Developing effective drying methods for minimizing quality defects for off-ground harvested almonds

Project No.: **HARV2.Pan**

Project Leader:
Professor Zhongli Pan
University of California, Davis, CA
Mailing Address: 3018 Bainer Hall, Department of Biological and Agricultural Engineering
University of California, Davis, One Shields Avenue, Davis, CA 95616
Phone: 530-400-3400
FAX: 530-752-2640
E-mail: zlpan@ucdavis.edu

Project Cooperators and Personnel:
Co-Principle Investigator
Franz Niederholzer
Farm Advisor – Orchard systems
UC Cooperative Extension Colusa County
PO Box 180
100 Sunrise Boulevard, Suite E
Colusa, CA 95932

Food Processing Lab at UCD:
Dr. Ragab Khir
Chang Chen
Dr. Yi Shen
Zhaokun Ning
Rentang Zhang
Xiangyu Cao
Xingzhu Wu
Lizhen Deng

Almond Board of California:
Guangwei Huang

A. Summary

To conduct the proposed research, a pilot-scale hot air column dryer of 6-feet height and a benchtop dryer were used. Three almond varieties of Nonpareil (NP), Monterey (MT), Fritz (FR) obtained from off-ground harvesting were dried at different temperatures of 45°C, 50°C, 55°C, and 60°C and air velocities of 1 m/s and 2 m/s. The initial almond characteristics, drying performance, dried product qualities and energy consumption for the off-ground harvested almonds were determined and compared with those of almonds harvested with the conventional method. The key findings and recommendations from this research project are summarized as follows:

1. Off-ground harvested almonds were cleaner and had less insect damage compared to conventionally harvested almonds.

2. The initial moisture content of in-hull almonds was much higher than that of in-shell almonds.
3. The drying time to dry the off-ground harveseted almonds from their intial moisture contents to kernels moisture content of about 6% ranged from 2.5 to 6 hours for the pilot-scale dryer and from 1.0 to 4.3 hours for the single-layer benchtop dryer.
4. The hot air drying had no adverse effect on the quality at even up to 60$_o$C drying since there were no significant differences in cavity, kernel color, concealed damage, and oil quality under the tested condtions. Thus, high temperature should be used for achiving high drying rate and throughput.
5. Drying kinetics of almonds were described using the Page model, and the modeling results can be used to predict the moisture content and drying time of almonds.
6. To chieve low drying energy cost, the drying conditions varied with varieties. For example, the hot air drying conditions for Nonpareil almonds was 55$_o$C and 1 m/s air velocity, which led to relative short drying time and lowest operating cost (as low as 1.5 cents per pound almond).
7. Up to 60% of the total energy was used for drying the hulls. While, only about 20% of energy was used to dry almond kernels.
8. The obtained results indicated a promising potential to separate freshly harvested amonds into in-shell and in-hull almonds and hulls based on their physical and areodaynamic properties prior to the drying process, which could significantly improve the drying performance, energy efficiency and moisture uniformity of dried almonds.

B. Objectives

The ultamte goal of this reseatch project was to study the hot air dyring performance and quality characteristics of off-ground harvested amondnds under different drying condtions. The initial charachtrisitics of freshely harvested almonds, drying performance, dried product qualities and energy consumption were investigated and compared with those of almonds from the conventional harvest. The specific objectives were to:

1. Investigate the characteristics of fresh off-ground harvested almonds, including bulk density, kernel color, weight ratios of different fractions (in-hull, in-shell, and hull only), and distribution of initial moisture contents (MC) of individual whole almonds and thier components (hull, shell, and kernel).
2. Determine the drying characteristics and dried product qualities of almonds of different varieties under different drying conditions, and compare the results from the conventional harvest.
3. Study the fesabltliy of sorting off-ground almonds into three groups, including in-hull almonds, in-shell almonds and hulls, based on their dimension characteristics and aerodynamic properties.
4. Develop drying kinetic models and recommend drying conditions to almond industry for efficient drying almomds with high product quality.

C. Results

a. Initial characteristics of off-ground harvested almonds

Table C.1 shows the initial MC distribution of off-ground harvested almonds and their components. It was found that the overall MC of in-hull almonds (16.2% to 21.8%) was higher than that of in-shell almonds (7.1% to 8.7%) for all three almond varieties. Additionally, the initial MC of kernels from in-hull almonds (7.8 % to 13.0%) was also higher than that of kernels from in-shell almonds (6.1% to 6.5%). The weight ratios of different components and bulk densities of the almonds are summarized in Table C.2. It was found that the overall bulk density of almonds was around 0.32 kg/m^3, and the hull had the lowest bulk density among the three fractions. Meanwhile, it was found that weight ratios of the three fractions varied with the varieties, and on average the in-hull almonds, in-shell almonds and hulls took up 62%, 12% and 36% of the total weight, respectively.

Table C.1 Initial moisture content distribution of off-ground harvested almonds and their components.

Variety	Moisture content distribution (% wb)					
	Overall	In-hull			In-shell	
		Hull	Shell	Kernel	Shell	Kernel
Nonpareil	20.9	23.7 (13.3-46.9)	9.2 (5.4-16.5)	7.8 (3.2-20.2)	8.7 (5.9-11.1)	6.1 (3.0-10.7)
Monterey	17.7	19.8 (12.2-51.9)	10.0 (6.7-25.5)	8.4 (3.6-23.3)	8.4 (5.9-15.1)	6.5 (3.5-19.3)
Fritz	20.8	27.1 (12.4-55.7)	15.3 (8.5-26.6)	13 (3.6-32.5)	9.9 (6.4-13.2)	6.5 (3.4-15.8)

The appearances of off-ground harvested and conventional harvested almonds are shown in Figure C.1. Meanwhile, the percentages of insect damage for almonds harvested by conventional method and off-ground method are shown in Table C.3. It was found that the off-ground harvested almonds consistently had much less insect damage (2.5% to 6.3%) and were cleaner compared to those harvested with the conventional method (4.5% to 11.4%), which may be attributed to the longer periods of time on ground. Meanwhile, it was found that Monterey variety had higher insect damage than the other two varieties.

Figure C.1 Appearance of off-ground harvested and conventional harvested almonds

Table C.2 Bulk density and initial weight ratios of almonds.

Variety	**Bulk density (kg/m^3)**				**Weight ratio (as is)**		
	Hull	**In-shell**	**In-hull**	**Overall**	**Hull**	**In-shell**	**In-hull**
Nonpareil	240	280	330	310	34%	10%	56%
Monterey	200	300	310	320	8%	14%	78%
Fritz	260	340	390	320	38%	11%	51%
Ave	240	310	340	310	26%	12%	62%

Table C.3 Insect infestation rate for diffeerrn almond varieties.

Variety	Days on ground	Insect infestation(%)	
		Conventional	Off-ground
Nonpareil	11	6.3	3.3
Monterey	14	11.4	6.3
Fritz	9	4.5	2.5

b. Benchtop drying

The drying characteristics and quality attributes of three almond varieties (Nonpareil, Monterey and Fritz) were investigated under drying temperarues of 45, 50, 55 and 60 ^{o}C; and air speed of 1 and 2 m/s in single layer in a benchtop hot air (HA) dryer. The initial and final MC, drying time and rate, and quality characteristics were determined. The overall initial MC, final MC, and drying time for Nonpareil almonds are shown in Table C.4 as an example. The detailed results realted to other varieties are shown in the appendex. It was found that the drying rates increased significantly with the increase in drying temperature and air speed, resulting in reduced drying time. The drying times of almonds under 60^{o}C and 2 m/s were 1, 1.5 and 1.75 h for Nonpareil, Monterey, Fritz varieties, respectively. Correspondingly, the drying times under 45^{o}C and 1 m/s were 2, 3, and 4.3 h, respectively. Similar trends were found for the other varieties.

Table C.4 Summary of benchtop drying tests under different drying conditions for Nonpareil variety.

Air velocity (m/s)	**Temp (°C)**	**Initial MC_{wb} (%)**		**Final MC_{wb} (%)**		**Drying time (min)**	**Overall drying rate (kg/min-kg)**	
		Ave	**Std**	**Ave**	**Std**		**Ave**	**Std**
1	45	21.25	0.64	16.70	0.71	120	5.8×10^{-4}	5.0×10^{-6}
	50	17.50	0.99	13.15	0.92	75	8.2×10^{-4}	3.5×10^{-5}
	55	17.75	0.64	13.05	0.49	60	1.1×10^{-3}	4.7×10^{-5}
	60	20.15	0.49	14.55	0.49	60	1.4×10^{-3}	2.3×10^{-5}
2	45	19.15	1.06	15.20	1.84	75	6.5×10^{-4}	5.8×10^{-5}
	50	15.05	0.64	11.55	0.64	75	6.2×10^{-4}	5.2×10^{-6}
	55	15.90	0.71	11.75	0.64	60	9.3×10^{-4}	2.3×10^{-5}
	60	15.85	0.35	11.60	0.71	45	1.3×10^{-3}	7.0×10^{-5}

Meanwhile, the drying characteristics of single in-shell and in-hull Nonpareil almonds were studied and compared. Figure C.2 shows the example drying curves of in-shell and in-hull almonds at 60 °C and 2 m/s. It was obvious that the in-shell almonds dried faster and more uniformly than in-hull almonds. In addition, the final MCs of in-hull almond were much higher (10.1% fo 14.8%) than those of in-shell almond (4.7% to 7.3%) after the same drying time.

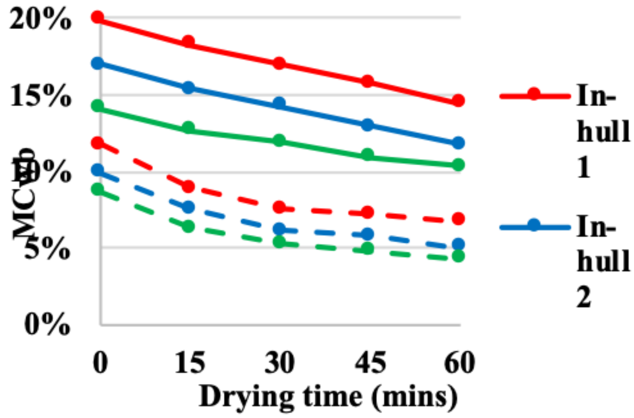


Figure C.2 Drying curves of in-shell and in-hull almonds at 60 °C and 2 m/s (Nonpareil variety)

Addtionaly, the color change before and after the drying process was studied. The whiteness index values of almond kernels in-shell and in-hull are shown in Figure C.3 (using Nonpareil as an example). The results showed that there was no significant color change before and after the drying, and no significant difference was observed among the in-hull and in-shell almonds after benchtop at different temperatures and air speeds and the almonds from conventional harvest. Similar results were found for the other varieties.

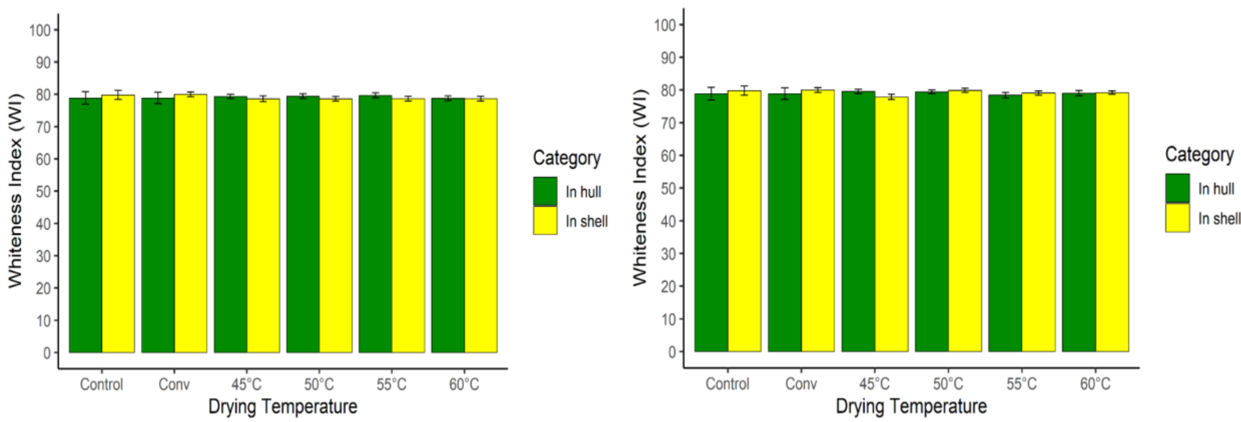


Figure C.3 Kernel whiteness of fresh almonds and dried almonds at different temperatures at air speed of 1 m/s (left) and 2 m/s (right) (Nonpareil)

The oil quality results (peroxide value (PV) and free fatty acid (FFA) amount) of dried almonds after benchtop drying under different drying conditions are shown in Figure C.4. It was found that the oil qualities varied with varieties, but the values were much lower than the industrial standard values (PV < 5.0 meq/kg; FFA < 1.5%). The influence of air temperature and speed on the oil quality was not significant. The results suggested that the hot air drying under tested conditions did not affect the quality of almonds.

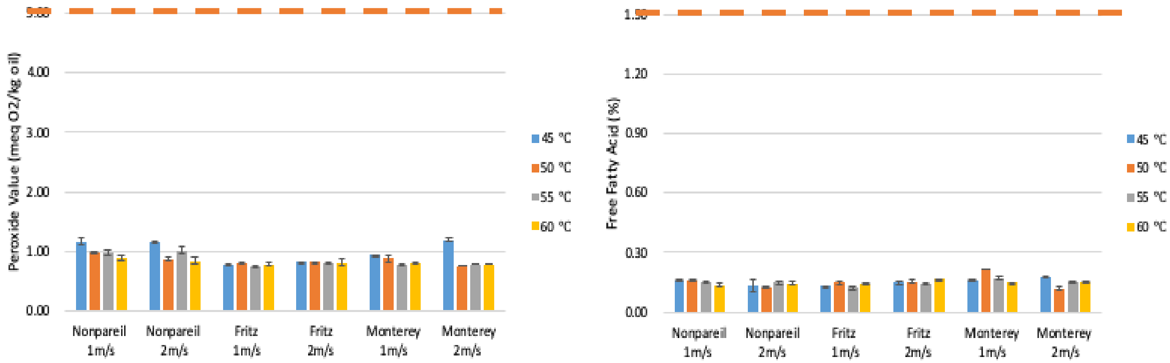


Figure C.4 Peroxide value (left) and free fatty acids (right) of almonds after benchtop drying

Figure C.5 shows that the color development (CD) scores of benchtop dried almonds were slightly higher than that after the conventional drying. The results may be due to the high drying rate in single layer HA drying. Even though, the CD scores were all lower than 4, which suggests that there was no significant concealed damage under the tested condtions. It was also found that increasing the air speed may lead to higher color development scores for the single layer drying, however, no adverse effect of high temperature on concealed damage of dried almonds was observed. Meanwhile, no cavity was observed in almonds dried under all tested conditions.

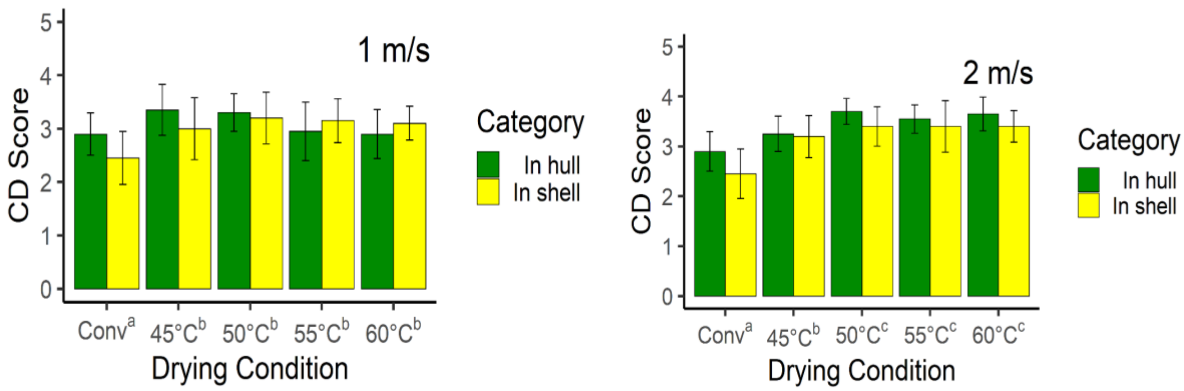


Figure C.5 Concealed damage (color development score) of almonds after benchtop drying for Nonpareil variety

c. Column drying

Although a previous research (Rogel-Castilloa et al., 2017) suggested that drying of almonds at 55$_o$C or more may result in severe concealed damage and kernel cavity. As discussed in the previous section, the benchtop drying results from our study indicated that drying at 60$_o$C did not cause any severe quality issues. Therefore, we attempted to scale up the technology, and investigated the drying performance, product quality and energy consumption in a pilot-scale under the same drying conditions and using the same batch of almonds.

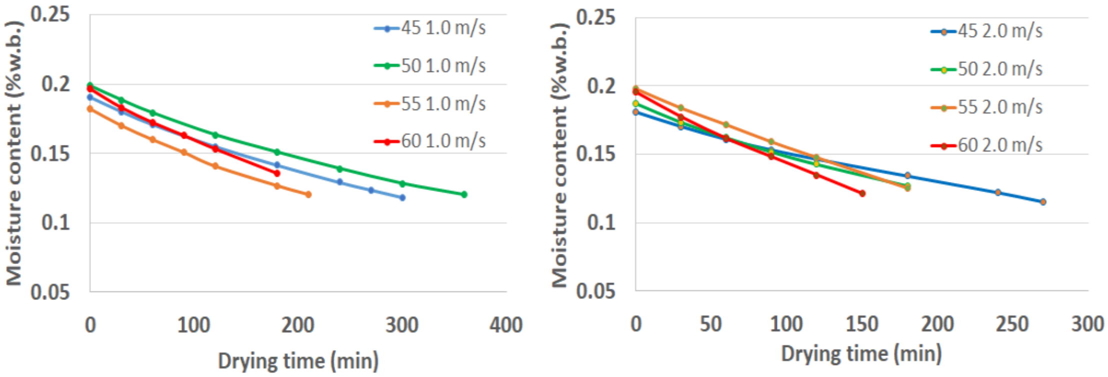


Figure C.6 Drying curves of almonds in the column dryer under different air temperatures and speeds for Nonpareil variety

The drying curves at different air temperatures and air speeds are shown in Figure C.6 (for Nonpareil as an example). It was found that the drying rate increased with the increase in drying air speed and temperature. For all tested varities and conditions, the drying time ranged from 2.5 h to 6.0 h, which was longer compared to the single-layer drying in the benchtop dryer as expected. Due to the distribution of temperature and relative humidity (RH) at different heights in the column dryer, the MCs at different locations in the column varied. As an example, the drying curves at different heights under 45$_{o}$C, 1 m/s and 2 m/s are shown in Figure C.7. It was found that almonds at higher locations in the column had higher MC, and the distribution of final MC in the column was more uniform at higher air speed. The variation of final MC for the overall almonds (9.32% to 13.62%) and almond kernels (5.21% to 6.51%) at different heights in the drying column are shown in Figure C.8. Regression analysis was conducted to determine the influence of drying air temperature and velocity on the moisture variation in the dryer. From the slope of the curves, it was found that the increase of drying temperature led to increased value of the slopes, which resulted in larger MC variation. Similar trends were observed for almond of other varieties.The static pressure of airflow at 0, 2, 4 and 6 ft in the column was 1.05, 0.55, 0.25 and 0 inch H_2O, respectively under 1 m/s air velocity; and 0.57, 0.32, 0.17 and 0.02 inch H_2O, respectively under 2 m/s air velocity.

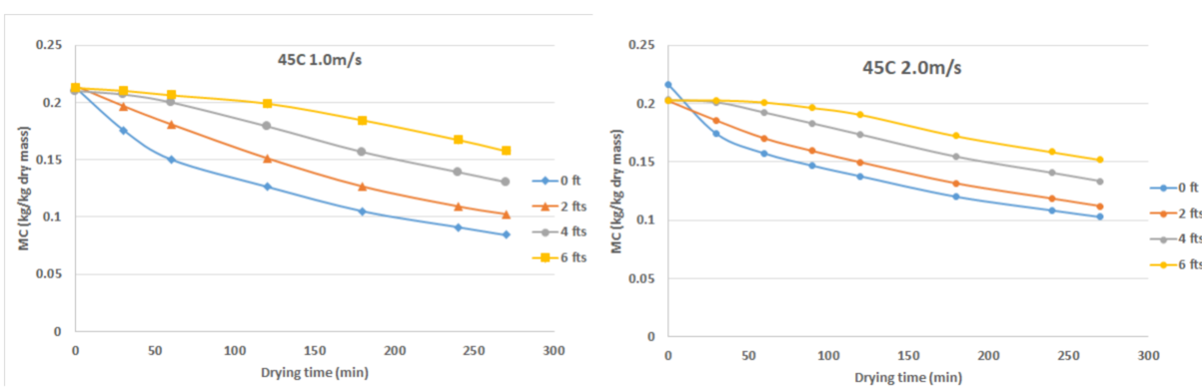


Figure C.7 Drying curves of almonds at different heights in the column dryer (Nonpareil)

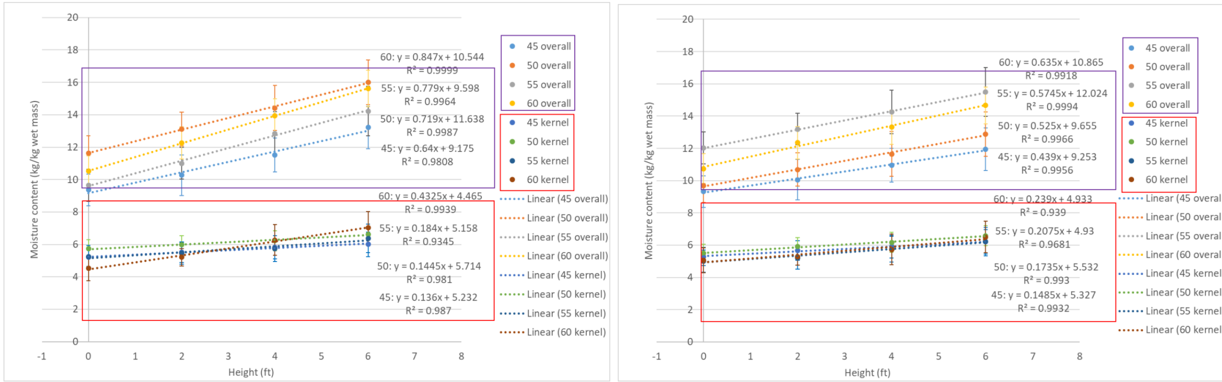


Figure C.8 Variation of final MC in the whole Nonpareil almonds and kernels at different heights in the column dryer with 1.0 m/s (left) and 2.0 m/s (right)

The product quality of almonds was evaluated using the same methods as in the benchtop study. The overall color development scores for the Nonpareil almonds by column drying at different drying conditions are shown in Figure C.9. It was found that the color development scores of HA dried almonds (1.7 to 2.7) were not significantly higher than those of almonds from conventional harvest (around 2.6), indicating no concealed damage. Meanwhile, the scores were slightly lower than those of almonds dried by benchtop dryer. For Nonpareil variety, the almonds dried at 2 m/s had a slightly higher CD scores than those dried at 1 m/s. However, for Monterey (CD scores: 1.5 to 2.9) and Fritz (CD scores: 1.5 to 3.3) varieties, no significant influence of drying temperature, air speed and locations in the column on the CD scores was observed. Although reported study in the literature showed that drying of almond at over 55oC may result in severe concealed damage, the CD scores of almonds dried at even up to 60oC were lower than 4, suggesting there was no significant concealed damage.

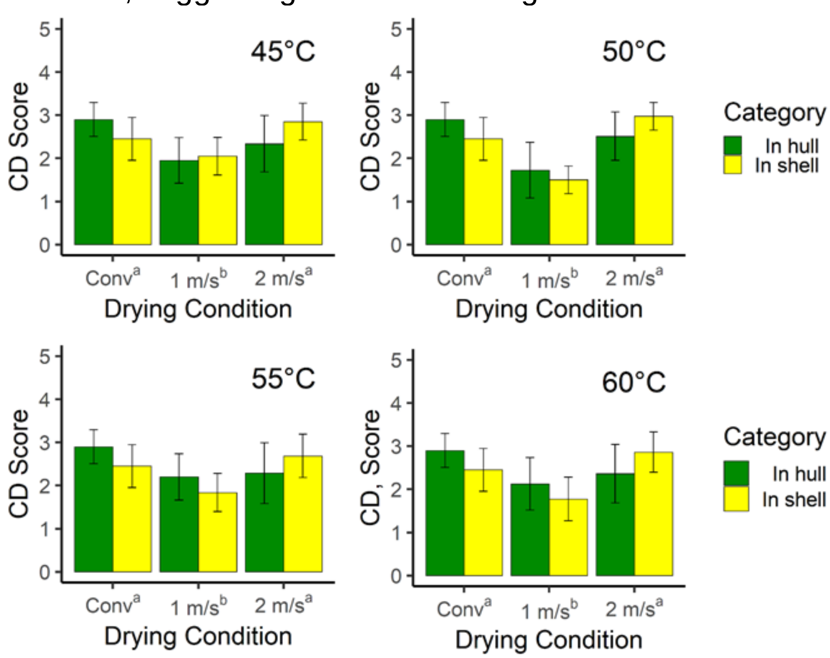


Figure C.9 Color development scores of almonds under different drying conditions (Nonpareil)

For the color of almond kernel, baed on the whiteness index, no significant difference was found between the HA dried almonds (77.6) and fresh-harvested almonds (77.9). These values were also very close to those of almonds dried by benchtop dryer. The results indicated that column drying with HA did not significantly affect the color of almond kernels. Meanwhile, no cavity was observed in almond kernels at different heights in the column under all of the drying conditions.

The oil quality results of almonds for Nonpareil variety dried at different heights in the column and under different drying conditions are shown in Figure C.10. The results suggested there was no significant difference in both PV and FFA of almonds at different locations in the column. The average PV of HA dried almonds ranged from 0.75 to 0.94 meq/kg, and the FFA ranged from 0.12 to 0.20% which were lower than those by conventional drying (PV: 1.01 meq/kg and FFA: 0.22%). Meanwhile, it was also found that the oil qualty of almonds dried by column dryer was slightly better than that those of almonds dried by benchtop dryer. The results suggested that almonds from off-groud havesting can be efficiently dried with high temperature without affecting the product quality.

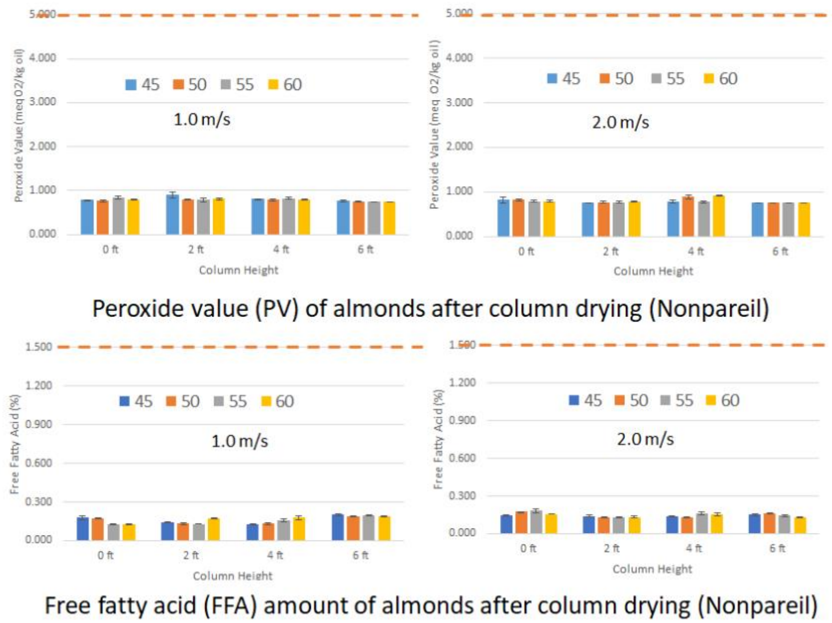


Figure C.10 Peroxide value and free fatty acid amount of almond oil (Nonpareil)

d. Modeling of drying kinetics and energy analysis

As shown in Table C.1 and C.4, the initial MC and final MC of almonds varied in each drying experiment, and the total drying times were no more than 6 hours, thus it is difficult to compare the drying time, drying rate and energy consumption directly. Therefore, the Page model was applied to 'standardize' the initial and final MC of almonds, then the energy consumption and drying time was calculated. An example of simulated results for Nonpareil variety was shown in Table C.5. It was found that both the specific energy consumption and energy cost increased with the increase in the drying temperature (as the temperature increased from 45 to 60$_{o}$C, the specific energy consumption (SEC) increased from 0.26 to 12.86 MJ/kg). When the air speed was doubled, the SEC almost also doubled, however, the drying time was not propotionally reduced. It was also found that the even though the IMC was similar, the Fritz almonds used shorter drying time compared to the Nonpareil variety. The results may be attributed to the fact that the Fritz almonds were smaller in size, and thus was dried faster. Considering the energy consumption, drying time and product quality, drying at 55$_o$C led to relatively low operating cost. However, the drying conditions with lowest energy cost varied with the almond variety.

Page model: $\boxed{\text{MR (Moisture Ratio)} = \exp(-kt^n)}$

Table C.5 Summary of standardized drying time and calculated energy consumption (Nonpareil)

Air velocity (m/s)	Temp (°C)	Initial MC_{wb} (%)	Final MC_{wb} (%)	Drying time (h)	Specific energy consumption (MJ/kg)	Energy cost (¢/lb)
1	45	20.77	11.98	5.32	9.26	1.8
	50	20.77	11.98	5	10.91	3.4
	55	20.77	11.98	4.55	11.95	2.1
	60	20.77	11.98	4.2	12.86	3.6
2	45	20.77	11.99	5.25	17.22	2.3
	50	20.77	11.97	4.4	18.32	3.8
	55	20.77	11.97	3.78	19.05	2.5
	60	20.77	11.93	3.2	18.88	3.7

Meanwhile, the percentages of energy consumption used for the drying of different almond components for Nonpareil variety are shown in Figure C.11. It was clearly found that up to 65% of the total energy was used for drying the hulls, and as low as about only 20% of energy was used for drying the kernels. The results clearly indicated that drying of hulls causes energy waste. In addition, drying of in-hull almonds and in-shell almonds together using a same condition will result in over-drying and under-drying problems, which affects the the moisture uniformity and quality of dried product. Therefore, it is necessary to develop an efficient sorting technologies to separate in-hull almonds, in-shell almonds, and hulls and determine appropriate drying conditions for drying in-hull and in-shell almonds separately, which can significantly improve of the drying efficiency, energy saving and uniformity of product quality.

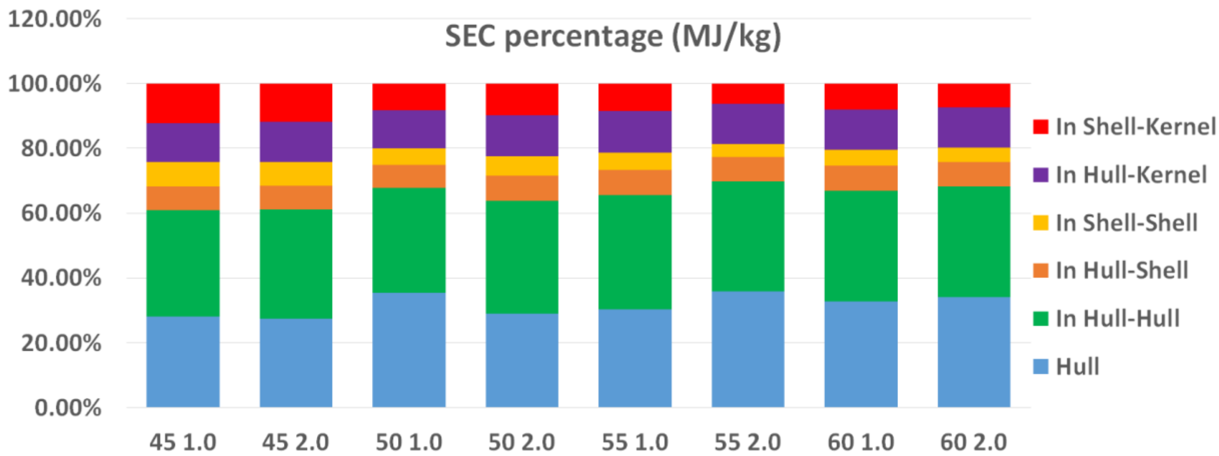


Figure C.11 Relative energy consumption by different almond components (Nonpareil)

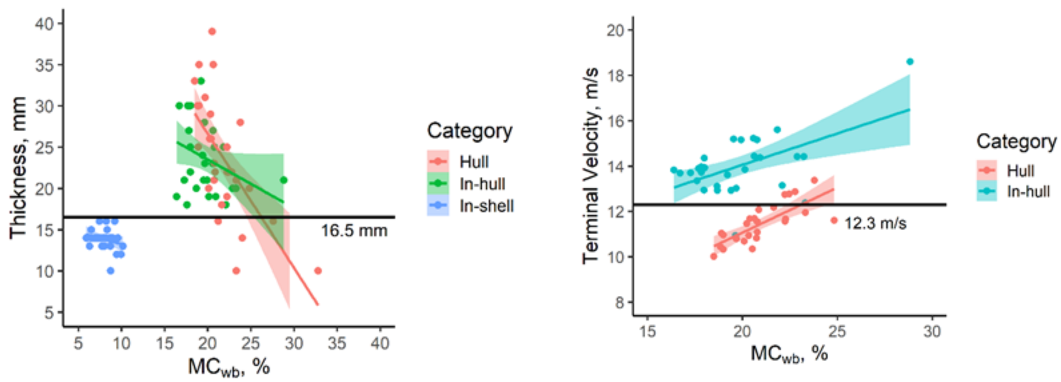
e. Separation of almonds

The axial dimensions of different fractions of almonds for the three varieties are shown in Table C.6. It was found that the length and width for the in-hull almonds, in-shell almonds and hulls were very similar, but the thickness of in-shell almonds differed significantly from the other two fractions. This means that the thickness can be used as the cutoff size for sorting in-shell almonds, in-hull almonds, and hulls for the three tested varieties. When the thickness values are set as 16.5 (Figure C.12), 21.3 and 21.1 mm, 100% of the in-shell almonds can be separated from in-hull almonds and hulls for Nonpareil, Monterey, and Fritz, respectively. However, it is also found that a small portion of in-hull almonds and hulls may fall into this dimension range. The mis-classification error rate for the dimension separation ranged from 5.6% to 13.3%.

Table C.6 Averages and standard deviations of axial dimensions of almonds of different varieties

Variety	Category	Axial dimension (mm)		
		length	width	thickness
Nonpareil	In-hull	37.53 ± 2.71	28.00 ± 2.52	23.63 ± 4.11
	In-shell	33.63 ± 2.43	21.80 ± 1.85	13.80 ± 1.21
	kernel	24.47 ± 1.60	13.93 ± 1.22	7.00 ± 0.53
	hull	38.13 ± 2.57	27.33 ± 4.23	23.70 ± 7.11
Monterey	In-hull	38.27 ± 3.22	24.80 ± 2.28	23.20 ± 1.99
	In-shell	37.97 ± 3.06	22.23 ± 1.50	17.37 ± 1.40
	kernel	24.93 ± 3.26	13.73 ± 1.83	8.33 ± 0.72
	hull	40.20 ± 2.99	24.77 ± 4.23	24.30 ± 3.78
Fritz	In-hull	35.93 ± 2.70	24.10 ± 2.45	24.47 ± 2.47
	In-shell	32.47 ± 2.69	20.33 ± 1.63	17.17 ± 1.26
	kernel	21.93 ± 1.71	12.47 ± 1.06	8.60 ± 1.18
	hull	36.27 ± 2.98	22.70 ± 6.08	28.27 ± 7.86

It was also found that the aerodynamic properties can be utilized to separate hulls from in-hull almonds. It was found that In-hull almonds had wider distribution of the MC than the hulls, and the terminal velocity of in-hull almonds was generally higher (Figure C.12). The obtained results indicated that when the air velocities were set at 12.3, 11.8, and 12.2 m/s all in-hull almonds can be separed from the hull fractions and some hulls fell in this group. The group contained about 96.7%, 90.0% and 93.3% in-hull almonds for Nonpareil, Monterey, and Fritz, respectively. The results confirm the potential to separate in-shell and in-hull almonds and hulls prior to the drying process, then only the in-hull and in-shell almopnds need to be dried separately, which will significantly improve drying throughput and energy efficiencies.



Classification of major fractions with thickness (Nonpareil)

Classification of major fractions with terminal velocity (Nonpareil)

Figure C.12 Classification of major fractions of almonds based on thickness and terminal velocity (Nonpareil)

The outreach activities to present and share the results have been listed in Section F.

