{ps}	2904	J/kg·K	Determined
Kernel	c_{pk}	2742	J/kg·K	Determined
Air	$c_{pa}(T)$	Interpolation	J/kg·K	Bergman (2011)
Effective moisture diffusivity				
Hull	$D_{eff,h}$	Polynomial	m ² /s	Determined
Shell	$D_{eff,s}$	Polynomial	m ² /s	Determined
Kernel	$D_{eff,k}$	Polynomial	m ² /s	Determined
Effective vapor diffusivity				
Hull	D_{vh}	Eqs. (6.57-59)	m ² /s	Determined
Shell	D_{vs}	Eqs. (6.57-59)	m ² /s	Determined
Kernel	D_{vk}	Eqs. (6.57-59)	m ² /s	Determined
Ambient pressure	P_{atm}	101,325	Pa	
Latent heat of vaporization	ΔH_v	2.26×10 ⁶	J/kg	Datt (2011)
Vapor diffusivity in air	D_{bin}	Eq. (6.64)	m ² /s	Marrero and Mason (1972)

Reynolds number of air	Re	1931-2255	n/a	Determined
Sherwood number of air	Sh	23.67-34.02	n/a	Determined
Schmidt number of air	Sc	0.57-0.59	n/a	Determined
Prandtl number of air	Pr	0.70-0.71	n/a	Determined
Nusselt number of air	Nu	25.56-36.49	n/a	Determined
Convective heat transfer coefficient	h	27.56-36.26	W/m ² ·K	Determined
Convective moisture transfer coefficient	h_m	0.027-0.039	m/s	Determined
Moisture transfer coefficient in air gap between hull and shell	h_{ma}	0.00274-0.00303	m/s	Determined
Moisture transfer coefficient in air gap between shell and kernel	h_{ma}	0.0038-0.00418	m/s	Determined

6.3.5 Model solving

The 3-D model was developed to simulate the moisture migration mechanism in in-hull almonds, taking into account structural changes occurring during convective hot air drying. This model incorporated shrinkage effects and moisture-dependent diffusion coefficients to enhance realism and predictive accuracy. Three distinct scenarios were modeled for comparative analysis:

- Scenario 1 (nsh_CD): This model assumed a constant moisture diffusivity coefficient and neglected shrinkage throughout the drying process.
- Scenario 2 (nsh_VD): This model incorporated a moisture-dependent diffusivity coefficient but still disregarded shrinkage.
- Scenario 3 (sh_VD): This model considered both a moisture-dependent diffusivity coefficient and the effects of shrinkage.

The finite element method (FEM) offers advantages in handling the drying simulation of objects with complex geometries and material discontinuities. Therefore, COMSOL Multiphysics® v.6.2 (Comsol Inc, Burlington, MA) was used to solve the partial differential equations governing the mass and heat transfer processes. The “Transport of Dilute Species” module was employed to solve for liquid water and water vapor conservation in the different almond components, while the “Heat Transfer in Solids” module was used for the heat transfer simulations. The computational domain utilized an extra fine mesh consisting of 295,597 tetrahedra with a minimum element quality of 0.1564 and a mesh volume of $1.319 \times 10^{-5} \text{ m}^3$. The “moving mesh” approach was implemented using the Arbitrary Lagrangian-Eulerian (ALE) method to account for shrinkage during drying. The simulations were run on a MacOS system with a 12-core CPU and an 18-core GPU.

6.3.6 Model validation

Samples of in-hull almonds from the same variety were dried at 45°C, 60°C, and 75°C, and the experimental values, including internal moisture and temperature profiles, were used to validate the model estimates. The model predictability and robustness were evaluated using the adjusted coefficient of determination (R_{adj}^2) and the root mean square error (RMSE):

$$R_{adj}^2 = 1 - \frac{(1-R^2)(n-1)}{n-p-1} \quad (6.69)$$

$$RMSE = \sqrt{\frac{\sum_1^n (MC_{exp,i} - MC_{pre,i})^2}{n}} \quad (6.70)$$

where n is the number of observations; p is the number of independent variables; $MC_{exp,i}$ and $MC_{pre,i}$ are the i th experimental and predicted moisture contents, respectively.

The maximum and average errors between experiments and simulations were calculated as described by Ousegui et al. (2010):

$$er_{max} = \max \left(\frac{abs(X_{exp}^i - X_{pre}^i)}{X_{exp}^i} \right)_i \quad (6.71)$$

$$er_{ave} = \frac{1}{n} \sum_{i=1}^n \frac{abs(X_{exp}^i - X_{pre}^i)}{X_{exp}^i} \quad (6.72)$$

6.4 Results and Discussion

6.4.1 Temperature profiles of different almond components

The temperature profiles of the three different almond components, including almond hull surface, shell surface, and kernel center, predicted by the models developed in this study closely matched the experimental temperature profiles across all drying temperatures, as illustrated in Figure 6.5 (derived from the model nsh_CD as an example). This agreement is further supported by higher values of R_{adj}^2 and lower values of RMSE, as shown in Table 6.4.

All models developed in this study accurately reproduced the experimental temperature increase during the drying process. Quantitatively, the maximum error (calculated using Eq. 6.71) was 5.1%, 3.1%, and 3.5% for the temperatures at the hull surface, shell surface, and kernel center, respectively, during drying at 45°C (Table 6.5). The corresponding values for drying at 60°C and 75°C were 3.6%, 3.2%, 4.4%, and 5.0%, 5.8%, 2.8%, respectively. These errors were predominantly observed at the beginning of the drying process. The average error (calculated using Eq. 6.72) was 1.4%, 1.3%, and 1.4% for the temperatures at the hull surface, shell surface, and kernel center, respectively, during the drying of 45°C. The corresponding values for drying at 60°C and 75°C were 1.4%, 1.7%, 1.6%, and 2.3%, 2.9%, 1.9%, respectively.

It was also observed that there was a temperature drop in the shell and kernel during the drying of 75°C at about 200 to 300 minutes. This was because the drying rate at 75°C was higher, leading to intense moisture evaporation from the hull, which absorbed heat and temporarily reduced the temperature. This caused a cooling effect, resulting in the observed temperature drop in both the

shell and kernel. Additionally, the significant moisture removal led to noticeable shrinkage in the hull, as shown in Figure 6.12.

Furthermore, it was found that all three models predicted slightly lower temperatures at the end of the drying process compared to the measured values, as shown in Table 6.6. For example, during drying at 75°C, the experimental final temperature at the shell surface was 70.8°C, while the temperatures predicted by the nsh_CD, nsh_VD, and sh_VD models were 69.8°C, 70.0°C, and 69.5°C, respectively. One potential reason for this discrepancy could be the use of constant thermal properties for the different almond components during the modeling process. Thermal properties could change with sample moisture content, temperature, and shrinkage during drying, as has been observed in cumin seeds (Singh & Goswami, 2000), pistachios (Hsu et al., 1991), and sheanut kernels (Aviara & Haque, 2001).

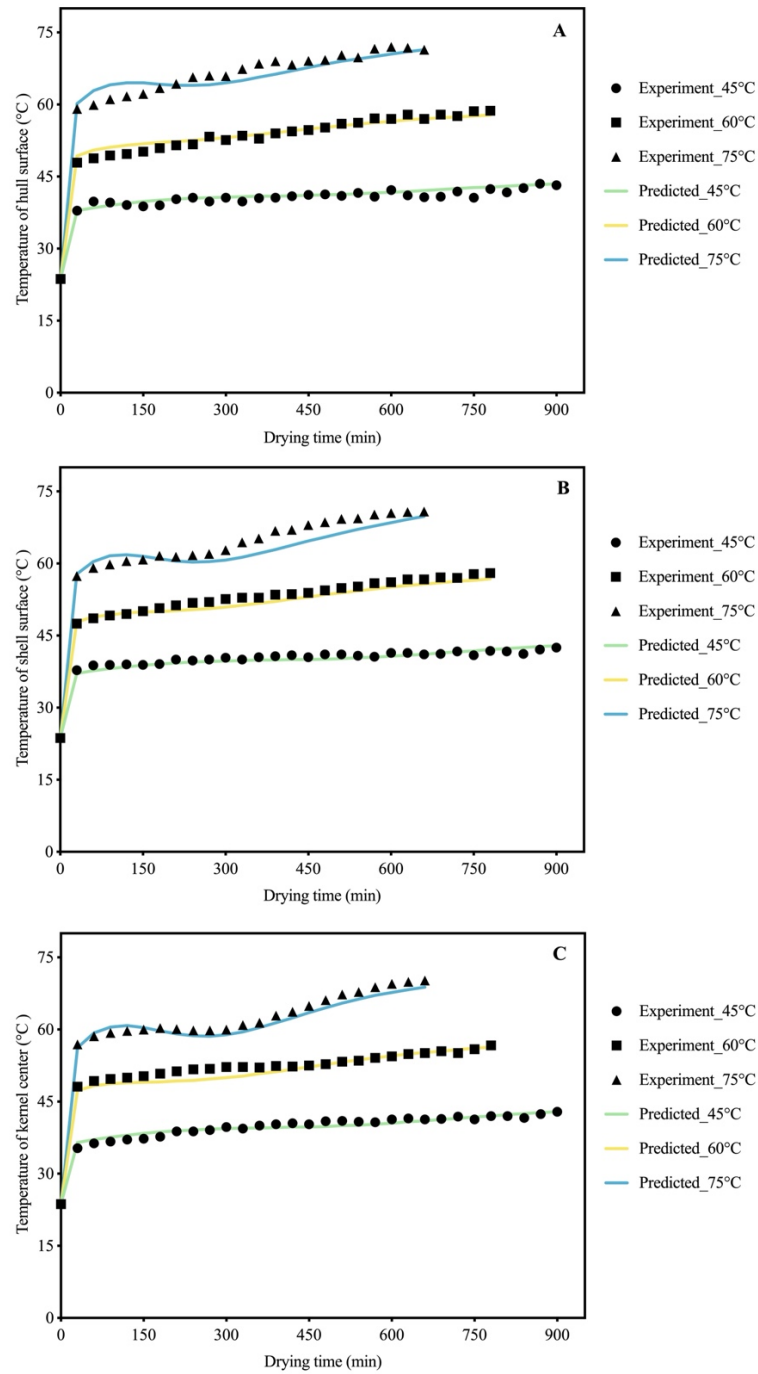


Figure 6.5 Experimental and predicted temperature profiles at different locations: (A) hull surface; (B) shell surface; (C) kernel center for the drying of 45, 60, and 75°C, respectively (using nsh_CD model as an example)

Table 6.4 R_{adj}^2 and RMSE of the drying model for temperature and overall moisture content in three different scenarios

Drying temperature (°C)	Model	Hull surface		Shell surface		Kernel center		Overall	
		R_{adj}^2	RMSE	R_{adj}^2	RMSE	R_{adj}^2	RMSE	R_{adj}^2	RMSE
		for T	for T	for T	for T	for T	for T	for MC	for MC
45	nsh_CD	0.942	0.773	0.960	0.624	0.962	0.661	0.976	0.080
	nsh_VD	0.945	0.753	0.958	0.635	0.958	0.694	0.969	0.091
	sh_VD	0.952	0.705	0.958	0.635	0.958	0.697	0.966	0.095
60	nsh_CD	0.980	0.904	0.972	1.044	0.961	1.141	0.979	0.080
	nsh_VD	0.981	0.880	0.974	0.994	0.960	1.151	0.981	0.075
	sh_VD	0.981	0.879	0.978	0.921	0.937	1.439	0.990	0.054
75	nsh_CD	0.963	1.793	0.944	2.177	0.979	1.265	0.946	0.133
	nsh_VD	0.968	1.673	0.955	1.943	0.987	0.993	0.954	0.123
	sh_VD	0.971	1.588	0.966	1.689	0.984	1.100	0.974	0.093

Table 6.5 Maximum and average errors between experiments and simulations predicted by model nsh_CD for three different drying temperatures

Almond component	Error	Drying temperature (°C)		
		45	60	75
Hull surface	er_max	5.1%	3.6%	5.0%
	er_ave	1.4%	1.4%	2.3%
Shell surface	er_max	3.1%	3.2%	5.8%
	er_ave	1.3%	1.7%	2.9%
Kernel center	er_max	3.5%	4.4%	2.8%
	er_ave	1.4%	1.6%	1.9%

Table 6.6 Experimental and predicted ending temperatures of three different almond components for different HA drying conditions

HA temperature (°C)	Location	Ending sample temperature (°C)			
		Experimental	Predicted		
			nsh_CD	nsh_VD	sh_VD
45	Hull surface	43.2	43.5	43.5	43.3
60		58.7	57.8	57.8	57.8
75		71.4	71.4	71.5	71.0
45	Shell surface	42.5	42.9	42.9	42.7
60		58	56.8	56.8	56.8
75		70.8	69.8	70.0	69.5
45	Kernel center	42.9	42.9	42.9	42.8
60		56.7	56.3	56.4	55.6
75		70.2	68.8	69.2	68.1

6.4.2 Spatial temperature distribution

The 3-D spatial temperature distribution and line graphs of temperature distribution along the length of the in-hull almond at different drying times are shown in Figure 6.6 and Figure 6.7-6.9, respectively. The results indicate that the temperatures in the hull and shell components increased more rapidly than in the kernel. The temperature gradient within the in-hull almond reached its maximum within the first 5 minutes of drying, as evidenced by the significant color changes in the 3-D spatial temperature distribution (Figure 6.6) and the steep incline in the line graphs (Figure 6.7-6.9). The magnitude of the temperature gradient was 7.7°C, 12.3°C, and 17.2°C for drying at 45°C, 60°C, and 75°C, respectively.

In addition, the outer layers of each component heated up quickly, while the inner layers lagged due to thermal resistance, as shown in Figure 6.7-6.9. As drying progressed, heat continued to

penetrate inward, reducing the temperature gradient, and after about 60 minutes of drying, the temperature became relatively uniform. Additionally, two significant temperature drops were observed across the air gaps between the hull and shell and between the shell and kernel at the beginning of drying (Figure 6.7-6.9). This phenomenon might be attributed to the low thermal conductivity of the air gaps and the evaporative cooling effect at the interfaces. As drying proceeded and moisture was gradually removed, the temperature drops diminished in the 45°C, 60°C, and 75°C drying models predicted by the nsh_CD model (left-hand side of Figure 6.7-6.9). However, in the models considering shrinkage (sh_VD), the temperature drops remained significant for drying at 60°C and 75°C, especially at the shell-kernel interface (right-hand side of Figure 6.7-6.9). This could be due to almond kernel shrinkage during drying, leading to a larger air gap between the kernel and shell.

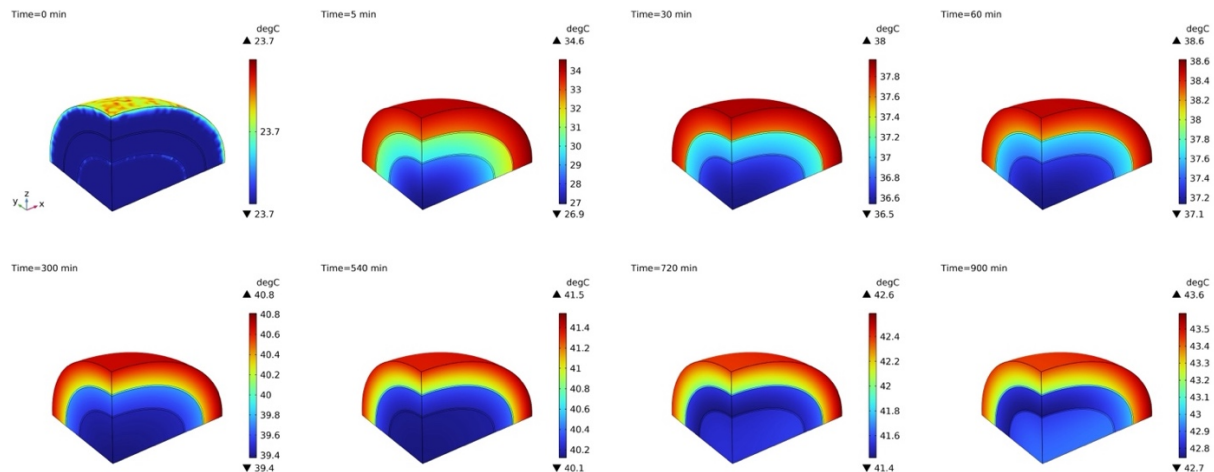


Figure 6.6 3-D spatial temperature distribution within the in-hull almond during the drying process (using the 45°C drying predicted by the nsh_CD model as an example)

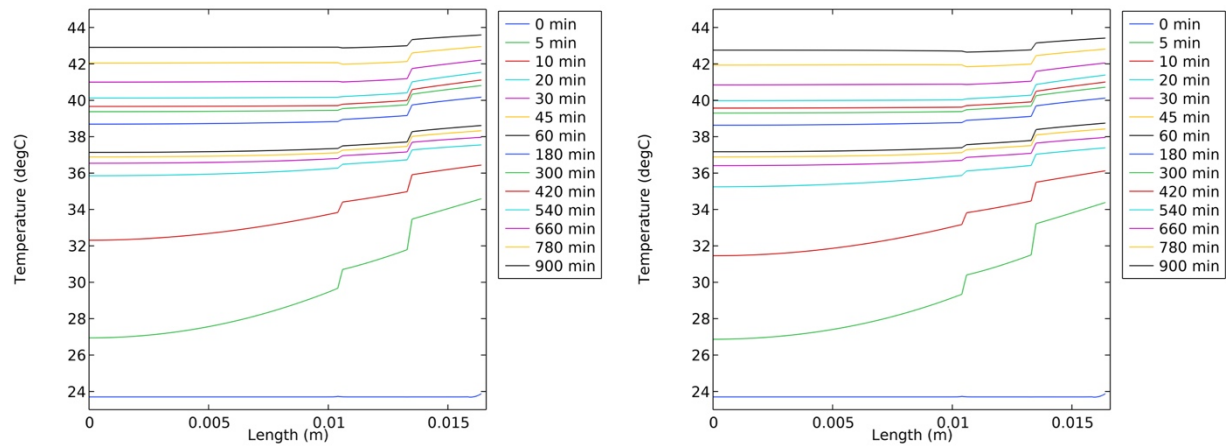


Figure 6.7 Temperature distribution along the length direction of the in-hull almond at different drying times during drying at 45°C predicted by model nsh_CD (left) and sh_VD (right)

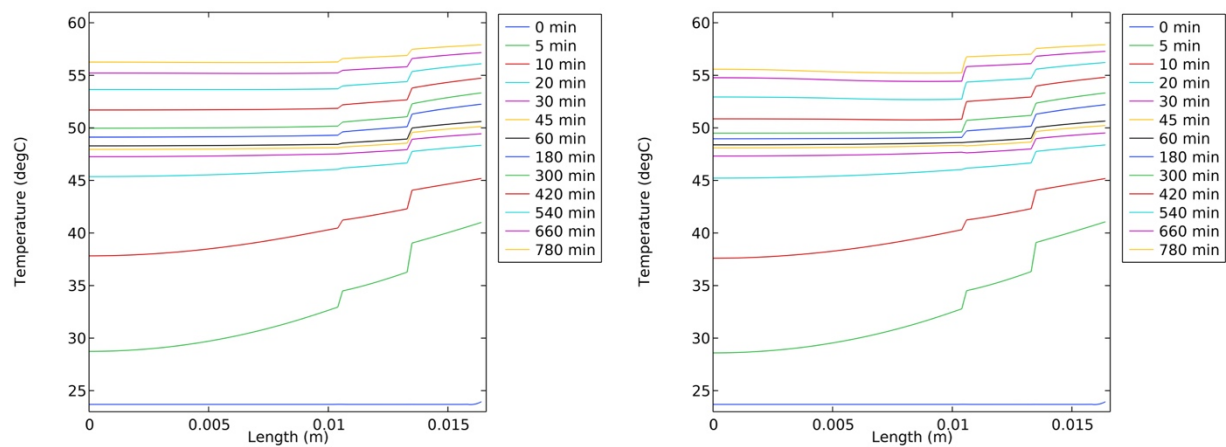


Figure 6.8 Temperature distribution along the length direction of the in-hull almond at different drying times during drying at 60°C predicted by model nsh_CD (left) and sh_VD (right)

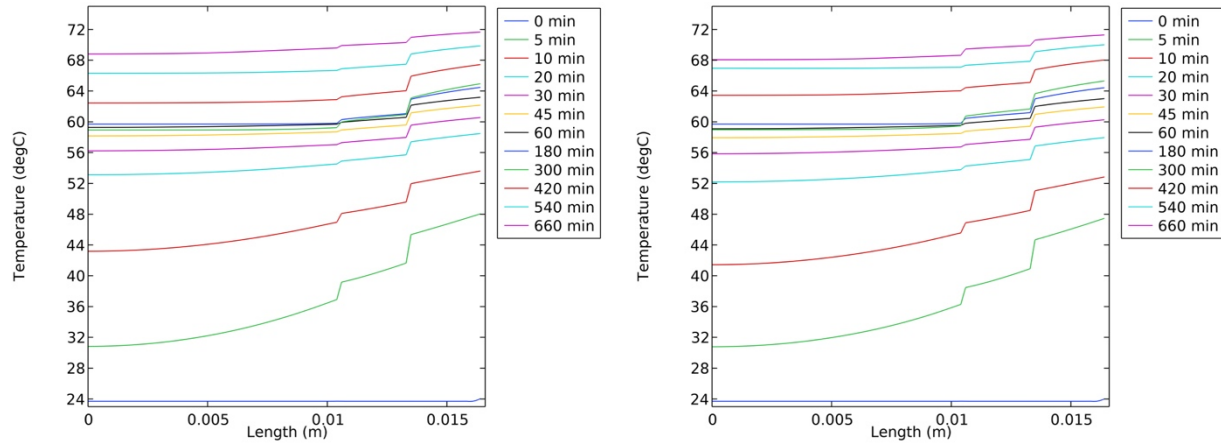


Figure 6.9 Temperature distribution along the length direction of the in-hull almond at different drying times during drying at 75°C predicted by model nsh_CD (left) and sh_VD (right)

6.4.3 Moisture migration considering variable moisture diffusivity coefficient

Figure 6.10 shows the overall moisture contents obtained from experimental data and model predictions using the nsh_CD and nsh_VD models for three drying air temperatures. The results indicate that moisture reduction during the initial 60 minutes of drying was nearly identical between the models and the experimental data. However, after 60 minutes, a greater discrepancy between the models and the experimental data was observed. As Srikiatden and Roberts (2007) noted, this could be because the early stage of drying is governed by external conditions, such as temperature, which were well-matched in both the experimental and predicted temperatures.

Notably, the drying curves predicted using both constant and moisture-dependent diffusivities did not differ significantly in this study for in-hull almond drying. This might be due to the relatively small variation in diffusivity values throughout the drying process. As shown in Table 5.7 of Chapter 5, the mean moisture diffusivities for the almond hull, shell, and kernel ranged from $9.70 \times 10^{-10} \text{ m}^2/\text{s}$ and $2.05 \times 10^{-9} \text{ m}^2/\text{s}$, 4.71×10^{-10} to $9.24 \times 10^{-10} \text{ m}^2/\text{s}$, and 5.82×10^{-11} to $3.75 \times 10^{-10} \text{ m}^2/\text{s}$, as drying temperature increased from 45°C to 75°C.

Nevertheless, predictions using moisture-dependent diffusivity showed a better fit to experimental data, particularly at the end of the drying process, when moisture diffusivity can become very low as moisture content decreases (Chirife, 1983; Rizvi, 2014). As shown in Figure 6.10 (see the enlarged views on the right-hand side), the model prediction using moisture-dependent diffusivity closely matched the experimental data at the end of drying, while the model with constant diffusivity slightly overestimated the final moisture content. No significant differences were observed for drying at 45°C, likely due to smaller variations in diffusivity at this lower temperature.