D. Discussion and Conclusions

The off-ground harvested almonds were cleaner and had much less insect damage than the conventional harvested almonds. Drying time of off-ground harvested almonds using hot air in column dryer ranged from 2.5 to 6 hours, and from 1.0 to 4.3 hour in single layer benchtop dryer. Meanwhile, it was found that even drying at up to 60$_o$C and 2 m/s did not cause quality defects (no cavity, no significant color change, no significant concealed damage and no deterioration of oil quality) in both single-layer drying and column drying. These findings suggested that it is applicable to use high temperature HA to dry almonds in a column dryer, which could improve the processing efficiency without compromising the product qualities. The drying time, final moisture distribution and energy consumption were influenced by the air temperature and air speed. The results suggested that the low energy cost (as low as 2.1 cents per pound of dried almond kernels) at drying condition of 55$_o$C and 1 m/s. Meanwhile, it was found the energy efficiency of the HA drying process can be improved since up to 60% of the energy was used for the drying of hulls. Therefore, sorting of freshly harvested almonds into hulls, in-hull and in-shell almonds based on their size and terminal velocity before drying and drying only the in-hull and in-shell almonds separately should significantly improve the energy efficiency and throughput.

E. Materials and Methods

The almonds used in this project were obtained from Nickels Soil Lab, Arbuckle, CA. Off-ground harvested almonds were transported to the Food Processing Lab, UC Davis and processed immediately. While the remaining almonds of the same batch were left on-ground for conventional natural drying and collected later (as shown in Table E.1). Harvested almonds included three major fractions: in-hull (IH) almonds, in-shell (IS) almonds, and hulls (As shown in Figure E.1). The weight ratios and bulk densities of these three major fractions were measured. The axial dimensions and moisture contents (MC) of each almond components (hull, shell, kernel) were measured carefully and recorded.

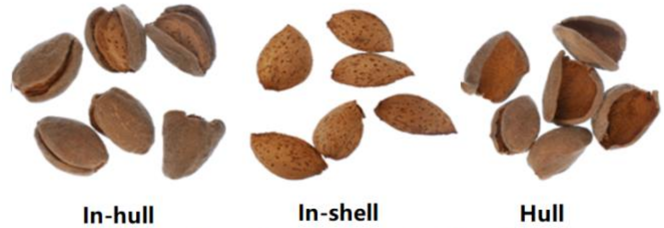


Figure E.1 Three fractions of harvested almonds

Table E.1 Collection dates of samples of off-ground and conventional harvested almonds

Variety	Category	Off-ground harvest date	Off-ground harvest amount (lb)	Conventional harvest date
Nonpareil	Soft shell	Sep 8th	1200	Sep 19th
Monterey	Semi-hard shell	Sep 17th	1200	Oct 1st
Fritz	Hard shell	Oct 1st	1200	Oct 10st

The benchtop drying experiments were performed in an Avantco CFD10 Dehydrator (Clark Associates, Inc., U.S.) integrated with a weighing system and temperature monitoring device (Figure E.2 A). The experimental design is summarized in Table E.2. 30 in-shell and 30 in-hull almonds were used for each test and duplicate experiments were conducted. The individual and overall drying curves were generated.

The pilot-scale HA drying experiments were performed under the same drying conditions with a constructed column dryer (Wizard Manufacturing Inc., CA, U.S.) with air velocity and temperature control (Figure E.2 B) using the same batches of almonds. Around 100 lbs almonds were used for each test. The drying rate, temperature, relative humidity and static pressure at 4 different heights in the column dryer were measured and recorded.

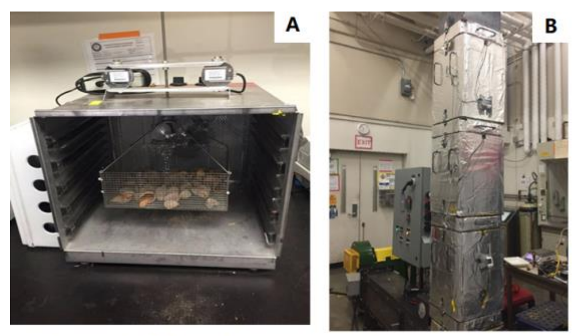


Figure E.2 A) Benchtop dryer and B) Column dryer

The drying kinetics of almonds were simulated with the Page model, which was used to standardize the MC and estimate the drying time, specific energy consumption (MJ/kg moisture removed) and energy cost of drying processes.

Table E.2 Summary of factors and their levels used for the pilot almond drying

Factor	Levels
Drying temperature	45, 50, 55, and 60°C
Air velocity	1 and 2 m/s
Height in the column	0, 2, 4, and 6 fts (column drying only)
Target final MC	12% wet basis

The insect damage ratio of fresh-harvested almonds (150 fresh almonds) was evaluated by visual inspection and recorded (Figure E.3). Incidence of kernel cavity at the cross-sectional surface was measured by visual Inspection (30 dried almonds). Concelaed damage was measured by splitting the roasted kernel (135$_{o}$C, 90 min) and determine the color development score (Figure E.3). Color of almond kernel flesh was measured with a chroma meter (Minolta Crop., Ramsey, Japan) and the whiteness index (WI) was calculated. Peroxide value, PV and Free fatty acid, FFA amount of extracted oils were measured using potentiometer according to the AOCS (American Oil Chemists Society) official methods Cd8-53 and Ca 5a-40, respectively.

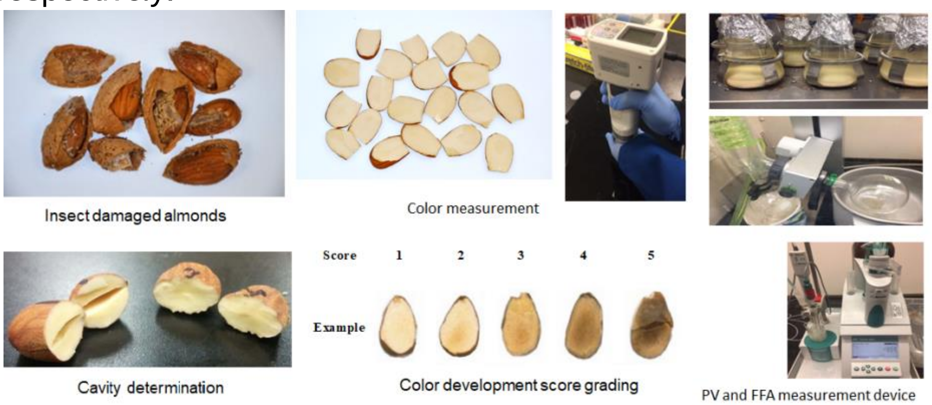


Figure E.3 Analytical methods for product qualities

Figure E.4 Terminal velocity measurement

The terminal velocity of individual almonds was measured using a cylindrical air column with a centrifugal fan and speed control. The terminal velocity was determined when a single almond was suspended above the sample holder (Figure E.4).

F. Publications that emerged from this work

Outreach publications

The Almond Conference 2019, Sacramento, 12/10/19-12/12/19

1. Presentation: Efficient drying of off-ground harvested almonds without quality concerns,
2. Poster: Developing effective drying methods for minimizing quality defects for off-ground harvested almonds: -- Part I. Performance of a pilot scale column dryer and product quality
3. Poster: Developing effective drying methods for minimizing quality defects for off-ground harvested almonds: -- Part II. Performance of a benchtop dryer and product quality
4. Poster: Performance of commercial dryers for off-ground harvested almonds

Institute of Food Technologiests (IFT) annual meeting 2020, Chicago, 07/12/20-07/15/20

1. Absrtact and Poster: Performance of Commercial Dryers for Off-Ground Harvested Almonds
2. Poster: Effect of Hot-Air Drying Condition on Quality of Almonds Harvested Off-ground
3. Poster: Drying and Quality Characteristics of Off-Ground Harvested Almonds under Hot Air Drying

American Society of Agricultural and Biological Engineers (ASABE) annual meeting 2020, Omaha, 07/12/20-07/15/20

1. Presentation: Effective drying methods for minimizing quality defects for off-ground harvested almonds – performance of pilot scale column dryer and product quality

2. Presentaion: Drying performance and quality characteristics of off-ground harvested almonds dried using commercial dryers

G. References Cited

Rogel-Castillo, C.; Luo, K.; Huang, G.; Mitchell, A.E. (2017). Effect of drying moisture exposed almonds on the development of the quality defect concealed damage. Journal of agricultural and food chemistry. 65, 8948-8956

Coates, M. Advanced procesisng of almonds dehydration (2018). https://industry.australianalmonds.com.au › wp-content › uploads › 2018/08

Geisseler, D.; Horwath, W.R. (2018) Almond Production in California, https://apps1.cdfa.ca.gov/FertilizerResearch/docs/Almond_Production_CA.pdf

Appendices

The appendix covers the specific data and results corresponding to reported data.

Appendix A.1 Summary of benchtop drying at different drying conditions.

Table AA.1 Summary of lab scale drying at different drying conditions (Monterey)

Air velocity (m/s)	Temp (℃)	Initial MC_{wb} (%)		Final MC_{wb} (%)		Drying time (min)	Overall drying rate (kg/min-kg)	
		Ave	Std	Ave	Std		Ave	Std
1	45	14.65	0.31	9.25	0.21	105	6.6E-04	1.9E-05
	50	18.11	0.32	12.78	0.36	75	9.9E-04	7.8E-04
	55	17.61	0.65	11.54	0.47	65	1.3E-03	1.8E-05
	60	16.54	0.78	11.32	1.02	45	1.6E-03	3.5E-04
2	45	14.65	0.71	9.37	0.28	105	6.5E-04	5.9E-04
	50	15.99	2.78	10.52	2.12	75	9.7E-04	1.5E-04
	55	19.99	1.01	14.64	0.26	65	1.2E-03	1.9E-05
	60	17.45	2.82	13.34	1.85	45	1.3E-03	3.7E-04

Table AA.2 Summary of lab scale drying at different drying conditions (Fritz)

Air velocity (m/s)	Temp (℃)	Initial MC_{wb} (%)		Final MC_{wb} (%)		Drying time (min)	Overall drying rate (kg/min-kg)	
		Ave	Std	Ave	Std		Ave	Std
1	45	17.86	0.48	11.59	0.43	110	7.7E-04	1.0E-04
	50	17.83	0.12	12.03	0.87	85	1.0E-03	8.0E-05
	55	19.90	0.87	13.87	1.11	50	1.7E-03	5.7E-06
	60	22.83	1.01	16.74	2.31	40	2.2E-03	1.7E-04
2	45	21.68	0.38	13.87	0.07	110	9.4E-04	3.8E-05
	50	17.88	0.63	11.81	0.68	85	1.0E-03	3.0E-05
	55	20.56	1.86	14.75	4.82	65	1.4E-03	2.9E-04
	60	20.91	1.72	14.97	1.53	50	1.7E-03	2.3E-04

Appendix A.2 Overall moisture contents and drying rate of benchtop drying

- *Nonpareil*

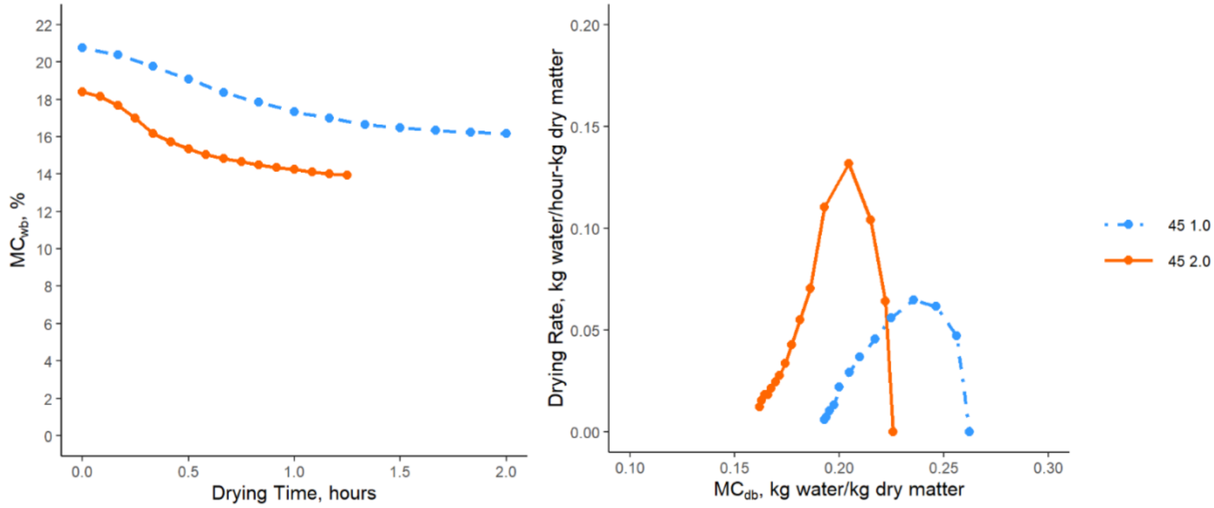


Figure AA.1 Moisture content and drying rate of benchtop drying at 45°C (Nonpareil)

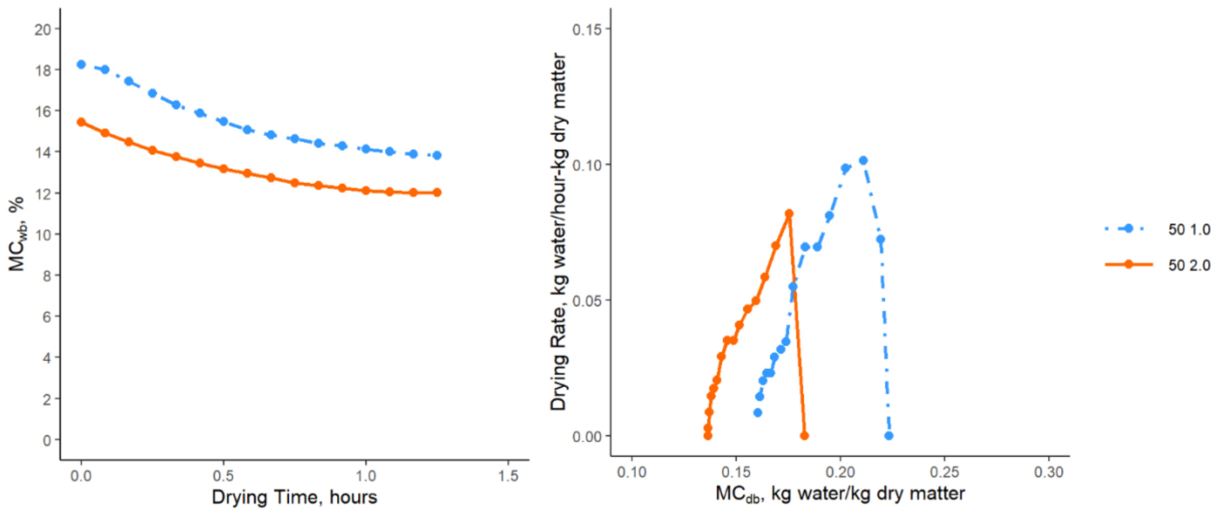


Figure AA.2 Moisture content and drying rate of benchtop drying at 50°C (Nonpareil)

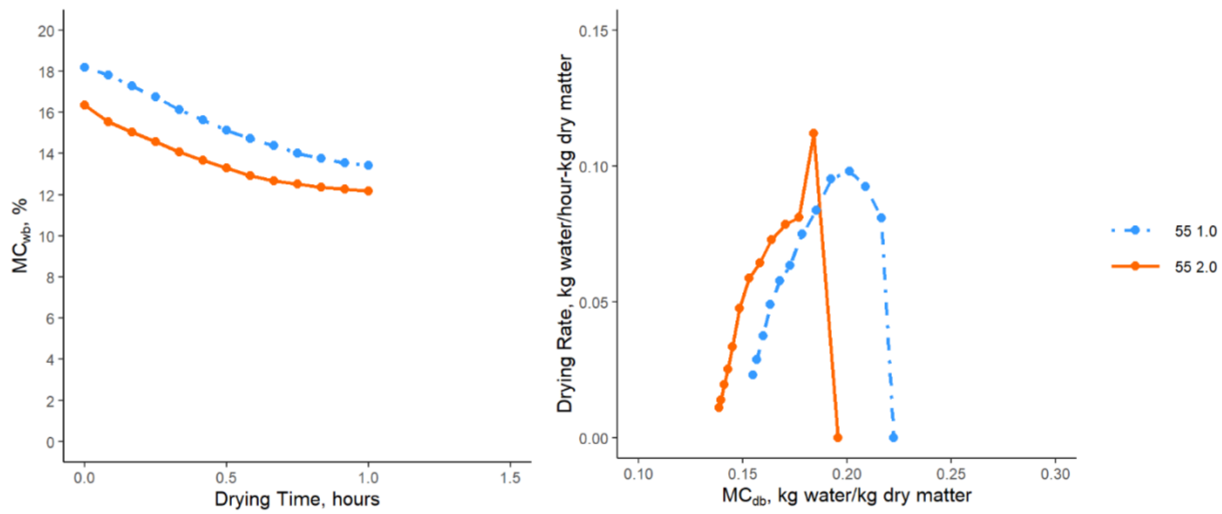


Figure AA.3 Moisture content and drying rate of benchtop drying at 55°C (Nonpareil)

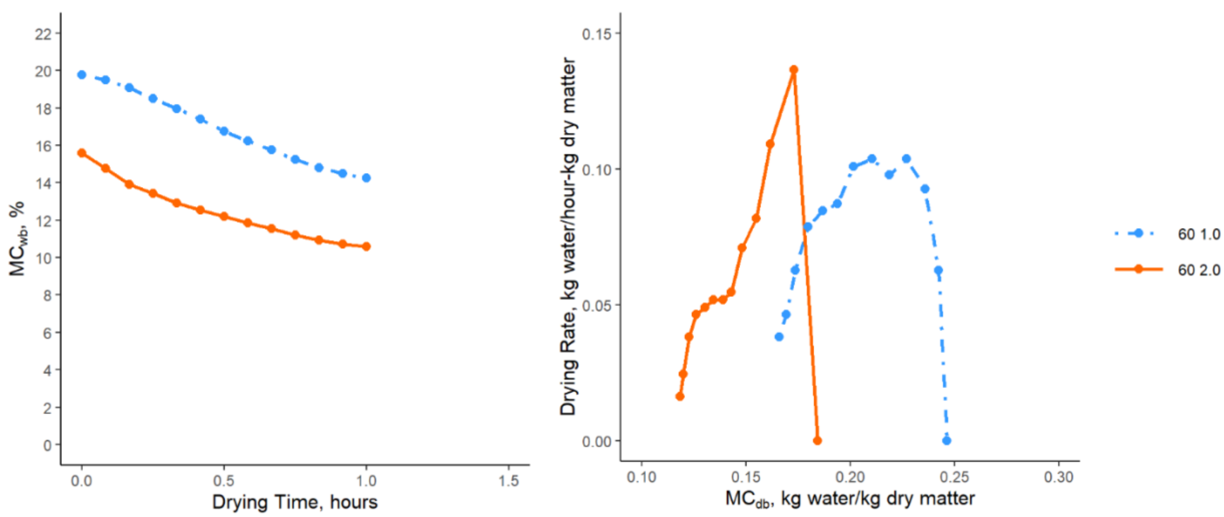


Figure AA.4 Moisture content and drying rate of benchtop drying at 60°C (Nonpareil)

- *Monterey*

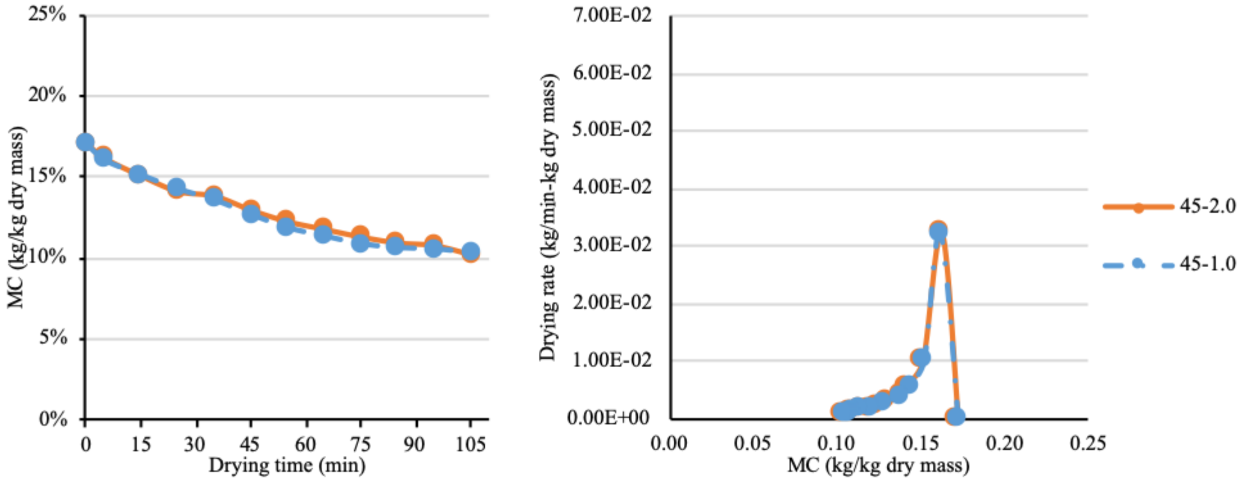


Figure AA.5 Moisture content and drying rate of benchtop drying at 45°C (Monterey)

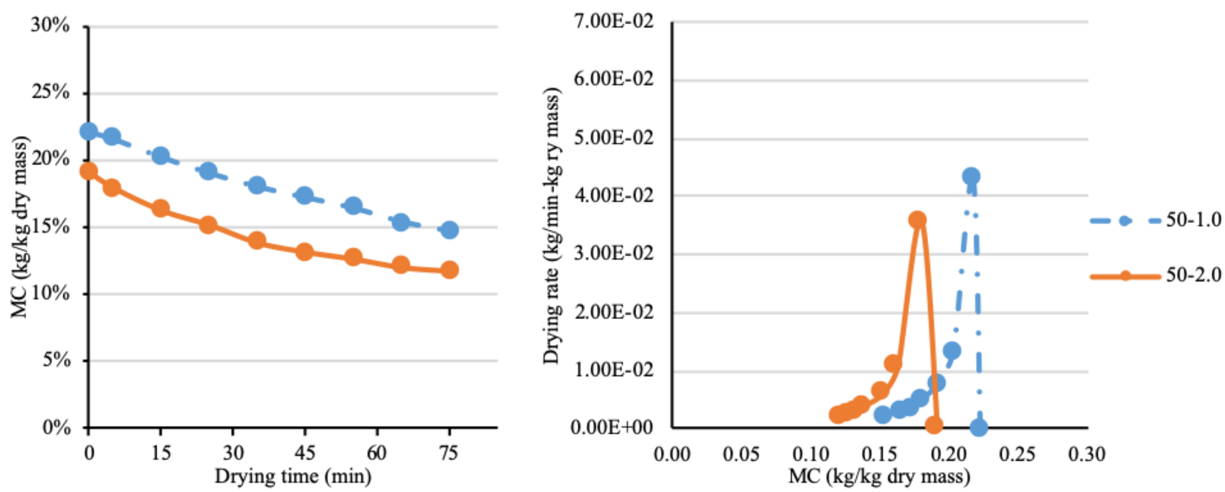


Figure AA.6 Moisture content and drying rate of benchtop drying at 50°C (Monterey)

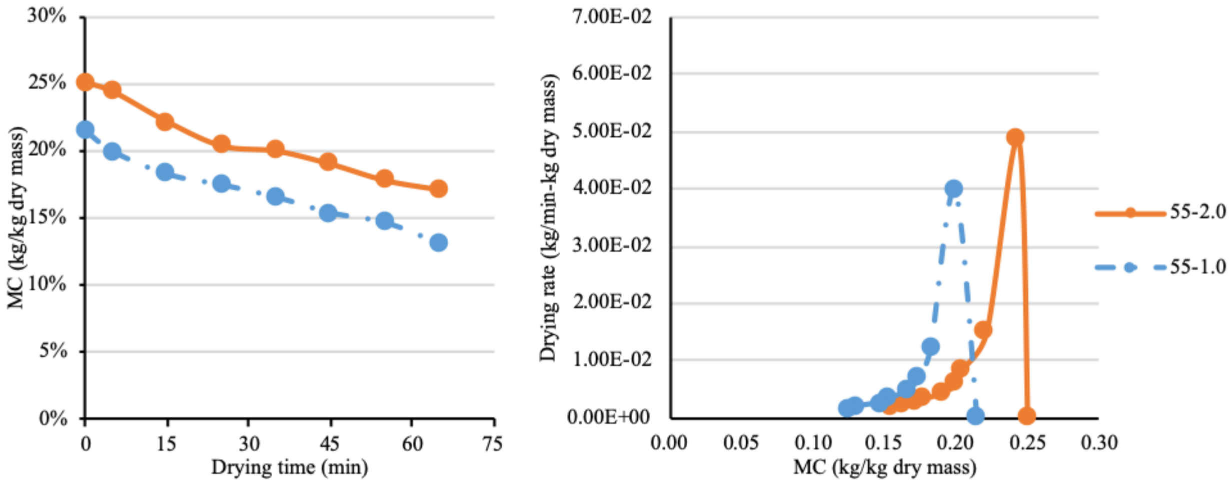


Figure AA.7 Moisture content and drying rate of benchtop drying at 55°C (Monterey)

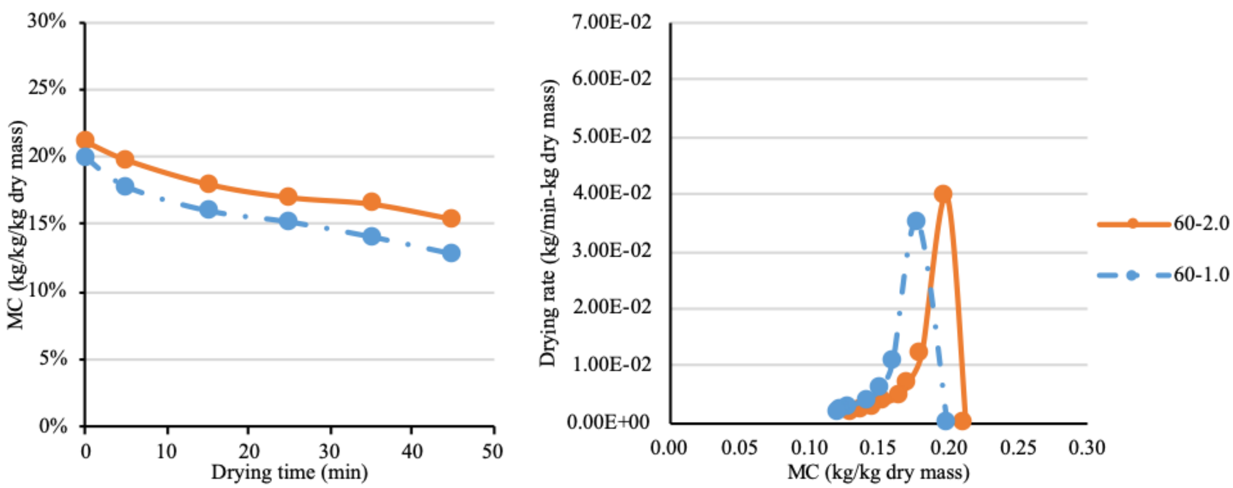


Figure AA.8 Moisture content and drying rate of benchtop drying at 60°C (Monterey)

- *Fritz*

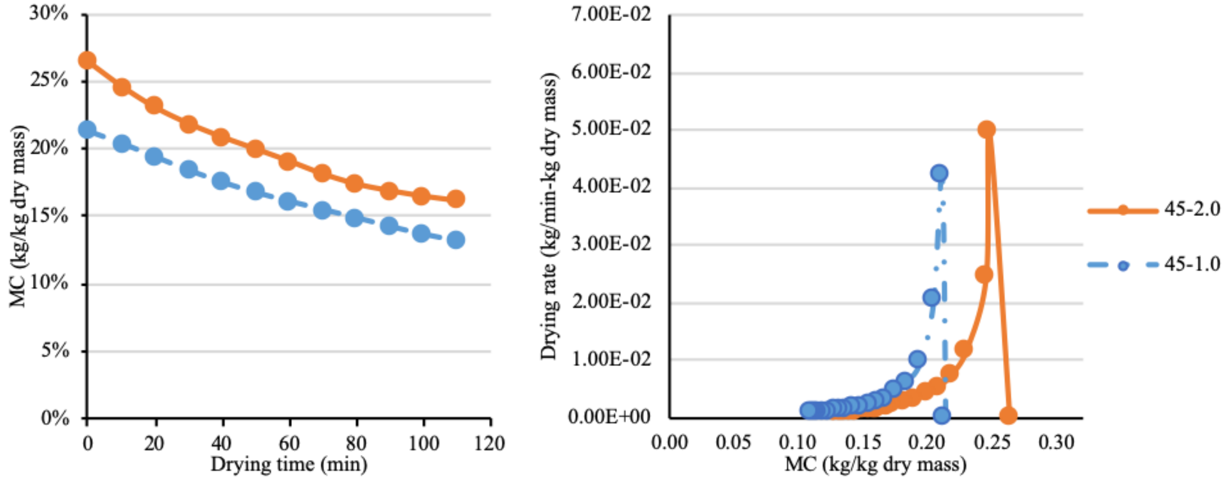


Figure AA.9 Moisture content and drying rate of benchtop drying at 45°C (Fritz)

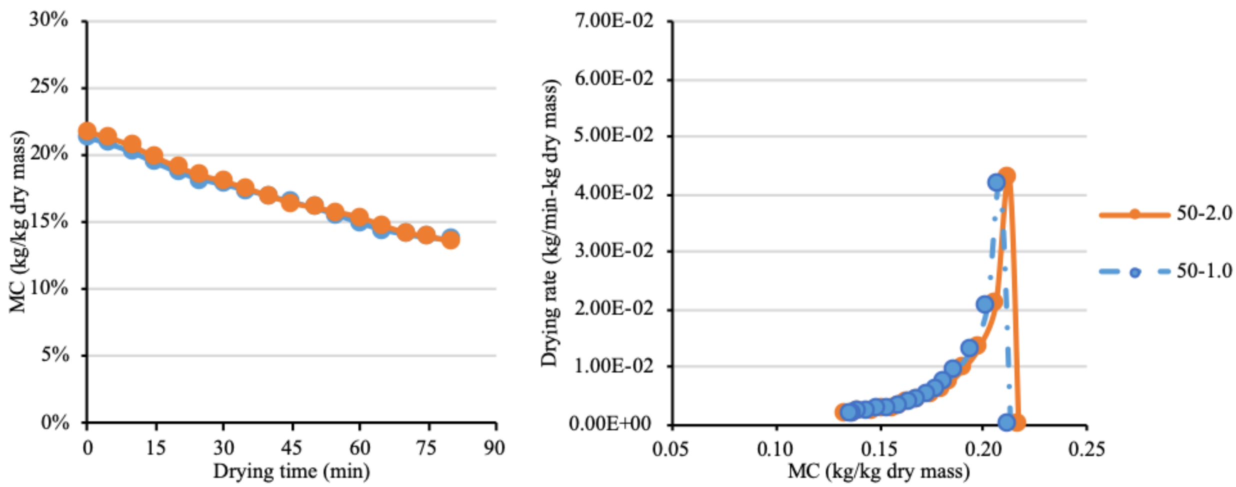


Figure AA.10 Moisture content and drying rate of benchtop drying at 50°C (Fritz)

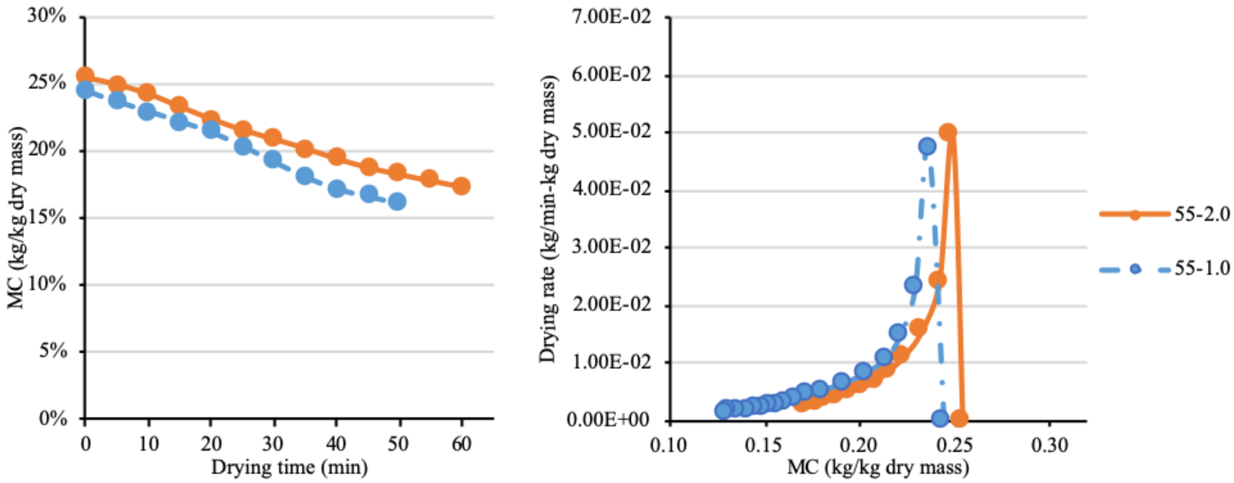


Figure AA.11 Moisture content and drying rate of benchtop drying at 55°C (Fritz)

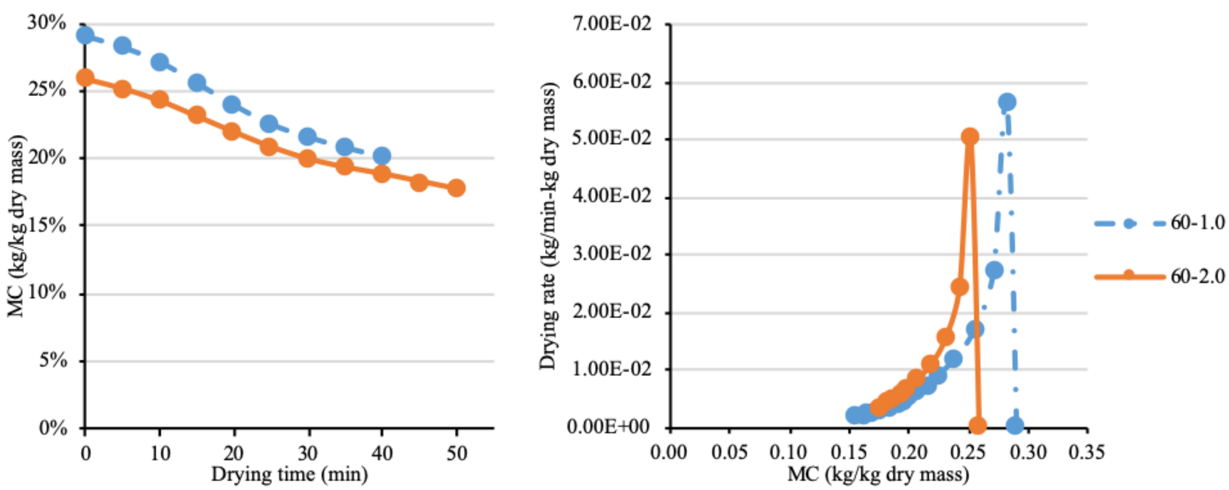


Figure AA.12 Moisture content and drying rate of benchtop drying at 60°C (Fritz)

Appendix A.3 Drying curve of individual in-hull and in-shell almonds

- *Nonpareil*

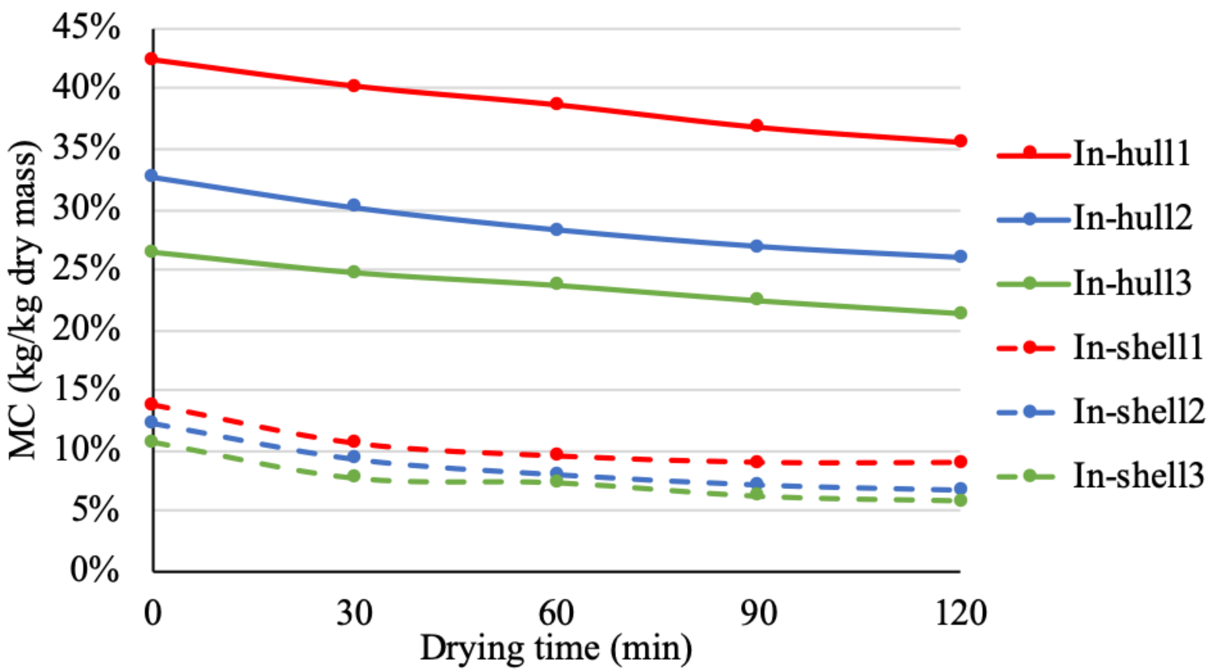


Figure AA.13 Drying curve of in-hull and in-shell almonds at 45 °C and 1 m/s

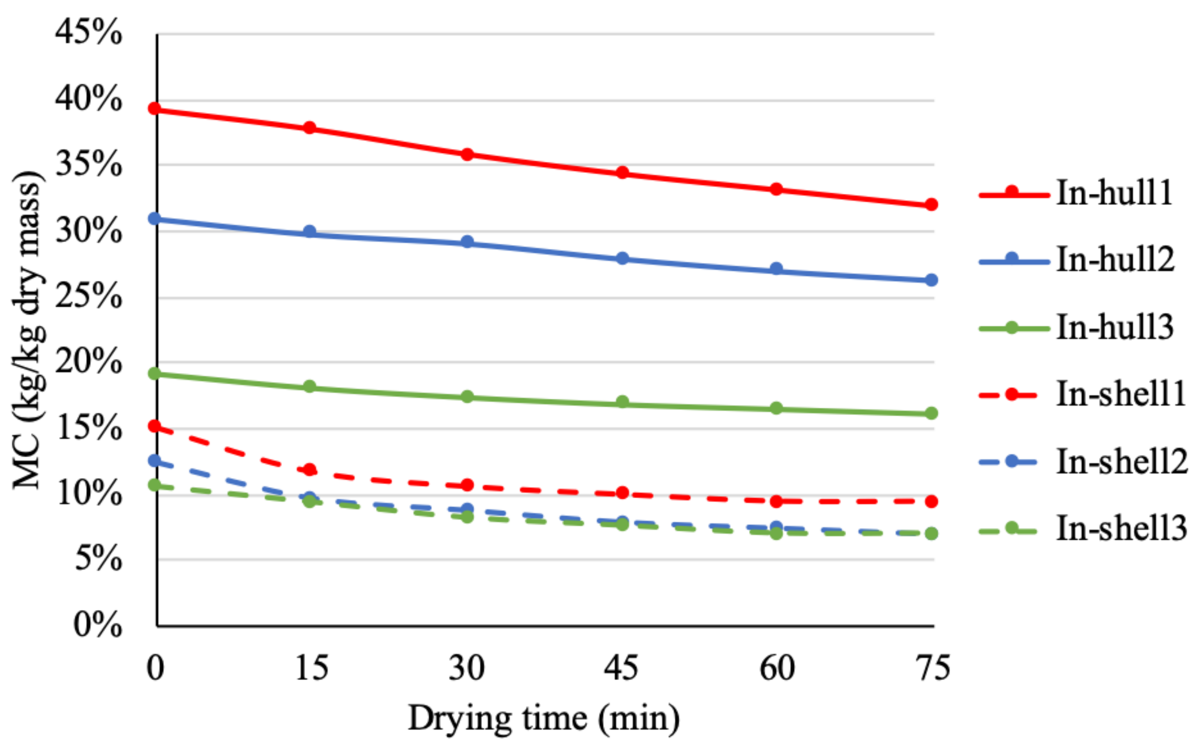


Figure AA.14 Drying curve of in-hull and in-shell almonds at 45 °C and 2 m/s

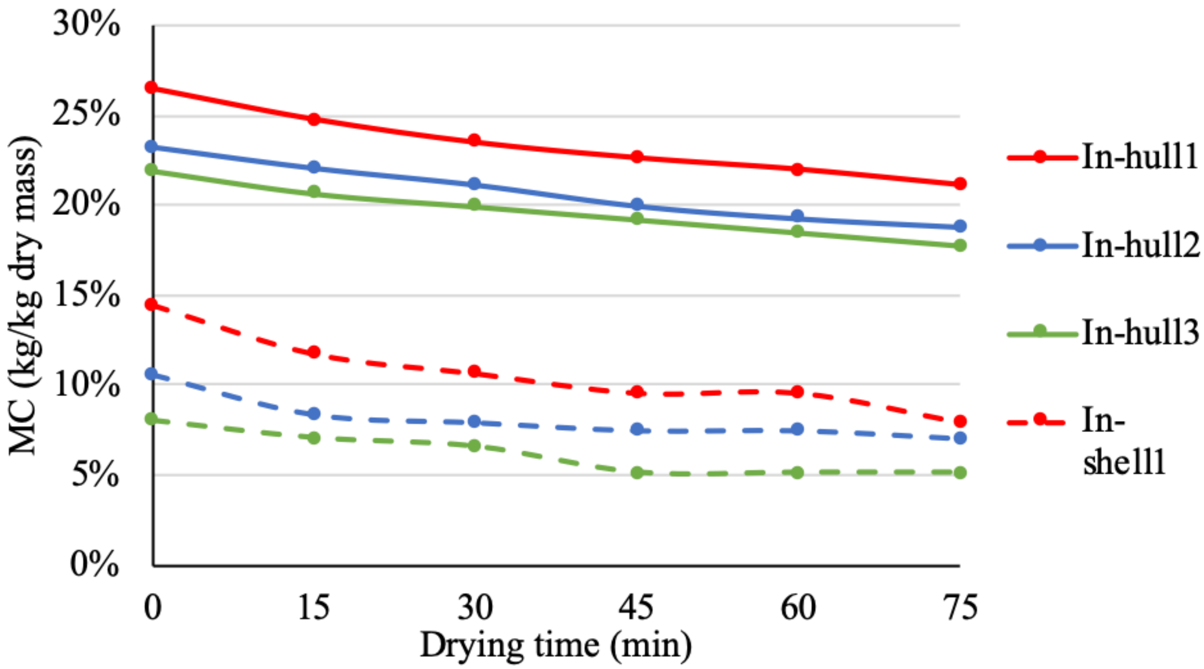


Figure AA.15 Drying curve of in-hull and in-shell almonds at 50 °C and 1 m/s

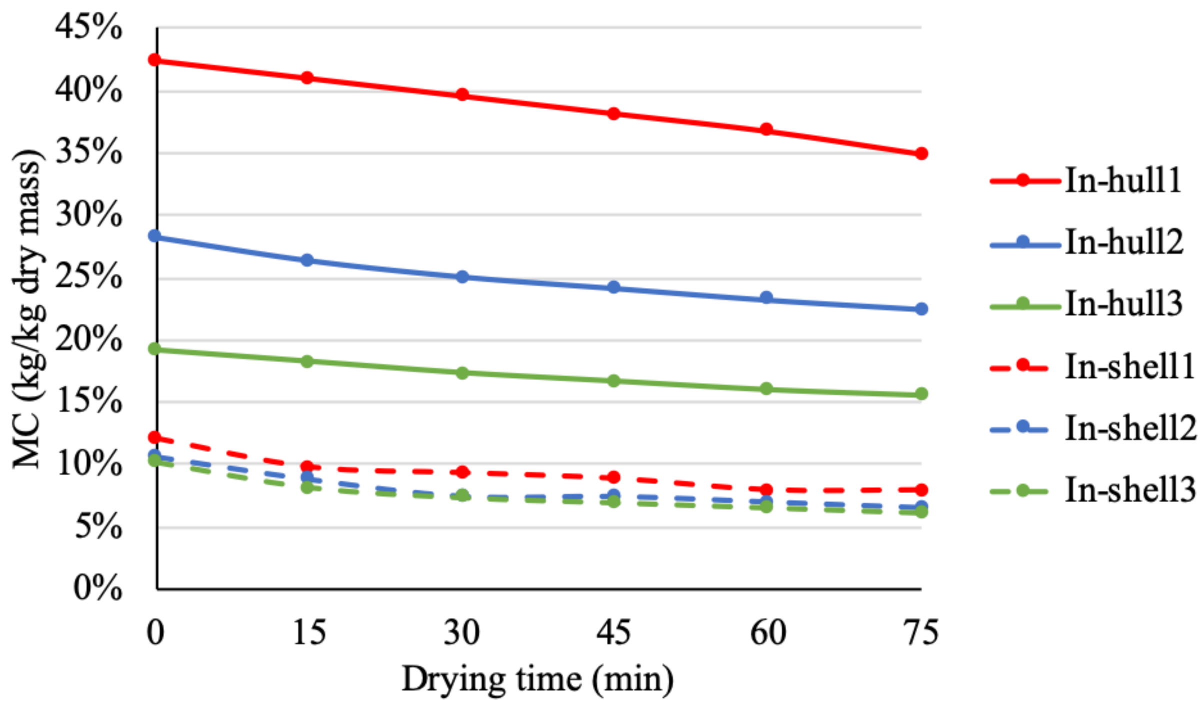


Figure AA.16 Drying curve of in-hull and in-shell almonds at 50 °C and 2 m/s

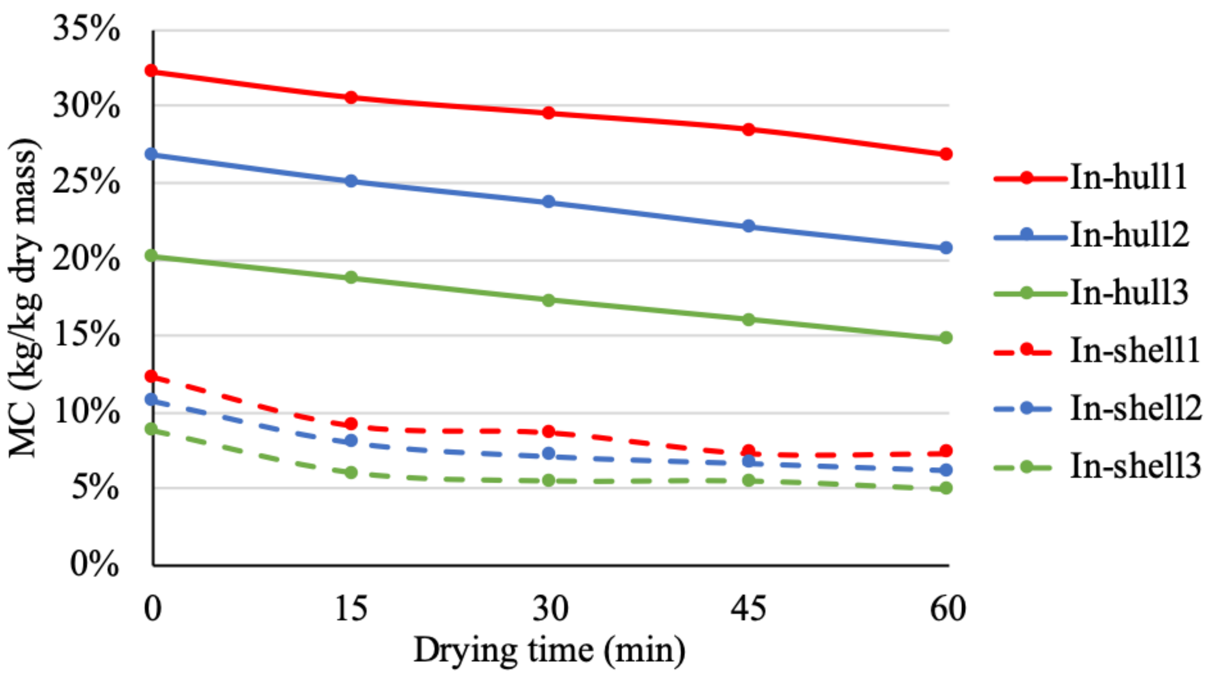


Figure AA.17 Drying curve of in-hull and in-shell almonds at 55 °C and 1 m/s

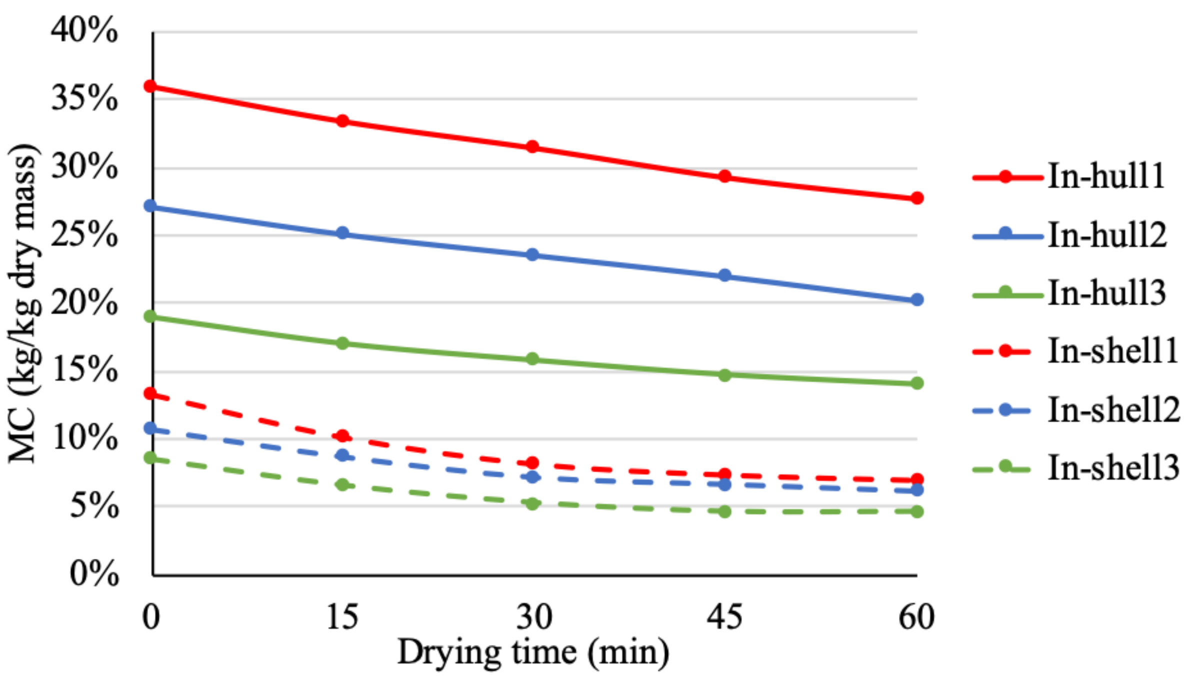


Figure AA.18 Drying curve of in-hull and in-shell almonds at 55 °C and 2 m/s

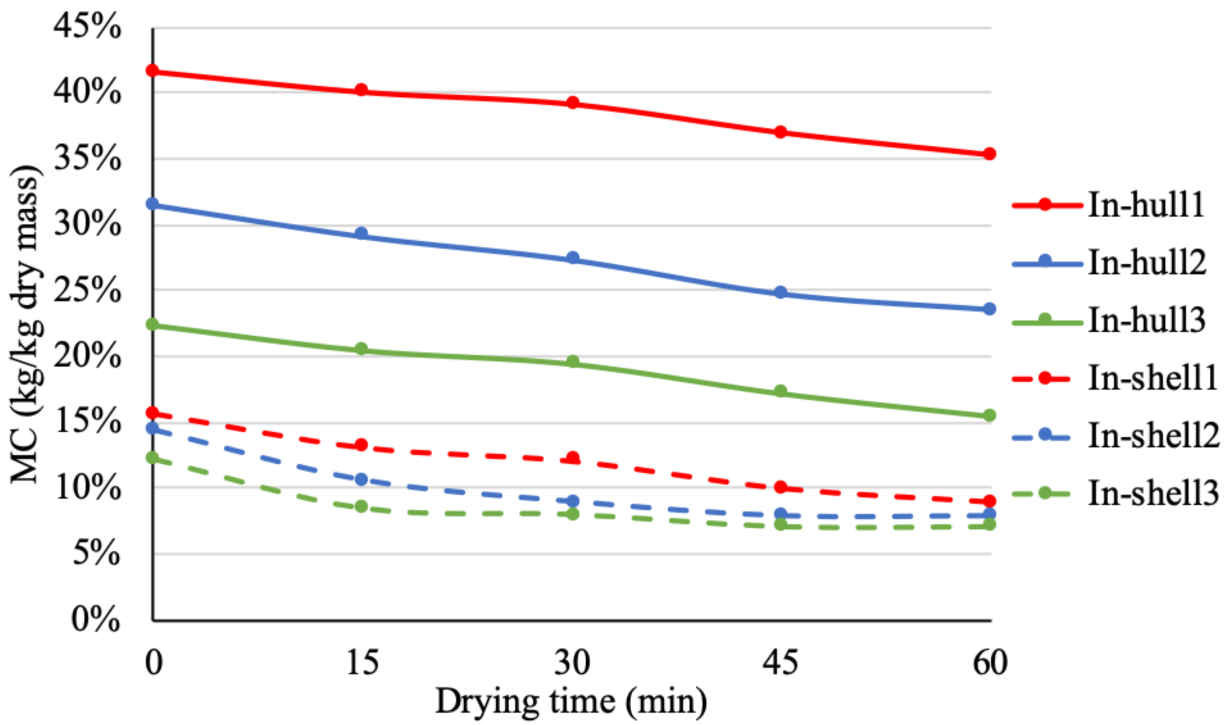


Figure AA.19 Drying curve of in-hull and in-shell almonds at 60 °C and 1 m/s

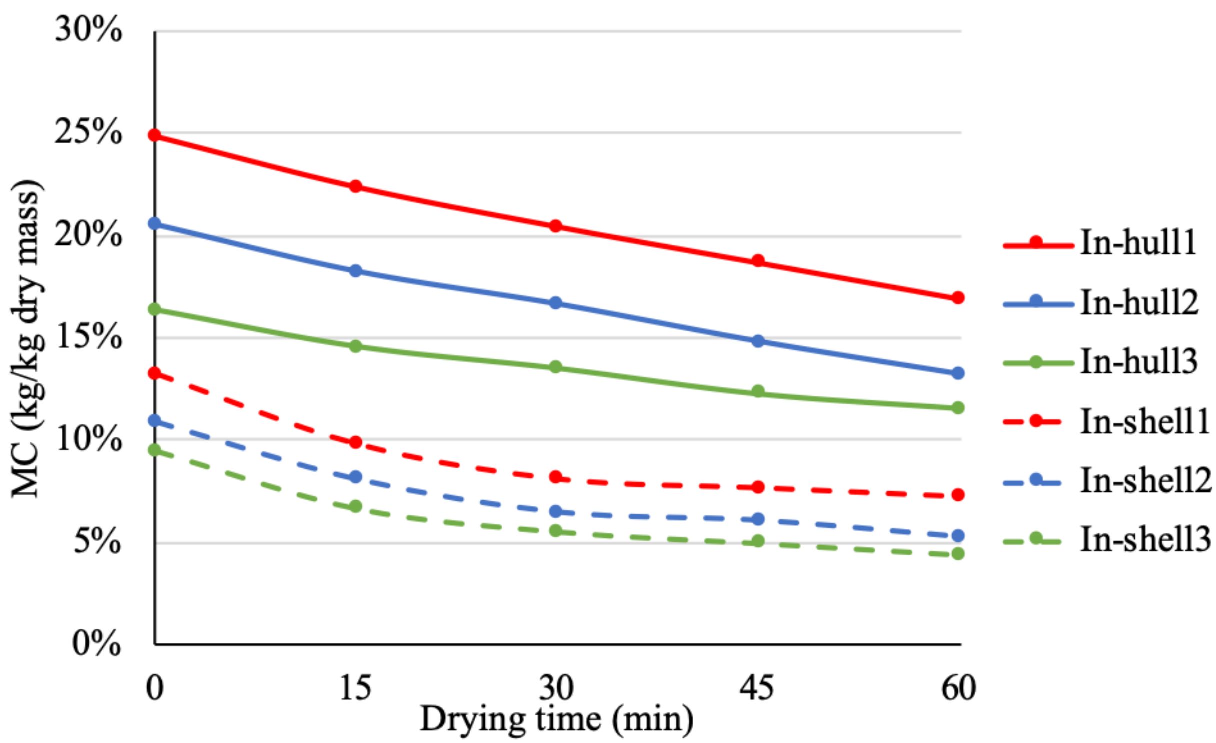


Figure AA.20 Drying curve of in-hull and in-shell almonds at 60 °C and 2 m/s

- *Monterey*

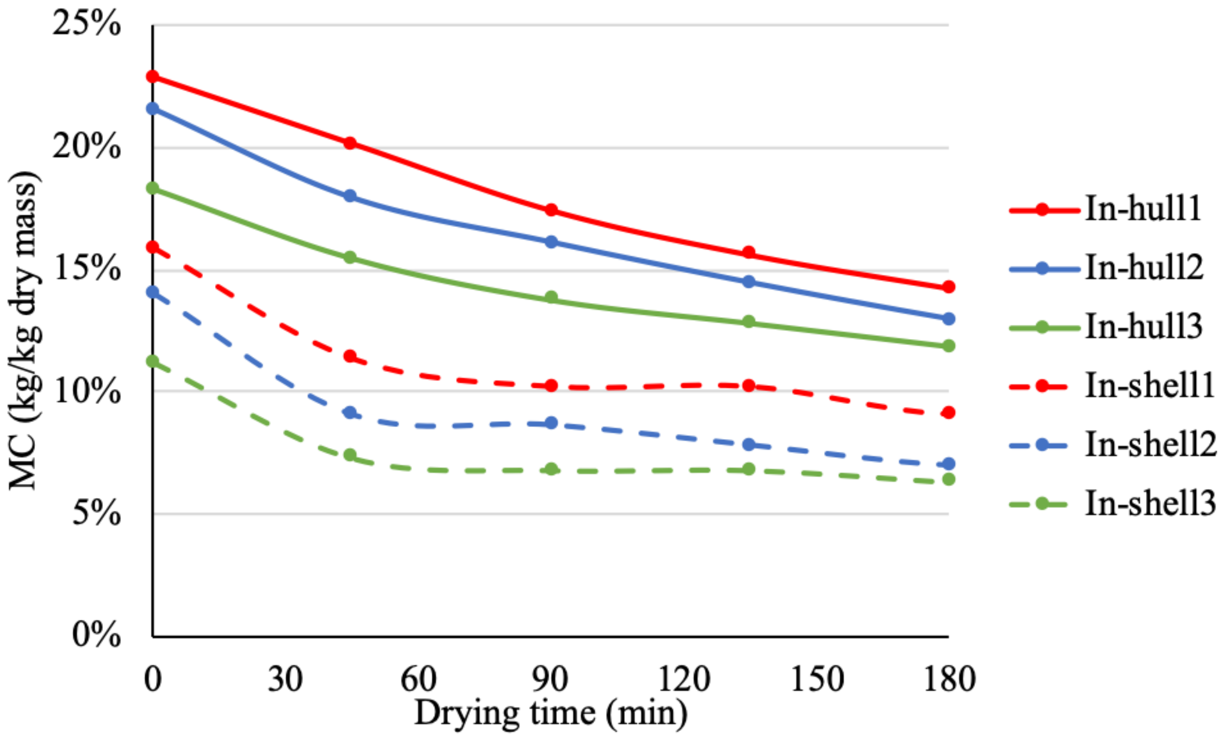


Figure AA.21 Drying curve of in-hull and in-shell almonds at 45 °C and 1 m/s

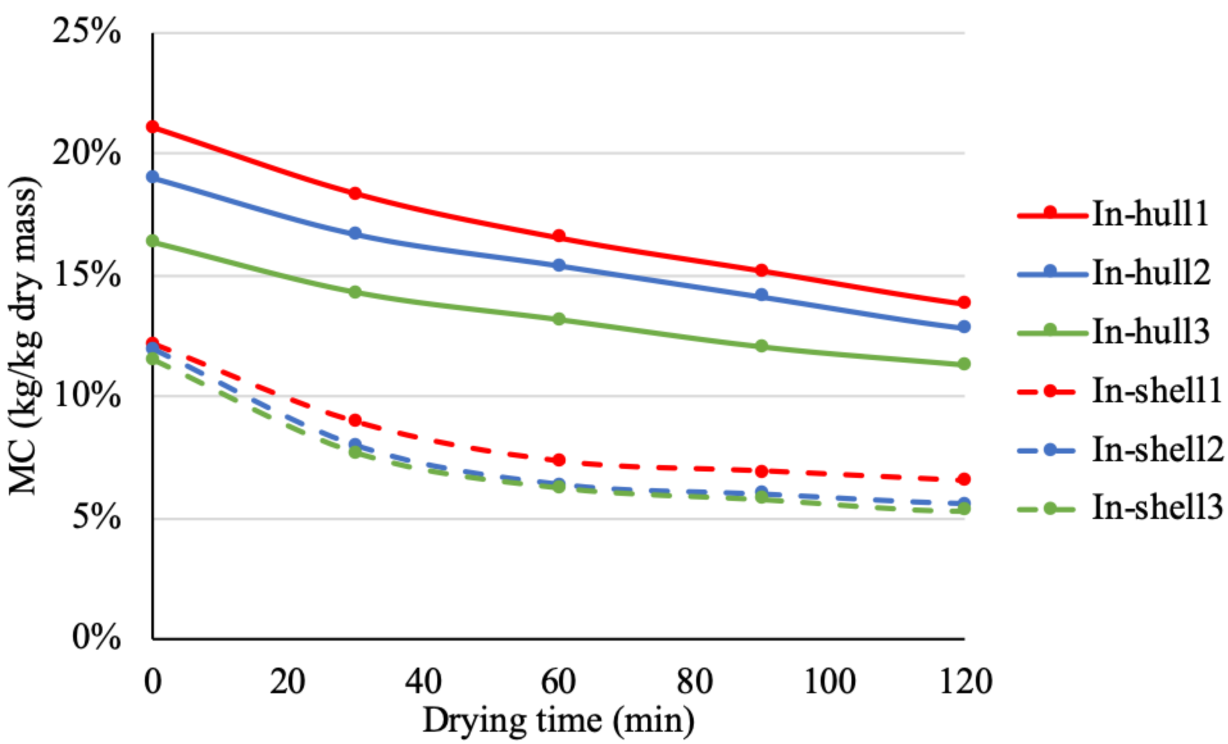


Figure AA.22 Drying curve of in-hull and in-shell almonds at 45 °C and 2 m/s

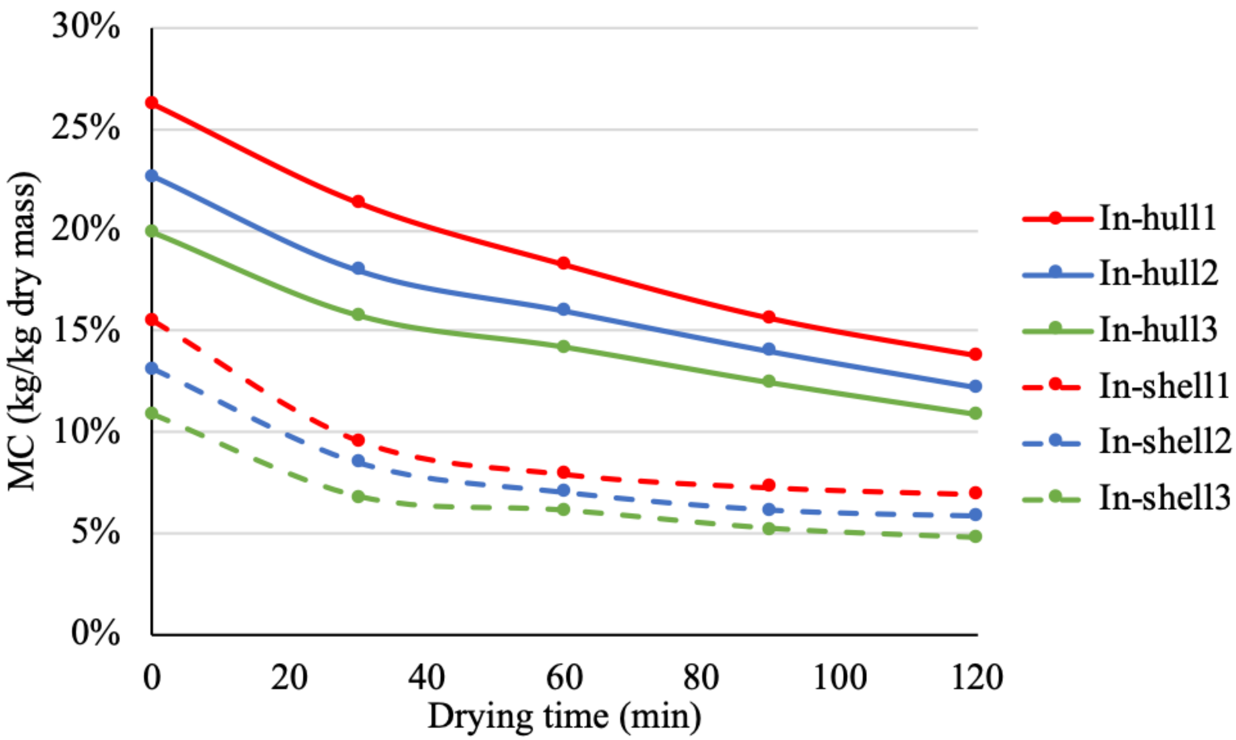


Figure AA.23 Drying curve of in-hull and in-shell almonds at 50 °C and 1 m/s

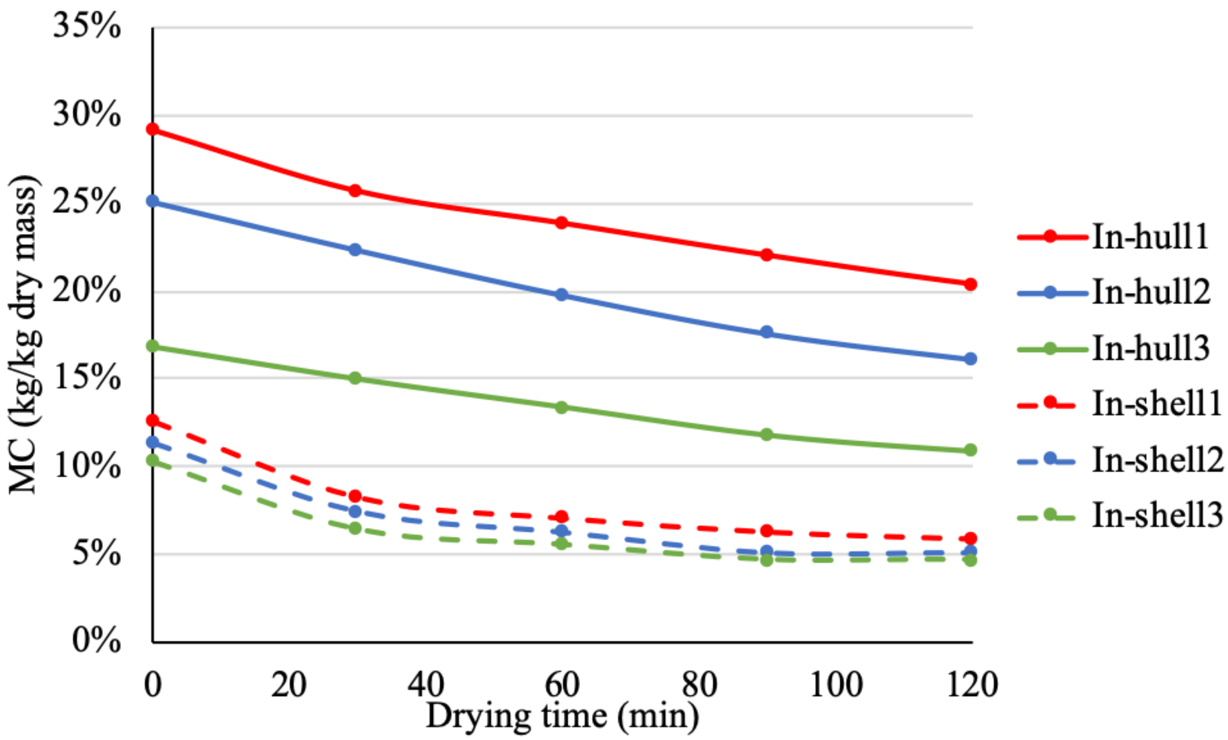


Figure AA.24 Drying curve of in-hull and in-shell almonds at 50 °C and 2 m/s

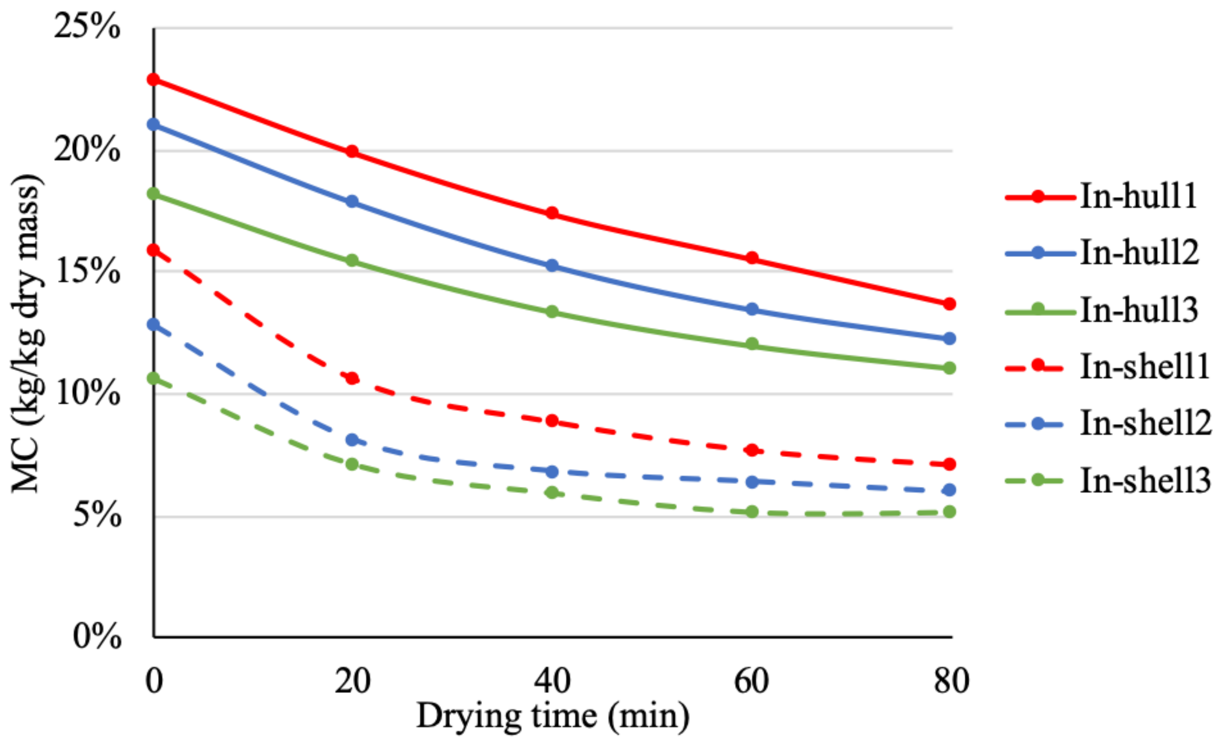


Figure AA.25 Drying curve of in-hull and in-shell almonds at 55 °C and 1 m/s

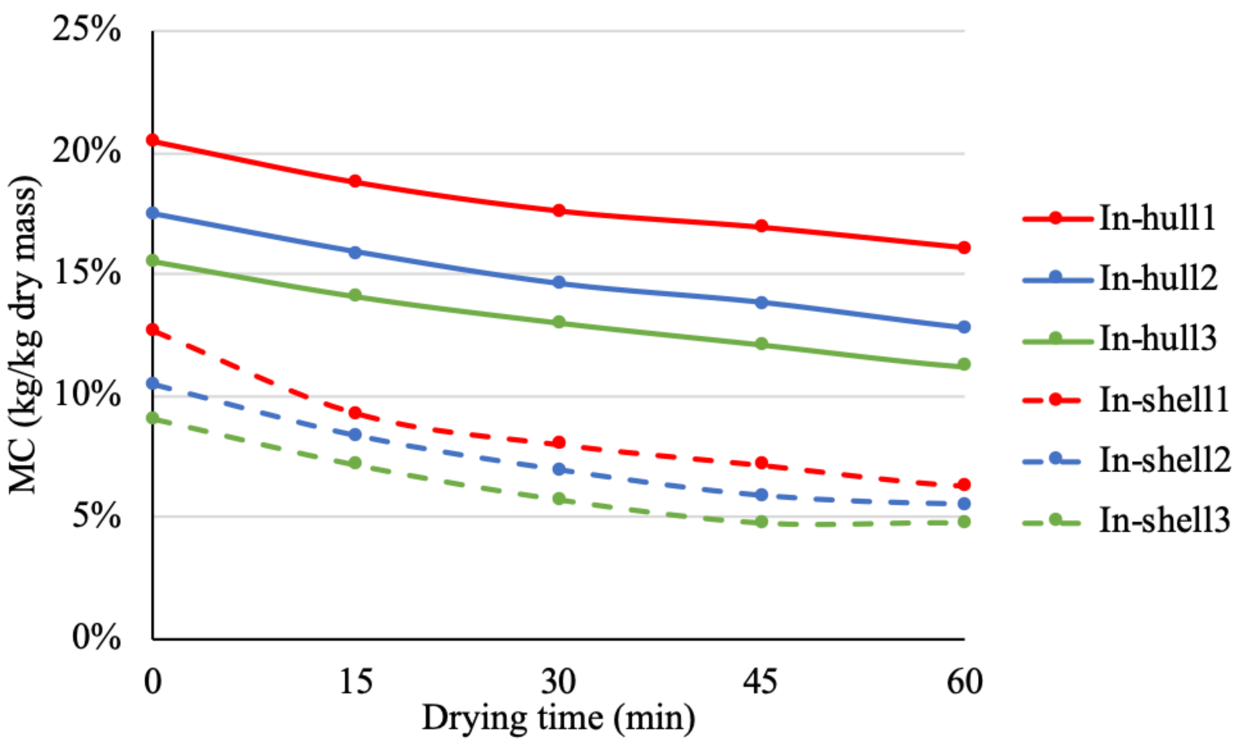


Figure AA.26 Drying curve of in-hull and in-shell almonds at 55 °C and 2 m/s