These findings were further supported by statistical analysis presented in Table 6.4. Models incorporating variable moisture diffusivity showed higher values of R_{adj}^2 (0.981 for 60°C and 0.954 for 75°C) compared to those using constant diffusivity (0.979 for 60°C and 0.946 for 75°C). These results are consistent with findings in the literature, such as those by Simal et al. (2006) and Rani and Tripathy (2020) for pineapple slices, Karim and Hawlader (2005) for banana slices, and Chen, Venkitasamy, et al. (2020) for walnuts, which demonstrated improved modeling accuracy by using variable moisture diffusivity.

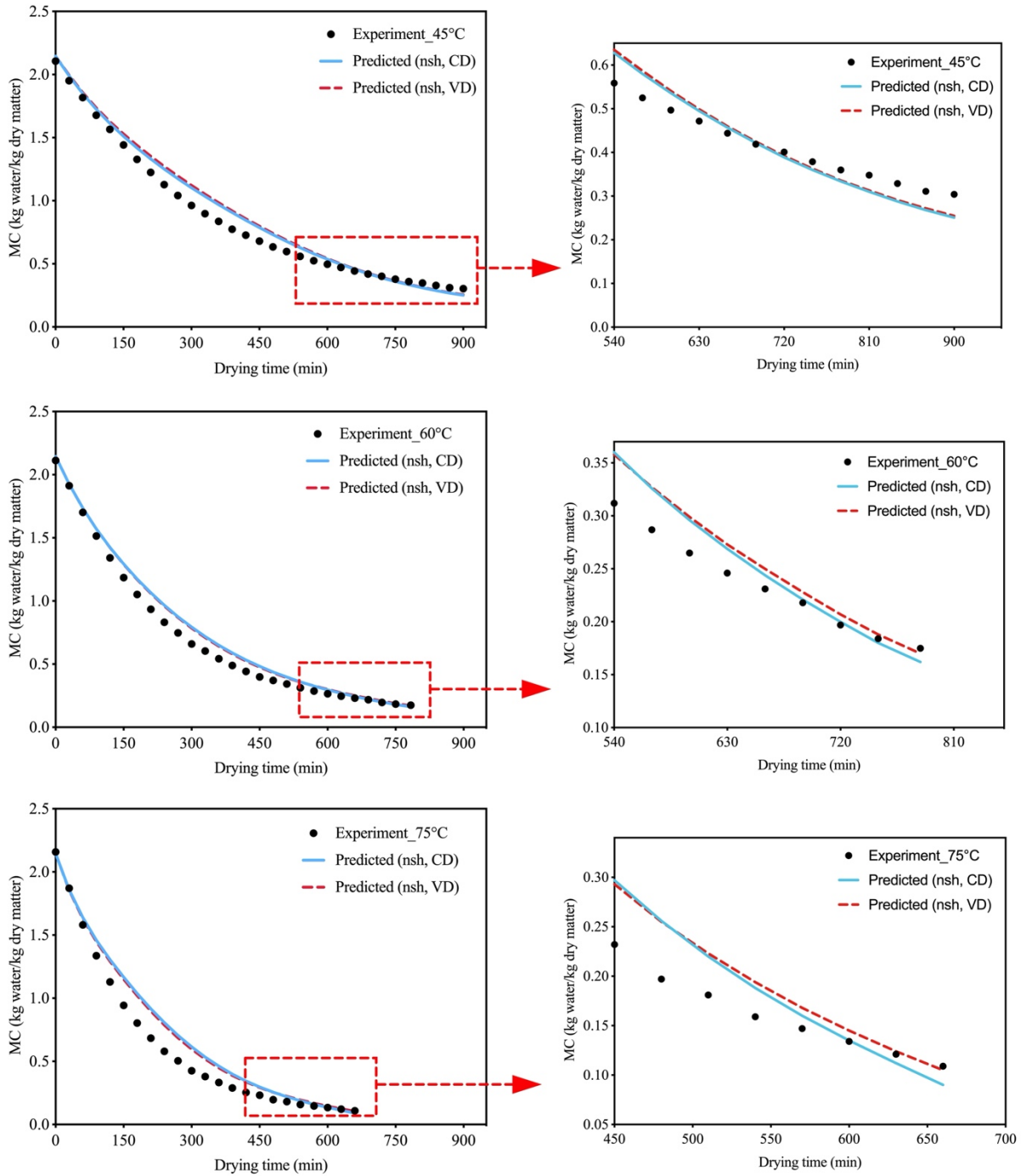


Figure 6.10 Experimental and predicted overall MC profiles for hot air drying at 45°C (top), 60°C (middle), and 75°C (bottom), with enlarged views at the end of drying (right-hand side).

*note: nsh refers to no consideration of shrinkage; CD and VD represent constant and variable moisture diffusivity coefficients, respectively

6.4.4 Effect of shrinkage consideration on moisture migration

Figure 6.11 compares the overall moisture content profiles obtained from experiments with model predictions using the nsh_VD and sh_VD models for three drying air temperatures. It was observed that the model accounting for the shrinkage effect during drying had smaller deviations from the experimental curves across all drying air temperatures compared to the model without shrinkage consideration. This was further confirmed by the statistical analysis presented in Table 6.4, which shows that the sh_VD models produced higher values of R_{adj}^2 (0.99 for drying at 60°C and 0.974 for drying at 75°C) compared to the nsh_VD models (0.981 for drying at 60°C and 0.954 for drying at 75°C). Therefore, neglecting the shrinkage effect could contribute to discrepancies between experimental data and predicted values, as reported by Chen and Johnson (1969), Mulet et al. (1987), and Simal et al. (1998).

Additionally, in terms of drying rate, the drying process was accelerated by shrinkage, as shown in Figure 6.11, during the middle stage of drying. This can be attributed to the reduced dimensions of the almond hull, which might result in a shorter path length for water molecules to diffuse within the almond. However, the dimensions of the almond kernel were also reduced during drying, leading to an increase in the thickness of the air gap between the kernel and shell. As a result, the drying process slowed down during the later stage of drying. As shown in Figure 6.11 (see the enlarged views on the right-hand side), the final moisture content predicted by the sh_VD model closely matched the experimental data. Therefore, the model that considered both shrinkage and variable diffusivity was more realistic and provided the best fit with the experimental drying curve for in-hull almond drying.

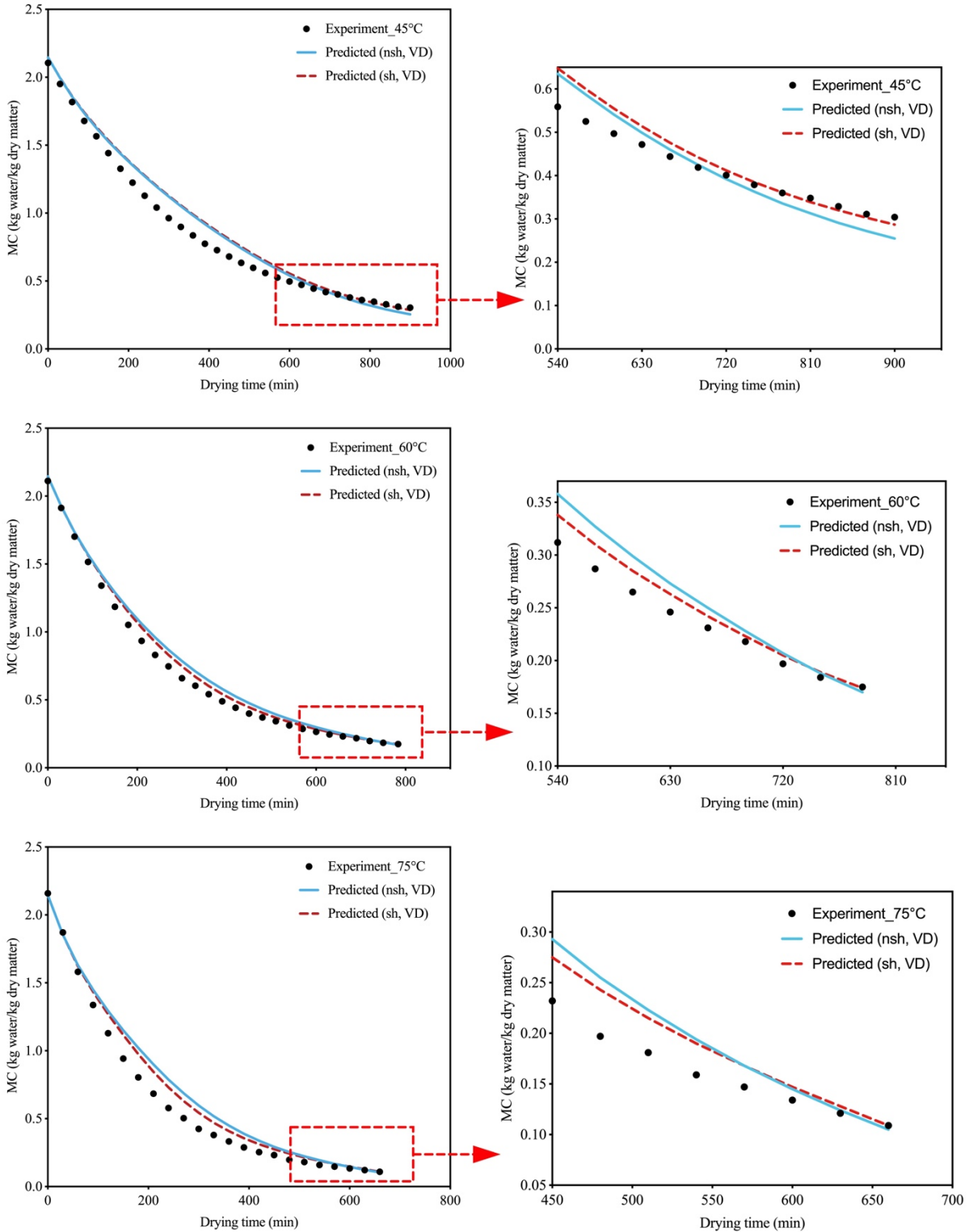


Figure 6.11 Experimental and predicted overall MC profiles for hot air drying at 45°C (top), 60°C (middle), and 75°C (bottom), with consideration of the shrinkage effect (represented by 'sh')

6.4.5 Spatial liquid water and water vapor distribution

Figure 6.12 illustrates the 3-D spatial moisture content distribution within the in-hull almond during drying at 75°C, as predicted by the sh_VD model. Using the same model prediction, Figure 6.13-6.15 depict the moisture profiles of the almond hull, shell, and kernel along the length, width, and thickness directions, respectively. The results indicate that moisture removal primarily occurred in the hull component within the first 60 minutes of drying, while the moisture contents in the shell and kernel did not decrease significantly, as reflected in the color change (Figure 6.12). Additionally, noticeable shrinkage of the almond hull became apparent after 60 minutes.

At the start of drying, the moisture content in the middle of the almond hull was higher than at both the outer and inner surfaces for all three directions, forming an “arch” shape, as shown in Figure 6.13-6.15. As drying progressed, this “arch” shape gradually disappeared. A similar trend was observed for the shell. This could be due to intense convective moisture transfer at the beginning of drying on both sides of the hull and shell, which became less intense later. This phenomenon aligns with the findings of Chen et al. (2022) in their study of in-shell walnut drying under hot air heating.

From the standpoint of moisture removal direction, the moisture in the almond hull was removed uniformly along the length, width, and thickness, as indicated by the color change in Figure 6.12. This might be because the hull was directly exposed to the drying conditions. However, moisture was removed more quickly along the length direction for the shell and kernel compared to the other two directions, as clearly seen in Figure 6.12 at 300, 420, and 660 minutes of drying. This may be associated with the non-isotropic shrinkage observed in the kernel. As noted in Chapter 5, the kernel experienced greater reductions in width and thickness than in length during drying.

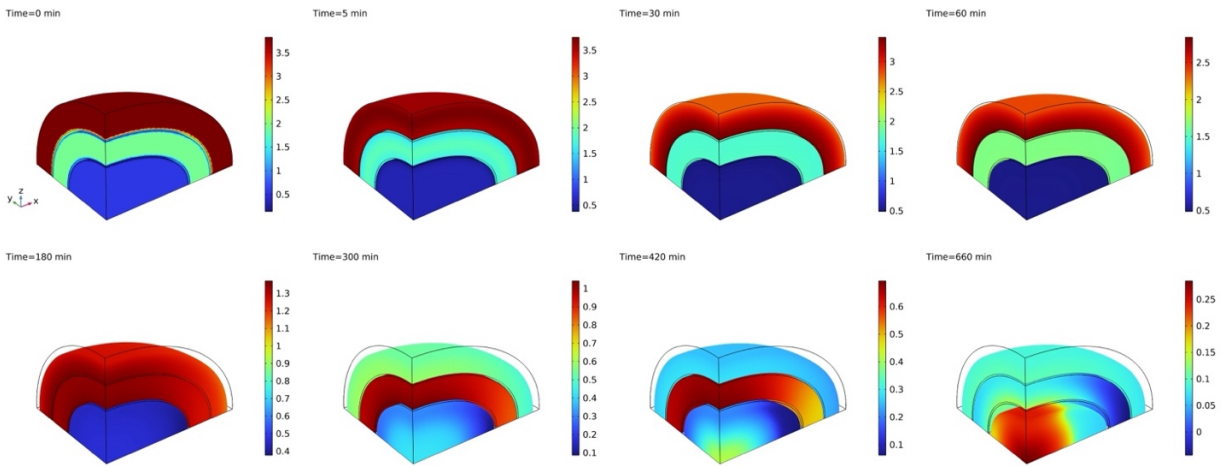


Figure 6.12 3-D spatial moisture content distribution within the in-hull almond during the drying process (using the 75°C drying predicted by the sh_VD model as an example)

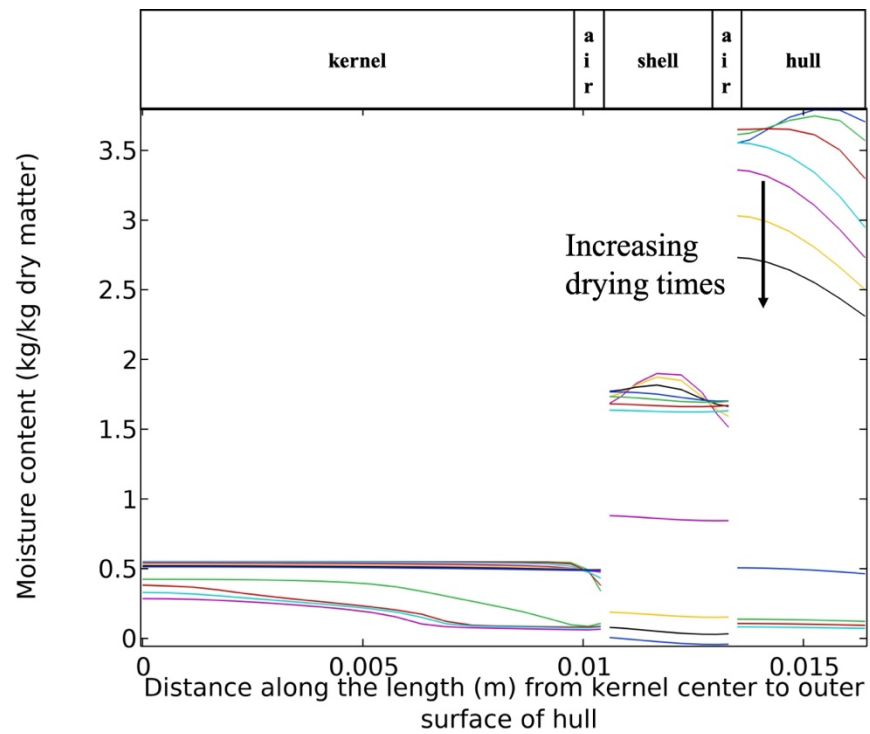


Figure 6.13 Spatial liquid moisture profiles (predicted by the sh_VD model) in the hull, shell, and kernel along the length direction at different drying times during drying at 75°C (3, 5, 10, 20, 30, 45, 60, 300, 540, 600, 660 minutes)

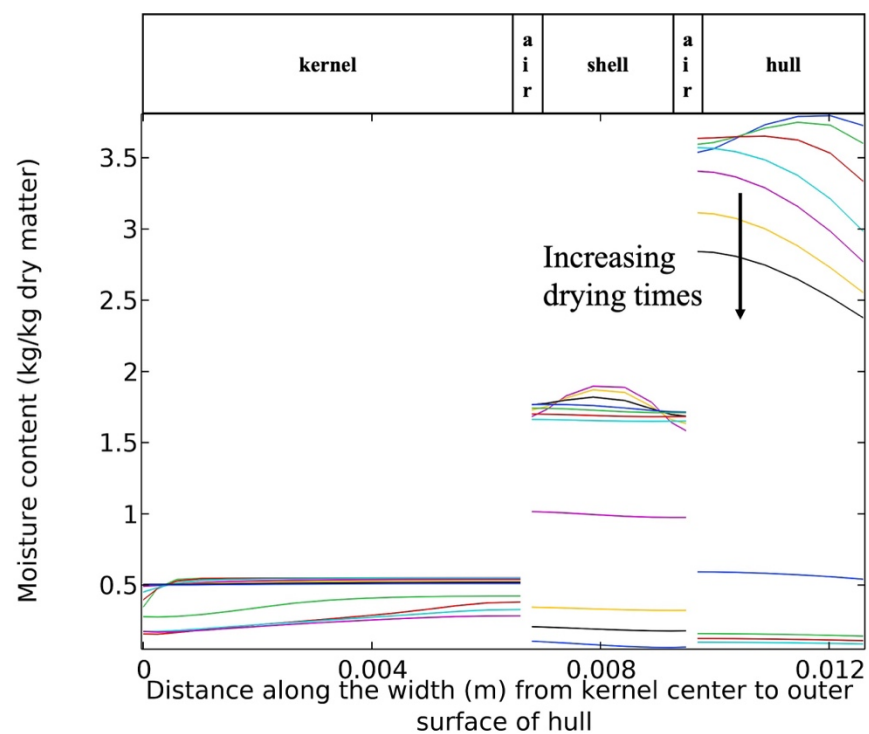


Figure 6.14 Spatial liquid moisture profiles (predicted by the sh_VD model) in the hull, shell, and kernel along the width direction at different drying times during drying at 75°C (3, 5, 10, 20, 30, 45, 60, 300, 540, 600, 660 minutes)

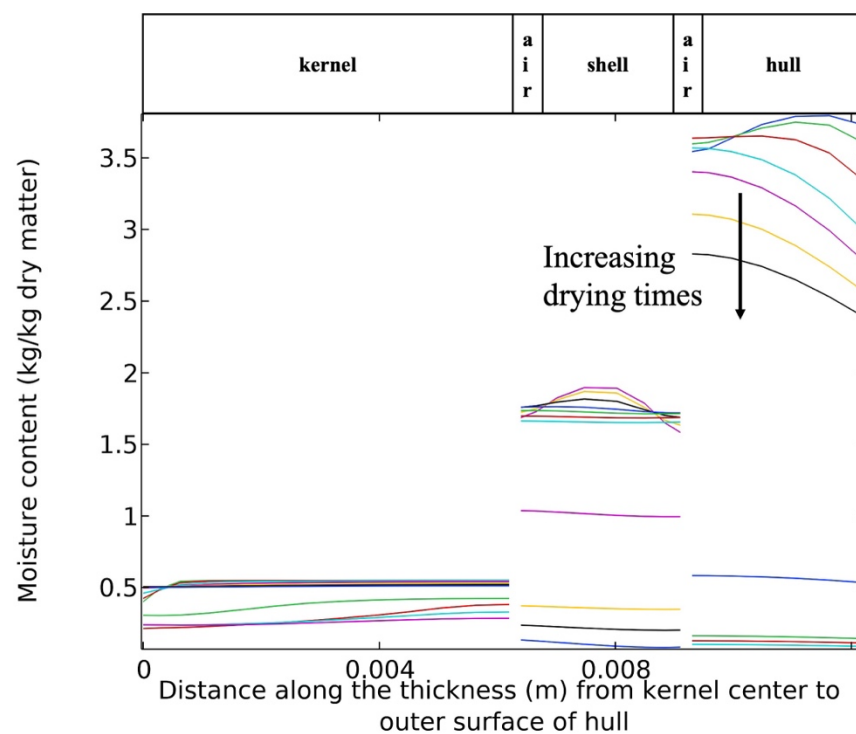


Figure 6.15 Spatial liquid moisture profiles (predicted by the sh_VD model) in the hull, shell, and kernel along the thickness direction at different drying times during drying at 75°C (3, 5, 10, 20, 30, 45, 60, 300, 540, 600, 660 minutes)

The spatial water vapor concentration across different almond components and air gaps along the length, width, and thickness of the in-hull almond during drying at 75°C, as predicted by the sh_VD model, is shown in Figure 6.16, 6.17, and 6.18, respectively. The results indicate that vapor concentration profiles are influenced by local moisture content, temperature, and the microstructure of the almond components being dried.

At the beginning of the drying process, the vapor concentration at and near the hull surface decreased more sharply compared to the shell and kernel. This could be due to the adequate supply of drying air, which allowed vapor generated in the high-porosity hull to be immediately removed by convection. Additionally, the vapor concentration in the shell exhibited a large gradient, which may be attributed to the low porosity of the shell, limiting vapor diffusion. As a result, vapor could not escape quickly enough, leading to high vapor concentration near the inner side of the shell. Meanwhile, the outer side of the shell, facing the hull, experienced lower vapor concentration, causing a steep gradient across the shell.

Notably, the vapor concentration in the kernel increased during the first 30 minutes, which could be related to a condensation process, where vapor generated in the shell and hull migrated inward and condensed in the cooler kernel. This was further confirmed by the evaporation rate analysis, where a negative evaporation rate indicated condensation, as shown in Figure 6.21. As drying progressed, the kernel heated up, and the vapor concentration began to decrease. Similar condensation behavior has been observed in the center of bread at the beginning of the baking process (Ousegui et al., 2010; Thorvaldsson & Skjöldebrand, 1998) and in the core of potato slab at the start of frying (Halder et al., 2007b).

During the middle stages of drying (60-300 minutes), the vapor concentration at any point in the almond decreased over time. By around 300 minutes, the hull and shell components began to dry out. However, the vapor in the kernel center started evaporating more readily from this point, particularly at 660 minutes of drying.

The vapor concentration profiles along the thickness and width directions were consistent with those observed in the length direction during the first 300 minutes of drying. After that, the vapor concentration gradient along the width and thickness directions became smaller compared to the length direction. This may be attributed to the non-isotropic shrinkage in the kernel, where larger shrinkage in the thickness and width directions resulted in a longer path for vapor to diffuse out, leading to a more gradual gradient.