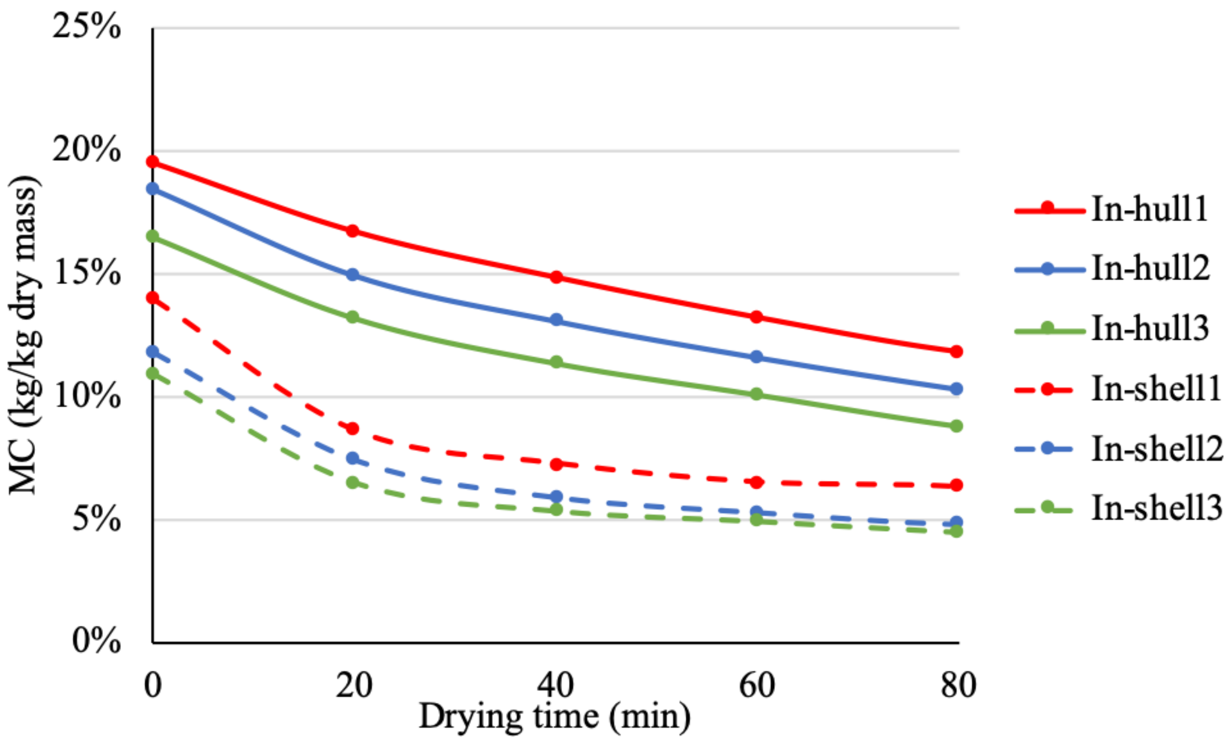


Figure AA.27 Drying curve of in-hull and in-shell almonds at 60 °C and 1 m/s

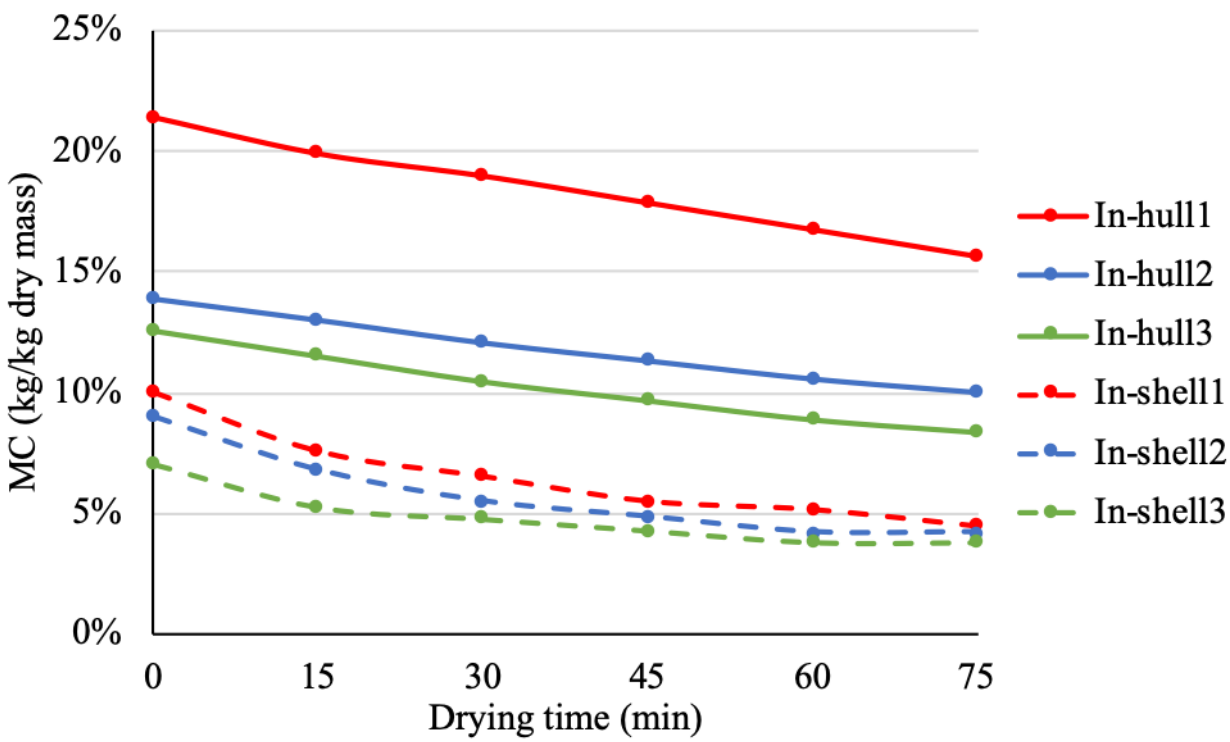


Figure AA.28 Drying curve of in-hull and in-shell almonds at 60 °C and 2 m/s

- *Fritz*

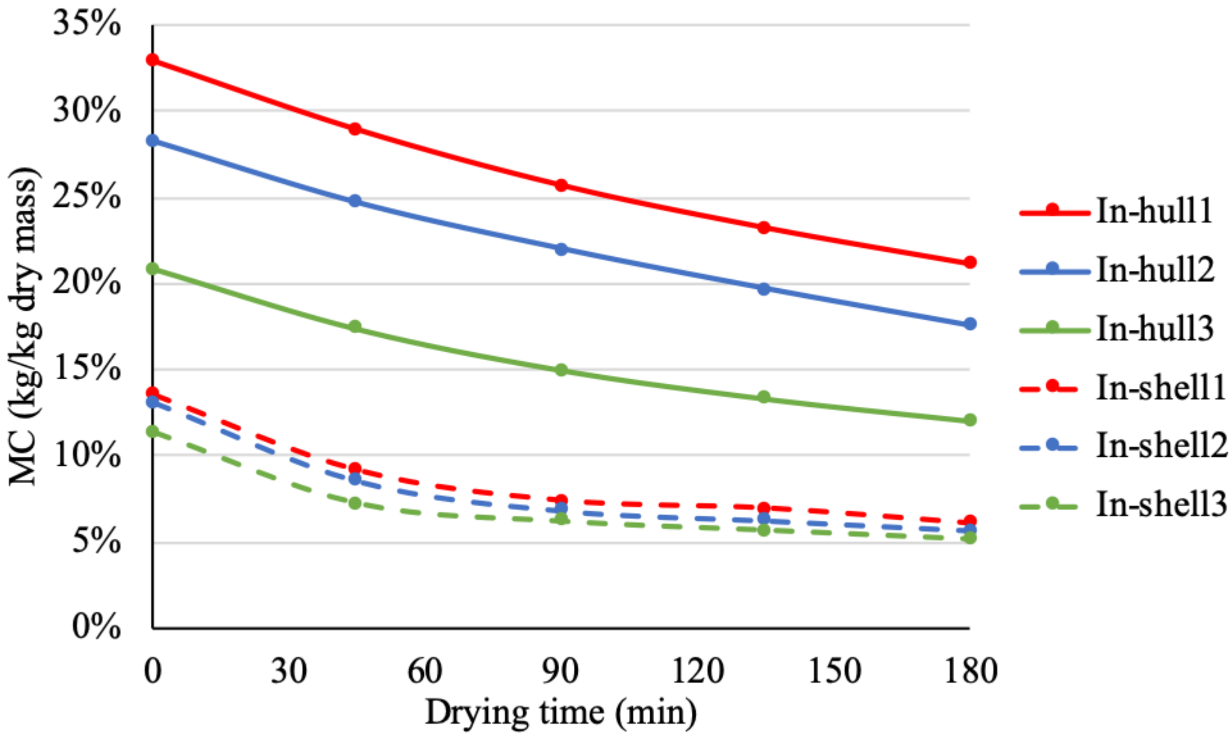


Figure AA.29 Drying curve of in-hull and in-shell almonds at 45 °C and 1 m/s

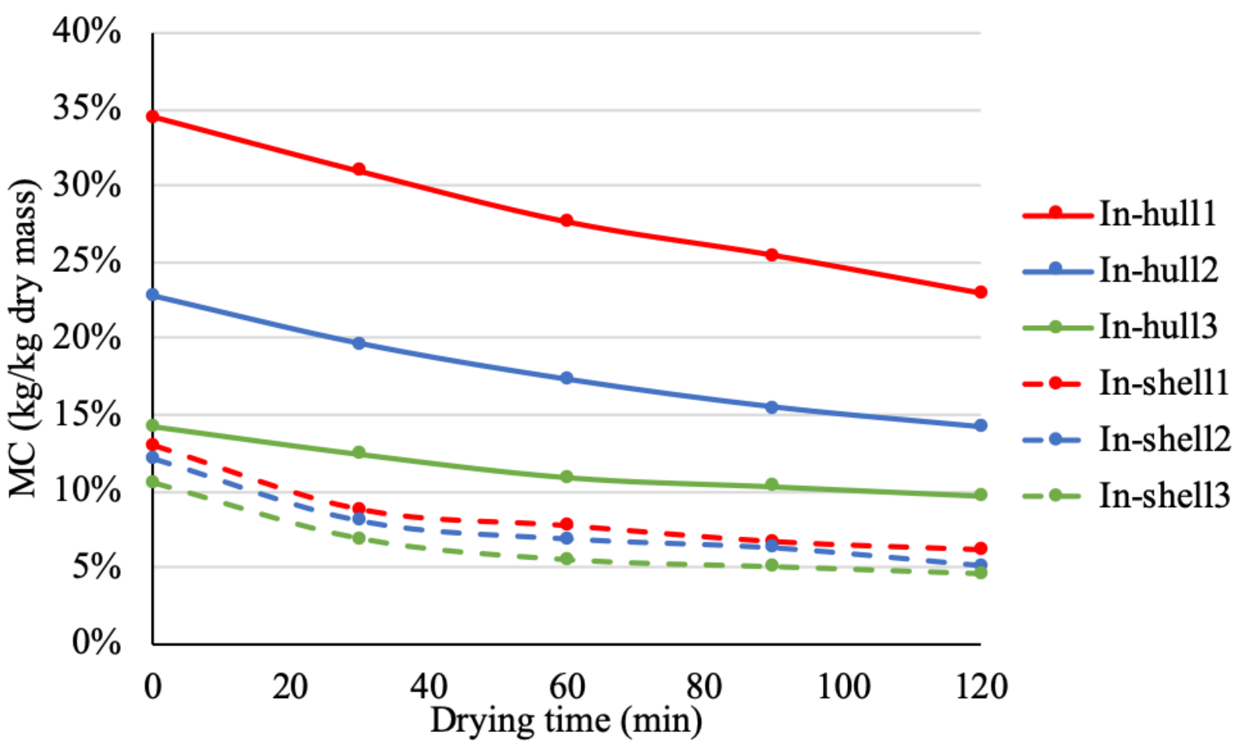


Figure AA.30 Drying curve of in-hull and in-shell almonds at 45 °C and 2 m/s

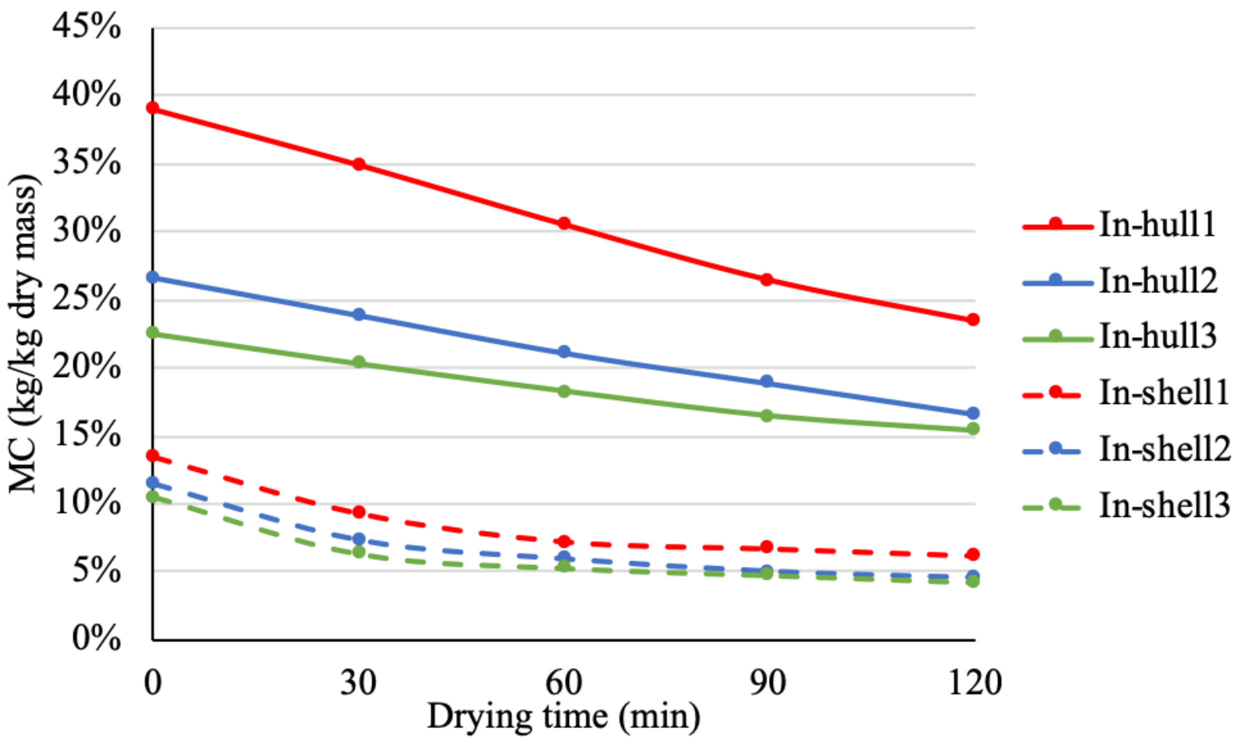


Figure AA.31 Drying curve of in-hull and in-shell almonds at 50 °C and 1 m/s

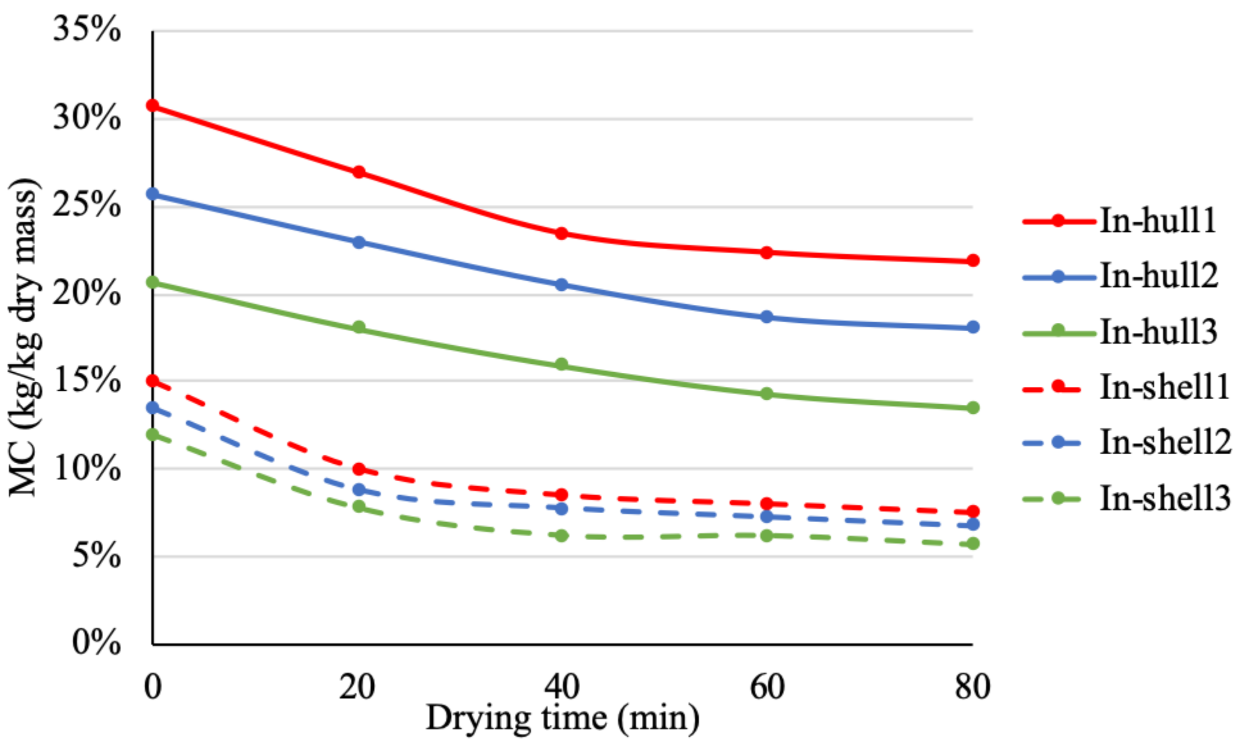


Figure AA.32 Drying curve of in-hull and in-shell almonds at 50 °C and 2 m/s

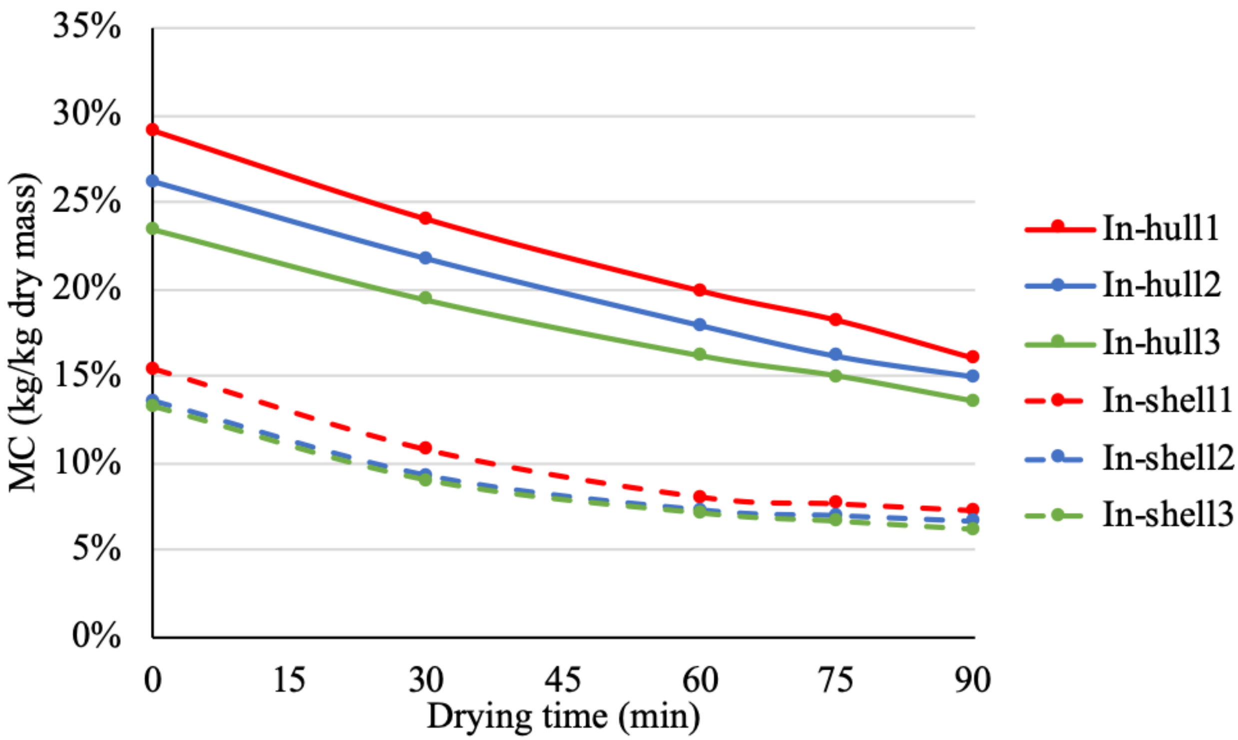


Figure AA.33 Drying curve of in-hull and in-shell almonds at 55 °C and 1 m/s

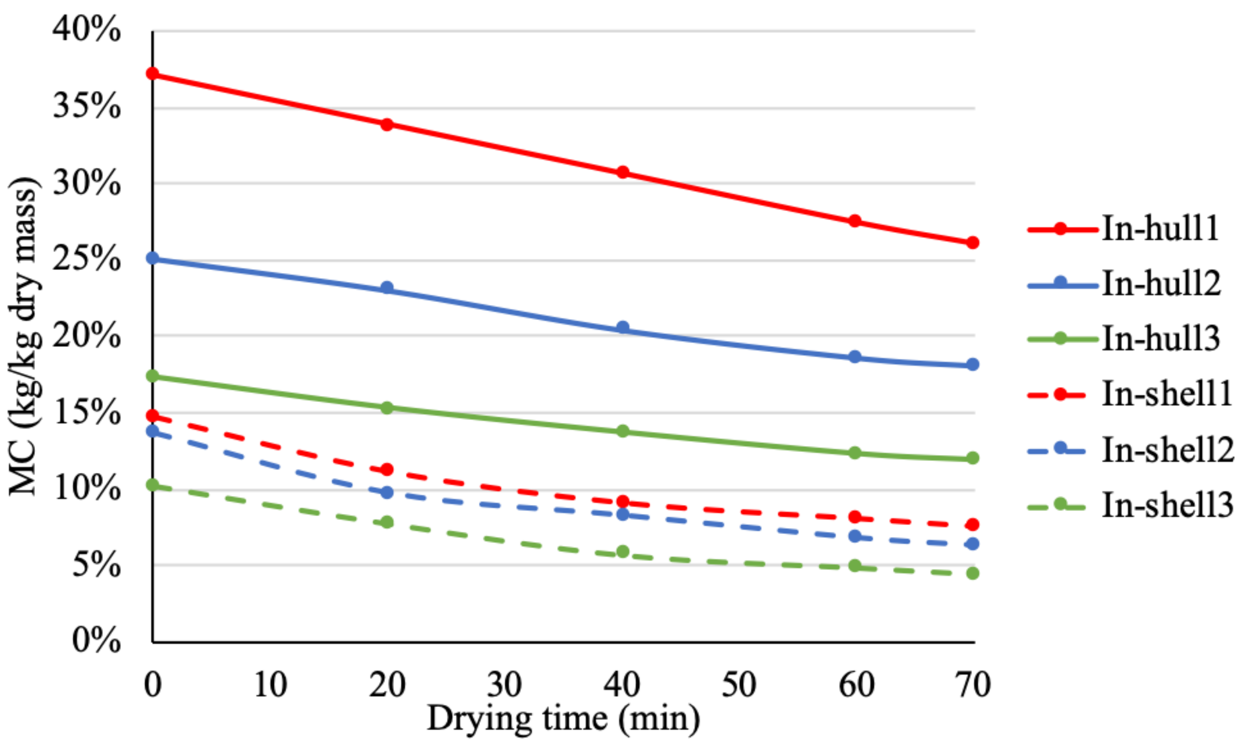


Figure AA.34 Drying curve of in-hull and in-shell almonds at 55 °C and 2 m/s

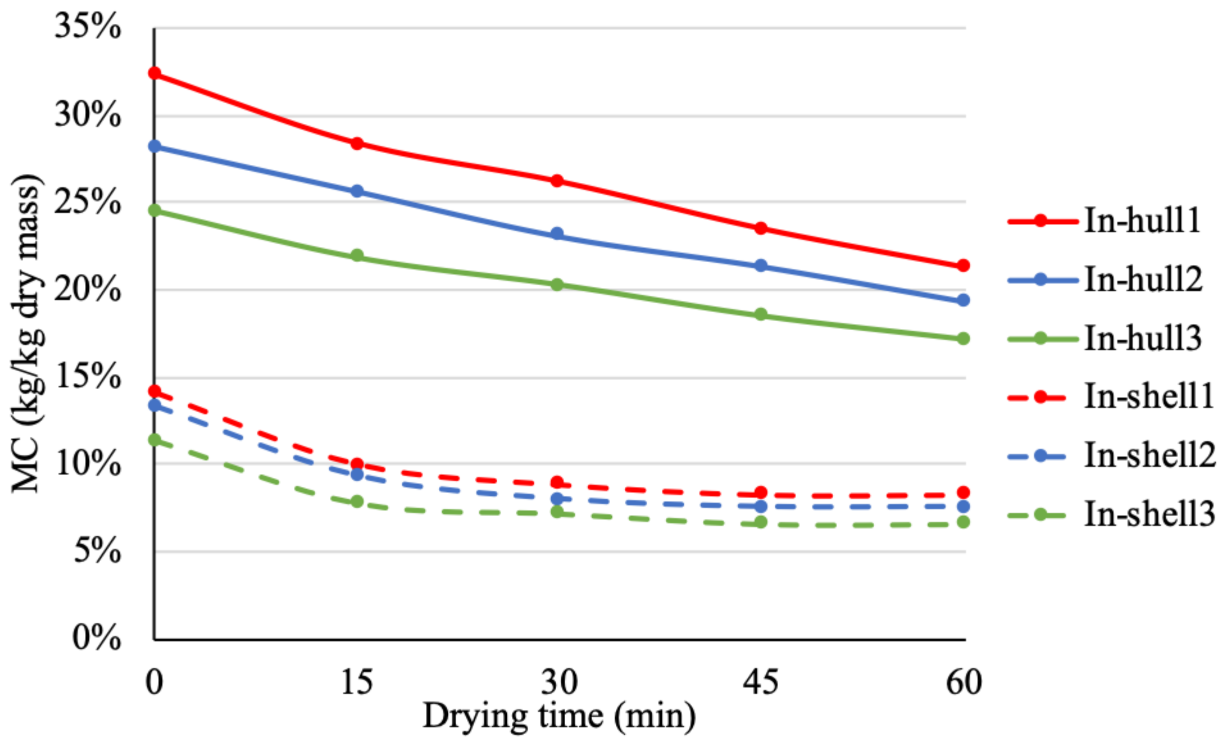


Figure AA.35 Drying curve of in-hull and in-shell almonds at 60 °C and 1 m/s

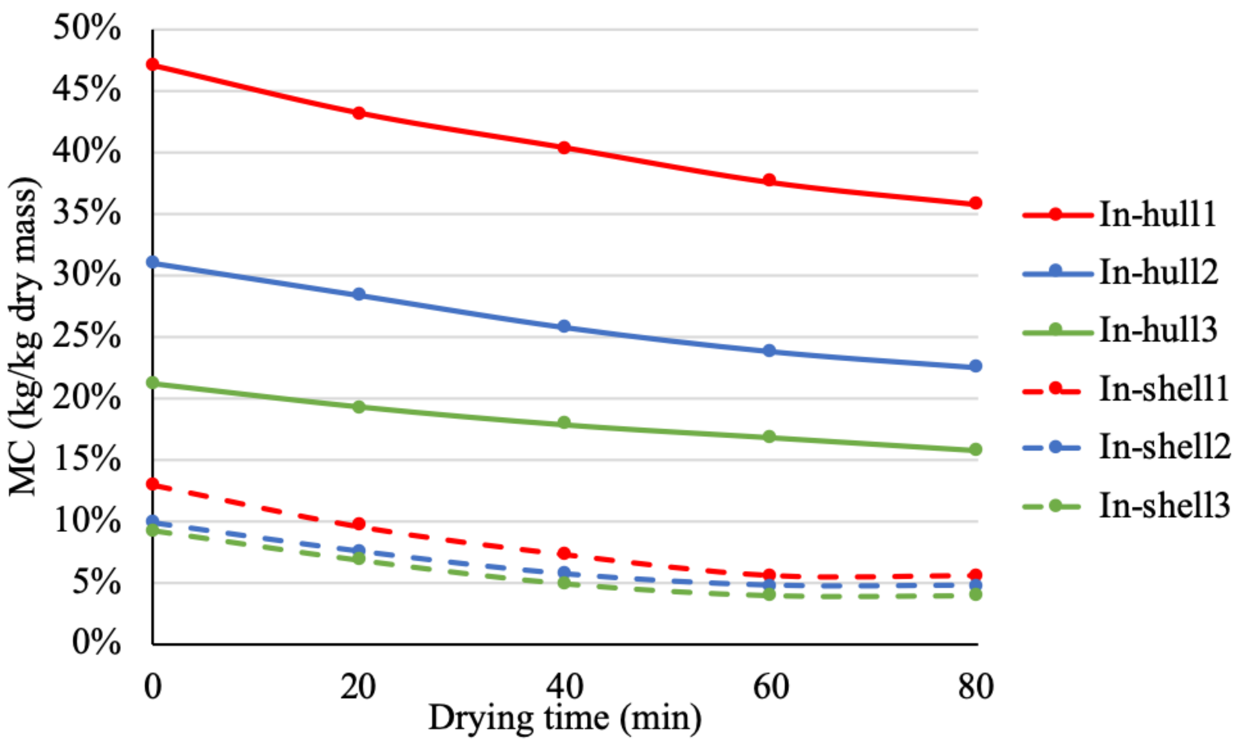


Figure AA.36 Drying curve of in-hull and in-shell almonds at 60 °C and 2 m/s

Appendix A.4 Whiteness index

- *Nonpareil*

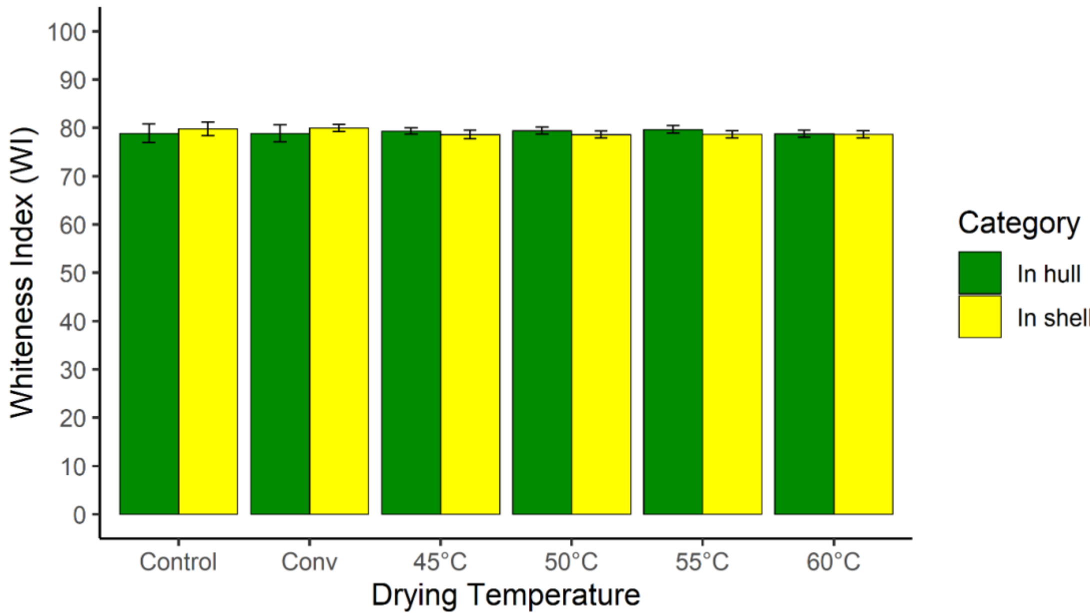


Figure AA.37 Final product kernel whiteness index for bench top drying of different temperature levels at 1.0 m/s (Nonpareil)

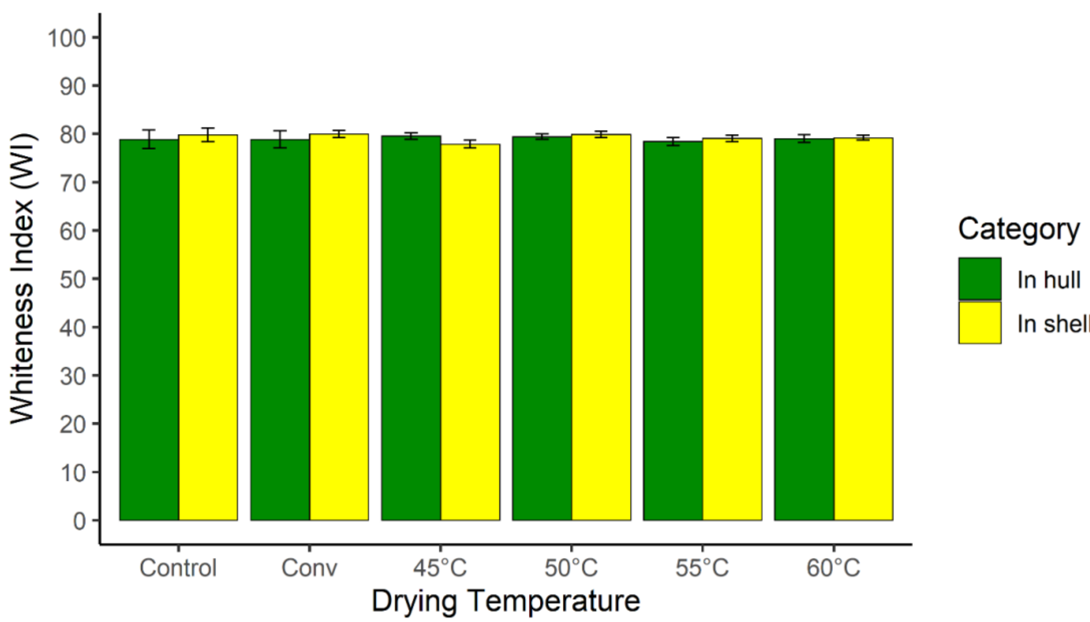


Figure AA.38 Final product kernel whiteness index for bench top drying of different temperature levels at 2.0 m/s (Nonpareil)

▪ *Monterey*

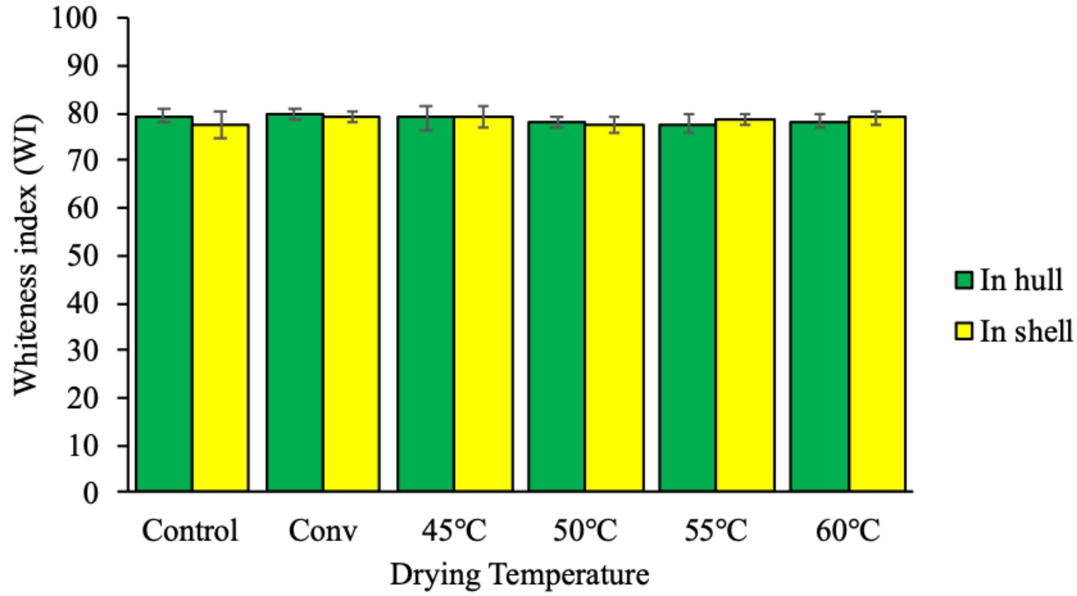


Figure AA.39 Final product kernel whiteness index for bench top drying of different temperature levels at 1.0 m/s (Monterey)

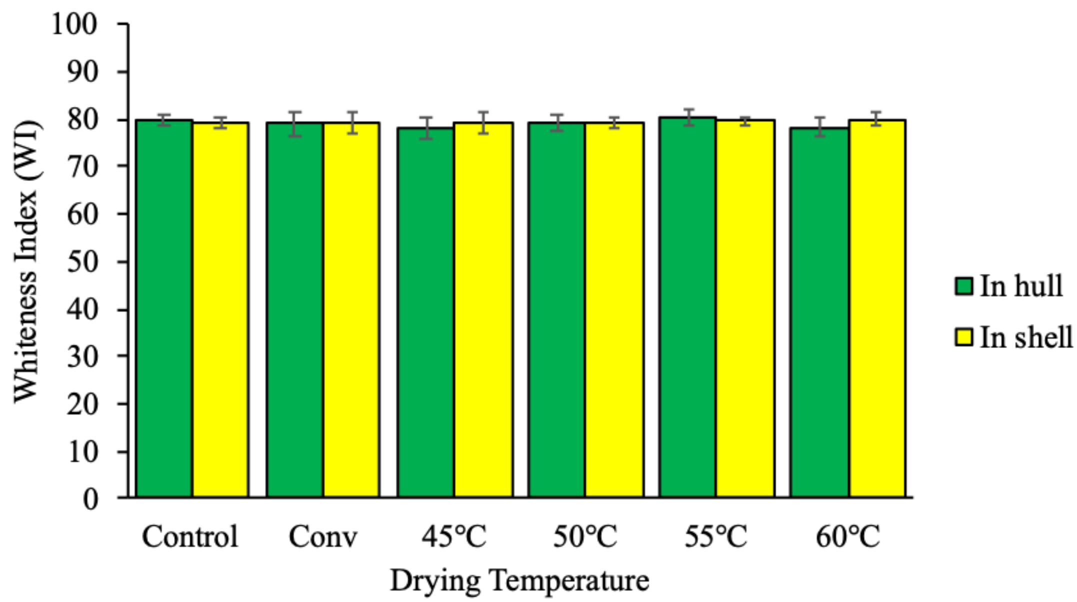


Figure AA.40 Final product kernel whiteness index for bench top drying of different temperature levels at 2.0 m/s (Monterey)

- *Fritz*

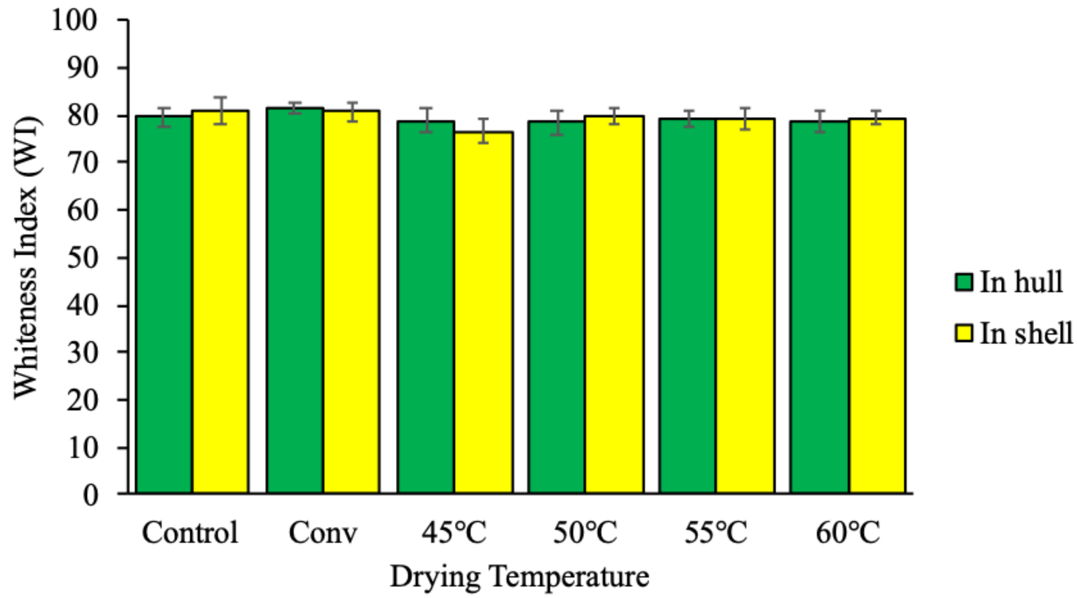


Figure AA.41 Final product kernel whiteness index for bench top drying of different temperature levels at 1.0 m/s (Fritz)

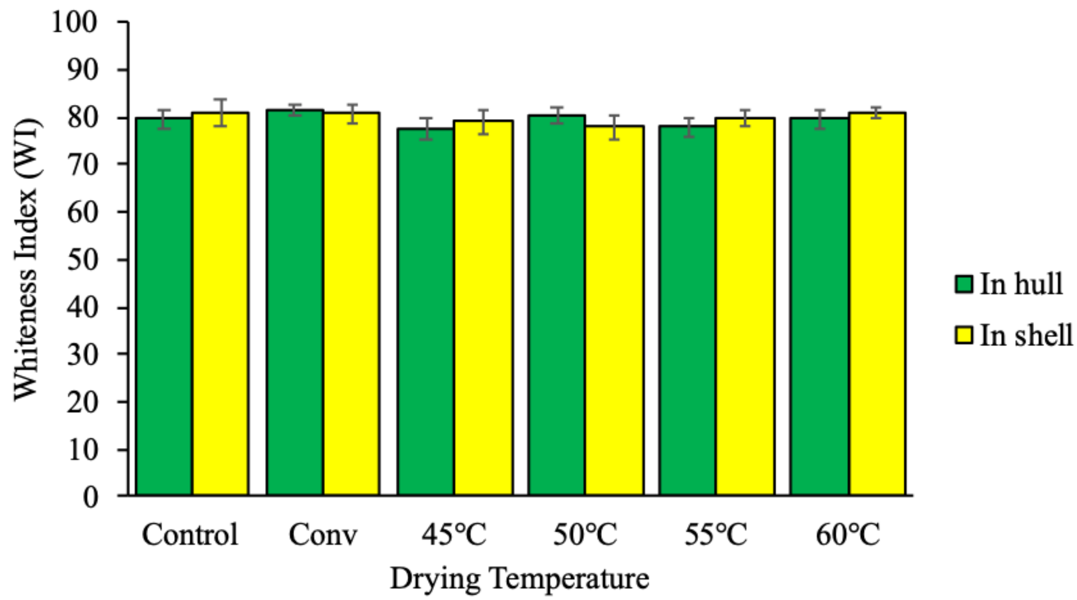


Figure AA.42 Final product kernel whiteness index for bench top drying of different temperature levels at 2.0 m/s (Fritz)

Appendix A.5 Color Development Scores

- *Nonpareil*

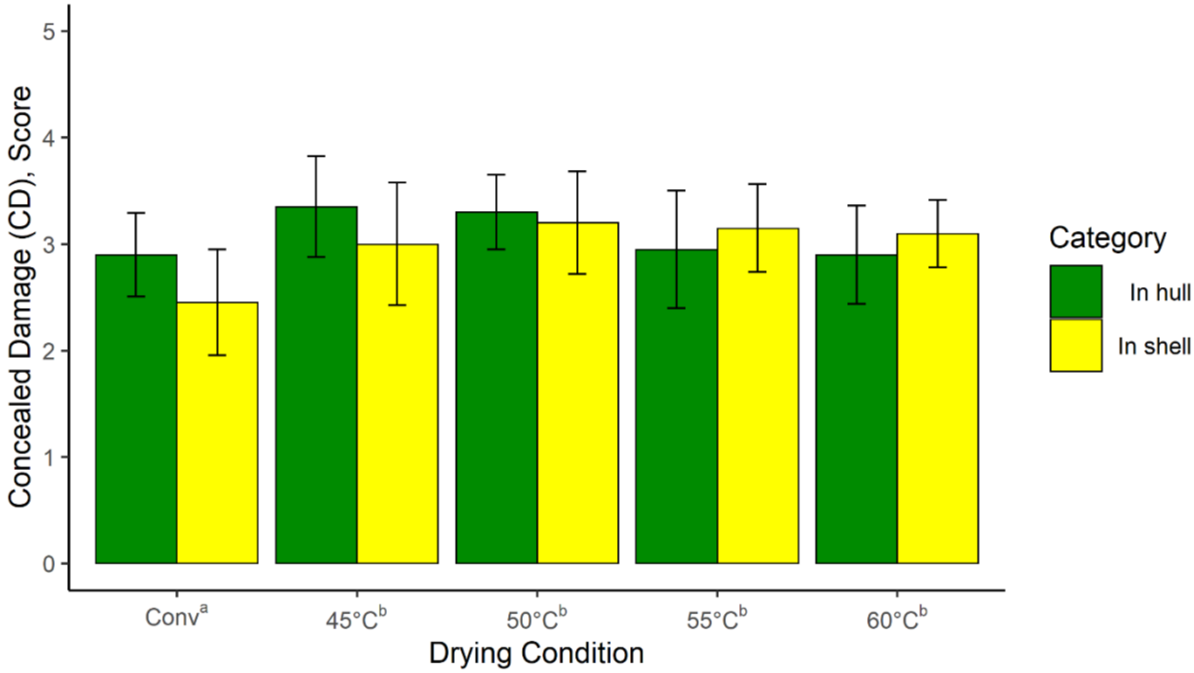


Figure AA.43 Color development scores for bench top drying of different temperature levels at 1.0 m/s (Nonpareil)

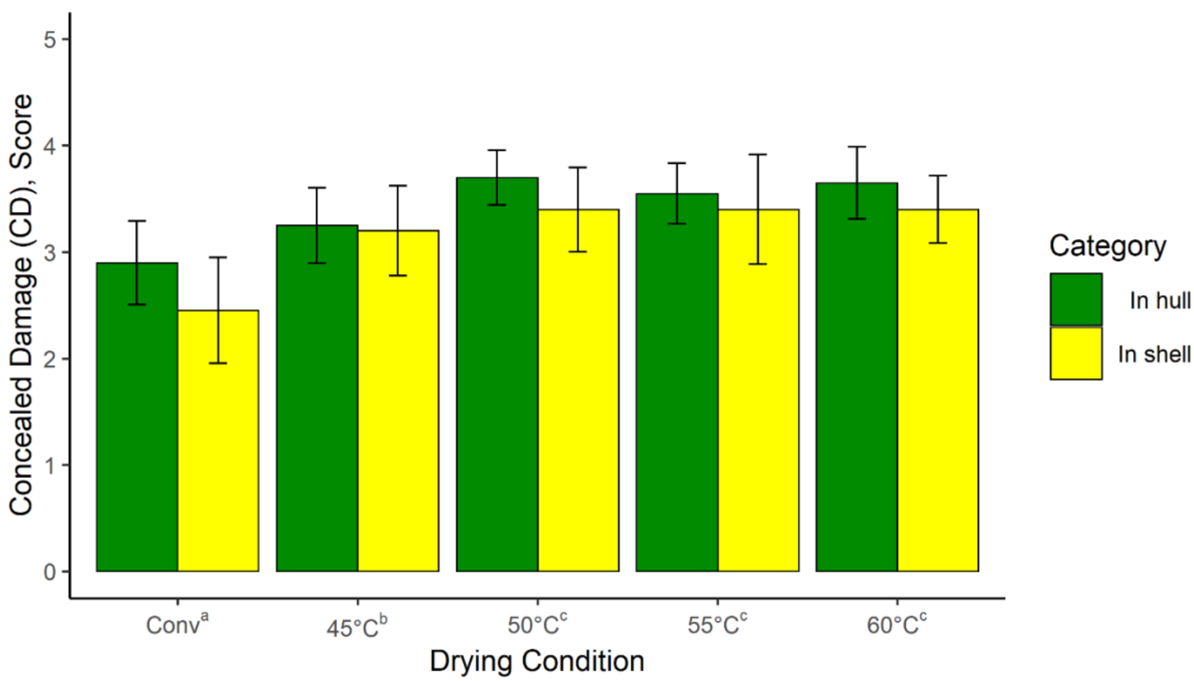


Figure AA.44 Color development scores for bench top drying of different temperature levels at 2.0 m/s (Nonpareil)

- *Monterey*

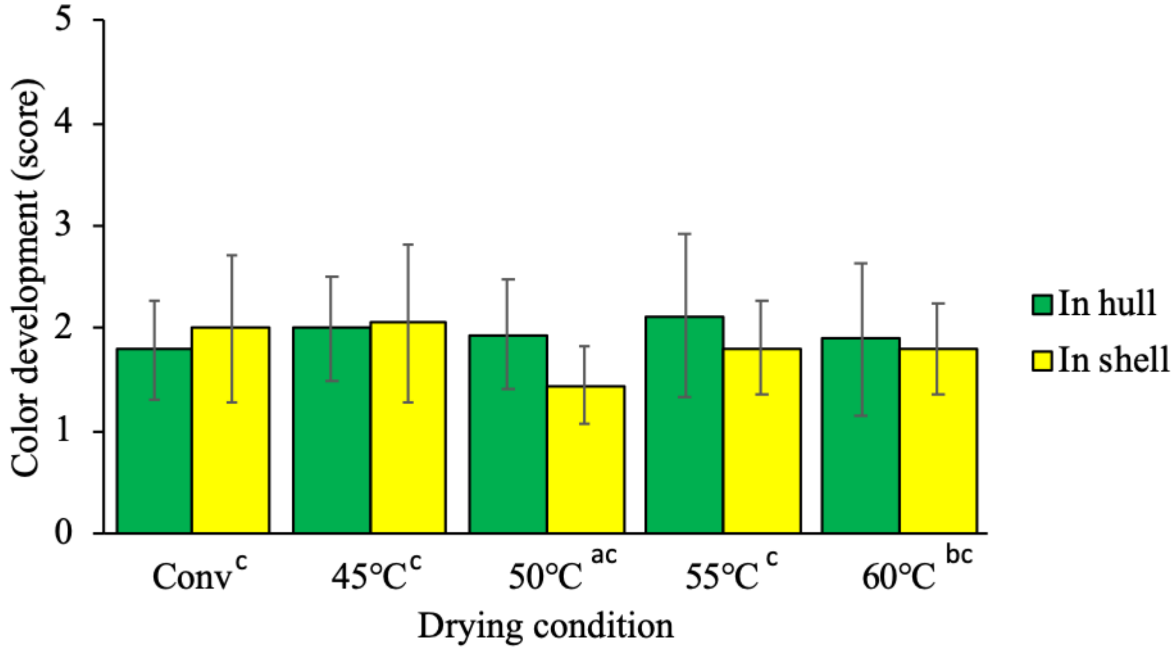


Figure AA.45 Color development scores for bench top drying of different temperature levels at 1.0 m/s (Monterey)

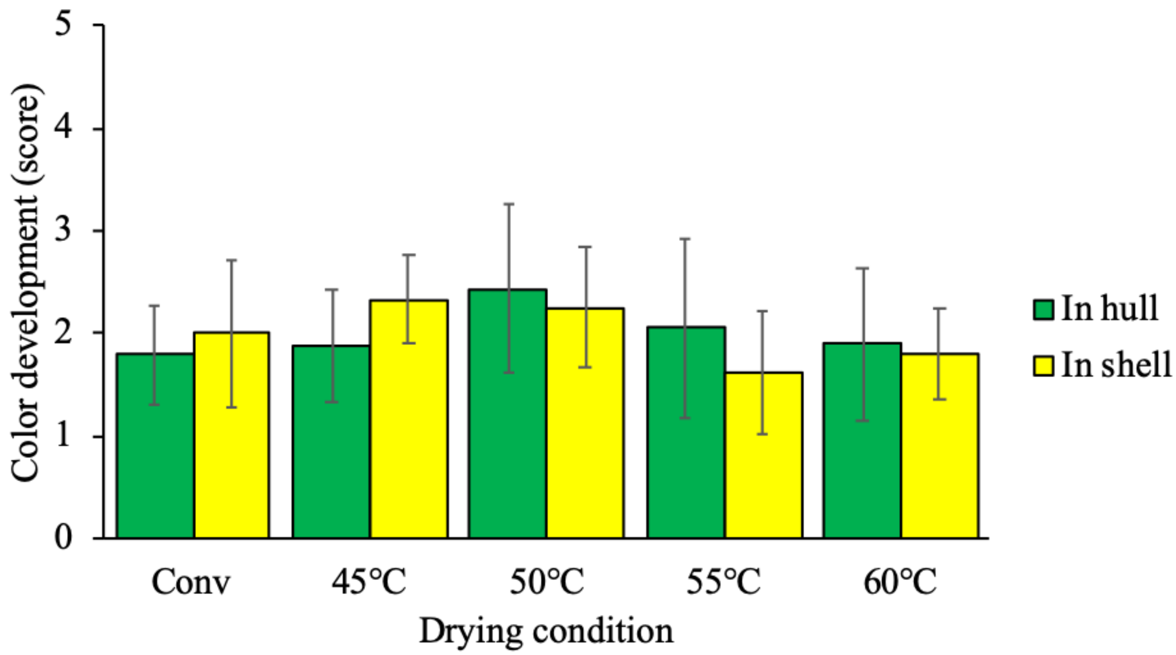


Figure AA.46 Color development scores for bench top drying of different temperature levels at 2.0 m/s (Monterey)

- *Fritz*

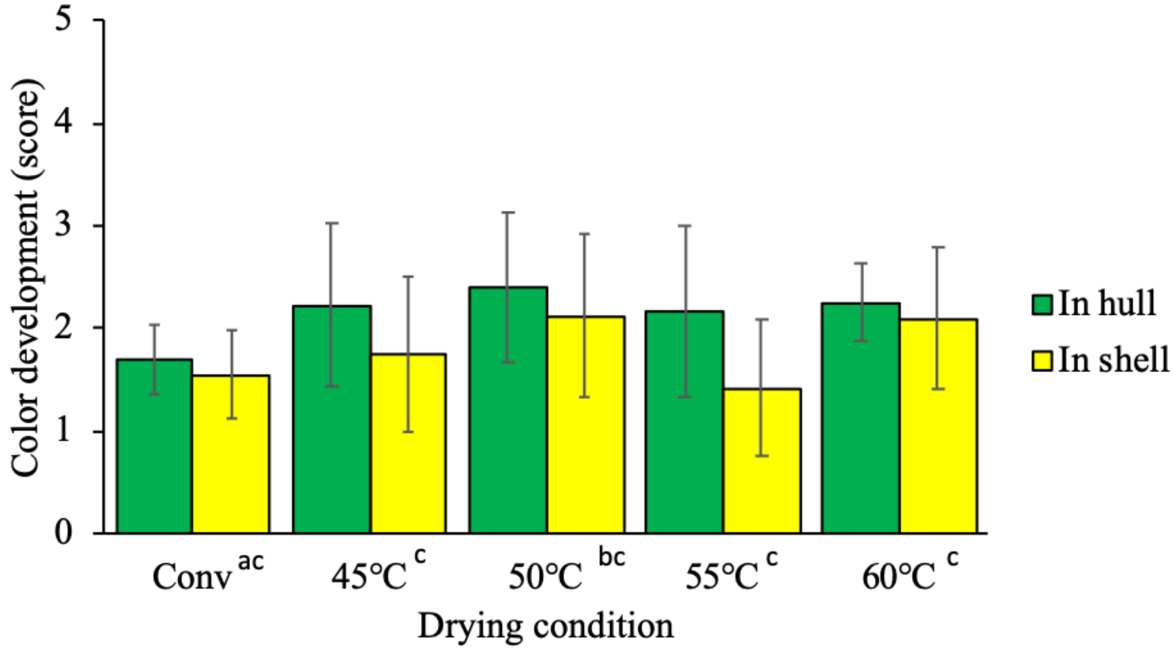


Figure AA.47 Color development scores for bench top drying of different temperature levels at 1.0 m/s (Fritz)

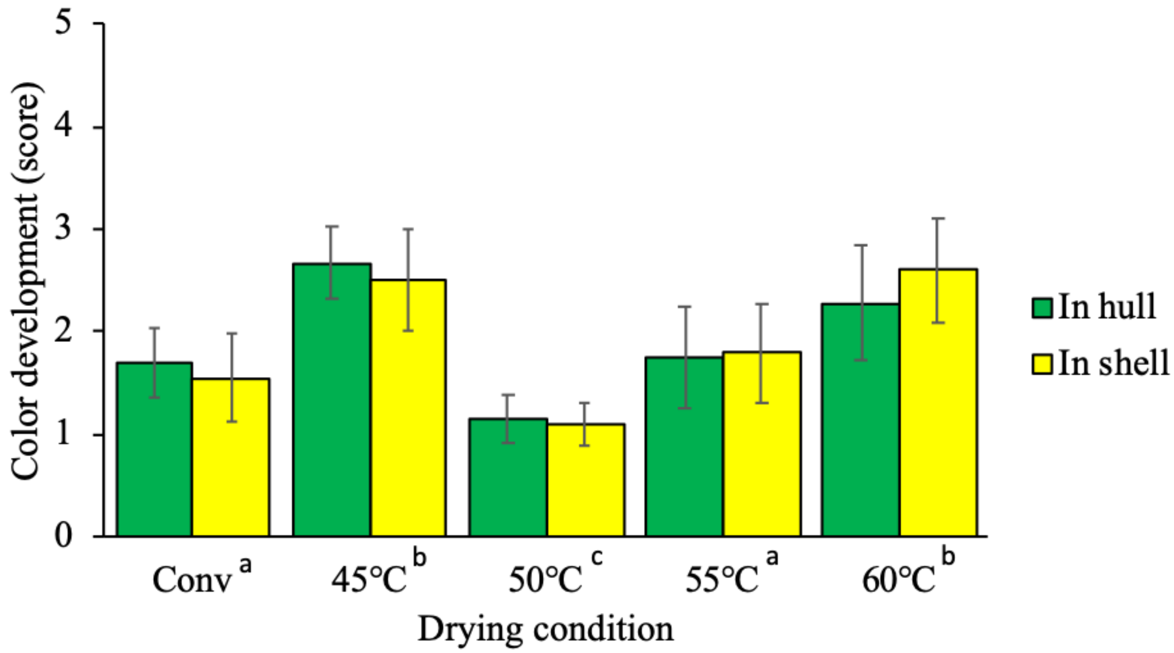


Figure AA.48 Color development scores for bench top drying of different temperature levels at 2.0 m/s (Fritz)

Appendix B.1 Summary of Pilot drying under different drying conditions

Table AB.1 Summary of drying performance and energy consumption (NP)

Air velocity (m/s)	Temp (°C)	Initial MC_{wb} (%)	Final MC_{wb} (%)	Drying time (h)	Overall drying rate (kg/h-kg)	Specific energy consumption (MJ/kg)	Energy cost (¢/lb)
		Ave	Ave		Ave		
1	45	17.52	10.35	4.5	0.0208	11.22	1.9
	50	20.86	13.01	5	0.0206	13.12	2.1
	55	18.21	12.65	3	0.0261	14.79	1.5
	60	19.65	13.56	3	0.0272	12.59	1.8
2	45	17.09	10.55	4.5	0.0180	21.78	2.9
	50	17.23	11.19	3	0.0231	18.58	2.5
	55	20.77	13.52	3	0.0314	18.20	2.9
	60	20.74	13.32	2.5	0.0387	17.56	2.8

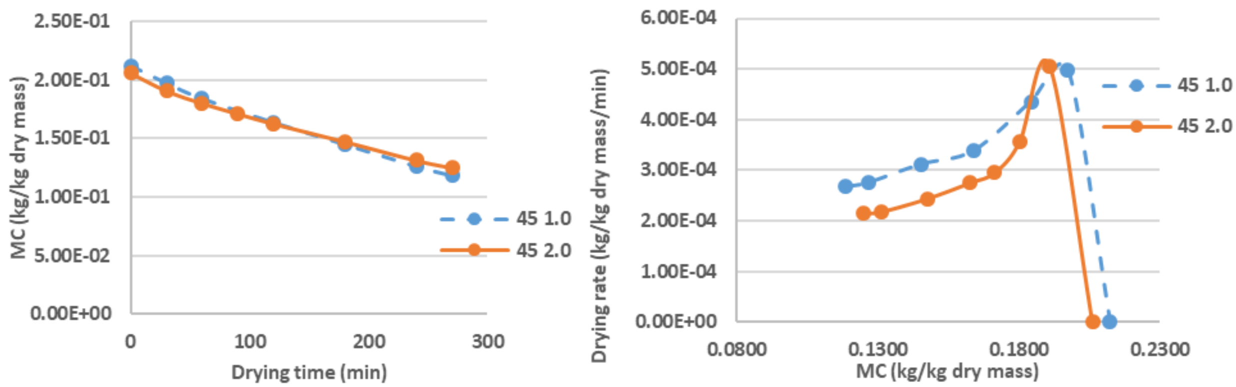


Figure AB.1 Moisture content and drying rate of column drying at 45°C (NP)

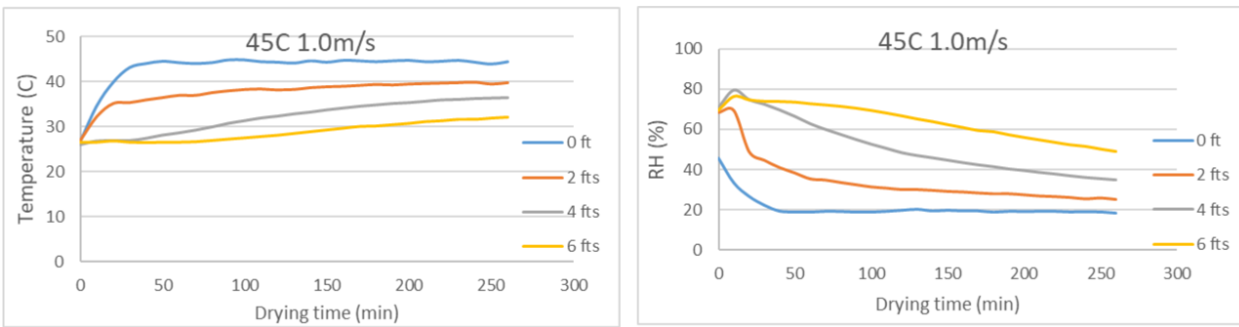


Figure AB.2 Temperature and RH of air in the column drying at 45°C 1 m/s (NP)

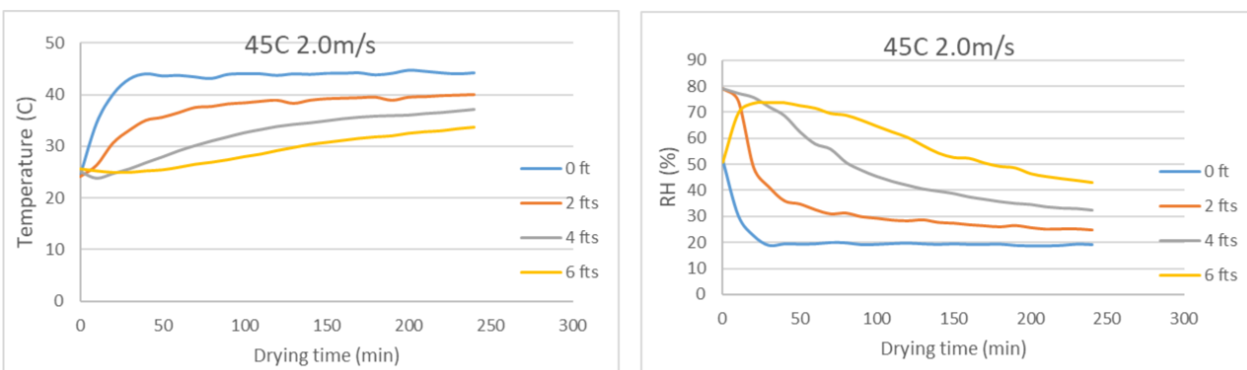


Figure AB.3 Temperature and RH of air in the column drying at 45°C 2 m/s (NP)

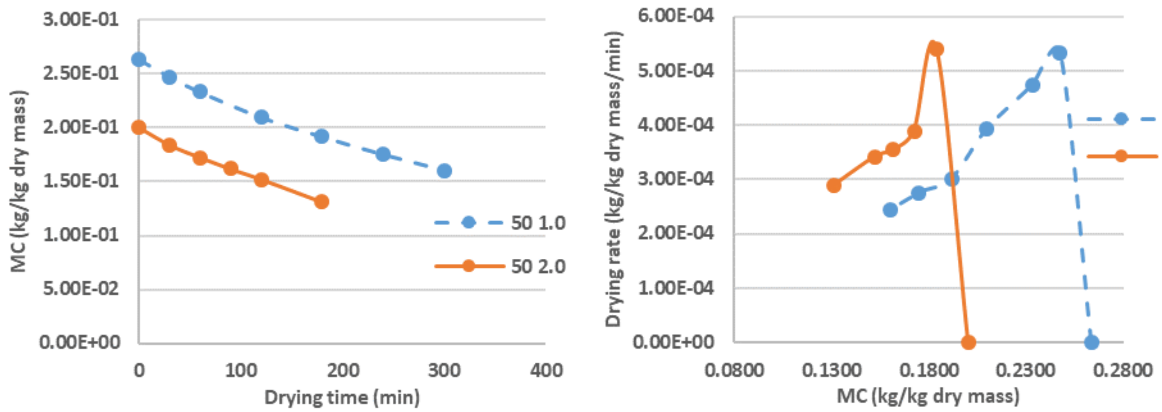


Figure AB.4 Moisture content and drying rate of column drying at 50°C (NP)

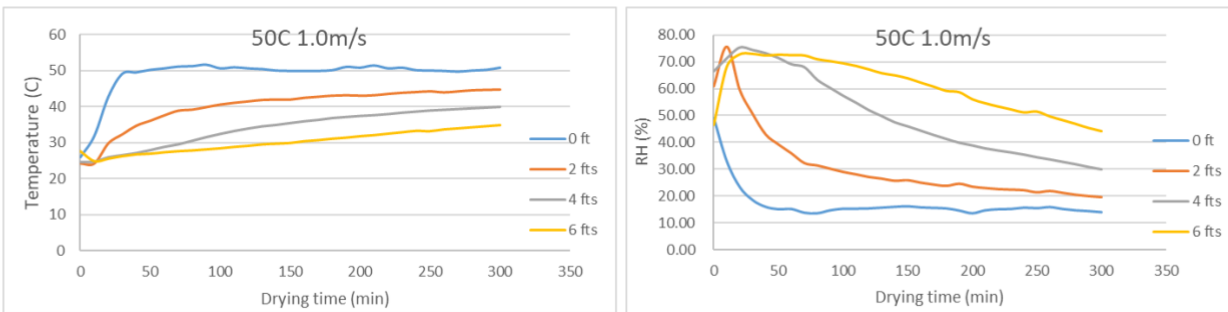


Figure AB.5 Temperature and RH of air in the column drying at 50°C 1 m/s (NP)

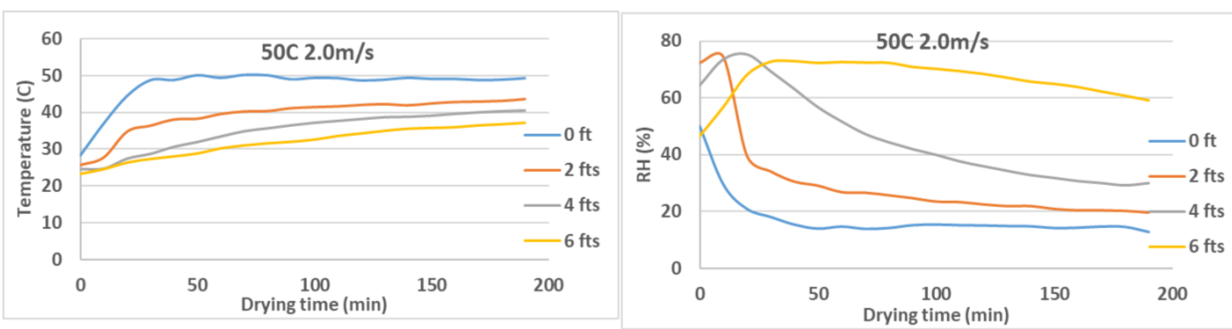


Figure AB.6 Temperature and RH of air in the column drying at 50°C 2 m/s (NP)

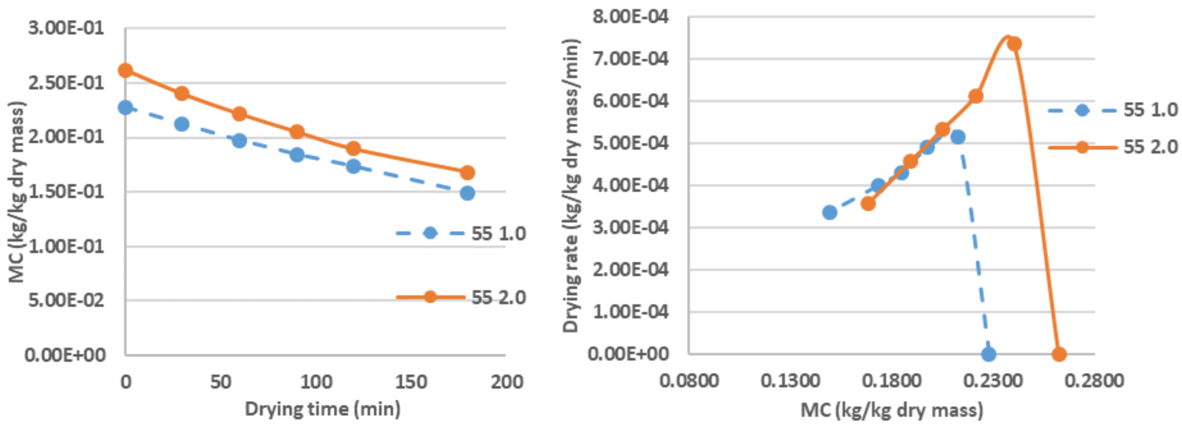


Figure AB.7 Moisture content and drying rate of column drying at 55°C (NP)

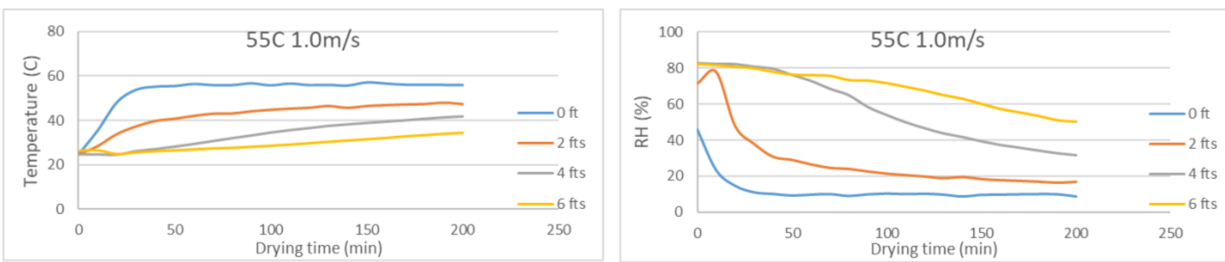


Figure AB.8 Temperature and RH of air in the column drying at 55°C 1 m/s (NP)

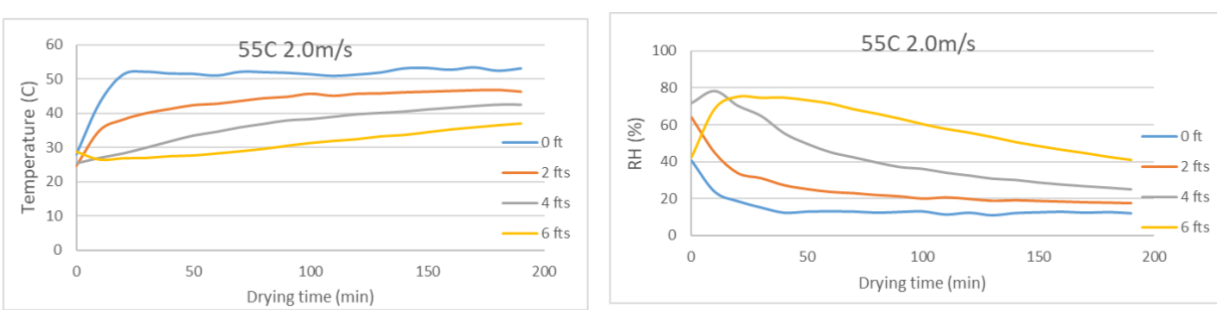


Figure AB.9 Temperature and RH of air in the column drying at 55°C 2 m/s (NP)