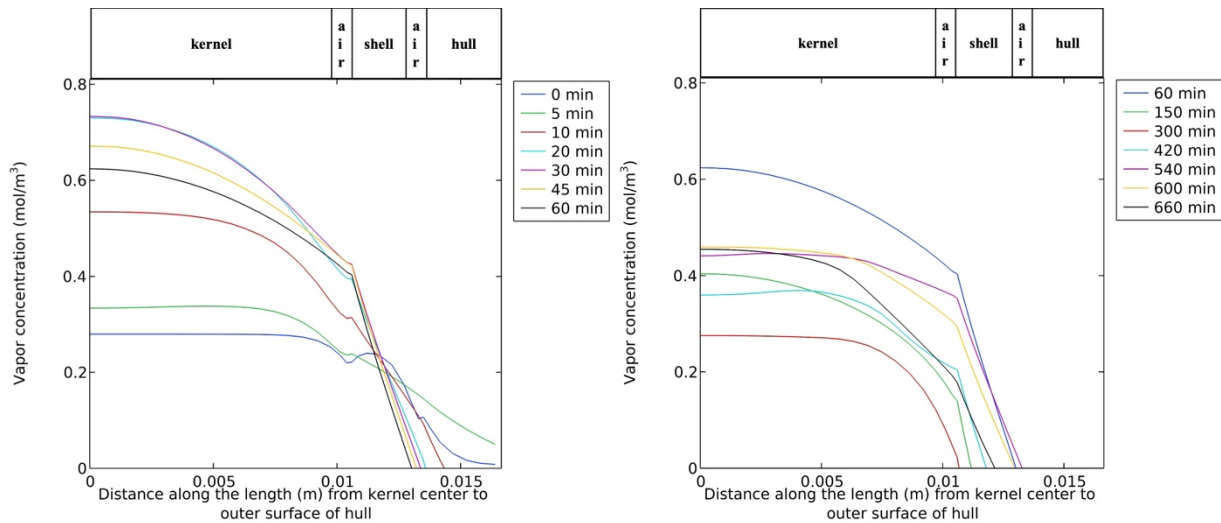


Figure 6.16 Spatial water vapor profiles (predicted by the sh_VD model) in the hull, shell, kernel, and air gaps along the length direction at different drying times (left: 0 to 60 minutes; right: 60 to 660 minutes) during drying at 75°C

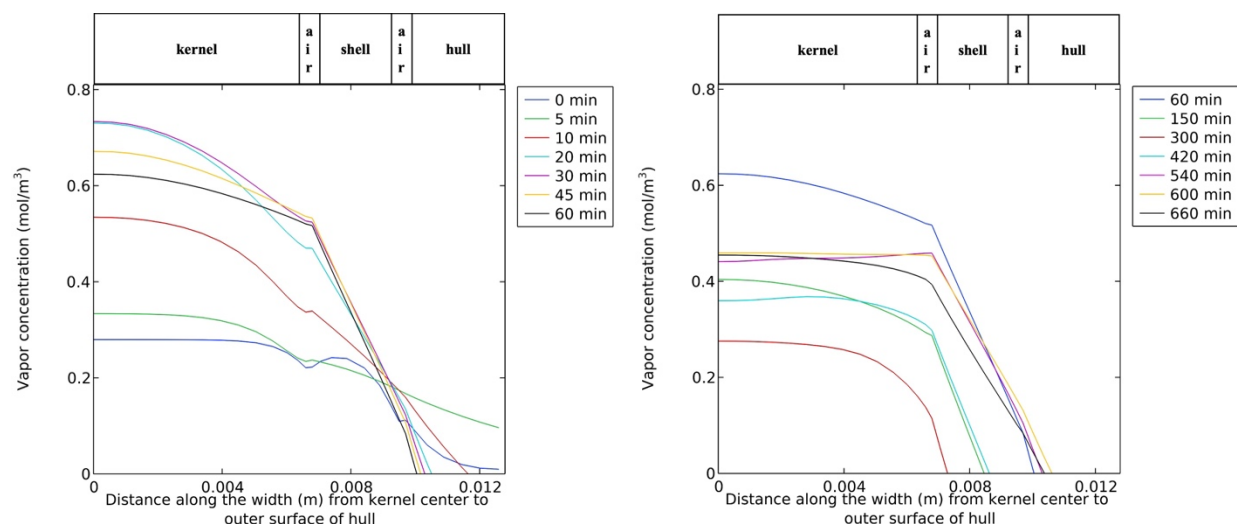


Figure 6.17 Spatial water vapor profiles (predicted by the sh_VD model) in the hull, shell, kernel, and air gaps along the width direction at different drying times (left: 0 to 60 minutes; right: 60 to 660 minutes) during drying at 75°C

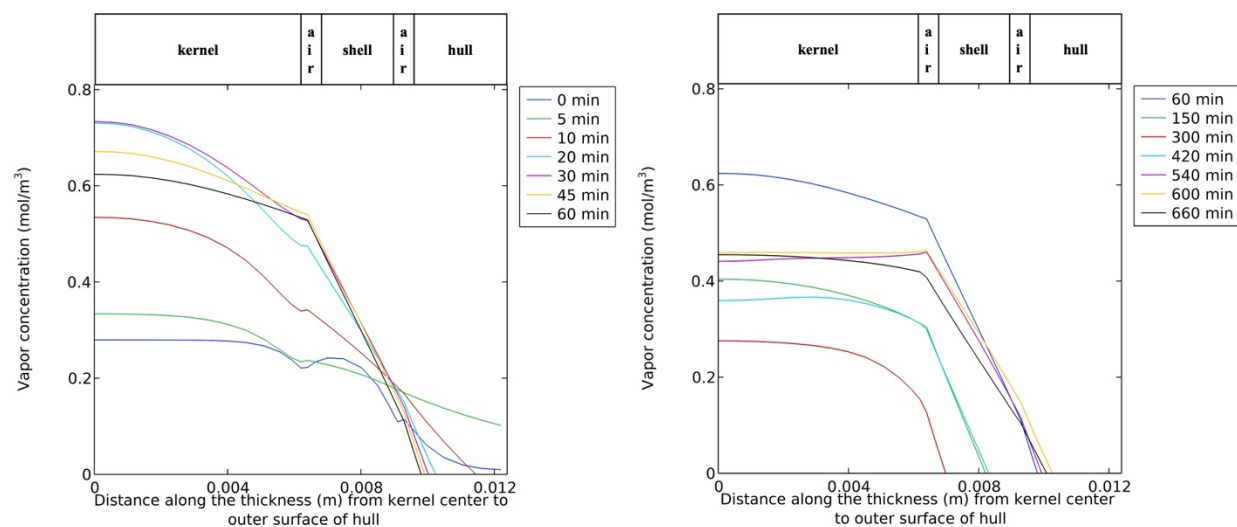


Figure 6.18 Spatial water vapor profiles (predicted by the sh_VD model) in the hull, shell, kernel, and air gaps along the thickness direction at different drying times (left: 0 to 60 minutes; right: 60 to 660 minutes) during drying at 75°C

6.4.6 Sensitivity of the model to non-equilibrium evaporation constant

The non-equilibrium evaporation constant “K” is a critical parameter in the model developed in this study. To the best of my knowledge, no previous studies have quantified this parameter for

the drying process of in-hull almonds. Halder et al. (2007a, 2007b) tested a range of K values from 1 to 1000 s⁻¹ for the frying process of potato slices and concluded that a value of 100 s⁻¹ was the most appropriate for achieving the best fit between the model estimates and the experimental moisture and temperature data. Ousegui et al. (2010) found that K values near 1 s⁻¹ were more suitable compared to other values (0.1 s⁻¹, 0.2 s⁻¹, and 0.5 s⁻¹) for the baking process of bread products. Mercier et al. (2014) demonstrated that a value of 100 s⁻¹ was accurate in capturing internal moisture transport during pasta drying. These studies highlight that K is strongly dependent on the system operating conditions. For a multidomain system such as in-hull almonds, which includes the hull, shell, and kernel, using different K values for different almond components in the simulation should be more appropriate.

Figure 6.19 and 6.20 illustrate the impact of the evaporation rate constant K on the overall temperature and moisture content profiles of in-hull almonds during drying at 75°C. The effect of K on temperature was found to be less significant than its effect on moisture content. Moreover, using the same K value for the hull, shell, and kernel components did not cause notable differences in the temperature profiles, but there was a significant difference in moisture content profiles. For moisture content, using the same K value (0.05 s⁻¹) for the hull, shell, and kernel resulted in large derivations between predicted and experimental values, as shown in Figure 6.20. It was also observed that using higher and uniform K values for the almond hull, shell, and kernel (e.g., K_h=K_s=K_k=0.65 s⁻¹) led to numerical convergence problems, which were also reported by Halder et al. (2007b). Therefore, using different K values for the hull, shell, and kernel is more reasonable for modeling the drying of in-hull almonds.

Additionally, Figure 6.20 shows that using higher K values for the hull, shell, and kernel (e.g., K_h=0.055 s⁻¹, K_s=0.7 s⁻¹, K_k=4.7 s⁻¹) resulted in lower overall moisture contents compared to

lower K values (e.g., $K_h=0.04 \text{ s}^{-1}$, $K_s=0.55 \text{ s}^{-1}$, $K_k=4.4 \text{ s}^{-1}$). This may be because higher K values lead to a more significant evaporation rate. $\dot{I}$. Consequently, the values $K_h=0.05 \text{ s}^{-1}$, $K_s=0.65 \text{ s}^{-1}$, $K_k=4.6 \text{ s}^{-1}$ were determined to be optimal for obtaining the best fit between the simulation results and experimental values.

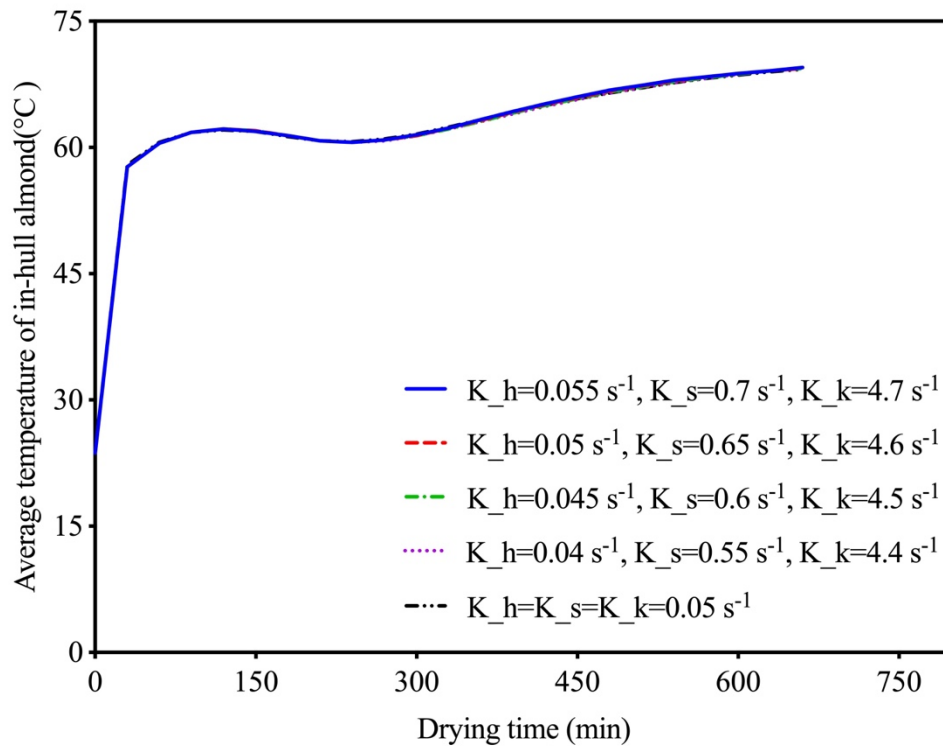


Figure 6.19 Impact of evaporation rate constant K on overall temperature of in-hull almond during drying (using air temperature of 75°C and sh_VD model as an example)

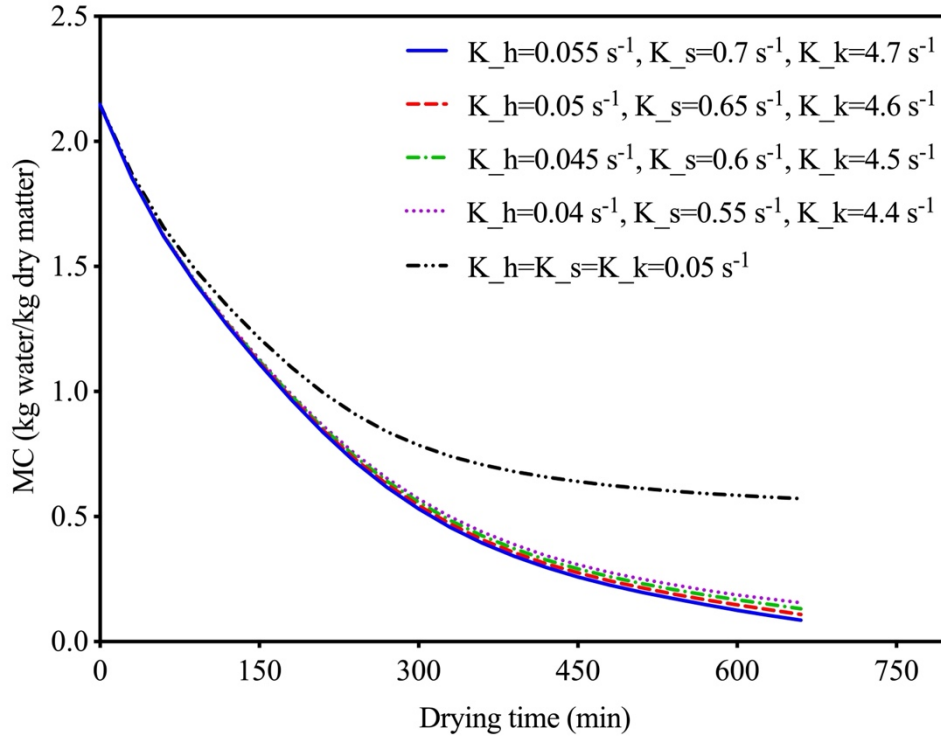


Figure 6.20 Impact of evaporation rate constant K on overall moisture content of in-hull almond during drying (using air temperature of 75°C and sh_VD model as an example)

Figure 6.21 shows the transient average evaporation rate of the almond hull, shell, and kernel at different K values. At the beginning of drying, evaporation started for the hull and shell, while a short period of condensation was observed in the kernel. This could be due to rapid evaporation in the hull and shell, causing excess vapor to move toward the cooler kernel region, as the vapor was not convected away due to surface mass transfer resistance. This phenomenon has also been reported by Halder et al. (2007b) and Ousegui et al. (2010). In terms of the evaporation rate curve, the rate increased with drying time, reached a maximum, and then decreased for the hull and shell, which can be attributed to the low remaining liquid water concentration. However, for the kernel, in addition to the first peak evaporation rate, a second peak was observed, likely when most of the water in the hull and shell had been lost. This suggests that while the drying of the hull and shell may have been complete, higher moisture levels remained inside the kernel.

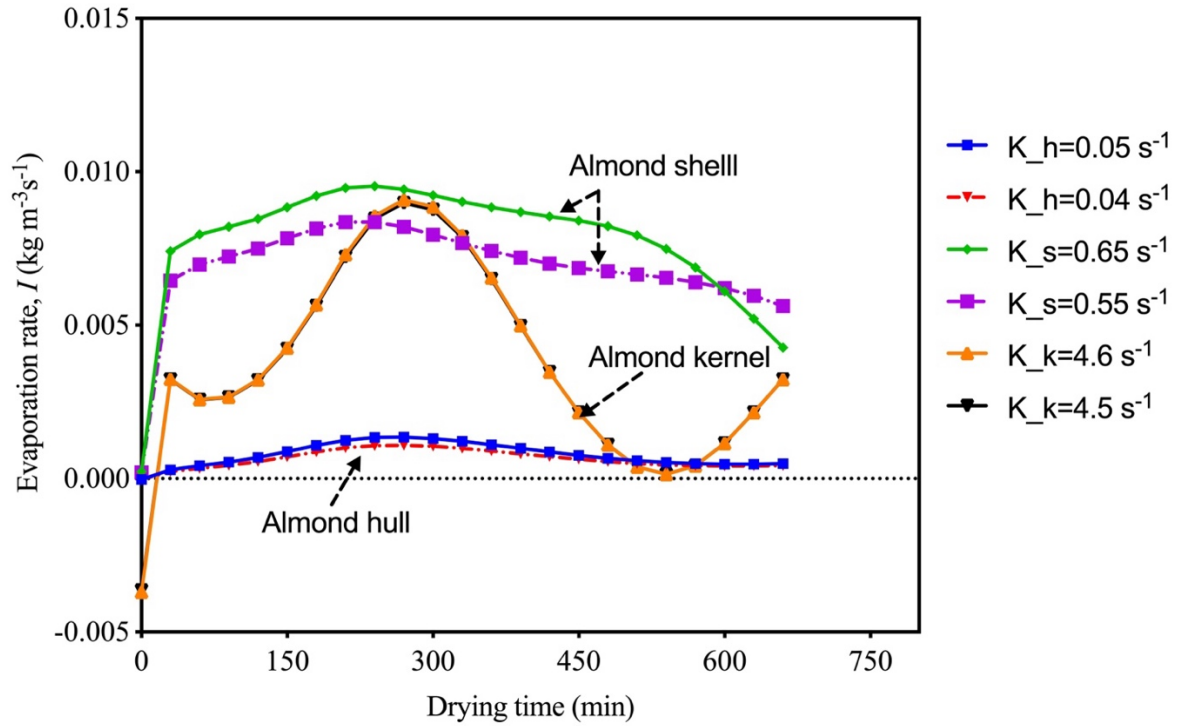


Figure 6.21 Average evaporation rate of different almond components at two different evaporation constant “K” values (using the drying of 75°C and sh_VD model as an example)

The sensitivity analysis of other input parameters in the model, such as porosity, initial moisture content, size of different almond components, convective mass transfer coefficient, moisture transfer coefficient in the air gap, and air gap thickness, will be addressed in future work. When dealing with models that have numerous interrelated input parameters, conducting a sensitivity analysis can be complex. The traditional one-at-a-time (OAT) method, also known as a ‘local’ sensitivity analysis, may not be appropriate as it may fail to capture the true sensitivity of the model to individual parameters (Hamby, 1994; Saltelli et al., 2010). Therefore, it is essential to consider parameter interactions using a variance-based method (Cukier et al., 1973; Saltelli et al., 2008; Sobol, 2001).

6.5 Conclusions

This study developed a simultaneous heat and moisture transfer model for in-hull almonds during hot air drying. The in-hull almond was modeled as a multi-domain system, including the hull, shell, kernel, and the air gaps between the hull and shell, as well as between the shell and kernel. The model also considered non-isotropic shrinkage, variable moisture diffusivity for different almond components, and a non-equilibrium approach to study the phase change of liquid water to water vapor during the drying process.

The modeling results showed good agreement with the experimental data for the tested hot air temperatures of 45°C, 60°C, and 75°C. The predicted results using constant moisture diffusivity did not differ significantly from those using variable moisture diffusivity, likely due to the relatively small variation in diffusivity values. However, neglecting shrinkage led to large deviations from the experimental data.

The evaporation rate constant K had a greater effect on overall moisture content than on temperature for in-hull almonds during the drying process. The predicted results using different evaporation rate constants for the hull, shell, and kernel provided a better fit to the experimental data compared to those using the same evaporation rate constant for all almond components. However, future work should focus on refining the approach to estimate the evaporation rate constant for the hull, shell, and kernel more precisely.

7 CHAPTER 7 PERFORMANCE EVALUATION OF COMMERCIAL DRYERS FOR DRYING OF OFF-GROUND HARVESTED ALMONDS

7.1 Introduction

Almond harvesting usually starts in early August and lasts through October, depending on cultivars and maturity. The onset of almond nut maturity is indicated by two distinct processes. The first process is hull dehiscence, where the hull splits along the suture line, gradually detaches from the shell and starts to dry out (Connell et al., 1989; Crisosto & Crisosto, 2020; Micke, 1996). The second process is the abscission layer that forms between the nut and the peduncle, and it usually happens around the same time as hull dehiscence (Crisosto & Crisosto, 2020).

The harvesting of almonds is considered ready when 100% of the hulls have started to dehisce. Conventional harvest typically includes four main steps, tree shaking, on-ground drying, sweeping, and picking up (Figure 1.4). Once the almonds are matured, they are shaken to the orchard floor by utilizing a piece of equipment, which clamps to the tree trunk and applies a vibrational force. The on-ground natural drying usually takes 1 to 2 weeks for the early harvested almonds, 4 to 7 days for the late-harvested almonds, where drying may have progressed while fruits remained in the trees, or even a prolonged period of time when the rainfall occurs during harvest (Micke, 1996; Venkitasamy et al., 2018). The actual number of days is determined based on the resulting moisture content of the kernels and outer hulls. The target water activity for stored almonds is below 0.65 (approximately moisture content of 6%) (Kader, 2013), and the maximum hull moisture of 12% ensures efficient hulling (Thompson et al., 1996).

Next, the dried almonds around the trees are swept into windrows by a mechanical sweeper and then picked up from the windrows by machines into trailers and transported to a site for stockpiling and fumigation or, most commonly, directly to a huller/sheller facility (Micke, 1996).

The current harvesting method of almonds is associated with three primary concerns, including dust generation, microbial contamination from soil, and insect damage. Dust production is predominantly observed during the final two steps of the harvesting process, as depicted in Figure 1.4, leading to significant particulate matter pollution that spans a wide area and poses health risks to millions of people. Furthermore, this dust carries contaminants, subsequently spreading them to the harvested almonds (ABC, 2021; Faulkner & Capareda, 2012). In addition, almonds come into direct contact with the ground and become thoroughly mixed with the top layer of orchard soil during the windrowing and picking-up processes (Harris & Ferguson, 2013).

Moreover, a significant concern arises when certain almonds prematurely detach from trees, become wet with irrigation water, and undergo repeated mixing. The presence of free moisture on these almonds creates a favorable environment for bacterial (e.g., *Salmonella*) and fungal (such as *Aspergillus flavus* and *Aspergillus parasiticus*) growth, resulting in the production of aflatoxin (Harris & Ferguson, 2013; Pier & Richard, 1992). Studies have shown that *Salmonella Enteritidis* PT 30 can proliferate in wet almond hull and shell slurries (Uesugi et al., 2006), wetted hulls (Danyluk et al., 2008), and wetted dusts (Du et al., 2010). Disturbingly, between 2001 and 2017, nine *Salmonella* outbreaks in the United States were directly linked to the consumption of raw almonds (Palumbo et al., 2017).

The harvested almonds remain in the orchard for extended periods, making them vulnerable to insect infestation. The prominent insect pest affecting almonds in California is the navel orangeworm (NOM), scientifically known as *Amyelois transitella* (Walker). Between 1980 and 1983, the losses incurred by almond growers and processors due to navel orangeworm damage amounted to over \$97 million (Rice et al., 1996). The extent of damage inflicted by navel orangeworm can range from barely noticeable pinhole entries to complete destruction of the

nutmeat. Female moths deposit their eggs either within or on the surface of almonds, as well as in proximity to fruits on twigs or fruit stems. Depending on the environmental temperature, the eggs hatch within a span of 4 to 23 days. Subsequently, the navel orangeworm larvae burrow into the kernel to feed on the nutmeat, leaving behind frass and webbing, thereby contaminating the kernels. Furthermore, during oviposition, the adult moths can introduce *Aspergillus* spp. fungus, which serves as an additional source of aflatoxins (Campbell et al., 2003; Harris & Ferguson, 2013). Almond orchards in California have witnessed navel orangeworm damage rates as high as 30% (Higbee & Siegel, 2009). Such damage directly impacts the marketability of the almond kernels, resulting in significant negative economic repercussions for almond producers (Campbell et al., 2003; Phillips et al., 1980).

Consequently, in response to these challenges, the Almond Board of California (ABC) and the almond industry have actively pursued the development of alternative harvesting approaches. Among these approaches, the off-ground/shake-catch harvesting method (illustrated in Figure 1.6) has emerged as a particularly promising solution. However, it is worth noting that the almonds harvested using this novel method exhibit higher moisture content, necessitating prompt drying to facilitate efficient handling of the large volume of the almonds while ensuring both quality and safety. To address this requirement, artificial dryers are employed, enabling earlier harvesting to mitigate the risks associated with mold growth, insect damage, and adverse weather conditions. Furthermore, the adoption of early harvesting practices has been recognized as a strategy for promoting sustainable irrigation, pest control, and disease management within almond cultivation (Smith et al., 2022).

The drying process plays a pivotal role in agricultural processing, requiring substantial energy consumption and directly influencing overall profitability (Taskin et al., 2024). Additionally,

improper drying can trigger reactions that lead to nutritional degradation, reduced enzyme activity, chemical changes, and the proliferation of microbial growth (Qu et al., 2016). In recent years, various dryer technologies have been developed for agricultural products. Most dryers rely on costly energy sources such as electricity, microwave power, infrared, liquefied petroleum gas, or solar energy combinations (Nwakuba et al., 2016). Convective air drying remains the most widely used method for drying agricultural products. This method includes several forms, such as active solar convective, microwave-convective, electrical-convective, heat pump, and hybrid convective dryers (Chen, Abd El Gebreil, et al., 2020; Darvishi, 2012; Hii et al., 2012; Nwakuba, 2011; Taskin et al., 2024). In industrial applications, most dryers use a convective approach, with hot air or direct combustion gases serving as the drying medium (Nwakuba et al., 2016).