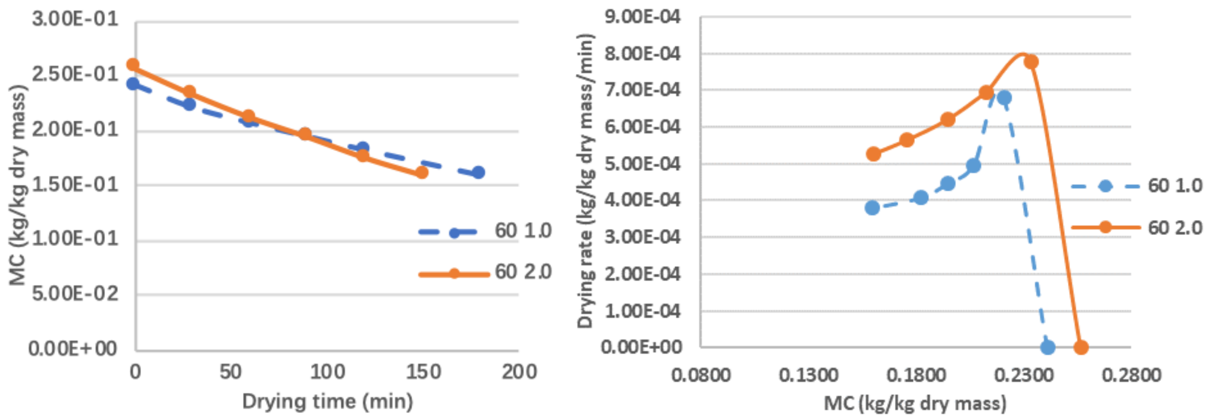


Figure AB.10 Moisture content and drying rate of column drying at 60°C (NP)

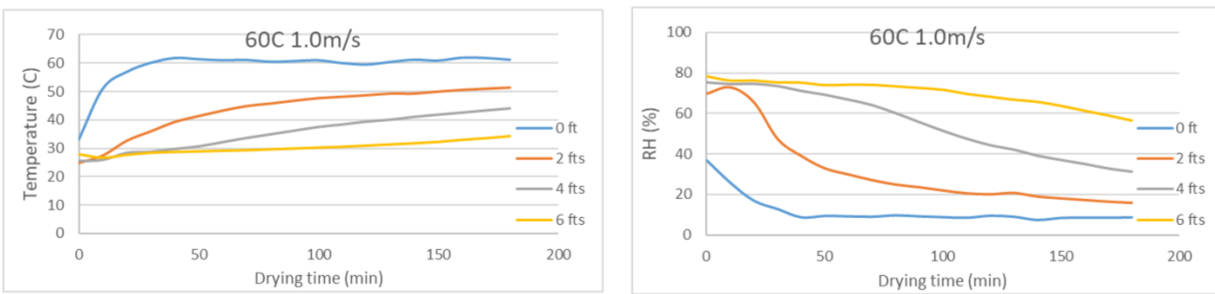


Figure AB.11 Temperature and RH of air in the column drying at 60°C 1 m/s (NP)

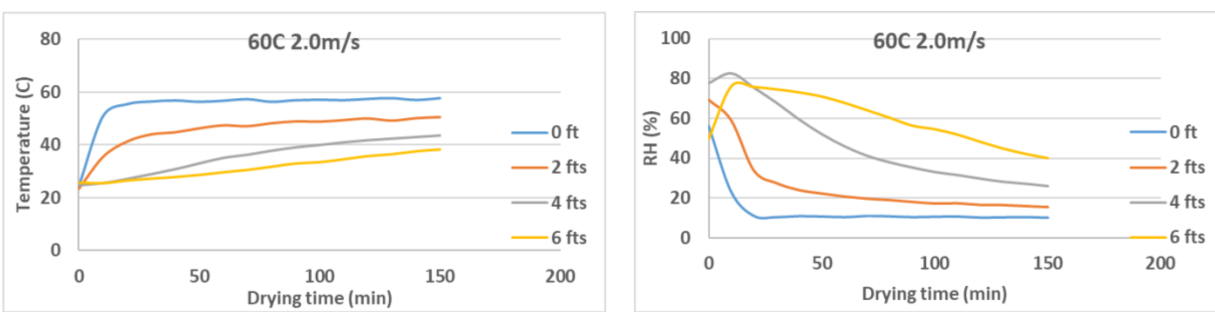


Figure AB.12 Temperature and RH of air in the column drying at 60°C 2 m/s (NP)

Table AB.2 Summary of drying performance and energy consumption (MT)

Air velocity (m/s)	Temp (°C)	Initial MC_{wb} (%)	Final MC_{wb} (%)	Drying time (h)	Overall drying rate (kg/h-kg)	Specific energy consumption (MJ/kg)	Energy cost (¢/lb)
		Ave	Ave		Ave		
1	45	18.84	10.29	5.5	0.0224	9.09	1.9
	50	18.01	10.06	5	0.0211	12.46	2.1
	55	17.25	10.52	3	0.0282	11.18	1.5
	60	17.18	10.85	3	0.0262	13.51	1.8
2	45	17.02	10.04	5	0.0180	22.59	3.2
	50	16.96	11.30	3	0.0253	16.49	2.4
	55	17.63	10.71	3	0.0301	19.01	2.9
	60	18.93	10.58	3.5	0.0303	23.75	4.0

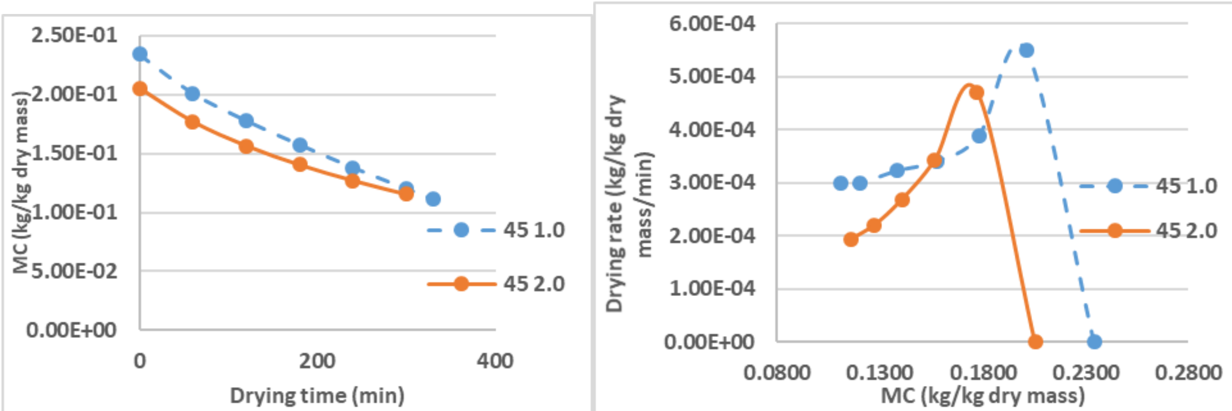


Figure AB.13 Moisture content and drying rate of column drying at 45°C (MT)

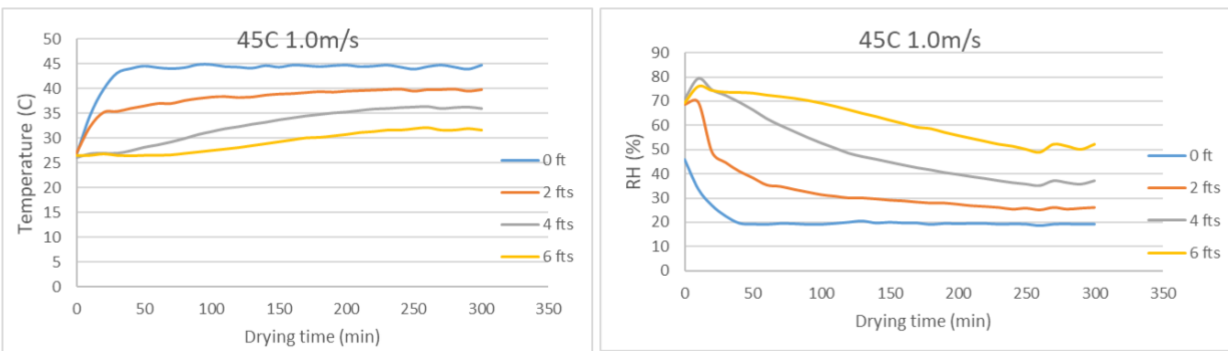


Figure AB.14 Temperature and RH of air in the column drying at 45°C 1 m/s (MT)

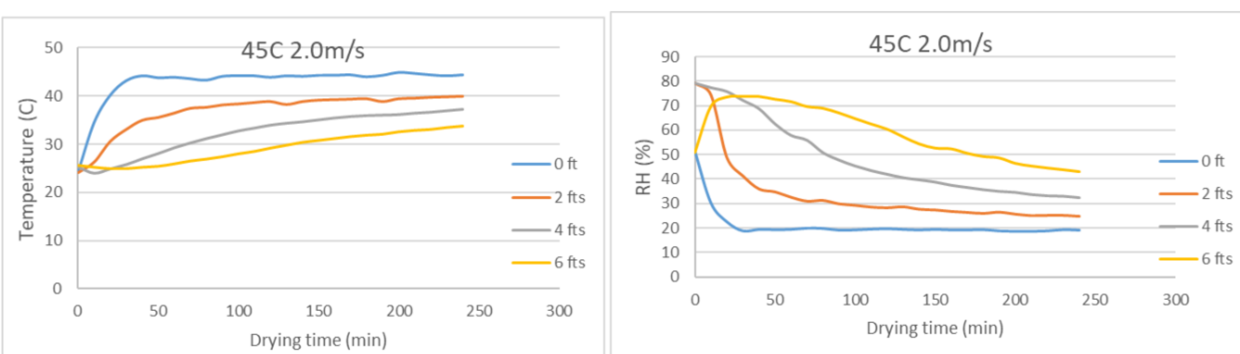


Figure AB.15 Temperature and RH of air in the column drying at 45°C 2 m/s (MT)

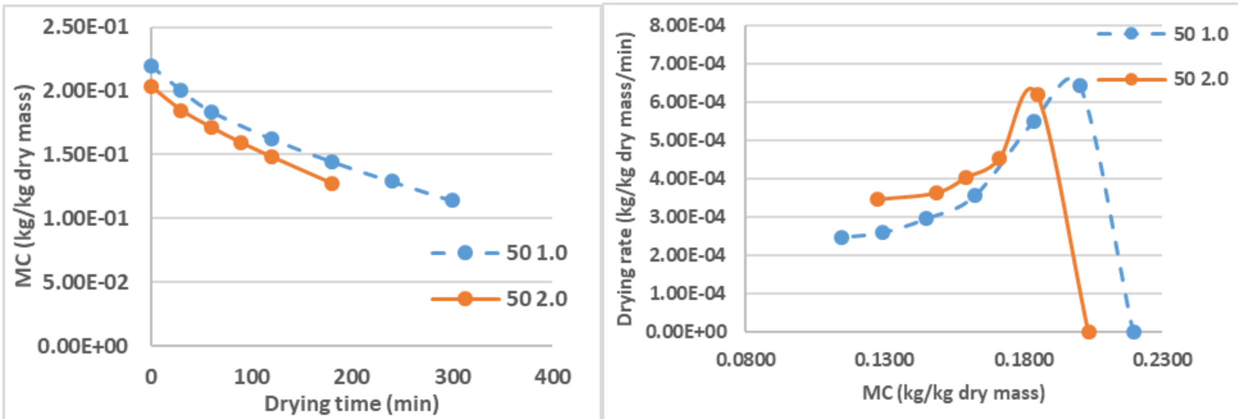


Figure AB.16 Moisture content and drying rate of column drying at 50°C (MT)

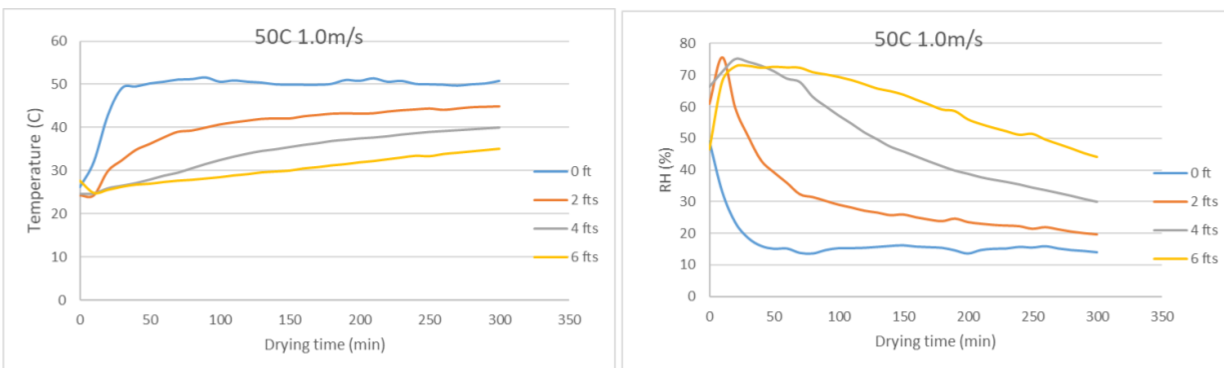


Figure AB.17 Temperature and RH of air in the column drying at 50°C 1 m/s (MT)

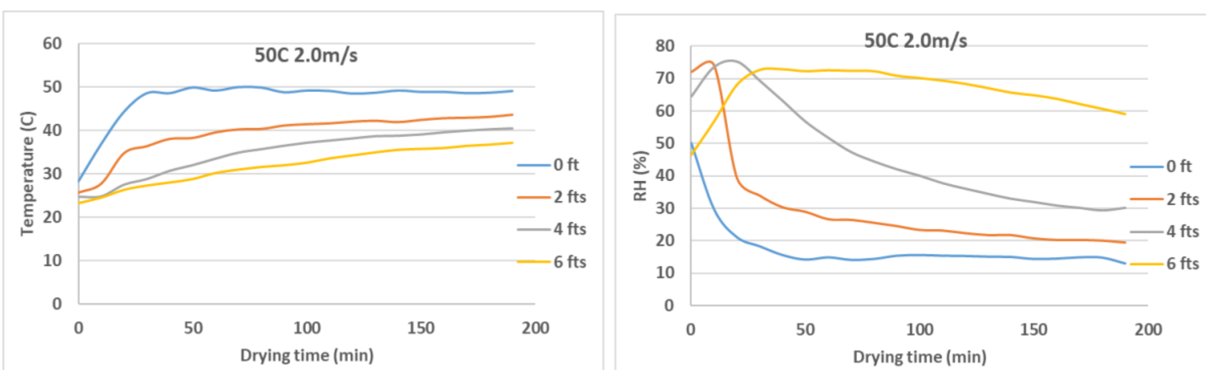


Figure AB.18 Temperature and RH of air in the column drying at 50°C 2 m/s (MT)

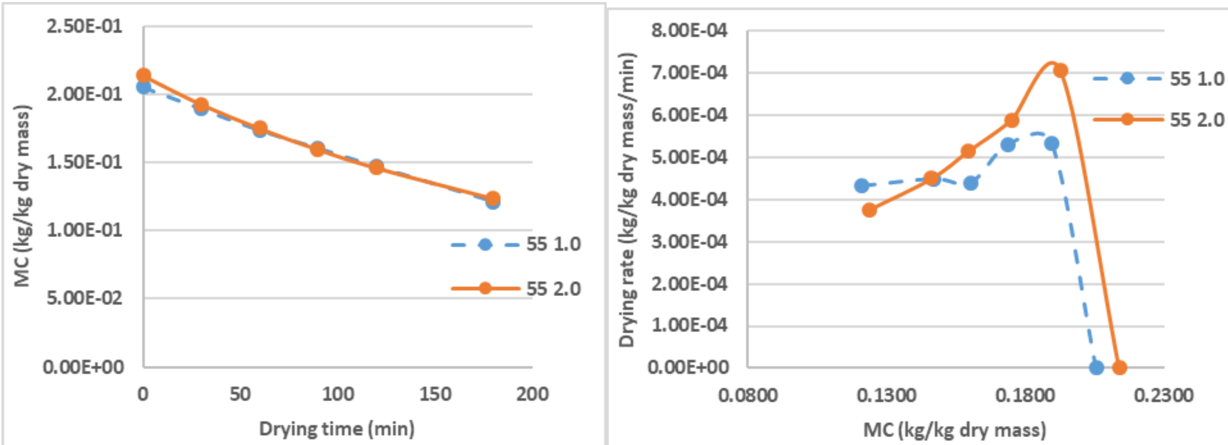


Figure AB.19 Moisture content and drying rate of column drying at 55°C (MT)

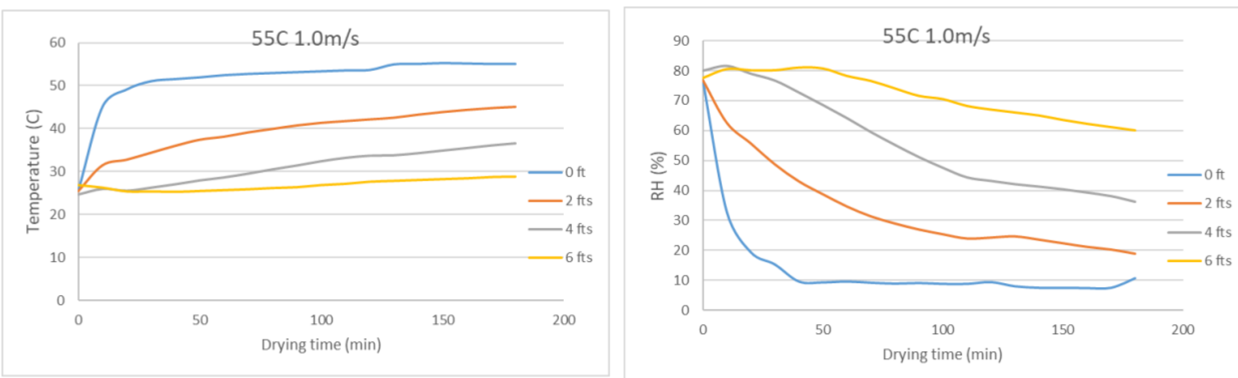


Figure AB.20 Temperature and RH of air in the column drying at 55°C 1 m/s (MT)

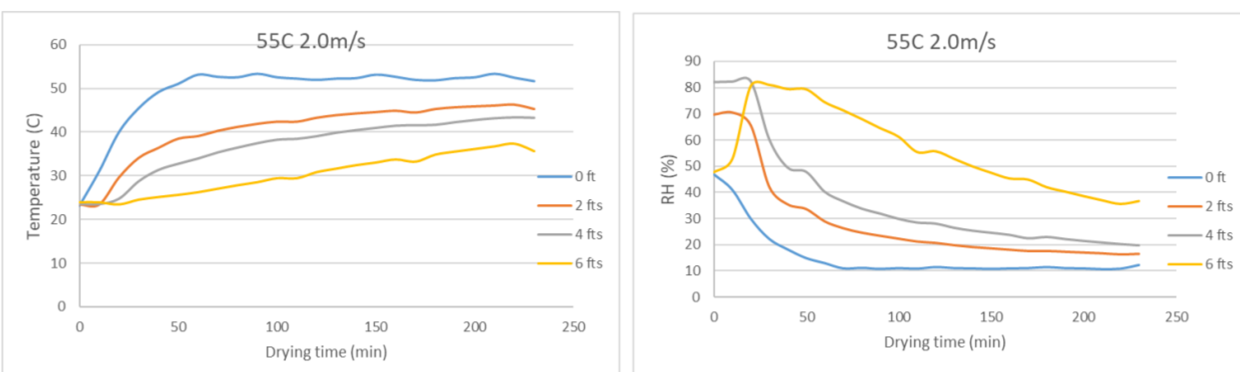


Figure AB.21 Temperature and RH of air in the column drying at 55°C 2 m/s (MT)

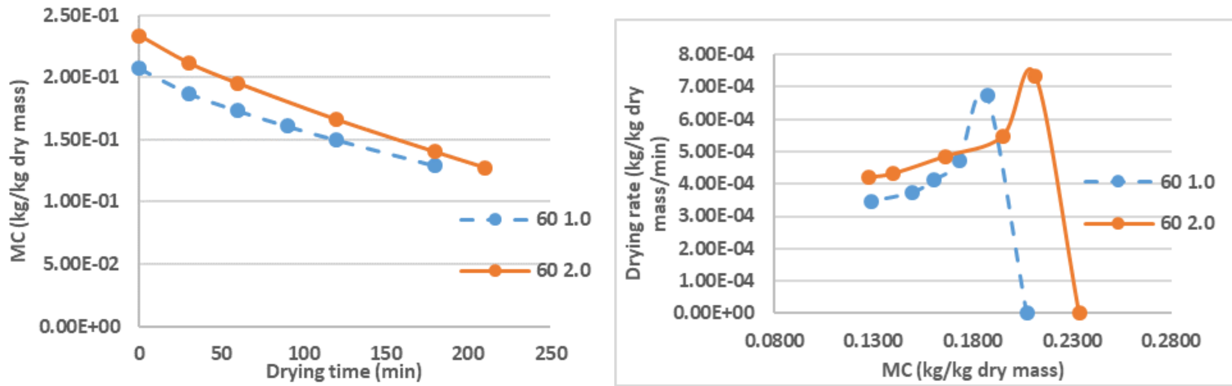


Figure AB.22 Moisture content and drying rate of column drying at 60°C (MT)

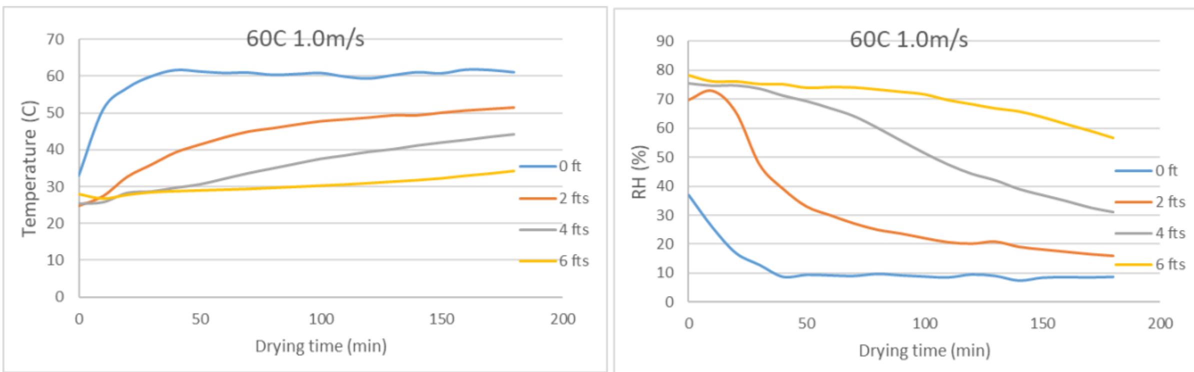


Figure AB.23 Temperature and RH of air in the column drying at 60°C 1 m/s (MT)

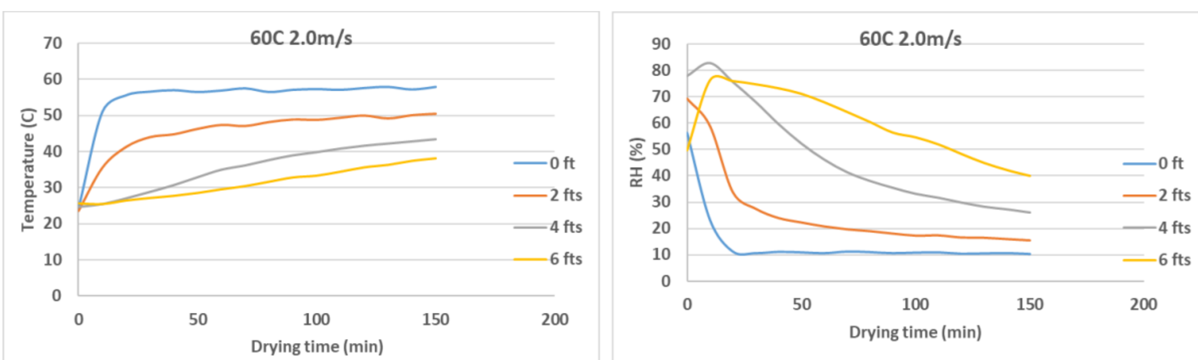


Figure AB.24 Temperature and RH of air in the column drying at 60°C 2 m/s (MT)

Table AB.3 Summary of drying performance and energy consumption (FR)

Air velocity (m/s)	Temp (°C)	Initial MC_{wb} (%)	Final MC_{wb} (%)	Drying time (h)	Overall drying rate (kg/h-kg)	Specific energy consumption (MJ/kg)	Energy cost ($/kg)
		Ave	Ave		Ave		
1	45	21.16	10.60	5	0.0308	7.17	0.0375
	50	20.67	11.07	5	0.0247	10.36	0.0465
	55	20.85	11.83	3.75	0.0343	9.38	0.0418
	60	21.63	12.40	3	0.0433	8.19	0.0389
2	45	20.14	10.69	5	0.0240	16.07	0.0701
	50	21.04	10.82	5	0.0265	19.08	0.0886
	55	21.91	12.07	3.5	0.0382	15.18	0.0748
	60	21.84	11.39	3	0.0564	22.52	0.0754

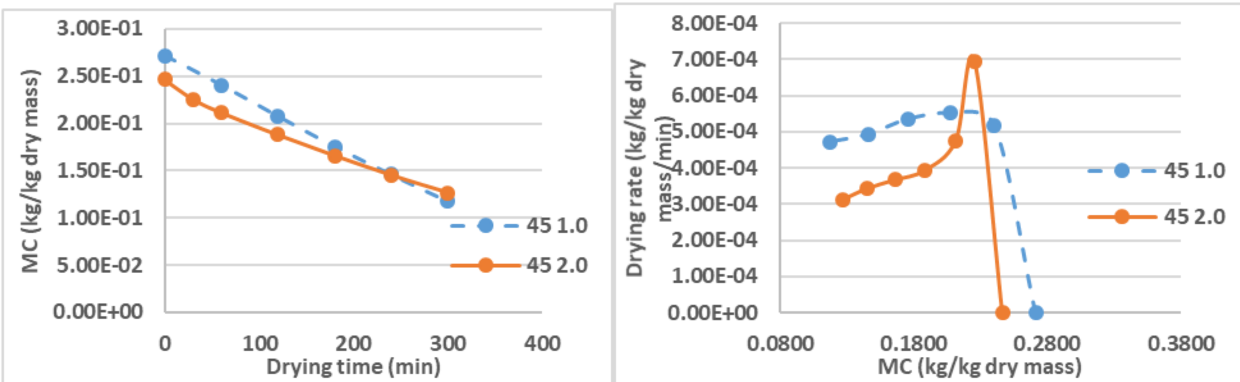


Figure AB.25 Moisture content and drying rate of column drying at 45°C (FR)

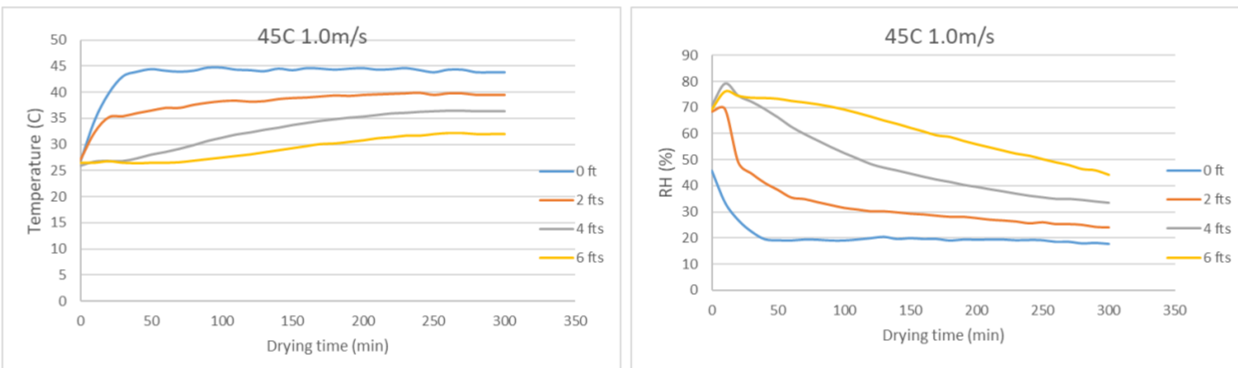


Figure AB.26 Temperature and RH of air in the column drying at 45°C 1 m/s (FR)

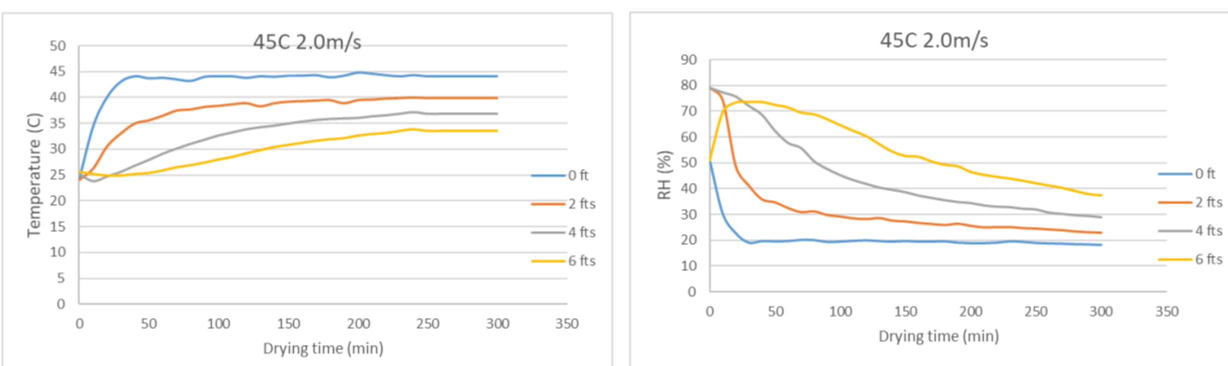


Figure AB.27 Temperature and RH of air in the column drying at 45°C 2 m/s (FR)

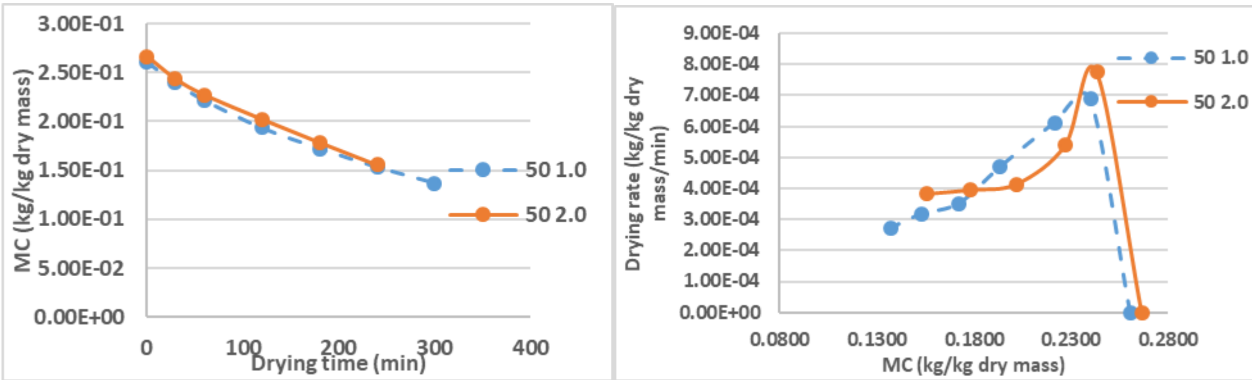


Figure AB.28 Moisture content and drying rate of column drying at 50°C (FR)

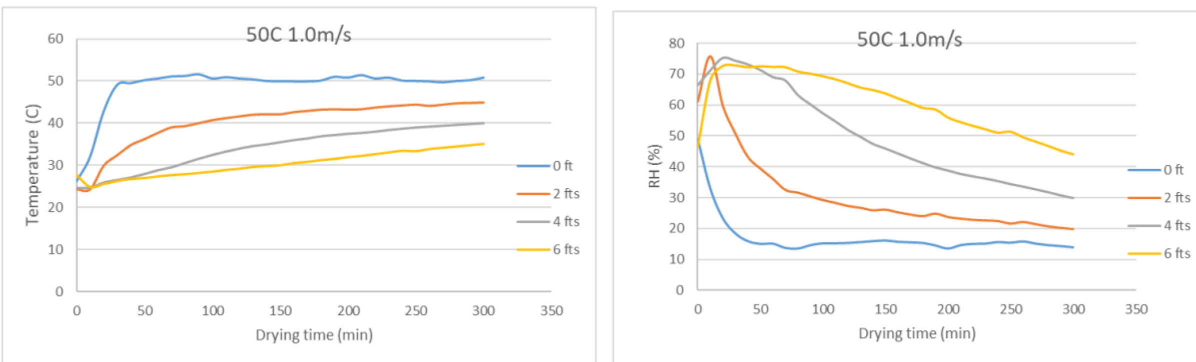


Figure AB.29 Temperature and RH of air in the column drying at 50°C 1 m/s (FR)

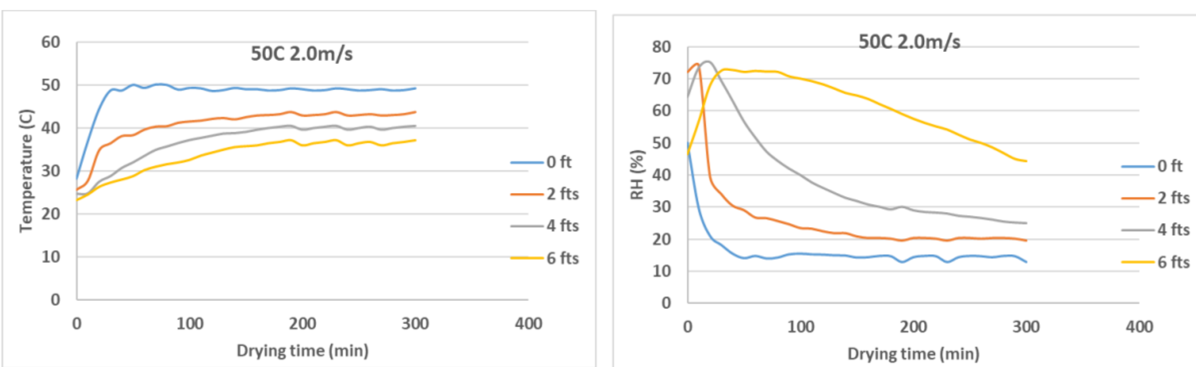
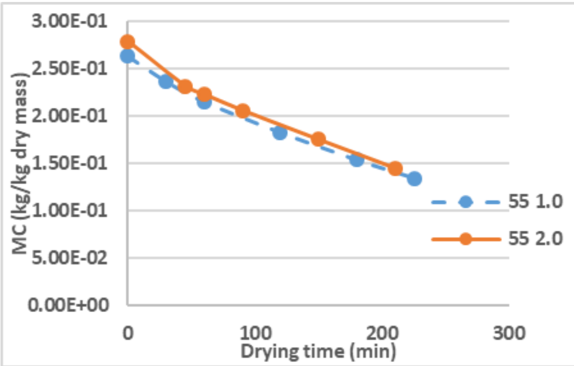


Figure AB.30 Temperature and RH of air in the column drying at 50°C 2 m/s (FR)



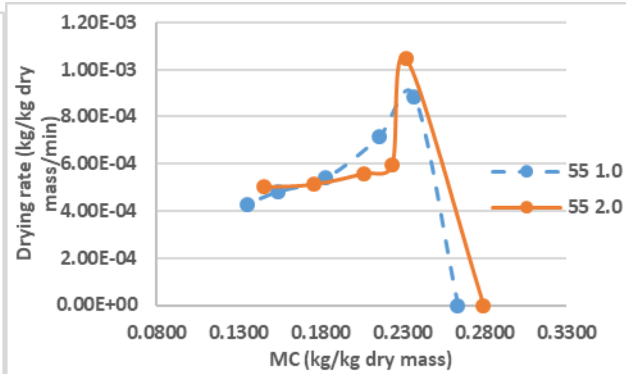
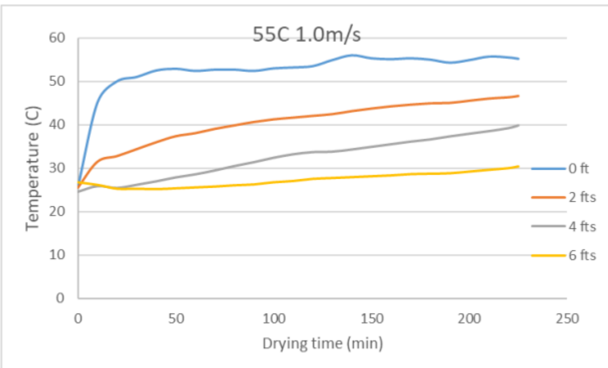


Figure AB.31 Moisture content and drying rate of column drying at 55°C (FR)



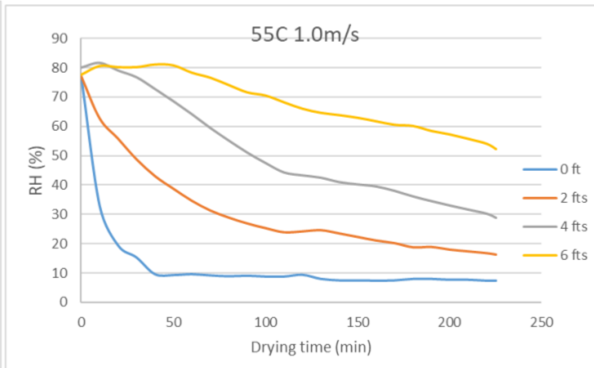
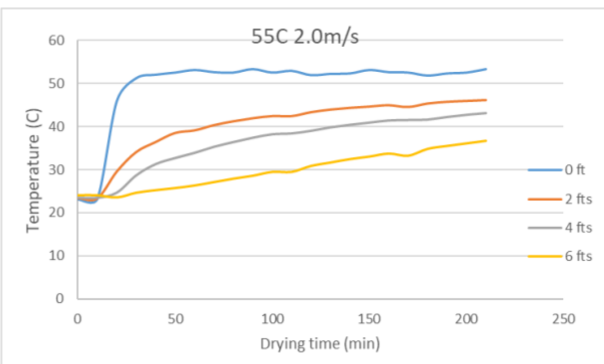


Figure AB.32 Temperature and RH of air in the column drying at 55°C 1 m/s (FR)



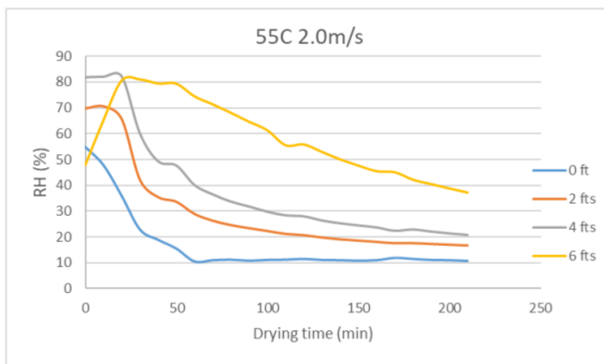


Figure AB.33 Temperature and RH of air in the column drying at 55°C 2 m/s (FR)

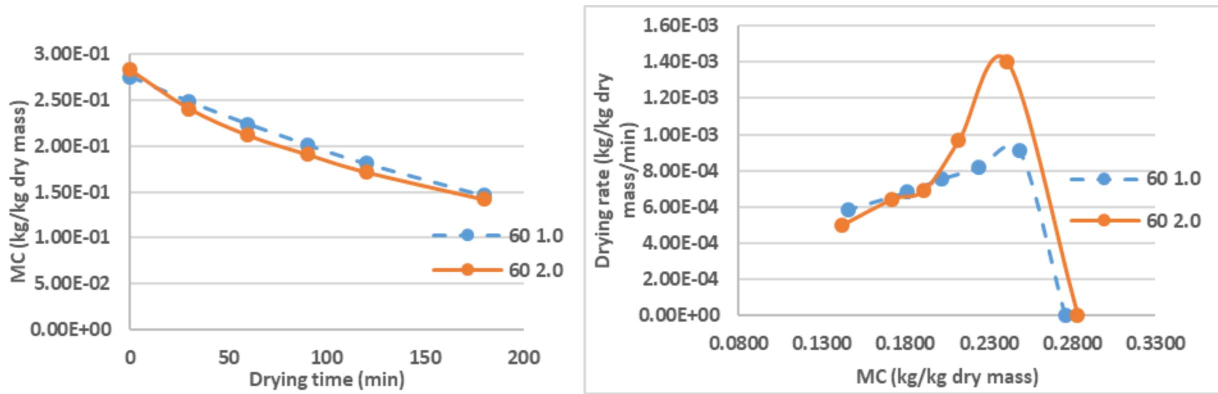


Figure AB.34 Moisture content and drying rate of column drying at 60°C (FR)

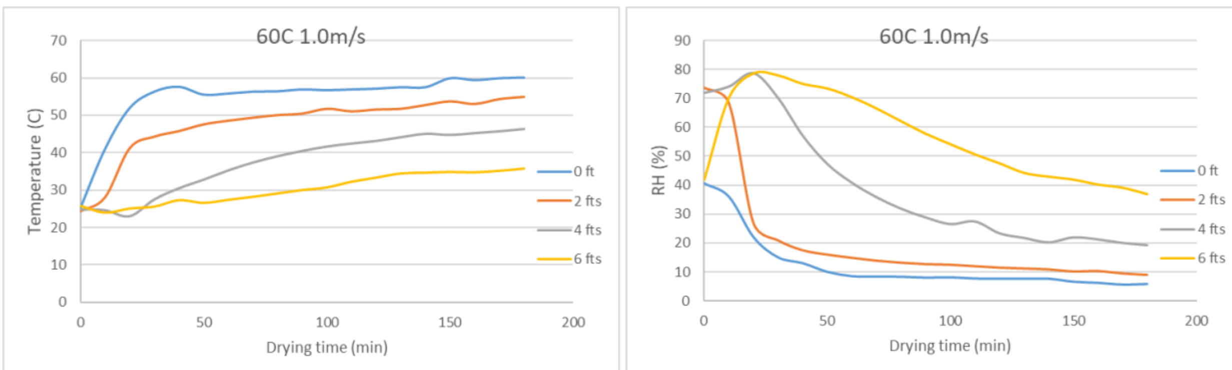


Figure AB.35 Temperature and RH of air in the column drying at 60°C 1 m/s (FR)

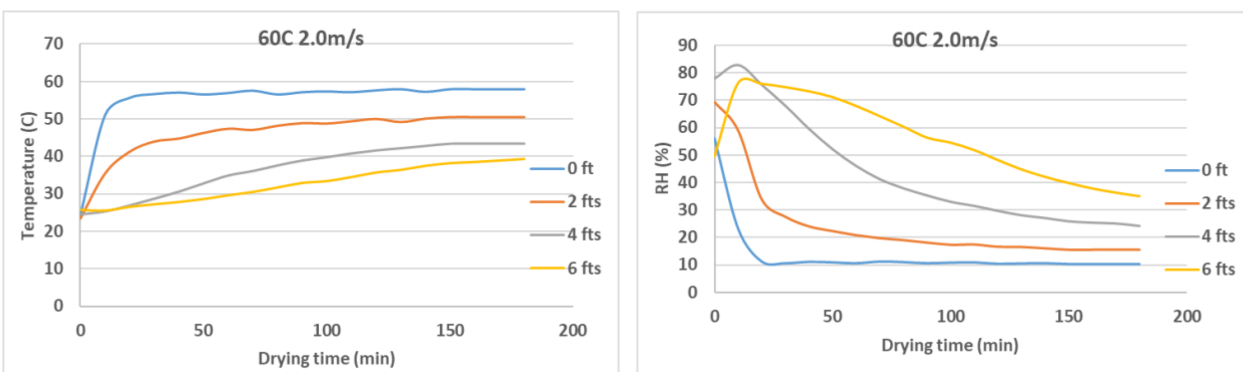


Figure AB.36 Temperature and RH of air in the column drying at 60°C 2 m/s (FR)

Appendix B.2 Summary of final product characteristics after pilot scale drying

The final moisture contents of overall almonds and almond kernels at different heights within the column dryer under different drying conditions are shown in Table 14 to 16 for Nonpareil, Monterey and Fritz varieties. The variation of MCs for overall almonds between the top and bottom layers in the column dryer ranged from 3.8 to 8.0% for different varieties. In term of final kernel MC, the variation ranged from 0.8 to 3.3 %, which was narrower compared with the overall almonds. Increasing of air velocity benefited the improvement of drying uniformity. It was also found that the condition with the lowest drying rate led to more uniform MC in the almond kernels. At the same time, the variations of final MC for the overall almonds and almond kernels at different locations in the drying column are shown in Figure AB.13 to Ab.18. Regression analysis was conducted to determine the influence of drying air temperature and velocity on the moisture variation in the dryer. From the slope of the curves, it was found that the increase of drying temperature led to increased value of the slopes, which resulted in larger MC variation.

Table AB.4 Summary of final MC of overall almonds and almond kernels (NP)

Air velocity (m/s)	Temp (°C)	Overall MC_{wb} (%)				Kernel MC_{wb} (%)			
		0 ft	2 ft	4 ft	6 ft	0 ft	2 ft	4 ft	6 ft
1	45	9.77 ± 0.98	10.27 ± 1.25	11.52 ± 1.04	13.62 ± 1.31	5.21 ± 0.56	5.51 ± 0.61	5.83 ± 0.71	6.01 ± 0.76
	50	11.64 ± 0.93	12.13 ± 1.00	14.42 ± 1.06	16.85 ± 1.13	5.75 ± 0.55	5.98 ± 0.55	6.23 ± 0.62	6.63 ± 0.62
	55	9.65 ± 1.00	11.01 ± 0.98	12.85 ± 1.35	14.23 ± 1.52	5.25 ± 0.69	5.46 ± 0.69	5.75 ± 0.80	6.38 ± 0.88
	60	10.53 ± 1.08	12.26 ± 1.04	13.93 ± 1.39	15.32 ± 1.37	4.52 ± 0.77	5.21 ± 0.53	6.27 ± 0.95	7.55 ± 0.98
2	45	9.32 ± 1.05	10.06 ± 1.13	10.95 ± 1.19	11.95 ± 1.08	5.30 ± 0.76	5.67 ± 0.84	5.91 ± 0.70	6.21 ± 0.85
	50	9.70 ± 0.97	10.69 ± 0.96	11.65 ± 1.24	12.66 ± 1.47	5.12 ± 0.47	5.92 ± 0.54	6.39 ± 0.60	6.59 ± 0.74
	55	12.03 ± 1.04	13.19 ± 1.14	14.27 ± 1.25	15.10 ± 1.37	4.82 ± 0.50	5.67 ± 0.51	6.43 ± 0.53	7.28 ± 0.71
	60	11.92 ± 1.07	12.51 ± 1.04	12.99 ± 1.20	14.35 ± 1.30	5.06 ± 0.44	5.30 ± 0.57	5.73 ± 0.50	6.51 ± 0.63

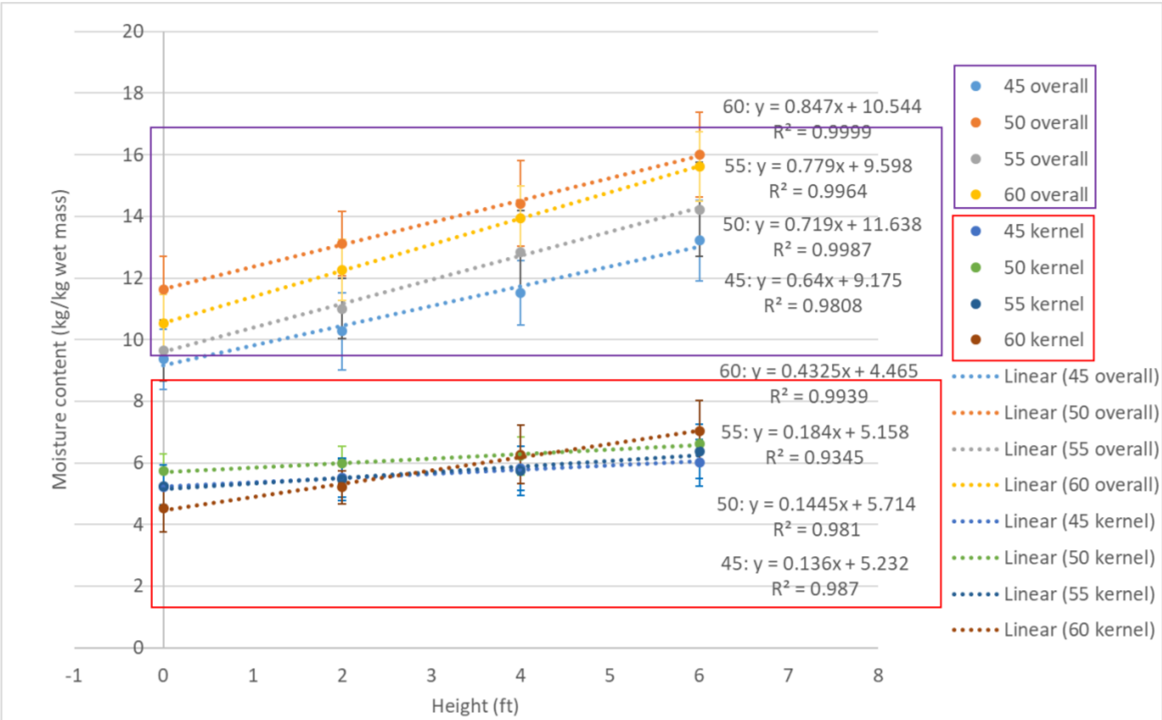


Figure AB.37 Variation of final MC in the overall almonds and almond kernels at different locations in the column dryer with 1.0 m/s air speed (NP)

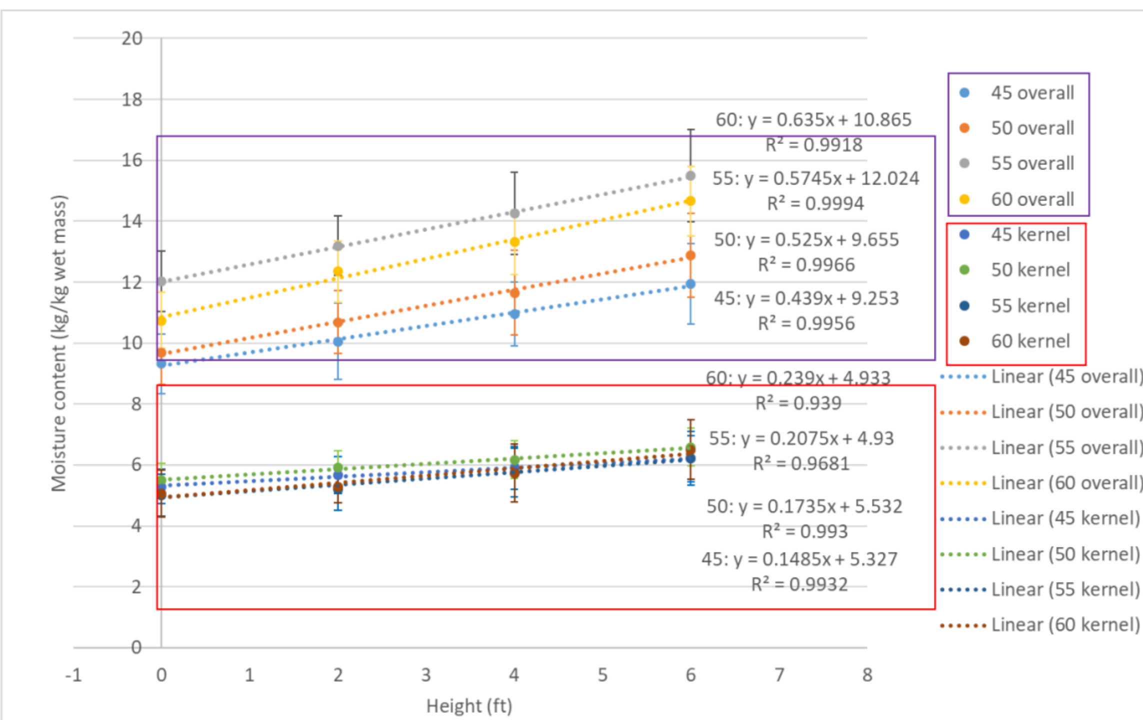


Figure AB.38 Variation of final MC in the overall almonds and almond kernels at different locations in the column dryer with 2.0 m/s air speed (NP)

Table AB.5 Summary of final MC of overall almonds and almond kernels (MT)

Air velocity (m/s)	Temp (°C)	Overall MC_{wb} (%)				Kernel MC_{wb} (%)			
		0 ft	2 ft	4 ft	6 ft	0 ft	2 ft	4 ft	6 ft
1	45	6.32 ± 1.07	7.93 ± 1.14	9.55 ± 1.67	13.07 ± 1.73	5.05 ± 0.90	5.29 ± 0.95	5.69 ± 0.85	6.01 ± 1.39
	50	6.99 ± 0.99	8.38 ± 1.19	10.67 ± 1.47	13.81 ± 1.80	4.21 ± 0.86	5.25 ± 1.08	5.94 ± 1.22	6.87 ± 1.77
	55	6.72 ± 1.06	9.36 ± 1.46	11.24 ± 1.71	14.23 ± 2.24	5.43 ± 0.92	6.24 ± 1.16	6.62 ± 1.47	7.25 ± 1.58
	60	6.86 ± 0.92	8.32 ± 1.29	10.31 ± 1.50	12.56 ± 1.64	5.00 ± 0.92	6.28 ± 1.11	6.85 ± 1.48	7.64 ± 1.58
2	45	8.61 ± 1.14	10.06 ± 1.42	10.88 ± 1.78	11.95 ± 1.66	5.15 ± 0.95	5.63 ± 1.11	5.88 ± 1.43	6.38 ± 0.85
	50	7.74 ± 1.14	9.39 ± 1.23	10.97 ± 1.64	12.50 ± 1.92	4.45 ± 0.91	5.52 ± 1.02	6.25 ± 1.25	6.59 ± 1.56
	55	7.71 ± 1.03	9.71 ± 1.33	11.63 ± 1.74	12.30 ± 1.85	4.86 ± 1.05	6.46 ± 1.26	6.96 ± 1.49	7.46 ± 1.89
	60	7.67 ± 1.05	10.06 ± 1.20	10.97 ± 1.32	12.78 ± 1.44	5.12 ± 0.64	6.31 ± 0.70	6.94 ± 0.87	8.15 ± 1.14

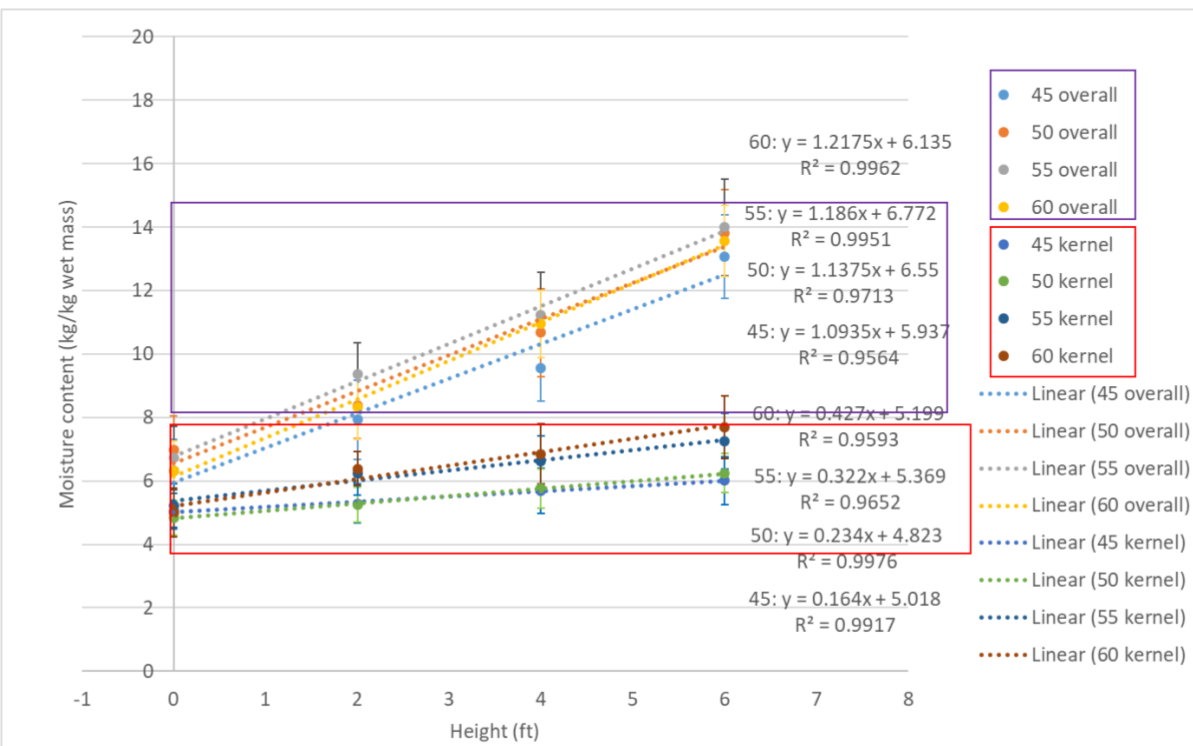


Figure AB.39 Variation of final MC in the overall almonds and almond kernels at different locations in the column dryer with 1.0 m/s air speed (MT)

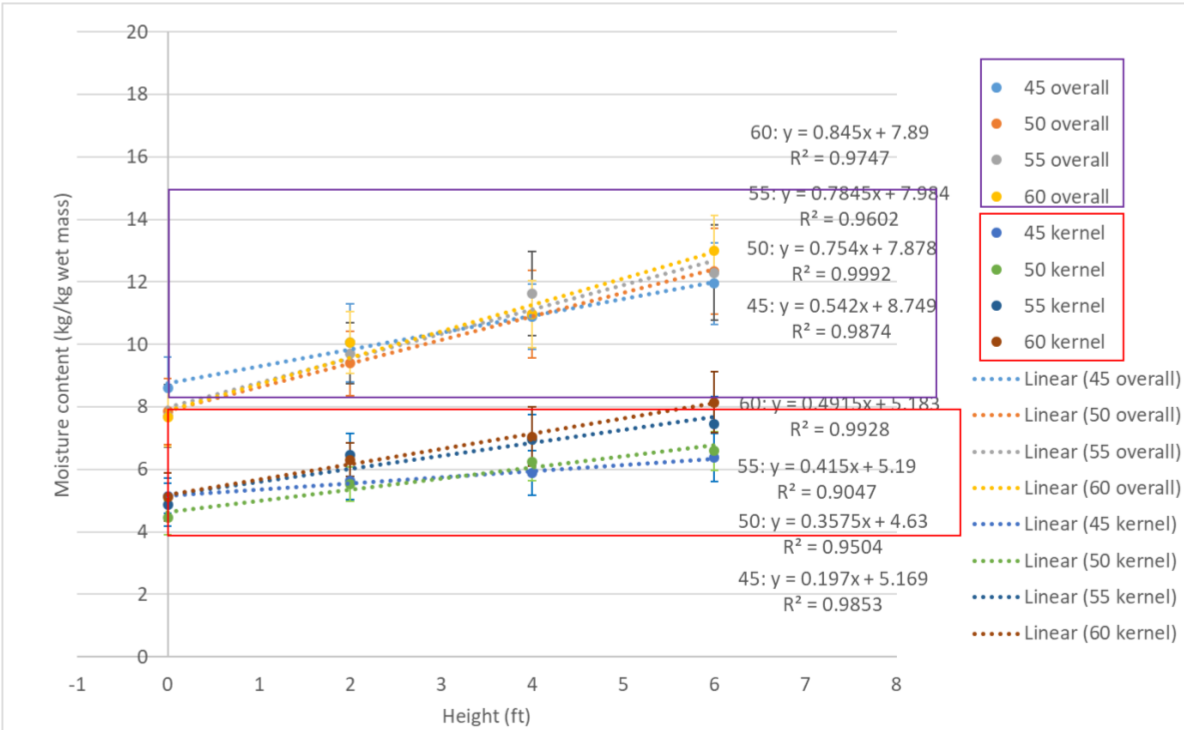


Figure AB.40 Variation of final MC in the overall almonds and almond kernels at different locations in the column dryer with 2.0 m/s air speed (MT)

Table AB.6 Summary of final MC of overall almonds and almond kernels (FR)

Air velocity (m/s)	Temp (°C)	Overall MC_{wb} (%)				Kernel MC_{wb} (%)			
		0 ft	2 ft	4 ft	6 ft	0 ft	2 ft	4 ft	6 ft
1	45	9.29 ± 1.07	9.58 ± 1.14	11.22 ± 1.04	14.89 ± 1.73	4.52 ± 0.56	5.56 ± 0.61	6.21 ± 0.85	6.97 ± 1.39
	50	9.03 ± 0.99	10.43 ± 1.19	12.65 ± 1.06	14.17 ± 1.80	4.19 ± 0.55	4.85 ± 0.55	5.71 ± 1.22	6.07 ± 1.77
	55	8.2 ± 1.06	9.87± 1.46	13.48 ± 1.71	15.41 ± 2.24	5.30 ± 0.69	6.07 ± 0.69	6.77 ± 1.47	7.37 ± 1.58
	60	7.19 ± 0.92	8.02 ± 1.29	12.58 ± 1.50	15.50 ± 1.64	4.33 ± 0.77	5.26 ± 0.53	6.95 ± 1.48	8.13 ± 1.58
2	45	9.40 ± 1.05	10.07 ± 1.13	12.22 ± 1.78	13.32 ± 1.66	4.56 ± 0.76	5.06 ± 0.84	5.44 ± 1.43	6.52 ± 0.85
	50	8.49 ± 0.97	10.63 ± 0.96	12.48 ± 1.64	15.42 ± 1.92	4.89 ± 0.47	5.31 ± 0.54	6.22 ± 1.25	7.00 ± 1.56
	55	7.99 ± 1.04	10.56 ± 1.14	12.38 ± 1.74	15.20 ± 1.85	4.23 ± 0.50	5.91 ± 0.51	7.37 ± 1.49	8.17 ± 1.89
	60	9.01 ± 1.07	11.06 ± 1.04	13.67 ± 1.32	15.89 ± 1.44	5.06 ± 0.44	6.22 ± 0.57	7.66 ± 0.87	8.31 ± 1.14

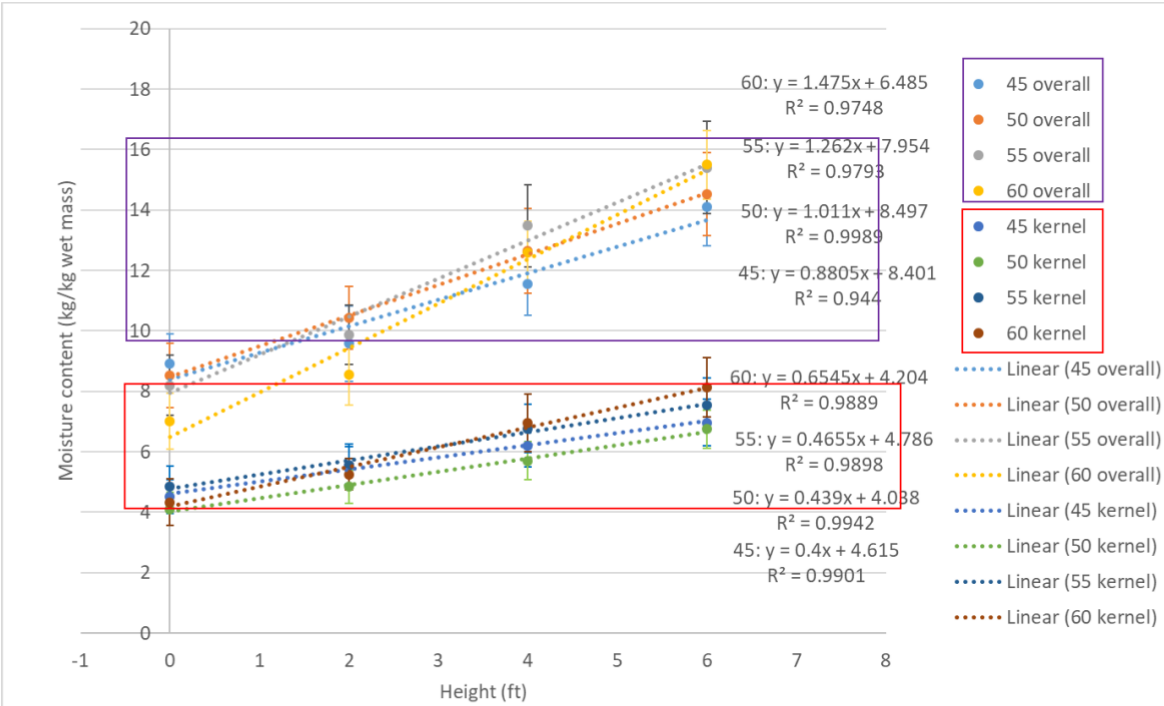


Figure AB.41 Variation of final MC in the overall almonds and almond kernels at different locations in the column dryer with 1.0 m/s air speed (FR)

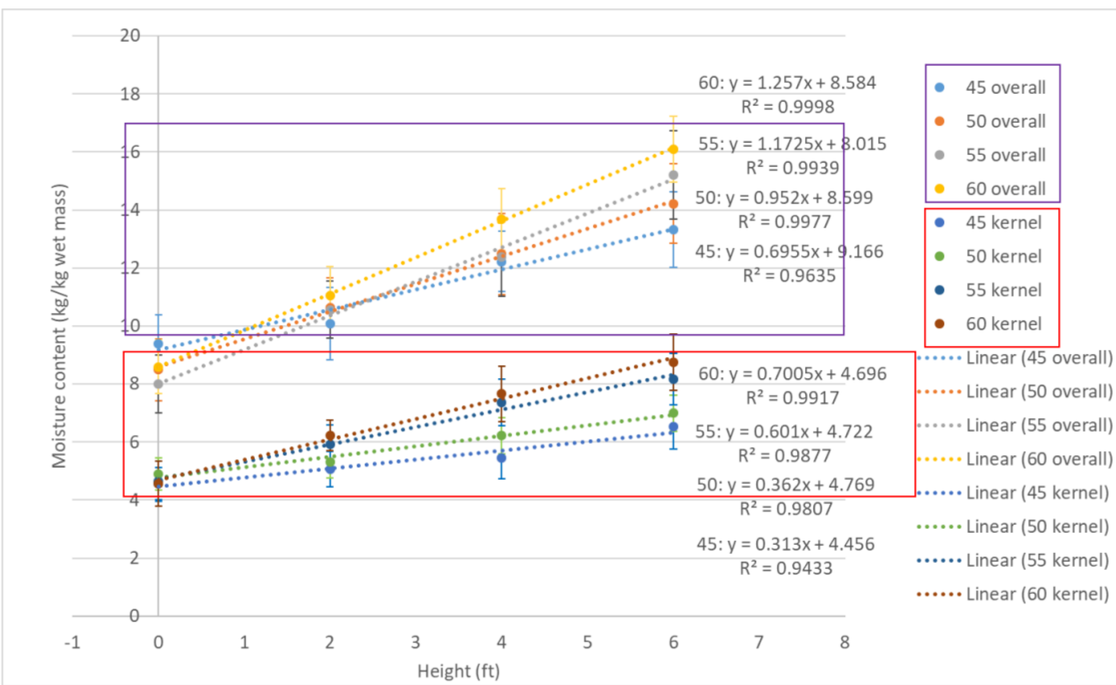


Figure AB.42 Variation of final MC in the overall almonds and almond kernels at different locations in the column dryer with 2.0 m/s air speed (FR)

Appendix B.3 Mathematical modeling of drying kinetics in pilot scale drying

Using the regression models, the initial and final moisture content of almonds in each test could be standardized, and the energy consumptions of the drying process for each variety could be estimated using the predicted drying time. The results are summarized in Table 17 to 19. It was found that both the specific energy consumption and energy cost increased with the increase in the drying air temperature. When the air speed was doubled, the SEC almost also doubled, however, the drying time was not greatly reduced. It was also found that the even though the IMC was similar, the Fritz almonds used shorter drying time compared to the Nonpareil variety. The results may be attributed to the fact that the Fritz almonds was smaller in size, and thus was dried faster.

Table AB.7 Summary of fitting parameters with the Page model (NP)

Air velocity (m/s)	**Temp (°C)**	**k**	**n**	**R_2**
1	45	-0.00386	0.8603	0.9985
	50	-0.00404	0.8615	0.9994
	55	-0.00419	0.8693	0.9994
	60	-0.00437	0.8748	0.9997
2	45	-0.00384	0.8630	0.9992
	50	-0.00417	0.8756	0.9999
	55	-0.00443	0.8893	0.9994
	60	-0.00478	0.9041	0.9999

Table AB.8 Summary of fitting parameters with the Page model (MT)

Air velocity (m/s)	**Temp (°C)**	**k**	**n**	**R_2**
1	45	-0.00354	0.9090	0.9993
	50	-0.00384	0.9138	0.9999
	55	-0.00414	0.9227	0.9989
	60	-0.00438	0.9291	0.9999
2	45	-0.00476	0.8427	0.9993
	50	-0.00525	0.8525	0.9994
	55	-0.00552	0.8639	0.9969
	60	-0.00591	0.8681	0.9985

Table AB.9 Summary of fitting parameters with the Page model (FR)

Air velocity (m/s)	Temp (°C)	k	n	R_2
1	45	-0.00390	0.8905	0.9993
	50	-0.00423	0.9078	0.9992
	55	-0.00456	0.9196	0.9995
	60	-0.00504	0.9351	0.9990
2	45	-0.00418	0.8767	0.9990
	50	-0.00463	0.8808	0.9994
	55	-0.00510	0.9046	0.9997
	60	-0.00594	0.9179	0.9987

Table AB.10 Summary of standardized drying time and energy consumption (NP)

Air velocity (m/s)	Temp (°C)	Initial MC_{wb} (%)	Final MC_{wb} (%)	Drying time (h)	Specific energy consumption (MJ/kg)	Energy cost (¢/lb)
1	45	20.77	11.98	5.32	9.26	1.8
	50	20.77	11.98	5	10.91	3.4
	55	20.77	11.98	4.55	11.95	2.1
	60	20.77	11.98	4.2	12.86	3.6
2	45	20.77	11.99	5.25	17.22	2.3
	50	20.77	11.97	4.4	18.32	3.8
	55	20.77	11.97	3.78	19.05	2.5
	60	20.77	11.93	3.2	18.88	3.7

Table AB.11 Summary of standardized drying time and energy consumption (MT)

Air velocity (m/s)	Temp (°C)	Initial MC_{wb} (%)	Final MC_{wb} (%)	Drying time (h)	Specific energy consumption (MJ/kg)	Energy cost ($/kg)
		Ave	Ave			
1	45	18.93	11.99	3.5	7.71	0.0258
	50	18.93	11.99	3.15	8.63	0.0292
	55	18.93	11.93	2.75	9.09	0.0306
	60	18.93	11.97	2.5	9.64	0.0325
2	45	18.93	11.95	3.75	15.57	0.0521
	50	18.93	11.93	3.15	16.56	0.0556
	55	18.93	11.94	2.8	17.75	0.0599
	60	18.93	11.98	2.5	18.75	0.0629

Table AB.12 Summary of standardized drying time and energy consumption (FR)

Air velocity (m/s)	Temp (°C)	Initial MC_{wb} (%)	Final MC_{wb} (%)	Drying time (h)	Specific energy consumption (MJ/kg)	Energy cost ($/kg)
		Ave	Ave			
1	45	21.63	11.95	4.7	7.43	0.0359
	50	21.63	11.99	3.87	7.66	0.0371
	55	21.63	11.94	3.3	7.89	0.0380
	60	21.63	11.98	2.72	7.59	0.0366
2	45	21.63	11.99	4.72	14.11	0.0679
	50	21.63	11.95	4.1	15.55	0.0749
	55	21.63	11.98	3.2	14.67	0.0709
	60	21.63	11.98	2.5	13.50	0.0650

Appendix B.4 Standardized energy consumption for pilot scale drying

The energy consumption was estimated for each drying test, and the results were standardized to the specific energy consumption (SEC, MJ/kg moisture removal), and are summarized in Tables AB.13 to AB.15. Correspondingly, the energy consumptions and percentage of SEC by each fraction and component were calculated and shown in Tables 11 to 13 and Figures 26 to 28. As a reference, the specific energy consumption of walnut drying in the same dryer at different temperatures (43 to 75$_{o}$C) ranged from 9.83 to 12.69 MJ/kg, which were similar to the values obtained in this study for almond drying. The energy cost for each drying test was estimated using the local electricity rate in Yolo county (14.08 ¢/kWh) and summarized in Tables AB.13 to AB.15.

It was found that lower air velocity resulted in less energy consumption for the almonds drying. In general, the trends of different temperature levels were not clear. This may be attributed to the fact that the energy consumption was related to the drying time and energy consumption rate under different conditions, and the IMC of each test was slightly different. When the total energy consumption was decomposed into different components, it was found that over 60% in average, was consumed for the drying of green hull, and only around 20% of energy was used for the drying of kernels.