To the best of the author's knowledge, no reported research has specifically investigated the feasibility of using current commercial dryers for almond drying. Therefore, the primary aim of this study is to evaluate the drying performance of existing commercial dryers for drying off-ground harvested almonds while addressing a critical information gap in both drying techniques and product quality assessment.

7.2 Specific Objectives

The specific objectives of this study are: 1) to determine the initial characteristics and moisture content (MC) distribution of off-ground harvested almonds and their components (hull, shell, and kernel); 2) to evaluate the drying performance and product quality of different commercial drying technologies, including tunnel drying, stadium drying, and trailer drying; 3) to compare the quality of almonds from off-ground harvest followed by drying using commercially available dryers with those from conventional harvest followed by natural drying; and 4) to analyze the energy consumption and cost of the tested commercial dryers under different conditions.

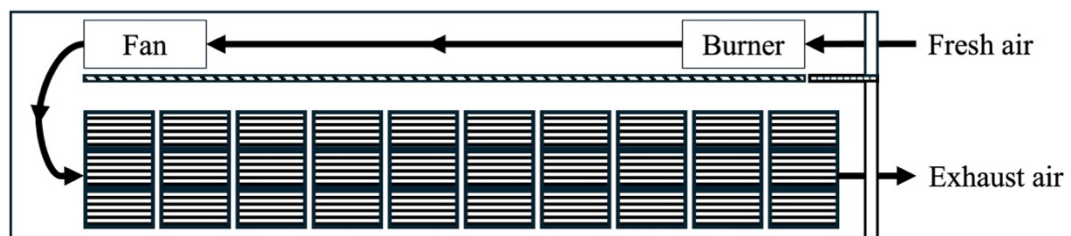
7.3 Materials and Methods

7.3.1 Drying equipment

Three different types of commercial dryers were used to conduct the drying test: tunnel dryers at Campos Brother Farms, Caruthers, CA; stadium dryers at Emerald Farm, Maxwell, CA; and trailer dryers at West Valley Hulling Company, Firebaugh, CA. Photos and schematic views of the dryers are shown in Figure 7.1-7.3. Detailed information on the drying facilities, almond varieties, harvest times, and drying conditions is provided in Table 7.1.



(a)

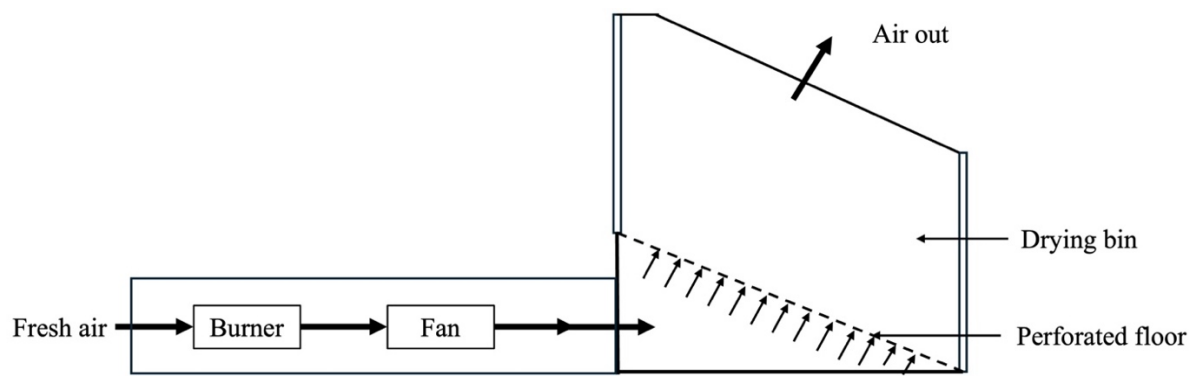


(b)

Figure 7.1 Tunnel dryers (a) and schematic view (b)



(a)

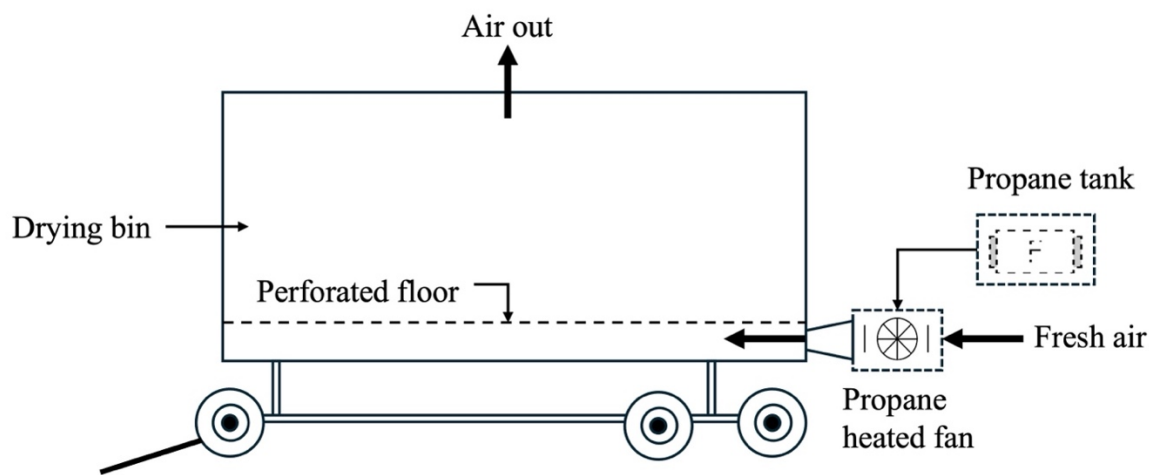


(b)

Figure 7.2 Stadium dryers (a) and schematic view (b)



(a)



(b)

Figure 7.3 Trailer dryers (a) and schematic view (b)

Table 7.1 Information of the almonds, dryers, and drying conditions

Dryer	Almond			Drying condition	
	Variety	Orchard	Harvest date	Type of drying	Air velocity
Tunnel	Independence	JY Farm	08/15	Ambient air started at daytime	1 m/s
				Ambient air started at nighttime	1 m/s
				Hot air at 46°C	1 m/s
Stadium	Monterey	Emerald Farm	09/23	Hot air at 35°C	0.7 m/s
	Fritz	Emerald Farm	09/23	Hot air at 35°C	0.7 m/s
Trailer	Monterey	Bakers Farm	10/08	Hot air at 43°C	1.2 m/s
				Hot air at 54°C	1.2 m/s

The tunnel drying used six tunnels to dry the Independence almond variety under three different drying conditions (two tunnels per condition): ambient air drying started during the daytime, ambient air drying started at nighttime, and hot air drying at 46°C. The air velocity for all three conditions was 1 m/s. The stadium drying used four bins (three assigned to Monterey and one to Fritz) with an air temperature of 35°C and an air velocity of 0.7 m/s. The trailer drying used four trailers to dry Monterey almonds under two different drying conditions (two trailers per condition) at 43°C and 54°C, with an air velocity of 1.2 m/s. In total, seven different tests were conducted for commercial drying of off-ground harvested almonds using these three existing drying facilities.

7.3.2 Initial characteristics of almonds

Almonds were harvested using two different methods: off-ground harvest and conventional harvest. The harvested almonds were categorized into three fractions: in-hull almonds, in-shell almonds, and hulls. Figure 7.4 illustrates the experimental procedures. In the conventional harvest, almonds were left on the ground for approximately 10 days to dry naturally. Only naturally dried almonds from the conventional harvest were sampled. For the off-ground harvest tests, fresh almonds (initial samples), almonds during drying, and dried almonds (final products) were collected.

For the off-ground harvest, fresh almonds (around 600 pieces) from each batch (Independence for tunnel drying, Monterey and Fritz for stadium drying, and Monterey for trailer drying) were collected to determine the initial characteristics, including moisture content, bulk density, weight ratio of fractions, insect infestation, kernel color and oil quality. Moisture contents of different components (hull, shell, kernel) from 30 in-hull and 30 in-shell almonds were measured individually to compare the moisture distributions of fresh in-hull and in-shell almonds. Overall and kernel moisture contents of a mixture (around 60 samples) were determined and used to derive the drying curves, with the initial measurement serving as the starting time point (t_0).

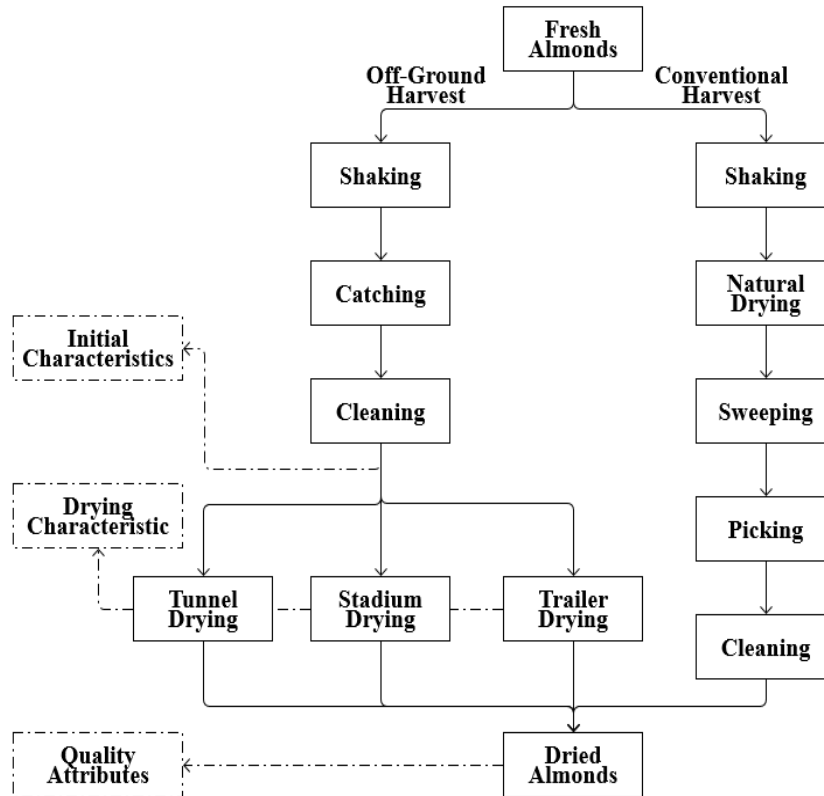


Figure 7.4 Flow diagram of the research approach

7.3.3 Determination of drying characteristics

For tunnel drying, 150 almonds from accessible locations within each drying unit, i.e., mid and bottom bins at the air inlet and outlet of each tunnel (Figure 7.1). For the stadium dryer, samples were taken from the top layer of each bin, and for the trailer dryer, from the top layer of each trailer. Almonds were collected at four different time points (t_1 , t_2 , t_3 , and t_4 at the end of drying), with samples taken 0.2 meters below the surface at the center of each bin using a 1L plastic beaker. Composite samples were produced from the relevant samples. Overall and kernel moisture contents of the composite samples (around 60 samples) were then measured to develop the drying curves. Drying characteristics, including drying time, throughput, ambient temperature/relative humidity (RH), air temperature/velocity, and energy usage, were recorded.

After drying, around 600 dried almonds were obtained for each composite sample from each test (seven tests in total). Thirty in-hull and thirty in-shell almonds were randomly selected and manually separated into their components to analyze the moisture content distribution of dried in-hull and in-shell almonds. The overall and kernel moisture contents of these samples were determined.

7.3.4 Quality of final product

7.3.4.1 *Moisture content*

The moisture content was measured using the standard oven drying method (105°C and 24 h). Specifically, the almond hulls, shells, and kernels were separated from whole almonds and weighed in aluminum weighing dishes. The MC of each sample was determined based on the initial and the dry weights of the sample, and the MC of the whole almond was then calculated using the following equation:

$$MC = \frac{(W_{hi} - W_{hd}) + (W_{si} - W_{sd}) + (W_{ki} - W_{kd})}{W_{hi} + W_{si} + W_{ki}} \times 100\% \quad (7.1)$$

where W_{hi} , W_{si} , and W_{ki} were the initial weights (wet) of the hulls, shells, and kernels (g), respectively; W_{hd} , W_{sd} , and W_{kd} were the final weights (dry) of the hulls, shells, and kernels (g), respectively.

7.3.4.2 *Insect damage rate*

The insect damage rate of almonds was quantified as the percentage of the numbers of insect damaged kernels in a 150 kernels sample (Figure 7.5).

7.3.4.3 *Incidence of cavity*

Incidence of cavity was visually inspected by cutting 10 in-shell and 10 in-hull kernels of each sample into halves at the cross-section.

7.3.4.4 *Color evaluation*

For kernel color measurement, 20 kernels (10 in-shells and 10 in-hulls) from each sample were opened into halves at the suture. The color at the center of core was determined in $L^*a^*b^*$ color space using Minolta Chroma Meter CM700d (Minolta Crop., Ramsey, Japan) and then converted into the whiteness index (WI) using the following equation (Pathare et al., 2013):

$$WI = 100 - \sqrt{(100 - L)^2 + a^2 + b^2} \quad (7.2)$$

7.3.4.5 *Concealed damage*

The concealed damage was evaluated by splitting 10 in-shell and 10 in-hull kernels of each sample after roasting (135°C and 90 mins) and inspecting the color development score using the reference (Figure 7.5) (Pearson, 1999).

7.3.4.6 *Oil quality*

Free fatty acid (FFA) and peroxide value (PV) are commonly used indicators of product oil quality. To evaluate the oil quality of the dried almonds, 15 g of almond kernels from the whole almonds was ground into a powder and mixed with 150 mL n-hexane in an Erlenmeyer flask. The flask was then placed in a shaker (MaxQ4000, Thermo Scientific, MA, USA) set at 3.33 Hz, 200 rpm, and 4 °C for 1 hour. The almond oil was extracted from the solvent using vacuum filtration and a rotary evaporator (R-3, Buchi, Switzerland). The FFA and PV of the extracted oil were determined using a potentiometer (Titrino plus 848, Metrohm, Riverview, USA), following the AOCS (American Oil Chemists Society) official methods Ca5a-40 and Cd8-53, respectively. All measurements were performed in triplicate.

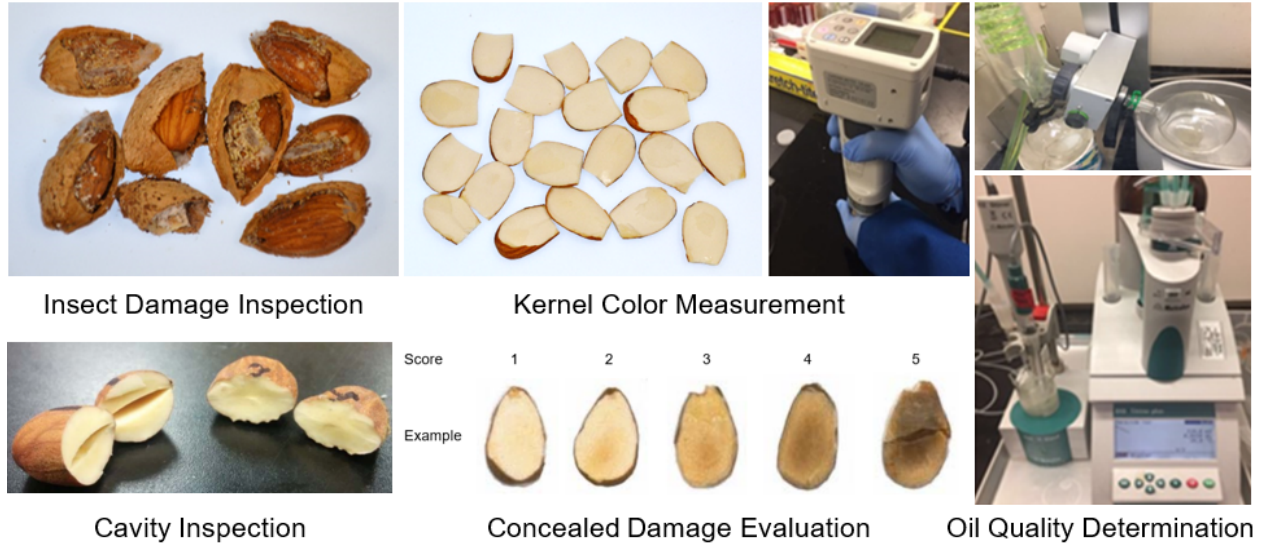


Figure 7.5 Evaluation of quality attributes

7.3.5 Energy consumption and cost

For the energy use and cost, the utility use of each drying test, consisting of electricity use for the blowers and natural gas or propane used for the burners, was calculated using the numbers obtained from the drying facilities. The total electricity consumption (kWh) was calculated as follows:

$$E_e = \frac{P \times t}{1000} \quad (7.3)$$

where t is the drying time (h); P is the power (W). In this study, a three-phase AC electric motor is used and calculated using the following equation (Fleckenstein, 2017):

$$P = \sqrt{3} \times U \times I \times PF \quad (7.4)$$

where U is the voltage (V); I is the current (A); PF is the power factor.

The usage of natural gas (NG_{use}) or propane (PP_{use}) was determined based on the initial and final readings from a meter installed on each device, with the difference representing its usage. The energy cost was presented on the basis of both dried whole almond and dried kernel, using the final kernel weight ratio, respectively. The high and low energy cost values were calculated using

charge rates of \$0.15 per kWh for off-peak, \$0.25 per kWh for peak, ¢90 per therm for natural gas, and \$1.75 per gallon for propane. The total energy cost (C_T) on the basis of the dried kernel was calculated as follows:

$$C_T = \frac{E_e \times R_e \times 100 + NG_{use} \times R_{ng} + PP_{use} \times R_{pp} \times 100}{m_a \times r} \quad (7.5)$$

where R_e is the electricity rate (\$/kWh); NG_{use} is the natural gas use (therm); R_{ng} is the natural gas rate (¢/therm); PP_{use} is the propane use (gallon); R_{pp} is the propane rate (\$/gallon); m_a is the output of the dried almonds (lb); r is the weight ratio of the dried kernels to the dried almonds.

The total amount of energy, E_T (MJ) used by the dryer is calculated by the sum of the energy consumed by the blower and heater:

$$E_T = E_e(kWh) \times 3.6 \left(\frac{MJ}{kWh} \right) + NG_{use}(therm) \times 99976.1 \left(\frac{btu}{therm} \right) \div 948 \left(\frac{btu}{MJ} \right) + PP_{use}(gallon) \times 3.78 \left(\frac{L}{gallon} \right) \times 23700 \left(\frac{btu}{L} \right) \div 948 \left(\frac{btu}{MJ} \right) \quad (7.6)$$

7.3.6 Dryer performance indicators

- Drying rate (DR)

The drying rate (DR) is determined using the following equation:

$$DR = \frac{M_i - M_f}{t} \quad (7.7)$$

where M_i and M_f is the sample initial and final moisture contents on a dry basis (kg/kg dry matter);

- Throughput (T_i)

The throughput of each dryer, T_i (kg/h) was determined based on the amount of input weight per unit of time using the following equation:

$$T_i = \frac{W_i}{t} \quad (7.8)$$

where i represents tunnel, stadium, and trailer dryers, respectively; W_i is the initial loading weight of each dryer (kg).

- Specific energy consumption (SEC) and specific moisture extraction rate (SMER)

The specific energy consumption (SEC), measured in MJ/kg, is the ratio of the energy input to the drying system to the moisture evaporated from the wet product. The specific moisture extraction rate (SMER) indicates how much moisture can be removed per unit of energy (kg/MJ) and is the reciprocal of SEC (Desa et al., 2020; Yahya et al., 2017).

$$SEC = \frac{E_T}{m_w} \quad (7.9)$$

$$SMER = \frac{m_w}{E_T} \quad (7.10)$$

where m_w is the mass of moisture removal from almonds during the drying process (kg).

- Coefficient of Performance (COP)

The coefficient of performance (COP) is used to evaluate the efficiency of the propane- or natural gas-heated fan. COP is a dimensionless value expressed as the ratio of the energy produced to the energy used by the propane- or natural gas- heated fan. It is calculated using the following equation (Mayanja, 2021; Oktay & Hepbasli, 2003; Yahya et al., 2016):

$$COP = \frac{\sum Q}{E_T} \quad (7.11)$$

where the total dissipated energy $\sum Q$ is the sum of sensible heat, which accounts for the energy required to raise the temperature of the drying material and air, and latent heat, which is used to evaporate the water. This total energy can be calculated using the following equation (Earle, 2013; Mayanja et al., 2021):

$$Q = \frac{W_i \times c_{p,a} \times \Delta T + m_a \times c_{p,air} \times \Delta T \times t + m_w \times L_v}{1000} \quad (7.12)$$

where $c_{p,a}$ is the specific heat capacity of the almonds, taken as 2.2 kJ/kg·K (ASHRAE, 2006); ΔT is the temperature difference between the almonds and drying air (K); L_v is the latent heat of vaporization of water (kJ/kg), obtained using interpolation from Table A.6 in Bergman (2011) for different drying conditions; $c_{p,air}$ is the specific heat capacity of air (kJ/kg·K), calculated from Table A.6 in Bergman (2011). $\dot{m}_a$ is the air mass flow rate (kg/s), determined using the following equation (Oktay & Hepbasli, 2003):

$$\dot{m}_a = \rho_{air} \times A \times v \quad (7.13)$$

where ρ_{air} is the air density (kg/m³); A is the cross-sectional area of the flow (m²); v is the air velocity (m/s).

7.4 Results and Discussion

7.4.1 Initial characteristics of off-ground harvested almonds

Figure 7.6 shows almonds from off-ground harvest and conventional harvest. Compared to the conventional harvest, the off-ground harvested almonds were much cleaner, with fewer foreign materials such as dust, leaves, rocks, and branches. The percentages of insect damage ranged from 0.8% to 3.3% for off-ground harvested almonds and from 2.0% to 10.0% for conventionally harvested almonds, as shown in Table 7.2. The higher percentage of insect damage in almonds from the conventional harvest can be attributed to the extended period (about 10 days) that the almonds remained on the ground. The off-ground harvest reduced insect damage by 57% to 67%, which is a significant improvement with this new harvesting practice.

Among the three fractions (hull, in-shell almonds, and in-hull almonds), in-hull almonds made up the largest proportion (0.50 to 0.80) of the total mass (Table 7.2). The specific weight ratios of the three fractions varied among the tested batches due to differences in almond varieties and maturities. The bulk densities of the almond mixtures ranged from 296.0 to 391.6 kg/m³, with the

highest bulk density observed in Fritz almonds, likely due to their higher moisture content. The densities of each fraction are also listed in Table 7.2.



Figure 7.6 Almonds from off-ground harvest (left) and conventional harvest (right)

Table 7.2 Initial characteristics of almonds before drying

Dryer types	Variety	Weight ratio				Bulk density (kg/m ³)			Insect damage (%, based on the numbers of kernels)	
		In-hull	In-shell	Hull	Overall	In-hull	In-shell	Hull	Conventi onal	Off- ground
Tunnel	Independence	0.50	0.17	0.33	318.7	341.6	311.8	297.8	10.0	3.3
Stadium	Monterey	0.56	0.28	0.16	306.2	329.6	348.9	249.7	9.1	2.8
Stadium	Fritz	0.80	0.04	0.17	384.4	391.6	329.2	313.1	7.7	3.3
Trailer	Monterey	0.68	0.07	0.25	280.3	296.0	301.3	169.2	2.0	0.8

The overall moisture contents of the four batches of almonds ranged from 20.0% to 44.3%, with Fritz almonds for stadium drying having the highest moisture content while Monterey almonds for trailer drying had the lowest (Table 7.3). In general, the in-hull almonds had much

higher average moisture levels (17.9% to 42.3%) with a wider range than the in-shell almonds (9.4% to 18.2%) due to the high moisture content of the hulls (Table 7.3). The kernel moisture content of in-hull almonds was higher than that of in-shell almonds (13.8% vs. 9.6%, 13.9% vs. 11.3%, 19.8% vs. 16.2%, and 8.0% vs. 7.8% for the four batches, respectively). Detailed information about the initial moisture contents and their distributions for each component (hull, shell, and kernel) for each batch can be found in Appendix A.1.

Table 7.3 Summary of initial moisture contents of the almond samples and the MC distributions of in-shell and in-hull almonds

Type of dryer	Variety	Category	Whole almond MC _{wb} (%)		Kernel MC _{wb} (%)	
			Average	Range	Average	Range
Tunnel	Independence	In hull	39.9	21.0-57.9	13.8	6.3-25.8
		In shell	10.7	7.3-15.9	9.6	6.0-13.7
		Hull	48.1	N/A	N/A	N/A
		Overall	37.6	N/A	12.9	6.0-25.8
Stadium	Monterey	In hull	26.2	9.9-51.4	13.9	4.5-29.2
		In shell	12.6	8.1-21.1	11.3	5.2-24.7
		Hull	38.8	N/A	N/A	N/A
		Overall	24.4	N/A	12.6	4.5-29.2
	Fritz	In hull	42.3	17.0-65.3	19.8	5.7-35.2
		In shell	18.2	10.8-32.4	16.2	8.1-31.0
		Hull	57.2	N/A	N/A	N/A
		Overall	44.3	N/A	17.7	5.7-35.2
Trailer	Monterey	In hull	17.9	9.6-48.9	8.0	5.1-27.1
		In shell	9.4	6.4-24.9	7.8	5.0-19.5
		Hull	28.6	N/A	N/A	N/A
		Overall	20.0	N/A	8.0	5.0-27.1

7.4.2 Drying performance

Figure 7.7 and 7.8 illustrate the moisture content and drying rate profiles of kernels (from in-shell and in-hull almonds, and overall) and almonds (hull, in-shell, in-hull, and overall) from tunnel hot air drying. In general, higher temperatures reduced the drying time, while high initial moisture levels contributed to longer drying times. The hulls and in-hull almonds exhibited higher drying rates compared to in-shell almonds but required longer drying times to reach the desired moisture levels due to their higher initial moisture content. The moisture content differences among the various fractions decreased gradually as the drying process progressed. The moisture content and drying rate profiles for the other dryers and conditions were similar and are provided in Appendix A.2.

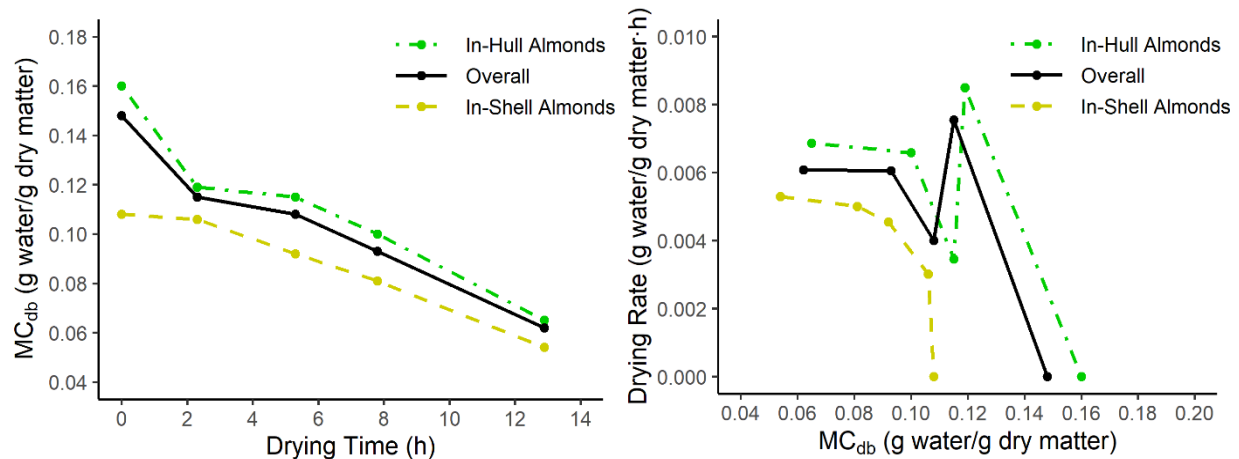


Figure 7.7 Kernel moisture content (left) and drying rate (right) profiles of tunnel hot air drying

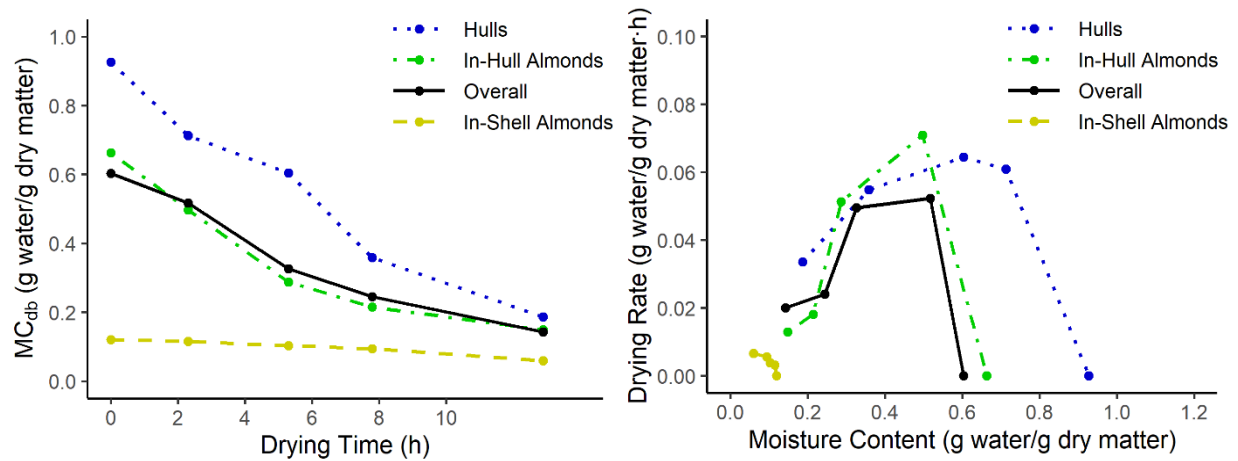


Figure 7.8 Almond moisture content (left) and drying rate (right) profiles of tunnel hot air drying

The tunnel hot air drying achieved a much shorter drying time (12.9 hours) to reach a lower moisture content (12.5%) compared to tunnel ambient air drying, which took over 47 hours (Table 7.4). The rapid drying with hot air was characterized by a steep rising period and a high drying rate during the constant rate period (Figure 7.7 and 7.8). The drying rate was 0.036 kg/kg·h, with each drying tunnel processing a throughput of 1.54 tons per hour (Table 7.4). This highlights the importance of using heated air drying for achieving high drying throughput. For ambient air drying, the effect of the starting time on drying was unclear, as the entire drying process was prolonged, taking two full days and nights.

Table 7.4 Summarized drying performance of tunnel drying under three different conditions

Condition	Initial MC _{wb} (%)		Final MC _{wb} (%)		Drying time (h)	Throughput per tunnel (ton/h)	Drying rate (kg/kg·h)
	Overall	Kernel	Overall	Kernel			
Ambient air started at daytime	37.6	12.9	16.8	7.8	51.8	0.35	0.008
Ambient air started at nighttime	37.6	12.9	17.9	8.0	47.5	0.38	0.008
Hot air at 46°C	37.6	12.9	12.5	5.8	12.9	1.54	0.036

For stadium drying, the drying times to reduce the kernel moisture content to about 4% ranged from 16.3 to 17.7 hours for Monterey almonds and 48.0 hours for Fritz almonds. The extended drying time for Fritz was due to its extremely high initial moisture content, as it was harvested too early (Table 7.5). The overall drying rate for Fritz was 0.015 kg/kg·h, which was slightly higher than Monterey's drying rate of 0.014 kg/kg·h, reflecting the difference in initial moisture levels.

Table 7.5 Summarized drying performance of stadium drying using two different varieties

Variety	Initial MC _{wb} (%)		Final MC _{wb} (%)		Drying time (h)	Throughput per stadium (ton/h)	Drying rate (kg/kg·h)
	Overall	Kernel	Overall	Kernel			
Monterey	24.4	12.6	7.8	3.9	16.9	0.42	0.014
Fritz	44.3	17.7	6.5	3.8	48.0	0.16	0.015

For the trailer drying of Monterey almonds, the drying times were 6.5 hours at 43°C and 5.8 hours at 54°C, with corresponding kernel moisture contents of 4.8% and 4.1%, respectively (Table 7.6). Increasing the drying temperature from 43°C to 54°C reduced the drying time from 6.5 to 5.8 hours, while also achieving a higher drying rate and throughput of 2.28 tons per hour. It is important to note that the almonds dried at 54°C had a significantly lower final moisture content, and the drying time could have been further reduced if the almonds were dried to the same final moisture level.

Table 7.6 Summarized drying performance of trailer drying under two different conditions

Condition	Initial MC _{wb} (%)		Final MC _{wb} (%)		Drying time (h)	Throughput per trailer (ton/h)	Drying rate (kg/kg·h)
	Overall	Kernel	Overall	Kernel			
Hot air at 43°C	20.0	8.0	8.3	4.8	6.5	2.06	0.025
Hot air at 54°C	20.0	8.0	7.8	4.1	5.8	2.28	0.037

7.4.3 Quality of dried almonds

7.4.3.1 *Final moisture content distribution of in-hull and in-shell almonds*

The moisture content distributions of dried in-hull and in-shell almonds from both off-ground and conventional harvests were measured, and the results are presented in Appendix A.3. In summary, the moisture distributions were found to be within wide ranges: 3.6-31.1% for Independence almonds after tunnel drying, 3.2-9.7% for Monterey almonds after stadium drying, 3.2-16.6% for Fritz almonds after stadium drying, and 1.6-11.9% for Monterey almonds after trailer drying. For tunnel drying, the in-hull almonds exhibited wider moisture ranges (8.4-25.2%, 8.5-31.1%, and 7.9-20.9% for ambient air drying started during the daytime, ambient air drying started at nighttime, and hot air drying, respectively) compared to the in-shell almonds (5.2-10.5%, 6.1-12.9%, and 3.6-10.2% for ambient air drying started during the daytime, ambient air drying started at nighttime, and hot air drying, respectively). Tunnel hot air drying produced almonds with a narrower range of moisture distribution compared to ambient air drying. Among the different components after commercial drying, the hull remained the wettest (5.1-39.4%), while the shell (1.1-20.0%) and kernel (1.2-16.1%) had closer moisture levels.

7.4.3.2 *Cavity and kernel color*

No cavity formation was observed in samples from both the conventional harvest and off-ground harvest, which were followed by mechanical drying. The sutures at the center of the almond kernels remained intact, as shown in Figure 7.9.

There were no significant differences in the whiteness index between dried and fresh products from both harvesting methods ($p\text{-value} > 0.05$). Detailed information about the whiteness index of in-hull and in-shell almonds from different commercial dryers and conditions is provided in Appendix A.4 for reference.

For tunnel drying of Independence almonds, the average whiteness index values were 77.5, 77.4, 77.6, 78.5, and 77.5 for almonds from the conventional harvest, off-ground harvest, ambient air drying started during the daytime, ambient air drying started at nighttime, and hot air drying, respectively. For stadium drying of Monterey almonds, the values were 80.4, 80.9, and 80.0 for conventional harvest, fresh, and hot air drying, respectively. For stadium drying of Fritz almonds, the values were 79.5, 80.9, and 80.8 for conventional harvest, fresh, and hot air drying, respectively. For trailer drying of Monterey almonds, the values were 80.0, 79.9, 80.0, and 80.3 for conventional harvest, fresh, hot air drying at 43°C, and hot air drying at 54°C, respectively. It appeared that Independence almonds were slightly darker than the other two varieties.



Figure 7.9 Cavity inspection (left) and kernel color measurement (right) of samples after commercial hot air drying

7.4.3.3 *Concealed damage*

There were no significant differences in concealed damage (CD) scores for all samples from both harvest methods (p -value > 0.05). Detailed information about the CD scores of in-hull and in-shell almonds from different commercial dryers and conditions is provided in Appendix A.5 for reference.

As an example, the CD scores of tunnel-dried almonds were 2.6 ± 0.8 for in-shell almonds and 2.8 ± 0.8 for in-hull almonds (Figure 7.10). The average CD scores for all tested conditions were

below 3, with low standard deviations, indicating no significant concealed damage for either harvest method.



Figure 7.10 Color development score results (left); Color development of samples from commercial hot air drying (right)

7.4.3.4 Oil quality

The results show that the peroxide value (PV) and free fatty acid (FFA) levels for all samples were well below the industry standards of 5 meq/kg of oil for PV and 1.5% for FFA. For tunnel drying, the hot air-dried almonds exhibited slightly higher PV than the fresh almonds, but the difference was minimal, and the difference between hot air-dried and conventionally harvested almonds insignificant. However, the FFA levels in the conventionally harvested almonds were higher compared to the other samples (Table 7.7).

Table 7.7 Summary of oil quality analyses for tunnel drying test

Oil quality		Fresh	Conv	AA1	AA2	HA
PV (meq/kg)	Ave	0.798 ^a	0.979 ^{ab}	0.890 ^a	0.894 ^a	1.084 ^b
	Std	0.044	0.004	0.138	0.078	0.094
FFA (%)	Ave	0.135 ^a	0.202 ^b	0.138 ^a	0.140 ^a	0.130 ^a
	Std	0.007	0.019	0.005	0.006	0.004

Table 7.8 presents the oil quality of almonds from stadium drying. The peroxide values were 1.109 meq/kg for hot air-dried Monterey and 1.092 meq/kg for hot air-dried Fritz (Table 7.8). There was no significant difference in peroxide values among the samples from fresh harvest, hot air drying, and conventional harvest. However, the free fatty acid levels of the almonds from hot air drying (0.130% for Monterey and 0.136% for Fritz) were significantly lower than those from the conventional harvest, indicating better oil quality (Table 7.8).

Table 7.8 Summary of oil quality analyses for stadium drying test

Oil quality		Monterey			Fritz		
		Fresh	Conv	HA	Fresh	Conv	HA
PV (meq/kg)	Ave	0.875 ^a	0.950 ^a	1.109 ^a	1.008 ^a	0.775 ^a	1.092 ^a
	Std	0.012	0.066	0.391	0.035	0.035	0.217
FFA (%)	Ave	0.140 ^b	0.183 ^c	0.130 ^a	0.273 ^b	0.164 ^c	0.136 ^a
	Std	0.010	0.005	0.002	0.001	0.000	0.002

For trailer drying, the dried almonds had an average peroxide value of 1.332 meq/kg at 43°C and 1.828 meq/kg at 54°C (Table 7.9). The peroxide values for hot air-dried almonds were slightly higher than those of conventionally harvested and fresh samples but remained well below the industrial standard of 5 meq/kg. Similarly, the free fatty acid (FFA) levels of almonds from hot air drying were 0.259% at 43°C and 0.311% at 54°C, which were higher than those of the conventional harvest and fresh samples but still far below the industrial standard of 1.5% (Table 7.9). The higher peroxide and FFA values might be due to the low initial moisture content of the almonds. Further studies are necessary to confirm the cause.

Table 7.9 Summary of oil quality analyses for trailer drying study

Oil quality		Fresh	Conv	43°C	54°C
PV (meq/kg)	Ave	0.854 ^a	0.814 ^a	1.332 ^b	1.828 ^c

	Std	0.018	0.022	0.035	0.152
	Ave	0.145 ^a	0.178 ^b	0.259 ^c	0.311 ^d
FFA (%)	Std	0.003	0.005	0.008	0.001

7.4.4 Energy and cost analysis

The energy and cost analysis were conducted based on utility usage and charge rates obtained from the drying facilities. The overall energy cost was calculated based on the weight of whole dried almonds and kernel weight, respectively, and is presented as a range, with electricity rates for peak and off-peak hours set at \$0.15 and \$0.25 per kWh. In general, the energy cost of tunnel drying was less than 5 cents to produce one pound of dried products. The estimated energy costs for ambient air drying started during the daytime, ambient air drying started at nighttime, and hot air drying was 2.7 to 4.5, 2.3 to 3.9, and 3.7 to 4.1 cents per pound of dried products, respectively (Table 7.10). The overall energy costs for hot air and ambient air drying were similar, as the long drying times associated with ambient air drying resulted in high electricity consumption despite the lack of energy used for heating.

For stadium drying, the estimated energy costs for drying Monterey and Fritz almonds were 1.5 to 2.0 and 4.9 to 6.5 cents per pound, respectively (Table 7.11). The higher drying cost for Fritz was due to its high initial moisture content and longer drying time. For trailer drying, the energy costs at 43°C and 54°C were 0.52 to 0.58 and 1.28 to 1.34 cents per pound, respectively (Table 7.12). These lower costs were attributed to the low initial moisture content and shorter drying times.

Table 7.10 Summary of energy consumption and cost analysis for tunnel drying

Condition	Electricity		Natural gas		Specific energy consumption (MJ/kg)	Overall cost (cents/lb dried almonds)	Overall cost (cents/lb dried kernels)
	Use (kWh per tunnel)	Cost (cents/lb dried kernels)	Use (m ³ per tunnel)	Cost (cents/lb dried kernels)			
Ambient air started at the daytime	1596.2	2.7-4.5	0.0	0.0	1.3	0.86-1.43	2.7-4.5
Ambient air started at nighttime	1463.7	2.3-3.9	0.0	0.0	1.2	0.79-1.32	2.3-3.9
Hot air at 46°C	397.5	0.6-1.0	1008.5	3.1	6.9	1.32-1.46	3.7-4.1

Table 7.11 Summary of energy consumption and cost analysis for stadium drying

Variety	Electricity		Natural gas		Specific energy consumption (MJ/kg)	Overall cost (cents/lb dried almonds)	Overall cost (cents/lb dried kernels)
	Use (kWh per bin)	Cost (cents/lb dried kernels)	Use (m ³ per bin)	Cost (cents/lb dried kernels)			
Monterey	229.2	1.1-1.9	72.9	0.8	2.8	0.5-0.7	1.9-2.6
Fritz	651.0	3.6-6.1	206.9	2.5	3.4	1.8-2.5	6.1-8.6

Table 7.12 Summary of energy consumption and cost analysis for the trailer drying

Condition	Electricity		Propane		Specific energy consumption (MJ/kg)	Overall cost (cents/lb dried almonds)	Overall cost (cents/lb dried kernels)
	Use (kWh per trailer)	Cost (cents/lb dried kernels)	Use (m ³ per trailer)	Cost (cents/lb dried kernels)			

43°C	50.02	0.09-0.15	0.08	0.43	1.2	0.18-0.20	0.52-0.58
54°C	44.25	0.09-0.15	0.19	1.19	2.9	0.41-0.42	1.28-1.34

7.4.5 Dryer performance indicators

The Specific Moisture Extraction Rate (SMER) and Coefficient of Performance (COP) for tunnel, stadium, and trailer dryers under different drying conditions are presented and compared with other dryers, as shown in Figure 7.11 and 7.12. For tunnel dryers, using ambient air started during the daytime, ambient air started at nighttime, and hot air resulted in SMER values of 0.77 kg/MJ, 0.83 kg/MJ, and 0.14 kg/MJ, respectively. The corresponding COP values were 4.8, 4.1, and 0.5. For stadium dryers, using a hot air temperature of 35°C, the SMER and COP for Monterey almonds were 0.17 kg/MJ and 3.1, respectively. The corresponding values for Fritz almonds were 0.29 kg/MJ and 2.7. For trailer dryers using hot air at 43°C and 54°C, the SMER and COP were 0.83 kg/MJ and 9.6, and 0.34 kg/MJ and 4.5, respectively. Perera and Rahman (1997) and Mayanja et al. (2021) reported that the SMER of most heated air dryers typically ranges from 0.03 to 0.36 kg/MJ. The results obtained in this study align with the literature, except for tunnel dryers using ambient air (daytime and nighttime) and trailer dryers using hot air at 43°C, which had relatively high SMER values, as shown in Figure 7.11 (Dryers A, B, and F).

Environmental temperature played a significant role in drying, especially for dryers exposed to external conditions. During the tunnel and trailer drying processes, the recorded environmental temperatures reached 37.2°C and 34°C, respectively, which facilitated moisture removal from the almonds. For the tunnel dryers using ambient air (Dryers A and B), the energy source was primarily the blower, while for tunnel dryers using hot air (Dryer C), additional energy from a burner was required. However, this extra energy input did not improve drying efficiency, leading to a lower COP (Figure 7.12). According to Kitanovski et al. (2009), a low COP indicates a less efficient

system. In contrast, the trailer dryers using hot air at 43°C (Dryer F) had a high COP. In addition to benefiting from favorable environmental conditions, the energy from the burner was effectively utilized during the drying process. This difference in efficiency may be attributed to the dryer design, as shown in Figure 7.3 and 7.5, with the trailer dryers being better insulated than the tunnel dryers. These results agreed with Nwakuba et al. (2016), indicating the dryer design, type, crop characteristics, and ambient environmental conditions are major factors affecting dryer energy consumption.

Stadium dryers demonstrated moderate SMER and COP values, with slight differences between Monterey and Fritz almonds. Monterey almonds, with lower initial moisture content, showed lower SMER and higher COP compared to Fritz almonds. Overall, the three commercial dryers tested can effectively dry off-ground harvested almonds without compromising product quality. Trailer dryers are particularly preferred due to their ease of temperature control and higher drying capacity. Future studies will optimize drying conditions to reduce drying time and cost.

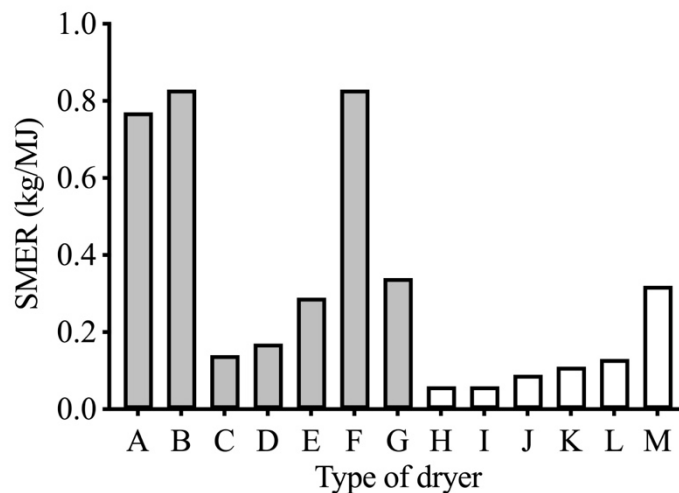


Figure 7.11 Bar plot comparing SMER of different dryers (A-G from this study and H-M from literature). (A) Tunnel dryers using ambient air started at daytime; (B) Tunnel dryers using ambient air started at nighttime; (C) Tunnel dryers using hot air of 46°C; (D) Stadium dryers using hot air of 35°C for Monterey almonds; (E) Stadium dryers using hot air of 35°C for Fritz almonds; (F) Trailer dryers using hot air of 43°C; (G) Trailer dryers using hot air of 54°C; (H)

Closed system heat pump dryer for ginger at 50°C (Chapchaimoh et al., 2016); (I) Convection solar dryer for bitter gourd (Vijayan et al., 2016); (J) Heat pump dryer for tomato slices at 45°C (Coşkun et al., 2017); (K) Solar dryer for cassava at 40°C (Yahya et al., 2016); (L) Solar assisted heat pump dryer for cassava at 45°C (Yahya et al., 2016); (M) Heat pump assisted hybrid photovoltaic thermal solar dryer for saffron at 45°C (Mortezapour et al., 2012).

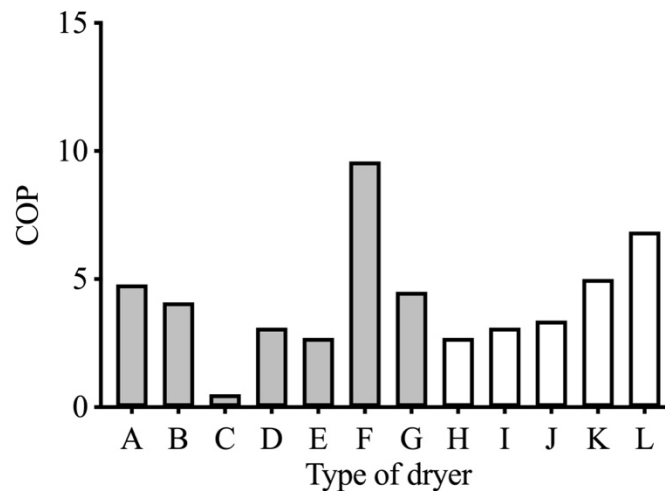


Figure 7.12 Bar plot comparing COP of different dryers (A-G from this study and H-L from literature). (A) Tunnel dryers using ambient air started at daytime; (B) Tunnel dryers using ambient air started at nighttime; (C) Tunnel dryers using hot air of 46°C; (D) Stadium dryers using hot air of 35°C for Monterey almonds; (E) Stadium dryers using hot air of 35°C for Fritz almonds; (F) Trailer dryers using hot air of 43°C; (G) Trailer dryers using hot air of 54°C; (H) Heat pump dryer for tomato slices at 45°C (Coşkun et al., 2017); (I) Solar assisted heat pump for mushrooms at 45°C (Şevik et al., 2013); (J) Solar assisted heat pump dryer for cassava at 45°C (Yahya et al., 2016); (K) Heat pump for mint leaves at 45°C (Ceylan & Gürel, 2016); (L) Stockpile heated and ambient air dryer for almonds at 55°C (Mayanja et al., 2023).

7.5 Conclusions

The key findings and recommendations from this study are summarized below:

- **Cleaner and Less Insect Damage in Off-Ground Harvested Almonds:** Off-ground harvested almonds were significantly cleaner, with less insect damage (0.8-3.3%) compared to conventional harvested almonds (2.0-10%). Off-ground harvesting reduced insect damage by 57-67%.

- **Moisture Content Differences in Almond Fractions:** Among the three fractions (in-hull almond, in-shell almond, and hull) of freshly harvested and dried almonds, hulls had the highest moisture content. In-hull almonds had higher moisture content than in-shell almonds.
- **Effect of Initial Moisture on Drying Time:** Initial moisture significantly affected drying time. The drying time for hot air drying ranged from 5.8 to 16.9 hours, with initial whole almond moisture levels of 20.0-37.6% reduced to 3.9-5.8% kernel moisture. Stadium drying of Fritz almonds required more time due to their extremely high initial moisture content.
- **Impact of Drying Temperature on Time and Cost:** Drying temperature played a critical role in drying time and cost. For tunnel drying, drying at 43°C reduced drying time by 74% but increased energy costs by 15% compared to ambient air drying. In trailer drying, hot air drying at 54°C reduced drying time by 11% but raised energy costs by 109% compared to drying at 43°C.
- **Product Quality After Drying:** Under all tested conditions, there were no cavities, concealed damage, or color changes in the almond kernels after drying. Only almonds from trailer drying had peroxide values (1.33-1.83 meq/kg) and free fatty acid levels (0.26-0.31%) significantly higher than conventionally harvested almonds but still far below the industry standards (5 meq/kg for peroxide value and 1.5% for free fatty acid level). The higher values may be due to low initial moisture, which requires further study.
- **Energy Costs for Drying:** Energy costs ranged from 0.18 to 1.91 cents per pound of whole dried almonds or 0.52 to 6.5 cents per pound of dried almond kernels, with electricity costs calculated at \$0.15 (off-peak) and \$0.25 (peak) per kWh. Energy costs were influenced by initial moisture content, dryer type, and drying conditions. Trailer drying was the most efficient method, with the lowest drying costs due to very low initial moisture. Low drying temperatures

resulted in longer drying times and higher energy costs due to fan electricity consumption. High initial moisture levels also significantly contributed to increased drying costs. Therefore, it is important to harvest almonds at an optimal moisture level.

- **Commercial Dryers for Off-Ground Harvested Almonds:** The available commercial dryers can be used to dry off-ground harvested almonds without compromising quality. However, further studies are needed to optimize drying conditions to reduce both drying time and cost.

8 SUMMARY AND FUTURE RESEARCH

8.1 Summary

This study demonstrated that off-ground harvesting can significantly reduce insect damage by 57-67% compared to conventional harvesting for almonds. Almonds left on the orchard floor remain at high risk for insect infestation. Insect development changes varied across farms and almond varieties, with Fritz almonds from Nickels Farm and Nonpareil almonds from Cutter Farm exhibiting the highest values, reaching 10.3% and 10.7%, respectively. Therefore, targeted pest management practices are essential.

Almonds harvested using the off-ground method must be dried mechanically for a short time to avoid mold growth. Early harvested almonds (EH) had significantly higher moisture content than standard harvested (SH) almonds. The average overall MC for EH almonds was approximately 63% (wet basis), while SH almonds had an average MC of about 22% for in-hull almonds and 8% for in-shell almonds. For EH in-hull almonds, the MC values were 76.3%, 46.8%, and 28.5% for hulls, shells, and kernels, respectively. SH in-hull almonds had MC values of 27.1% for hulls, 15.3% for shells, and 13.0% for kernels. The hull had the highest MC in both EH and SH almonds, followed by the shell and kernel.

For SH almonds, drying loose hulls results in unnecessary energy consumption, while drying in-hull almonds and in-shell almonds together can lead to over- or under-drying. To address this issue, a dimension- and terminal velocity-based sorting approach was developed to efficiently separate loose hulls while minimizing product loss. The first step used a cut-off size of 21.1 mm to effectively sort in-shell almonds with 100% accuracy. The second step separated in-hull almonds from loose hulls using a terminal velocity threshold of 12.2 m/s. Some in-hull almonds and loose hulls with smaller thicknesses were misclassified into the in-shell fraction, with

misclassification rates of 6.7% and 23.3%, respectively. Despite this, these error rates are relatively low and acceptable for practical applications.

This research systematically examined the heat and moisture transfer mechanisms in in-hull almonds using both experimental and theoretical modeling methods. This is the first study to simultaneously determine the effective moisture diffusivities (D_{eff}) of almond hull, shell, and kernel during in-hull almond hot air drying, accounting for shrinkage and the almond's natural ellipsoidal shape. If neither shrinkage nor shape effects were considered, the most significant relative difference in D_{eff} was up to 31.6% for the kernel during drying at 60°C. Polynomial equations were developed to correlate D_{eff} with moisture content, and these equations effectively captured the dynamic changes in D_{eff} for almond components during in-hull drying, with adjusted R-squared (R_{adj}^2) values exceeding 0.973 for the hull, 0.926 for the shell, and 0.978 for the kernel, indicating high model accuracy.

As the hot air temperature increased from 45°C to 75°C, the average D_{eff} for the almond hull, shell, and kernel increased from 9.70×10^{-10} to 2.05×10^{-9} m²/s, 4.71×10^{-10} to 9.24×10^{-10} m²/s, and 5.82×10^{-11} to 1.45×10^{-10} m²/s, respectively.

The study also revealed the existence of air gaps between the hull shell, as well as between shell and kernel. The almond components displayed varying degrees of shrinkage. As a result, multiphase moisture transfer (involving liquid water and water vapor), non-isotropic shrinkage, variable moisture diffusivity, and a non-equilibrium approach to phase change during drying were incorporated into the model. The model, which accounted for shrinkage and variable moisture diffusivity, showed good agreement with experimental data, with R_{adj}^2 values exceeding 0.966, 0.990, and 0.974 for hot air temperatures of 45°C, 60°C, and 75°C, respectively. For final overall moisture content predictions, the nsh_CD model produced large deviations of 17.4%, 7.4%, and

17.4% at 45°C, 60°C, and 75°C, respectively, whereas the sh_VD model yielded errors of 5.6%, 0.6%, and 0.2%. The model also simulated the spatial distribution of liquid moisture concentration, water vapor concentration, and temperature at various drying stages in the almond.

This study evaluated the drying performance of three commercial dryers for off-ground harvested almonds. All three dryers were capable of drying almonds without compromising product quality. Among the evaluated dryers, trailer dryers presented superior performance with higher SMER (0.34-0.83 kg/MJ) and COP (4.5-9.6) and lower energy costs (¢0.52-¢1.34/lb of dried product). Trailer dryers were also preferred due to their ease of temperature control and larger drying capacity. Future studies will optimize drying conditions to reduce drying time and cost.

8.2 Drying Strategy for Off-ground Harvested Almonds

Drying off-ground harvested almonds is a highly energy-intensive process, particularly due to the high moisture content in the almond hulls. A potential strategy to mitigate energy consumption involves removing the hulls before the drying process. For almonds with loose hulls, it is recommended to first separate these loose hulls from in-hull and in-shell almonds using a terminal velocity-based sorting method. The loose hulls, which have a relatively lower economic value, can then be subjected to natural drying methods, thereby significantly reducing the energy demands of the drying system.

After separating the loose hulls, in-hull almonds and in-shell almonds can be further segregated based on their dimensional characteristics using a size-based sorting technique. This separation enables drying treatments to be adjusted to the specific moisture and structural properties of each category. By drying in-hull almonds and in-shell almonds independently, the risk of over-drying or under-drying can be minimized, ensuring uniform product quality and reducing post-processing losses.

Additionally, incorporating advanced drying technologies, such as infrared-assisted drying, can further enhance energy efficiency while preserving almond quality and safety. This comprehensive strategy not only helps lower the overall energy consumption but also addresses the economic and sustainability challenges associated with almond processing.

8.3 Future Research

- No hull splitting was observed in this study. However, the exact cause remains unclear. It is important to consider hull splitting in future models, as well as the potential for airflow within the almond.
- Since almond hulls had the highest moisture content, using high-temperature drying at the beginning of the process could significantly remove moisture from the hull and increase almond temperature. This approach could serve as a new drying strategy for almonds, potentially improving microbial safety by killing microbes at high temperatures.
- Future studies could also explore the quality attributes, energy consumption, and economic analysis of drying off-ground harvested almonds after sorting them into in-hull and in-shell almonds before the drying process.
- To further reduce energy costs and optimize the use of trailer dryers, additional drying conditions and almond varieties should be explored.

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10 APPENDIX

10.1 Appendix A.1 Initial Moisture Content Distribution

Tunnel Drying

Table A.1 Summary of initial moisture contents of Independence in-hull and in-shell almonds for tunnel drying (ambient air started at daytime)

MC _{wb} (%)	Whole almond		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	39.9	14.4-64.1	13.8	3.9-30.5	22.2	8.2-50.8	46.8	20.2-73.7
In shell	10.7	9.0-19.7	9.6	6.9-19.0	16.3	12.7-22.2	N/A	N/A

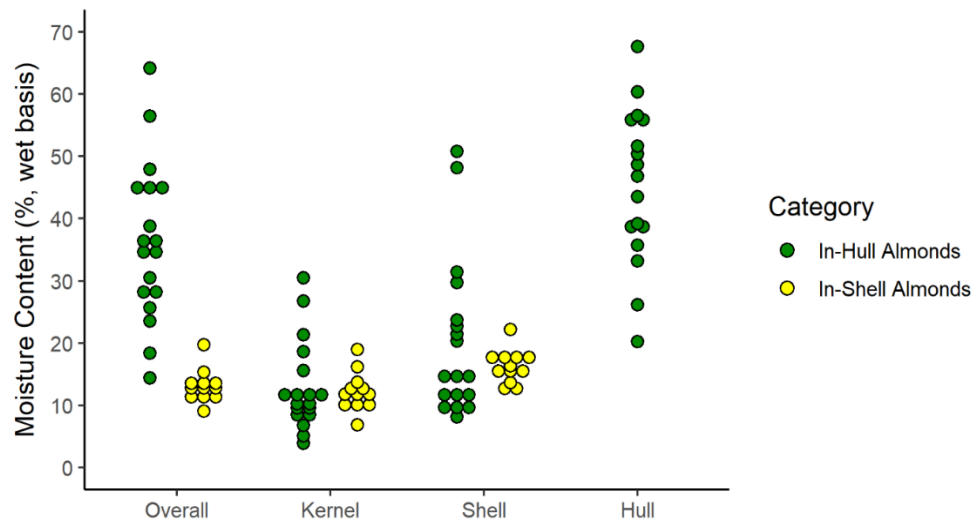


Figure A.1 Initial moisture content distributions of Independence in-hull and in-shell almonds for tunnel drying (ambient air started at daytime)

Table A.2 Summary of initial moisture contents of Independence in-hull and in-shell almonds for tunnel drying (ambient air started at nighttime)

MC _{wb} (%)	Whole almond		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	39.0	17.6-58.7	14.1	5.8-23.6	19.5	8.9-34.1	50.6	27.2-73.1
In shell	14.5	11.0-24.3	13.5	10.1-23.1	16.7	10.8-27.3	NA	NA

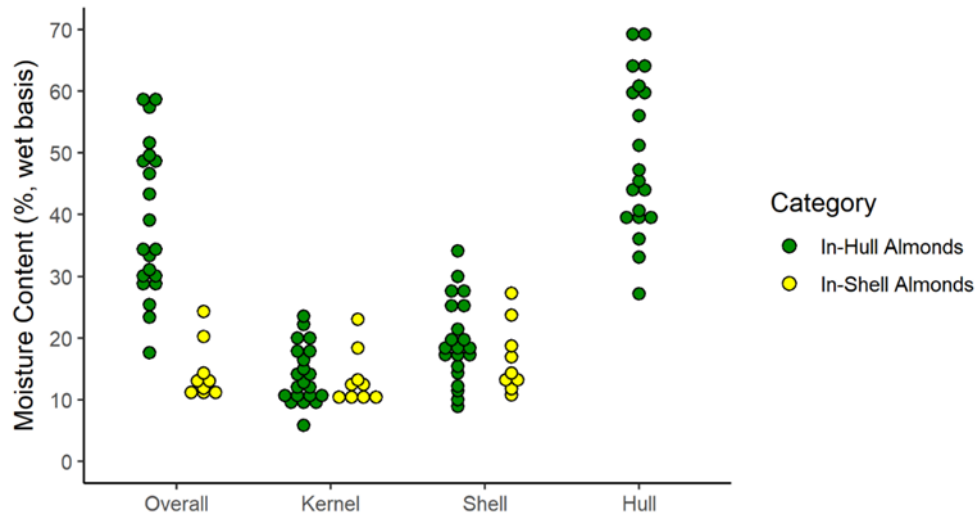


Figure A.2 Initial moisture content distributions of Independence in-hull and in-shell almonds for tunnel drying (ambient air started at nighttime)

Table A.3 Summary of initial moisture contents of Independence in-hull and in-shell almonds for tunnel drying (hot air)

MC _{wb} (%)	Overall		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	37.2	21.0-57.9	13.3	6.3-25.8	19.4	11.1-37.8	49.4	30.5-70.8
In shell	10.6	7.3-15.9	9.5	6.0-13.7	13.6	9.6-21.2	NA	NA

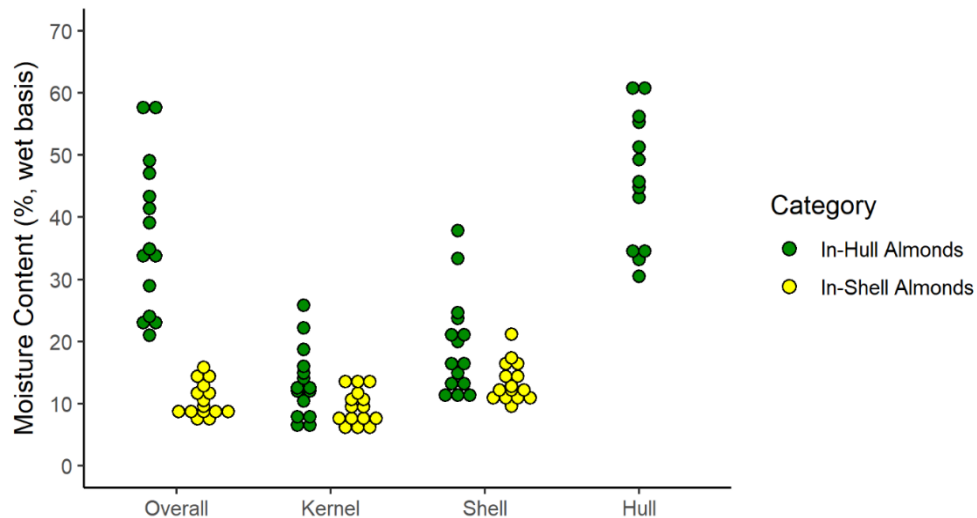


Figure A.3 Initial moisture content distributions of Independence in-hull and in-shell almonds for tunnel drying (hot air)

Stadium Drying

Table A.4 Summary of initial moisture contents of Monterey in-hull and in-shell almonds for stadium drying

MC _{wb} (%)	Whole almond		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	26.2	9.9-51.4	13.9	4.5-29.2	17.2	8.5-42.0	35.7	13.8-66.1
In shell	12.6	8.1-21.1	11.3	5.2-24.7	13.6	10.2-19.1	N/A	N/A

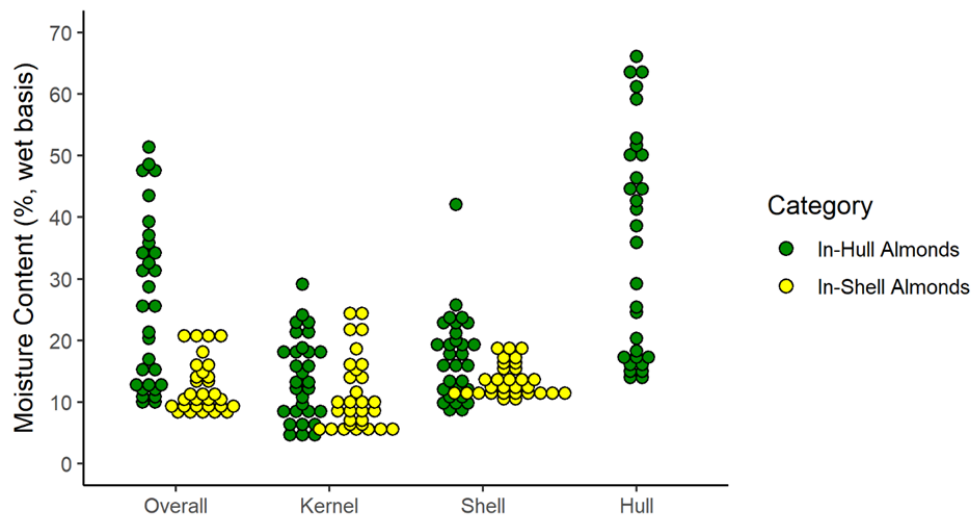


Figure A.4 Initial moisture content distribution of Monterey in-hull and in-shell almonds for stadium drying

Table A.5 Summary of initial moisture contents of Fritz in-hull and in-shell almonds for stadium drying

Category	Whole almond MC _{wb} (%)		Kernel MC _{wb} (%)		Shell MC _{wb} (%)		Hull MC _{wb} (%)	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	42.3	17.0-65.3	19.8	5.7-35.2	26.5	10.6-41.6	53.3	24.1-78.2
In shell	18.2	10.8-32.4	16.2	8.1-31.0	20.6	13.6-34.3	NA	NA

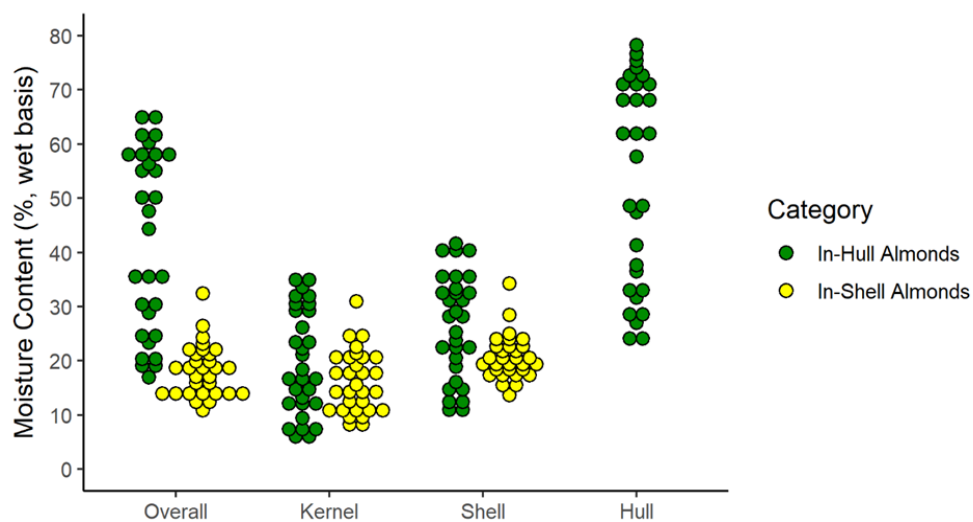


Figure A.5 Initial moisture content distribution of Fritz in-hull and in-shell almonds for stadium drying

Trailer Drying

Table A.6 Summary of initial moisture contents of Monterey in-hull and in-shell almonds for trailer drying

Category	Whole almond MC _{wb} (%)		Kernel MC _{wb} (%)		Shell MC _{wb} (%)		Hull MC _{wb} (%)	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	17.9	9.6-48.9	8.0	5.1-27.1	10.3	6.9-31.4	25.8	14.8-68.6
In shell	9.4	6.4-24.9	7.8	5.0-19.5	11.2	0.7-30.1	N/A	N/A

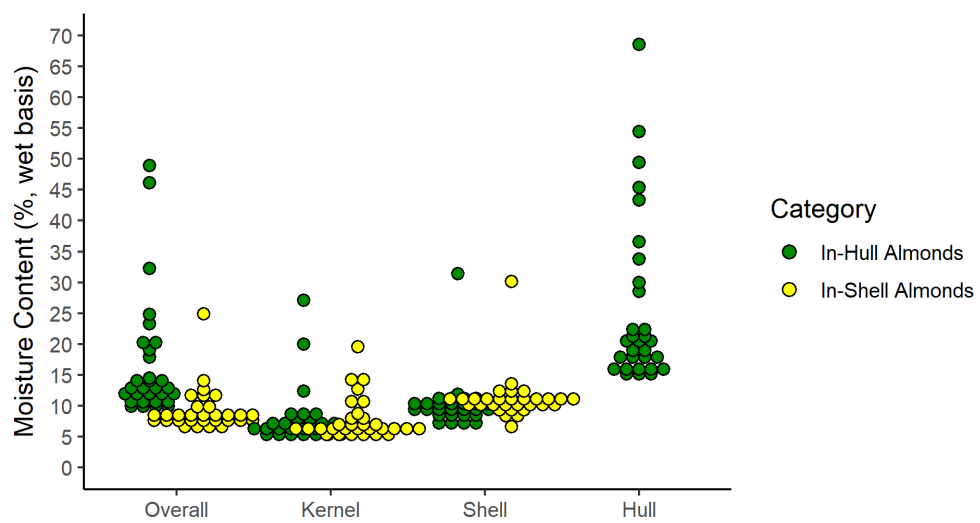


Figure A.6 Initial moisture content distribution of Monterey in-hull and in-shell almonds for trailer drying

10.2 Appendix A.2 Moisture Content and Drying Rate Profile

Tunnel drying

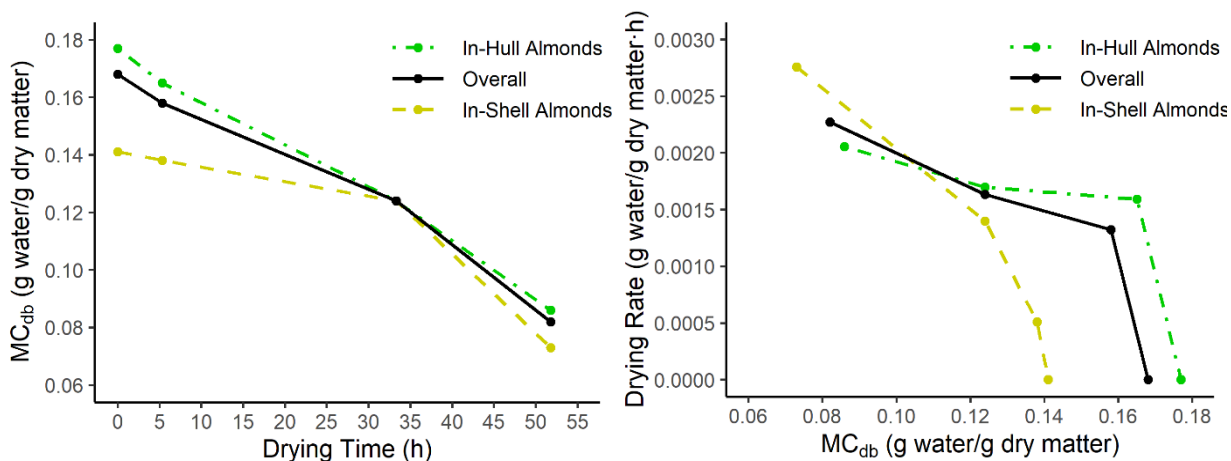


Figure A.7 Kernel moisture content (left) and drying rate (right) profiles for tunnel ambient air drying started at daytime

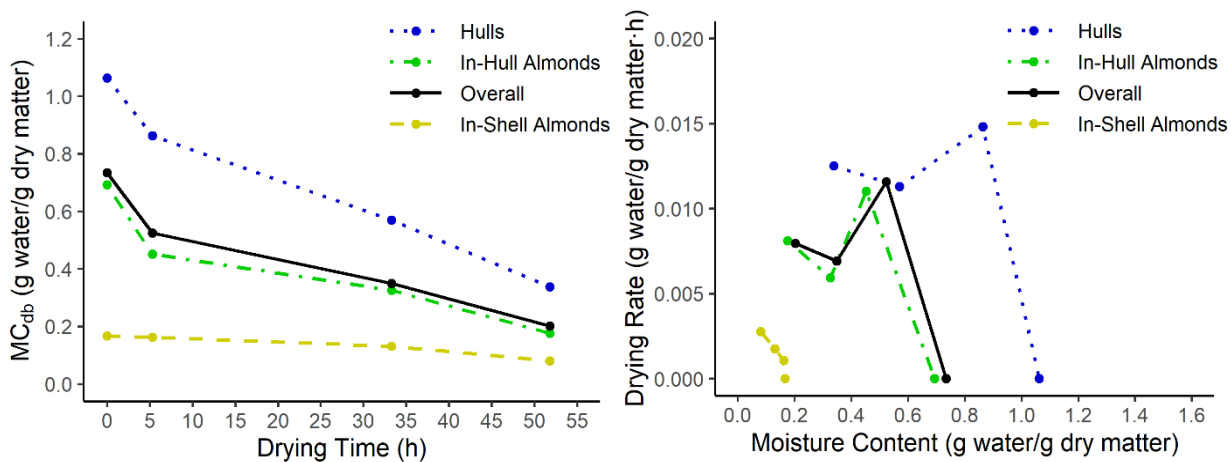


Figure A.8 Whole almond moisture content (left) and drying rate (right) profiles for tunnel ambient air drying started at daytime

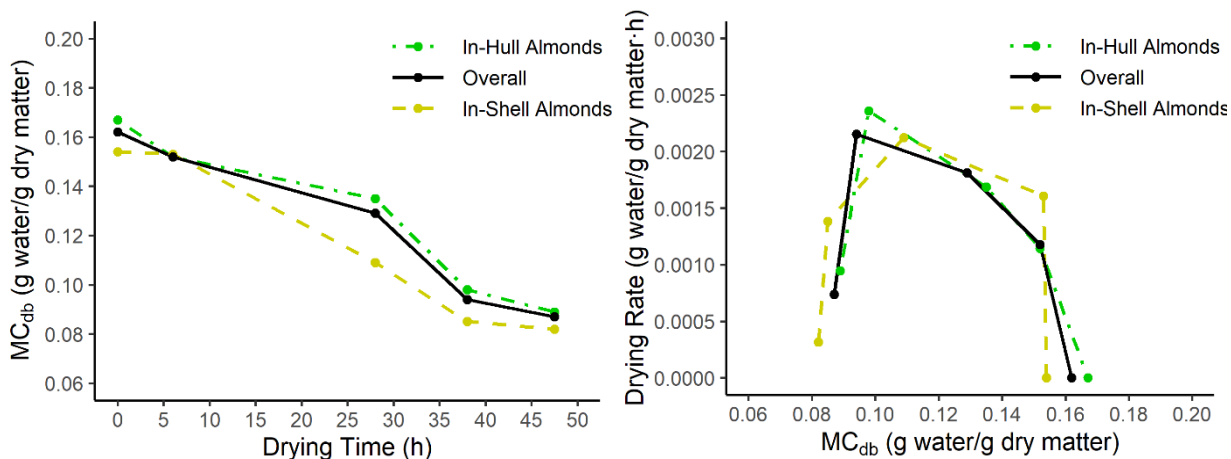


Figure A.9 Kernel moisture content (left) and drying rate (right) profiles for tunnel ambient air drying started at nighttime

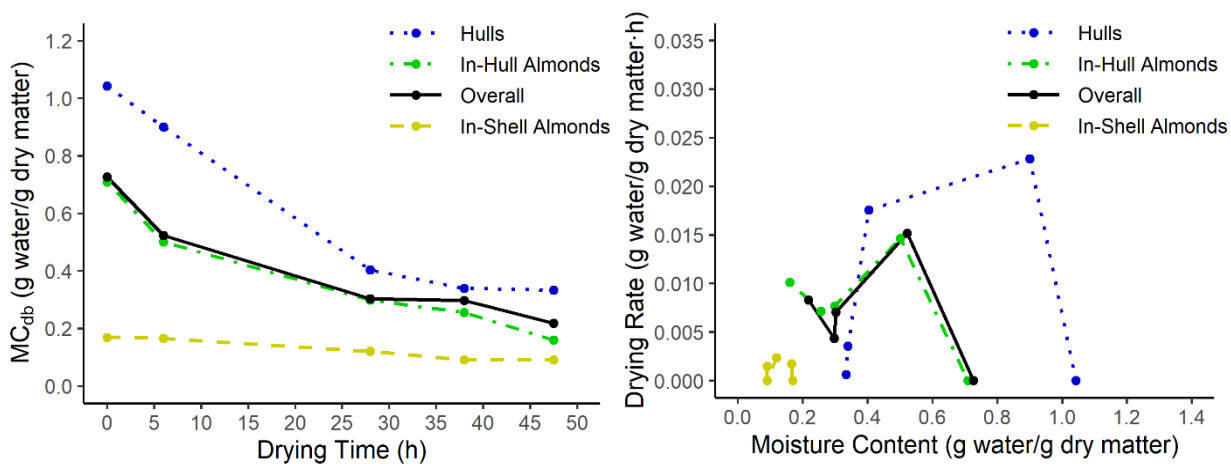


Figure A.10 Whole almond moisture content (left) and drying rate (right) profiles for tunnel ambient air drying started at nighttime

Stadium drying

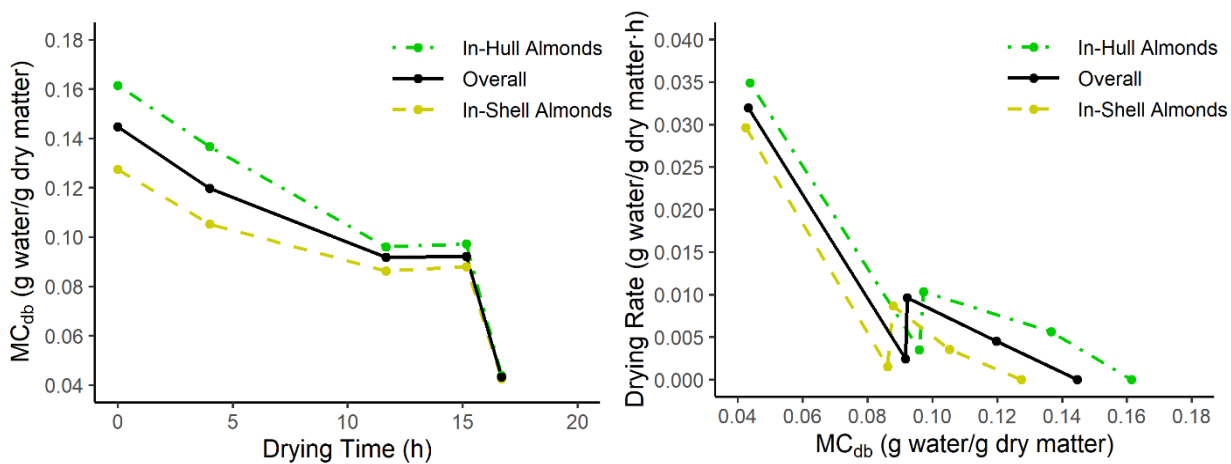


Figure A.11 Kernel moisture content (left) and drying rate (right) profiles for stadium drying of Monterey almonds

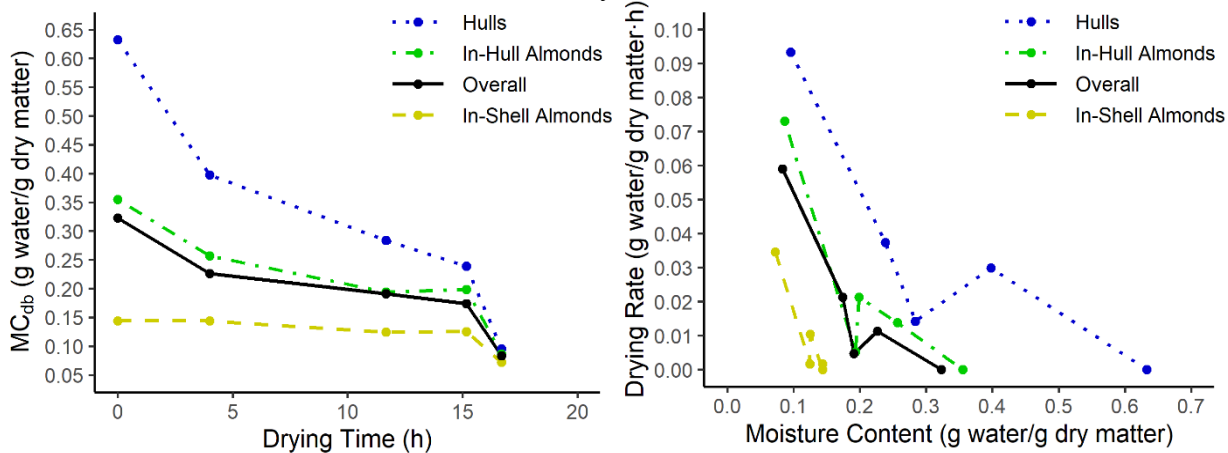


Figure A.12 Whole almond moisture content (left) and drying rate (right) profiles for stadium drying of Monterey almonds

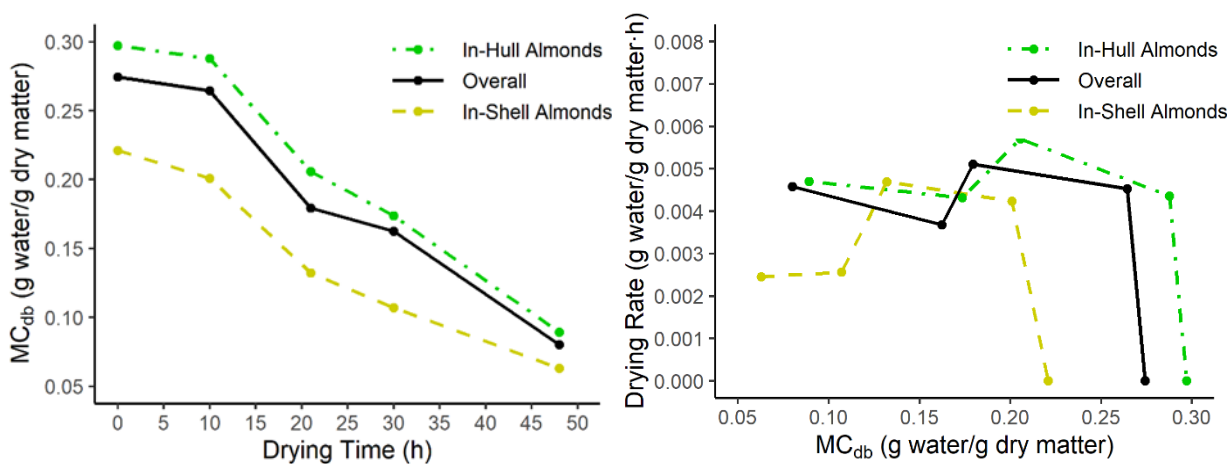


Figure A.13 Kernel moisture content (left) and drying rate (right) profiles for stadium drying of Fritz almonds

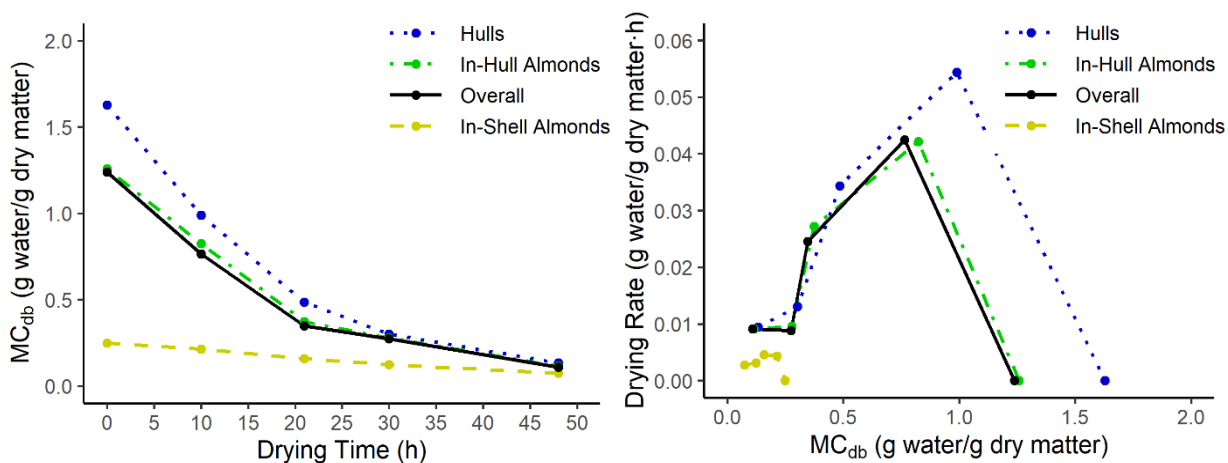


Figure A.14 Whole almond content (left) and drying rate (right) profiles for stadium drying of Fritz almonds

Trailer drying

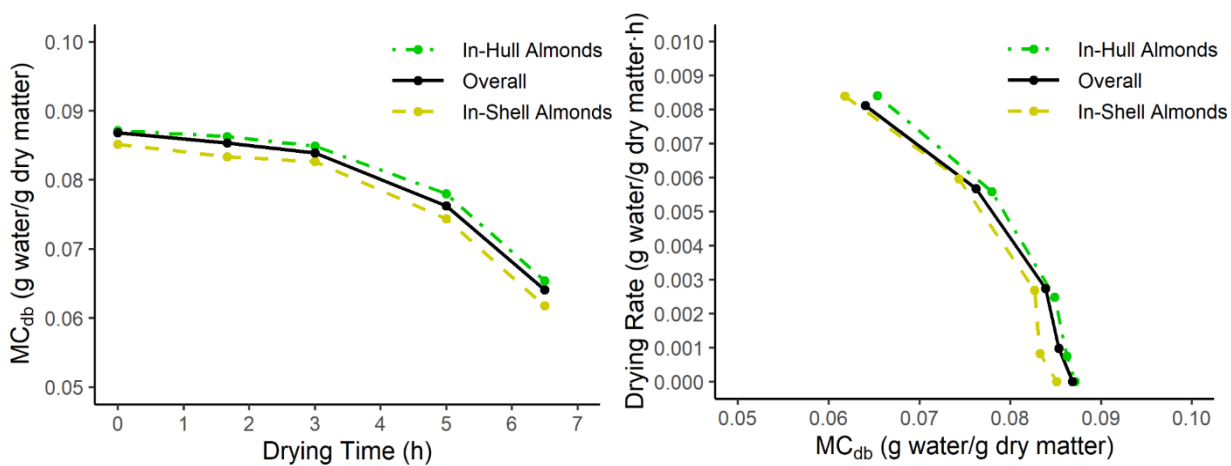


Figure A.15 Kernel moisture content (left) and drying rate (right) profiles for trailer drying at 43°C

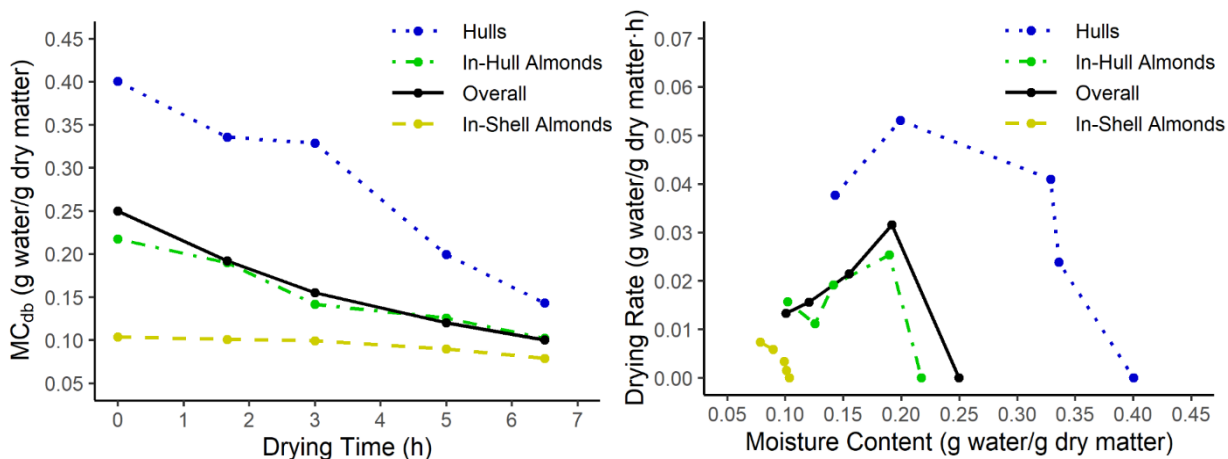


Figure A.16 Whole almond moisture content (left) and drying rate (right) profiles for trailer drying at 43°C

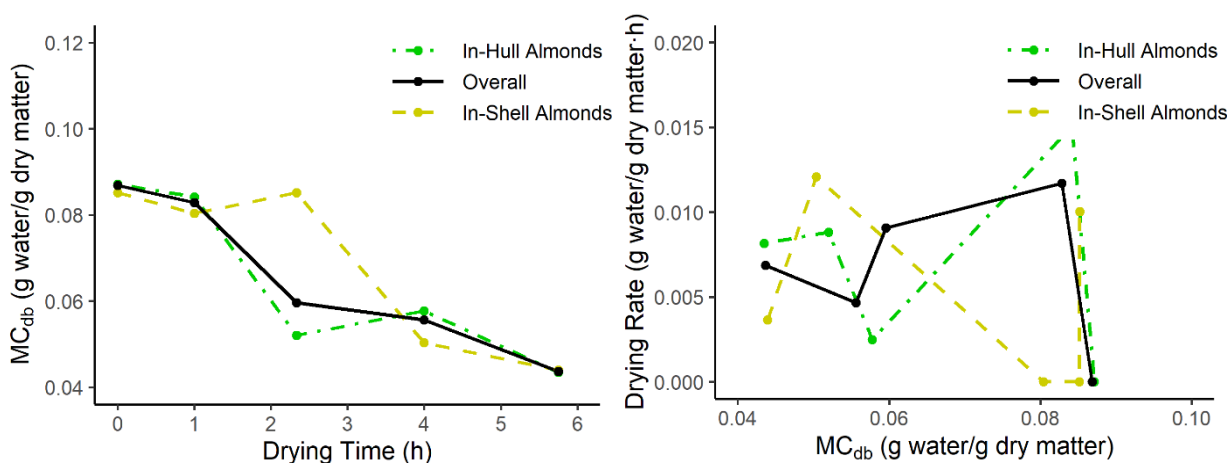


Figure A.17 Kernel moisture content (left) and drying rate (right) profiles for trailer drying at 54°C

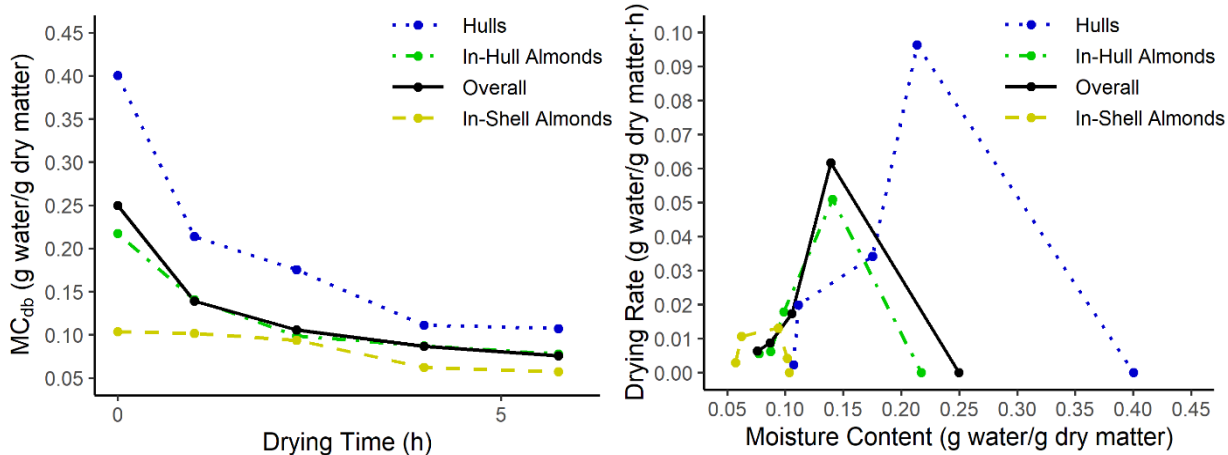


Figure A.18 Whole almond moisture content (left) and drying rate (right) profiles for trailer drying at 54°C

10.3 Appendix A.3 Final Moisture Content Distribution

Tunnel drying

Table A.7 Summary of final moisture content of Independence in-hull and in-shell almonds from conventional harvest

MC _{wb} (%)	Whole almond		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	4.6	2.0-6.2	2.8	1.3-5.8	5	1.5-10.9	5.5	0.9-7.2
In shell	3.2	2.1-4.0	2.3	1.5-3.9	5.5	3.6-6.9	N/A	N/A

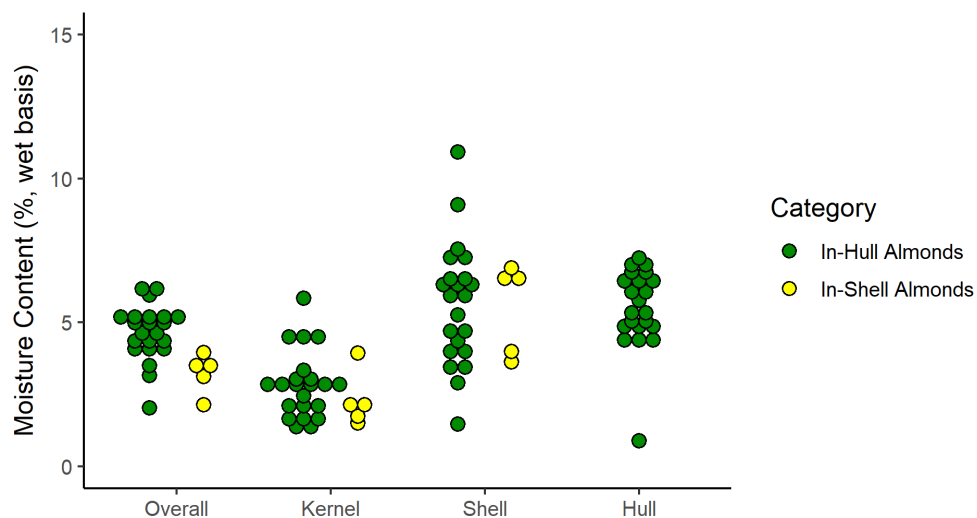


Figure A.19 Final moisture content distribution of Independence in-hull and in-shell almonds from conventional harvest

Table A.8 Summary of final moisture content of Independence in-hull and in-shell almonds from ambient air drying started at daytime

MC _{wb} (%)	Whole almond		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	14.5	8.4-25.2	8.1	3.3-17.6	11.3	4.4-19.6	18.7	11.4-31.4
In shell	7.4	5.2-10.5	6.8	4.8-9.9	9.1	5.9-12.5	N/A	N/A

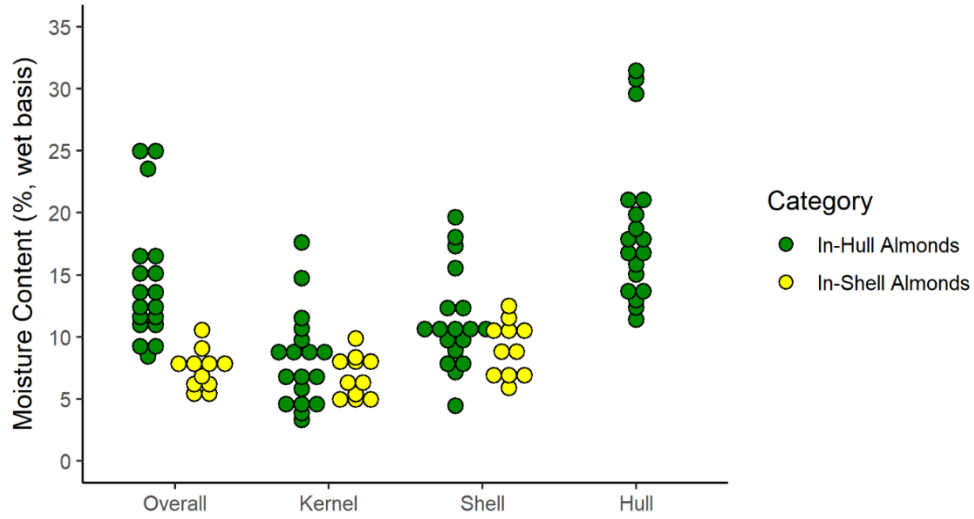


Figure A.20 Final moisture content distribution of Independence in-hull and in-shell almonds from ambient air drying started at daytime

Table A.9 Summary of final moisture content of Independence in-hull and in-shell almonds from ambient air drying started at nighttime

MC _{wb} (%)	Whole almond		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	15.7	8.5-31.1	8	3.7-15.4	11.3	5.3-20.0	20.7	11.1-39.4
In shell	8.4	6.1-12.9	7.6	5.4-12.7	10.6	7.8-14.3	N/A	N/A

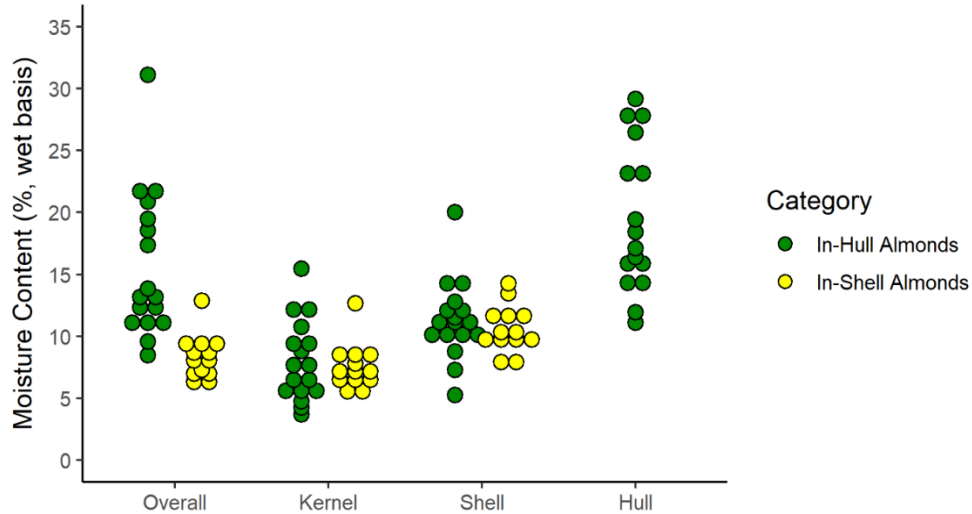


Figure A.21 Final moisture content distribution of Independence in-hull and in-shell almonds from ambient air drying started at nighttime

Table A.10 Summary of final moisture content of Independence in-hull and in-shell almonds from hot air drying

MC _{wb} (%)	Whole almond		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	12.8	7.9-20.9	6.1	4.4-10.0	9.4	5.9-13.4	17.2	8.7-28.5
In shell	5.6	3.6-10.2	5.1	2.5-9.6	6.9	4.0-11.3	N/A	N/A

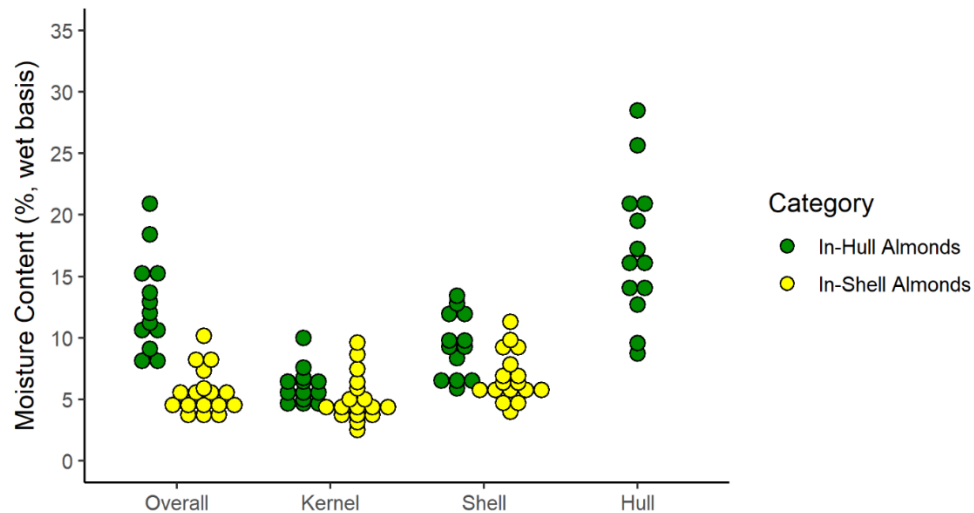


Figure A.22 Final moisture content distribution of Independence in-hull and in-shell almonds from hot air drying

Stadium drying

Table A.11 Summary of final moisture content of Monterey in-hull and in-shell almonds from conventional harvest

MC _{wb} (%)	Whole almond		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	8.6	7.3-12.5	4.6	2.9-6.6	7.7	4.8-10.3	11.4	9.5-14.8
In shell	5.9	2.4-8.3	4.6	1.0-6.3	7.6	4.3-10.5	N/A	N/A

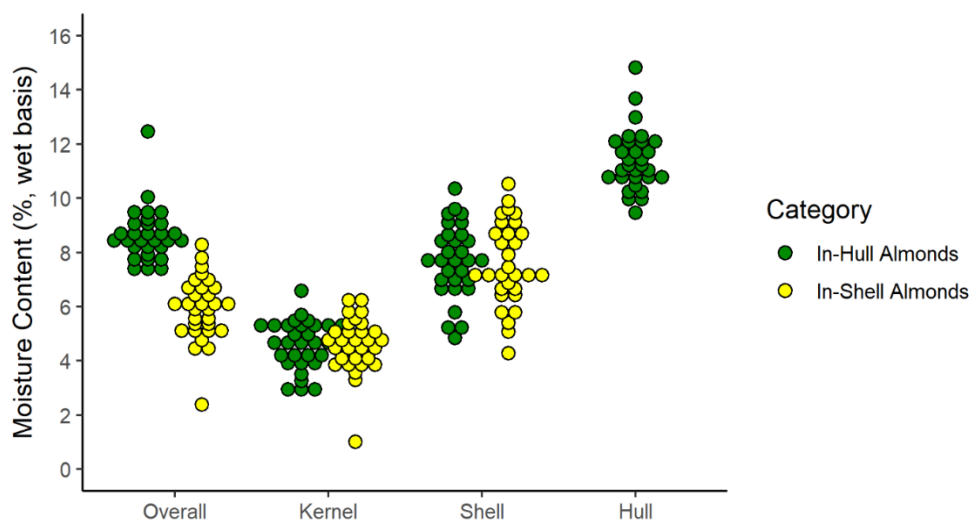


Figure A.23 Final moisture content distribution of Monterey in-hull and in-shell almonds from conventional harvest

Table A.12 Summary of final moisture content of Fritz in-hull and in-shell almonds from conventional harvest

MC _{wb} (%)	Whole almond		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	6.4	5.1-7.4	3.8	2.6-5.2	6.6	5.5-7.9	8.0	6.7-10.2
In shell	5.5	4.7-6.7	4.0	2.5-5.8	7.1	4.8-8.3	N/A	N/A

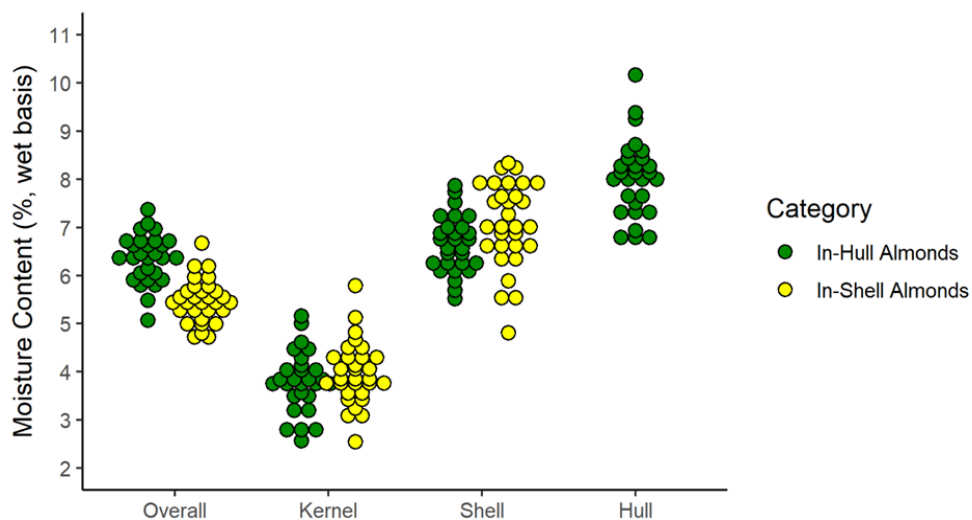


Figure A.24 Final moisture content distribution of Fritz in-hull and in-shell almonds from conventional harvest

Table A.13 Summary of final moisture content of Monterey in-hull and in-shell almonds from stadium hot air drying

MC _{wb} (%)	Whole almond		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	7.2	5.1-9.7	4.5	2.3-7.6	6.7	4.1-11.1	9.3	6.6-11.6
In shell	5.6	3.2-8.5	4.2	1.6-6.7	7.0	4.4-15.3	N/A	N/A

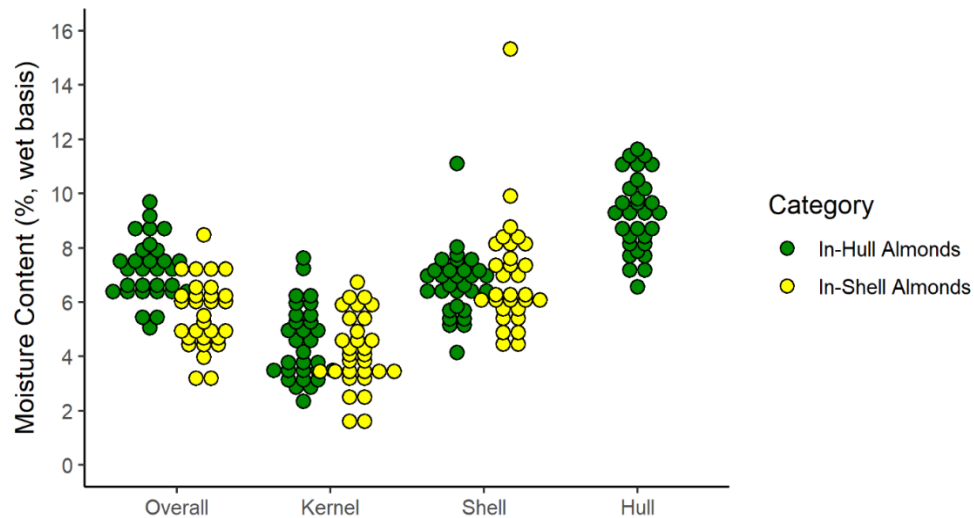


Figure A.25 Final moisture content distribution of Monterey in-hull and in-shell almonds from stadium hot air drying

Table A.14 Summary of final moisture content of Fritz in-hull and in-shell almonds from stadium hot air drying

MC _{wb} (%)	Whole almond		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	8.8	4.9-16.6	6.5	2.2-16.1	8.4	4.3-15.0	10.3	5.8-17.9
In shell	5.6	3.2-9	4.7	1.2-9.2	6.8	3.3-9.4	N/A	N/A

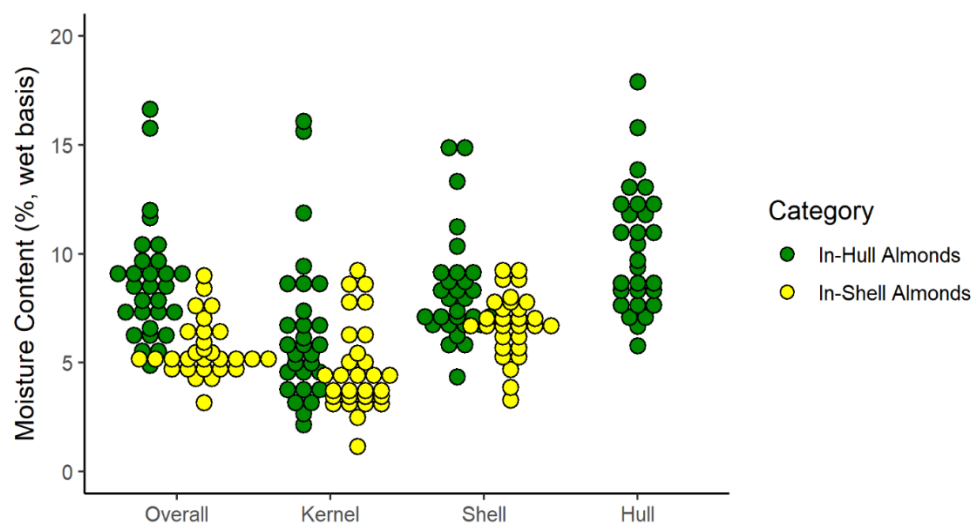


Figure A.26 Final moisture content distribution of Fritz in-hull and in-shell almonds from stadium hot air drying

Trailer drying

Table A.15 Summary of final moisture content of Monterey in-hull and in-shell almonds from conventional harvest

MC _{wb} (%)	Whole almond		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	6.2	5.3-7.5	3.8	2.9-5.1	7.1	5.1-8.8	8.0	6.6-12.2
In shell	5.3	4.3-7.1	4.0	3.3-5.2	7.1	5.5-11.1	NA	NA

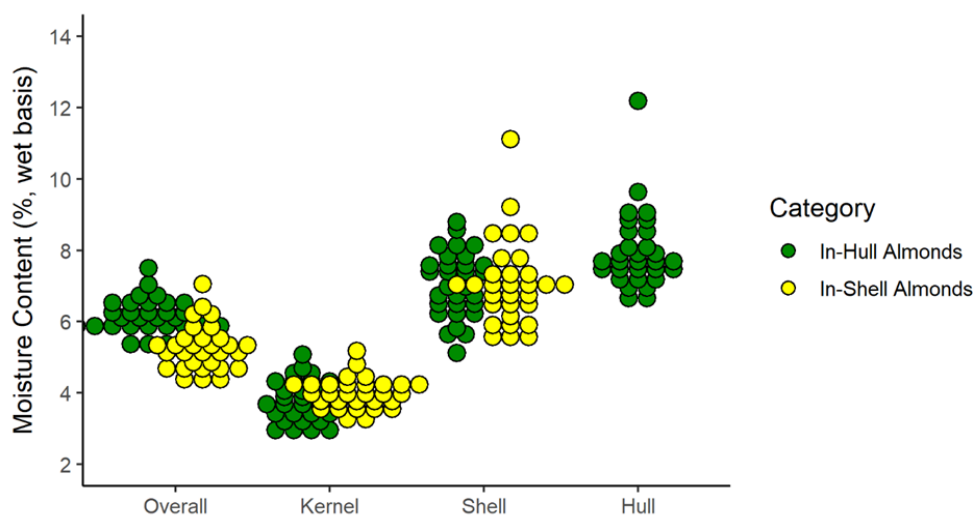


Figure A.27 Final moisture content distribution of Monterey in-hull and in-shell almonds from conventional harvest

Table A.16 Summary of final moisture content of Monterey in-hull and in-shell almonds from trailer hot air drying at 43°C

MC _{wb} (%)	Whole almond		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	5.5	3.9-11.9	4.0	2.3-11.8	4.7	2.8-9.1	7.4	5.1-13.3
In shell	4.4	2.6-7.3	4.2	2.0-8.9	4.5	1.8-6.7	N/A	N/A

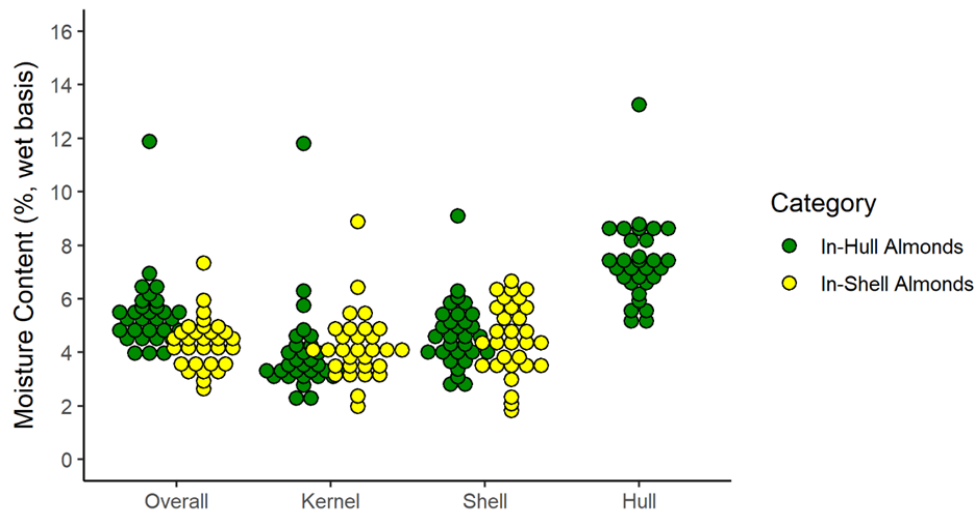


Figure A.28 Final moisture content distribution of Monterey in-hull and in-shell almonds from trailer hot air drying at 43°C

Table A.17 Summary of final moisture content of Monterey in-hull and in-shell almonds from trailer hot air drying at 54°C

MC _{wb} (%)	Whole almond		Kernel		Shell		Hull	
	Ave	Range	Ave	Range	Ave	Range	Ave	Range
In hull	5.8	4.4-7.3	3.5	2.0-8.1	3.8	2.8-6.3	9.4	6.8-12.1
In shell	3.7	1.6-5.6	3.5	1.9-6.4	3.9	1.1-6.3	NA	NA

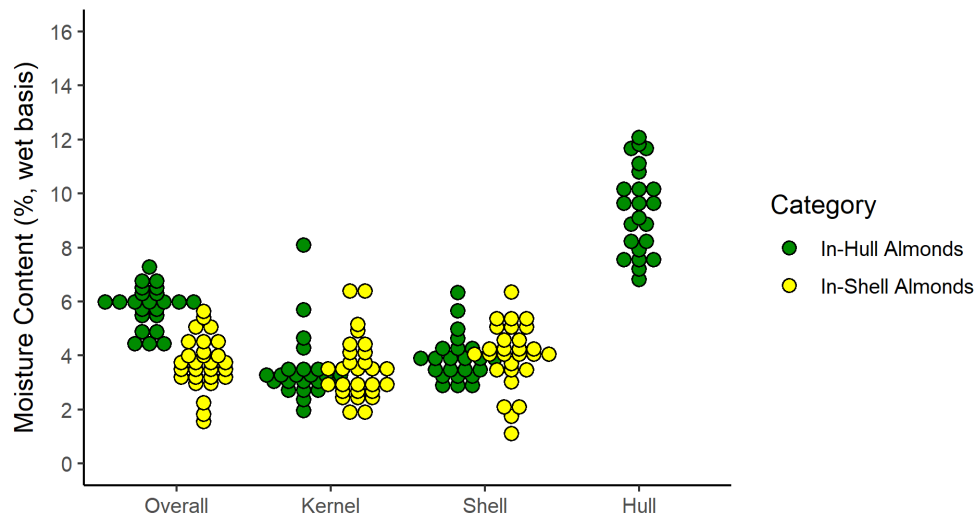


Figure A.29 Final moisture content distribution of Monterey in-hull and in-shell almonds from trailer hot air drying at 54°C

10.4 Appendix A.4 Kernel Color

Tunnel drying

Table A.18 Summary of kernel color result of Independence almonds

WI	Control (before drying)		Conv		AA1		AA2		HA	
	IH	IS	IH	IS	IH	IS	IH	IS	IH	IS
Ave	77.9	76.9	77.1	77.9	77.8	77.4	78.8	78.1	77.3	77.7
Std	1.7	1.7	1.5	1.6	1.2	2.2	1.1	1.3	2.1	2.0

Stadium drying

Table A.19 Summary of kernel color result of Monterey almonds

WI	Control		Conv		HA	
	IH	IS	IH	IS	IH	IS
Ave	81.0	80.7	81.0	79.8	79.4	80.6
Std	0.3	1.5	0.4	1.4	2.7	0.9

Table A.20 Summary of kernel color result of Fritz almonds

WI	Control		Conv		HA	
	IH	IS	IH	IS	IH	IS
Ave	79.6	82.1	79.7	79.3	80.8	80.7
Std	2.7	2.2	1.4	0.8	1.0	2.0

Trailer drying

Table A.21 Summary of kernel color result of Monterey almonds

WI	Control		Conv		43°C		54°C	
	IH	IS	IH	IS	IH	IS	IH	IS
Ave	79.9	79.8	80.1	79.8	80.5	79.4	80.4	80.2
Std	0.9	1.5	1.0	0.9	1.7	0.5	0.8	1.2

10.5 Appendix A.5 Concealed Damage

Tunnel drying

Table A.22 Summary of color development score result of Independence almonds

	Conv		AA1		AA2		HA	
	IH	IS	IH	IS	IH	IS	IH	IS
Ave	2.4	2.5	2.2	2.3	2.3	2.7	2.8	2.6
Std	0.4	0.7	0.5	0.6	0.9	0.9	0.8	0.8

Stadium drying

Table A.23 Summary of color development score result of Monterey almonds

CD	Conv		HA	
	IH	IS	IH	IS
Ave	2.4	2.2	2.3	1.9
Std	0.5	0.7	0.6	0.5

Table A.24 Summary of color development score result of Fritz almonds

CD	Conv		HA	
	IH	IS	IH	IS
Ave	1.9	2.0	2.2	1.9
Std	0.5	0.7	0.7	0.6

Trailer drying

Table A.25 Summary of color development score result of Monterey almonds

CD	Conv		43°C		54°C	
	IH	IS	IH	IS	IH	IS
Ave	1.9	1.5	1.7	1.6	1.6	1.9
Std	0.6	0.6	0.7	0.3	0.3	0.5