Table AB.13 Summary of specific energy consumption by each part (NP)

Air velocity (m/s)	Temp (°C)	Specific energy consumption (MJ/kg)					
		Hull	IH-H	IH-S	IH-K	IS-S	IS-K
1	45	3.15	3.69	0.82	1.35	0.84	1.38
	50	4.63	4.25	0.94	1.55	0.66	1.08
	55	4.49	5.20	1.16	1.90	0.78	1.27
	60	4.12	4.31	0.96	1.57	0.62	1.01
2	45	5.96	7.34	1.63	2.68	1.59	2.59
	50	5.40	6.44	1.43	2.35	1.12	1.83
	55	6.52	6.18	1.37	2.26	0.71	1.16
	60	5.98	5.98	1.33	2.18	0.79	1.29

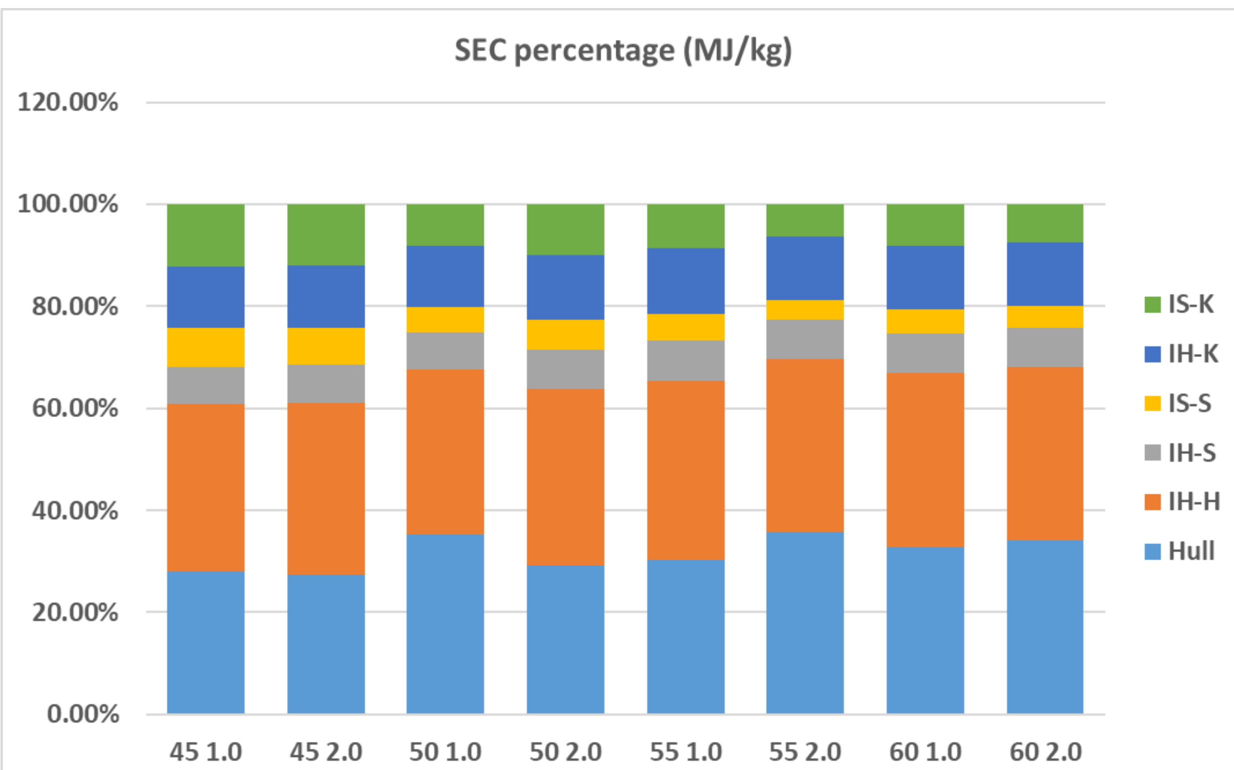


Figure AB.43 Specific energy consumption (SEC) for column dryer at different drying conditions (NP)

Table AB.14 Summary of specific energy consumption by each part (MT)

Air velocity (m/s)	Temp (°C)	Specific energy consumption (MJ/kg)					
		Hull	IH-H	IH-S	IH-K	IS-S	IS-K
1	45	2.55	2.61	1.04	1.09	0.86	0.94
	50	4.40	3.53	1.41	1.47	0.79	0.86
	55	3.39	3.43	1.37	1.43	0.74	0.81
	60	4.42	4.04	1.61	1.69	0.84	0.91
2	45	6.18	6.65	2.66	2.78	2.08	2.25
	50	4.79	4.99	2.00	2.09	1.26	1.36
	55	6.81	5.63	2.25	2.36	0.94	1.02
	60	8.09	7.06	2.82	2.95	1.35	1.47

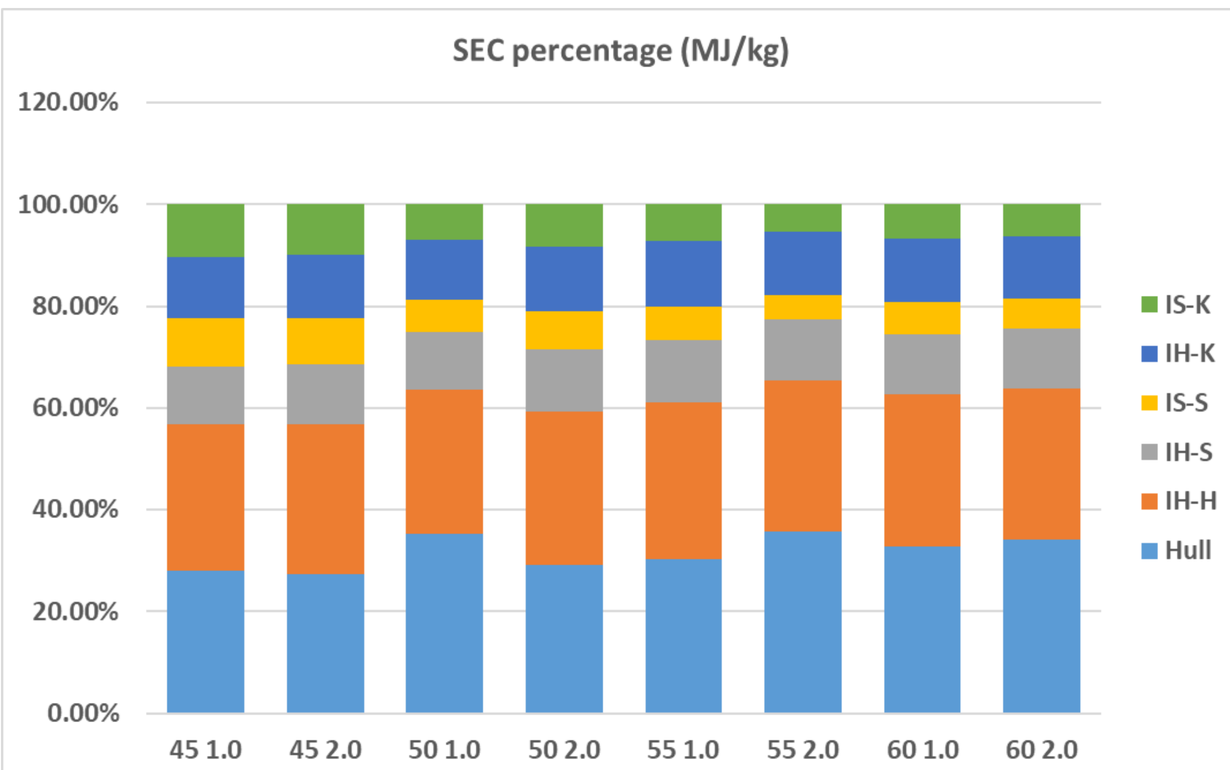


Figure AB.44 Specific energy consumption (SEC) for column dryer at different drying conditions (MT)

Table AB.15 Summary of specific energy consumption by each part (FR)

Air velocity (m/s)	Temp (°C)	Specific energy consumption (MJ/kg)					
		Hull	IH-H	IH-S	IH-K	IS-S	IS-K
1	45	2.01	2.06	0.82	0.86	0.68	0.74
	50	3.66	2.93	1.17	1.23	0.66	0.71
	55	2.84	2.88	1.15	1.20	0.62	0.68
	60	2.68	2.45	0.98	1.02	0.51	0.55
2	45	4.39	4.73	1.89	1.98	1.48	1.60
	50	5.55	5.78	2.31	2.42	1.46	1.58
	55	5.44	4.50	1.80	1.88	0.75	0.81
	60	7.67	6.70	2.68	2.80	1.28	1.39

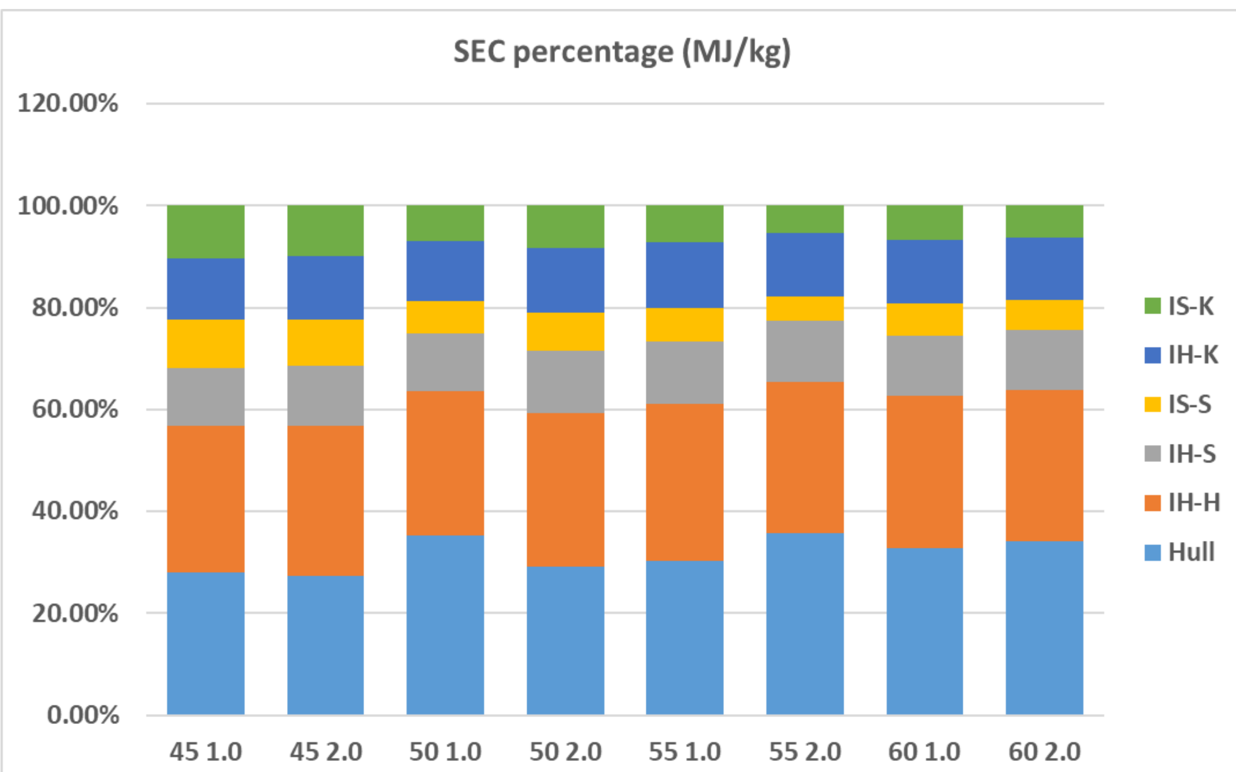


Figure AB.45 Specific energy consumption (SEC) for column dryer at different drying conditions (FR)

Appendix B.5 Whiteness index and Color development score

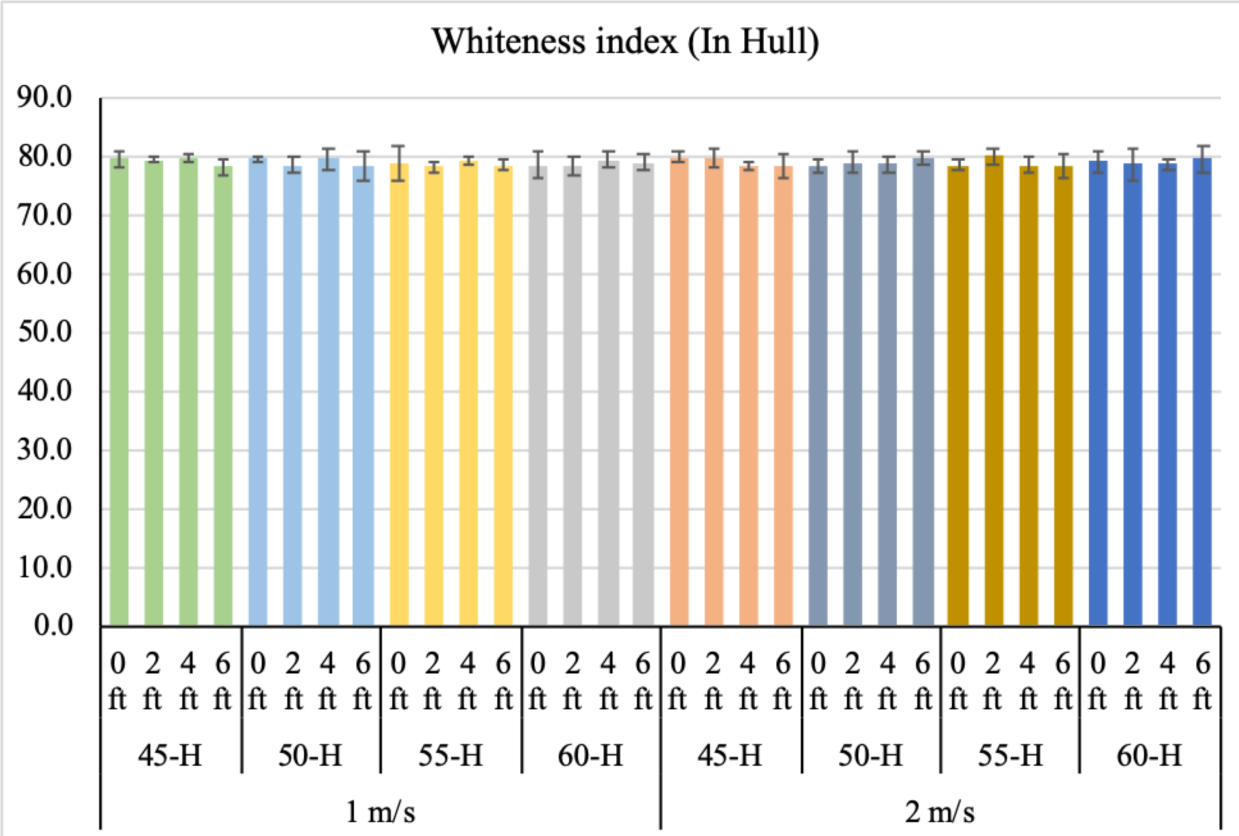


Figure AB.46 Whiteness index of in-hull almonds for Nonpareil variety

Figure AB.47 Whiteness index of in-shell almonds for Nonpareil variety

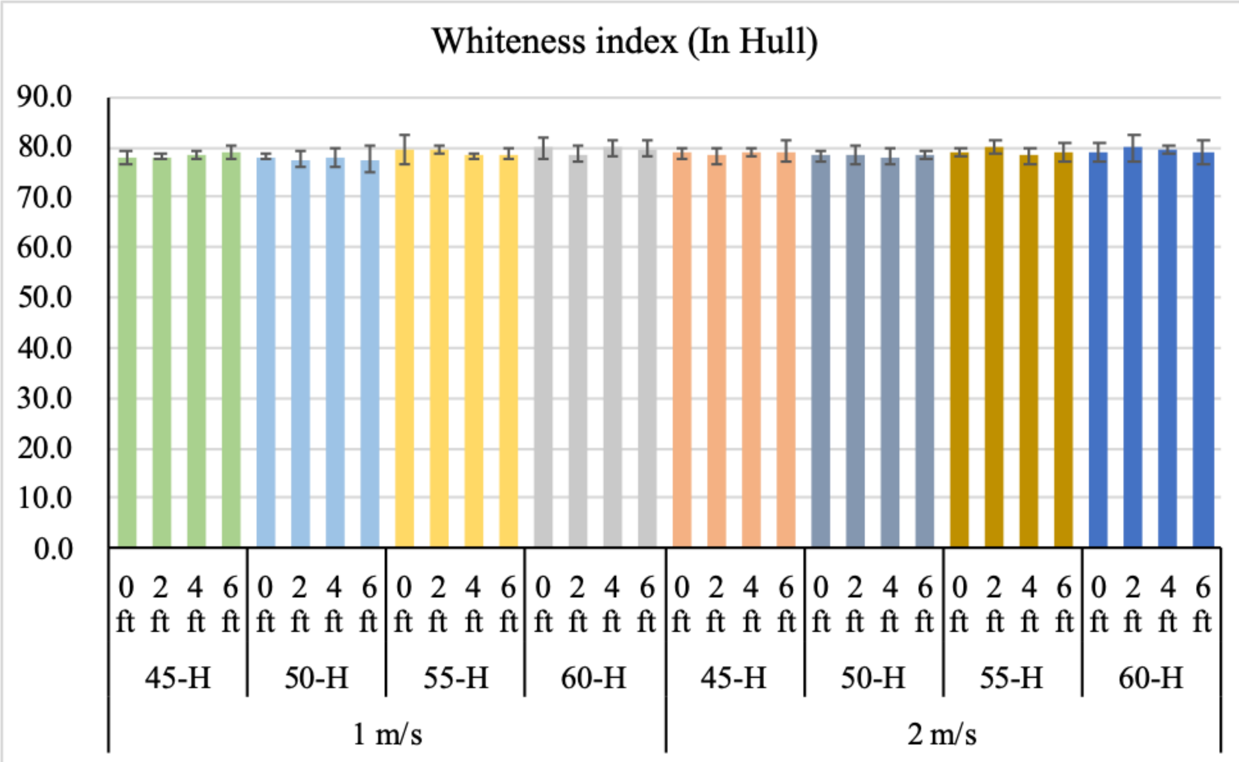


Figure AB.48 Whiteness index of in-hull almonds for Monterey variety

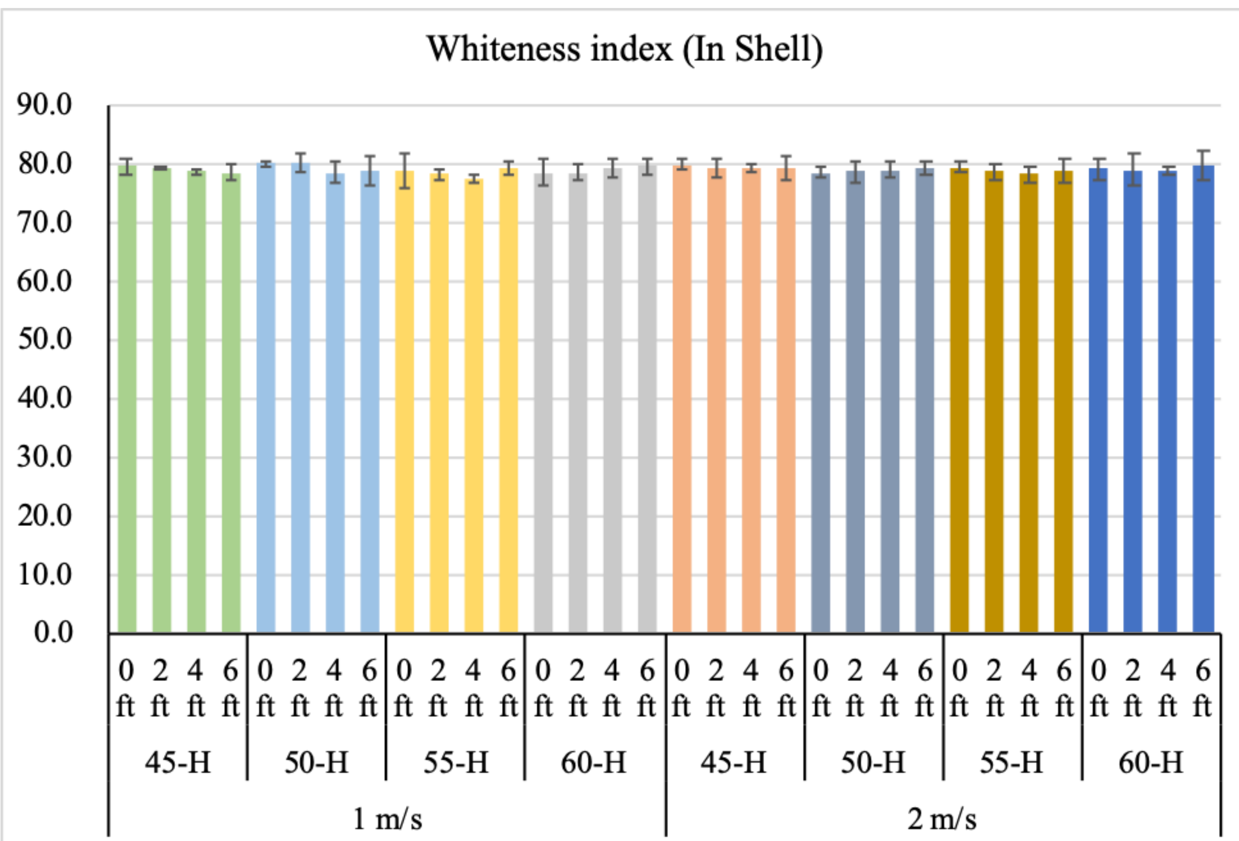


Figure AB.49 Whiteness index of in-shell almonds for Monterey variety

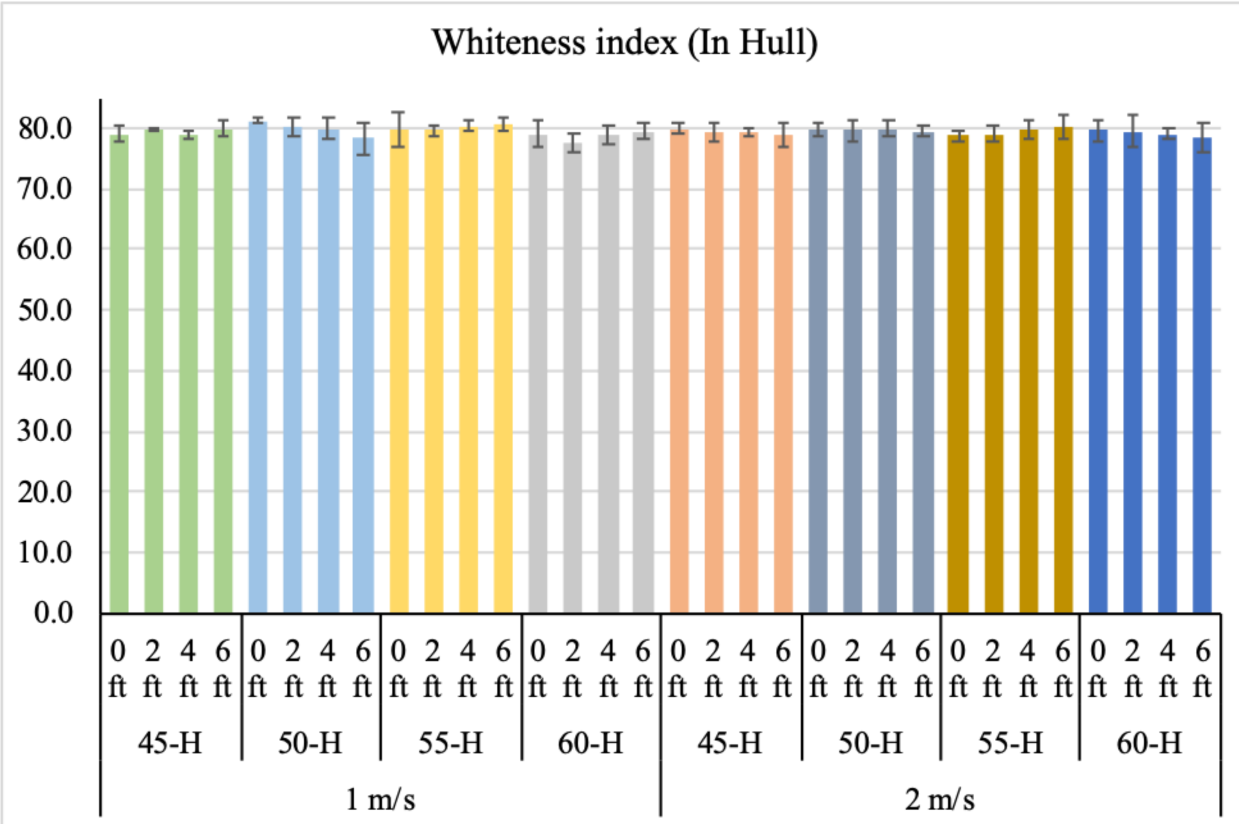


Figure AB.50 Whiteness index of in-hull almonds for Fritz variety

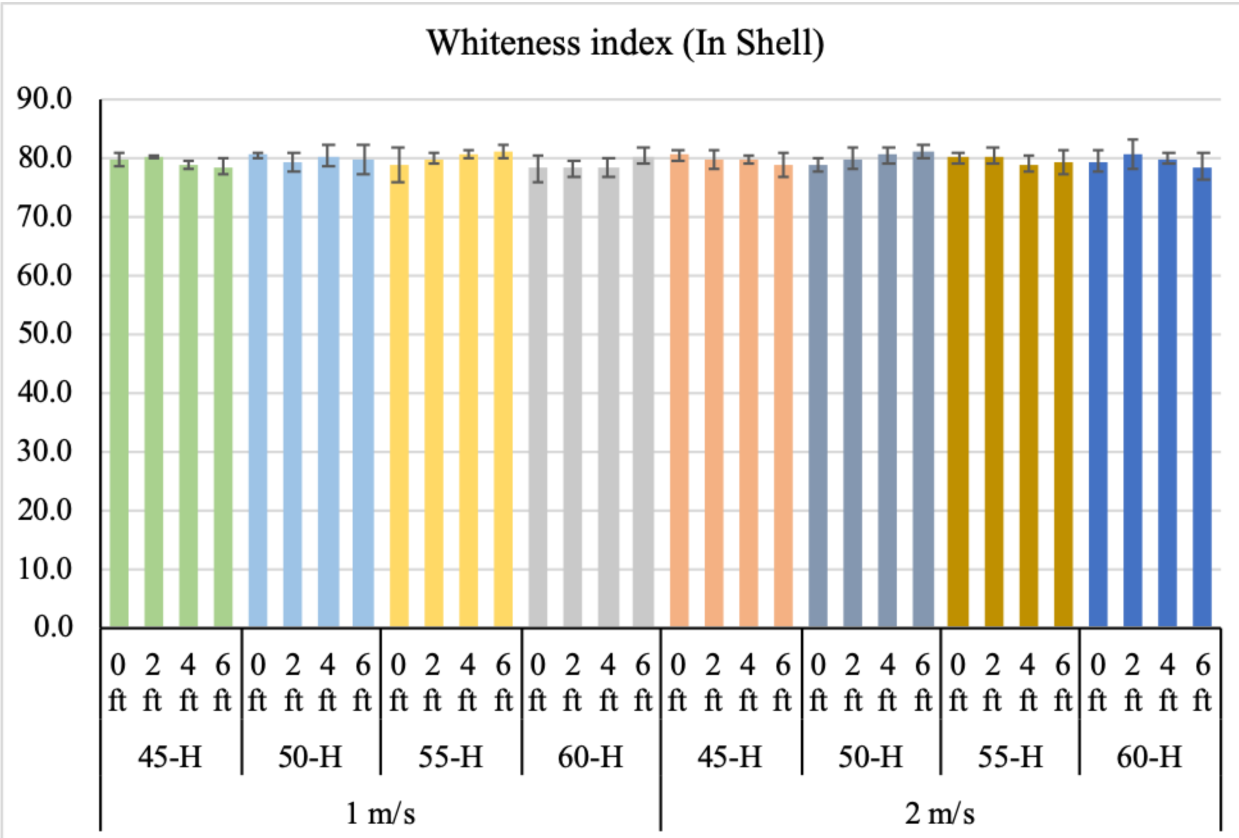


Figure AB.51 Whiteness index of in-shell almonds for Fritz variety

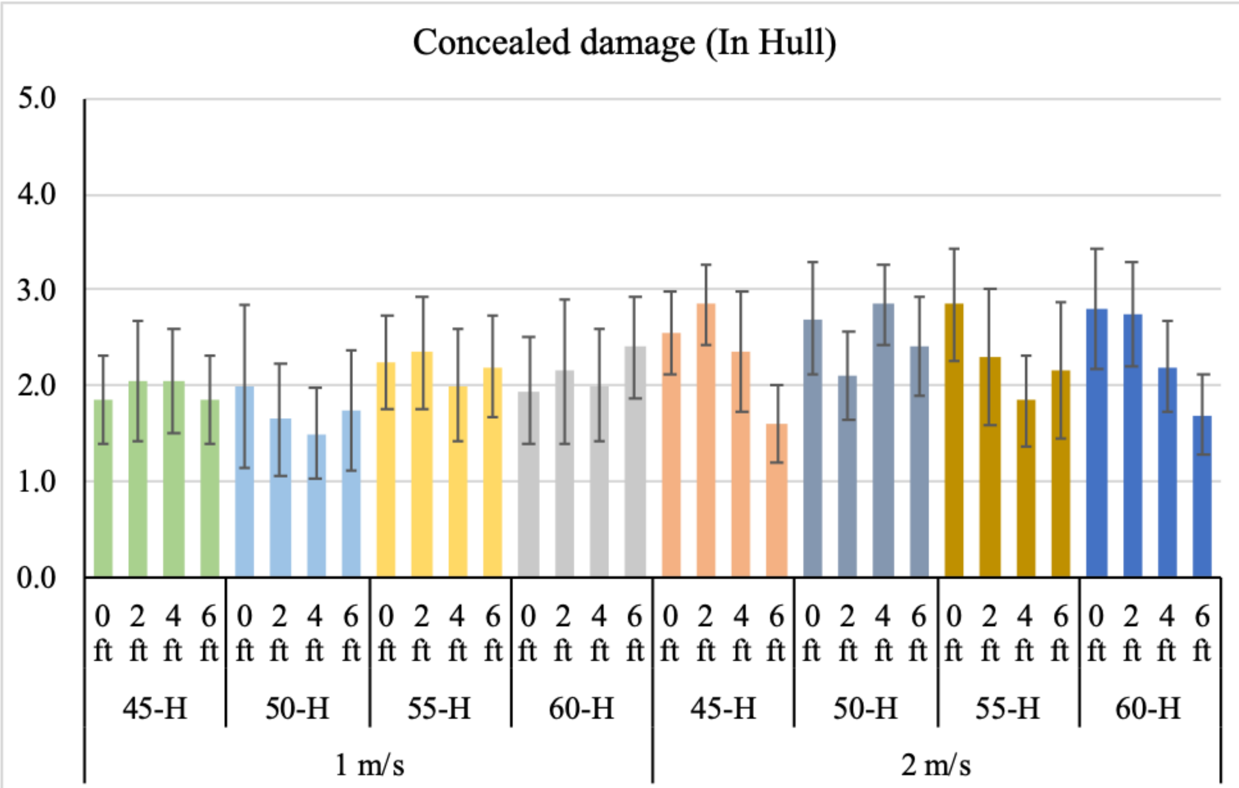


Figure AB.52 Color development score of in-hull almonds for Nonpareil variety

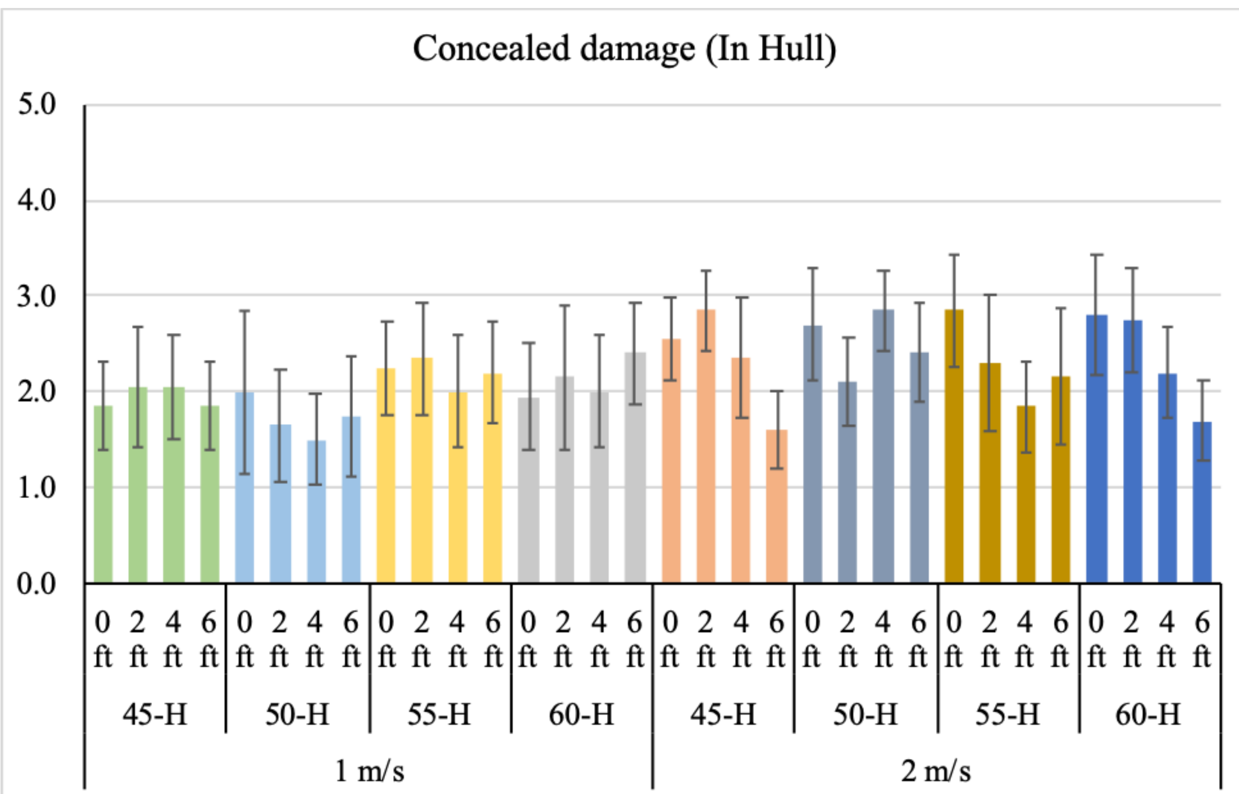


Figure AB.53 Color development score of in-shell almonds for Nonpareil variety

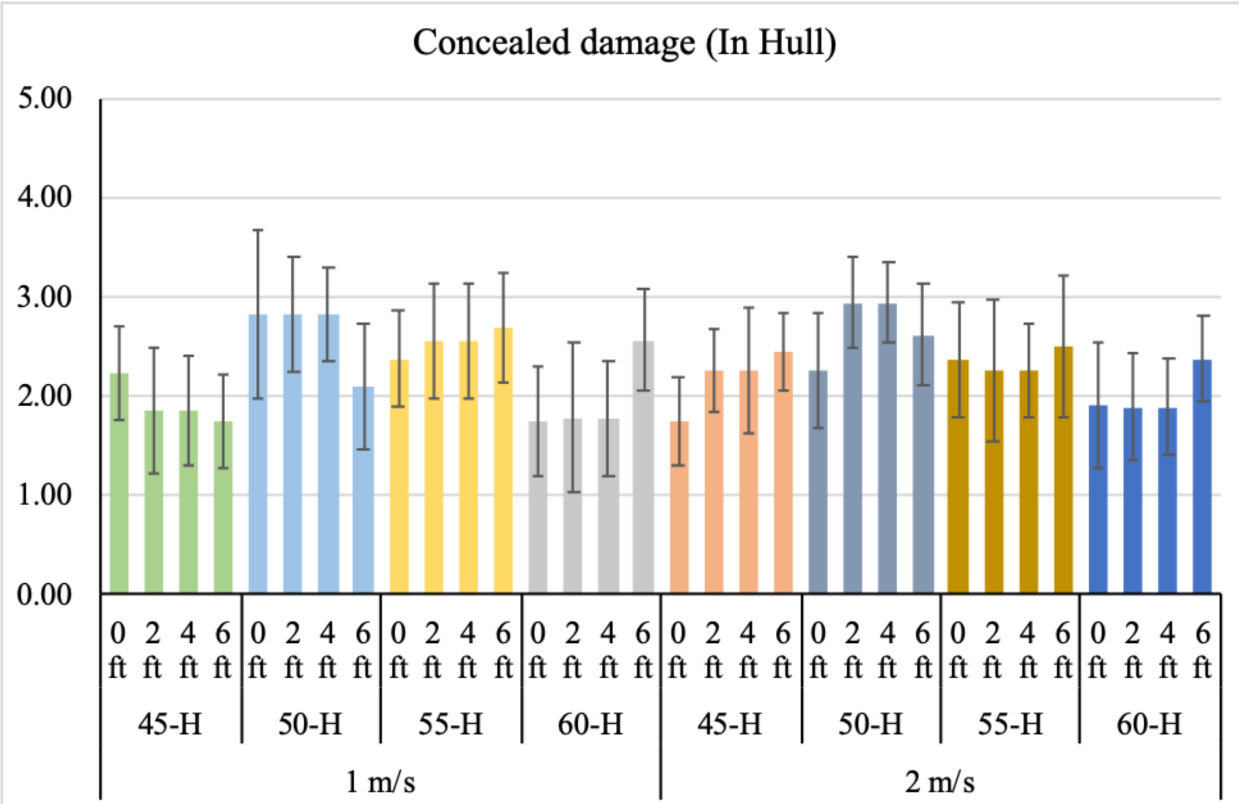


Figure AB.54 Color development score of in-hull almonds for Monterey variety

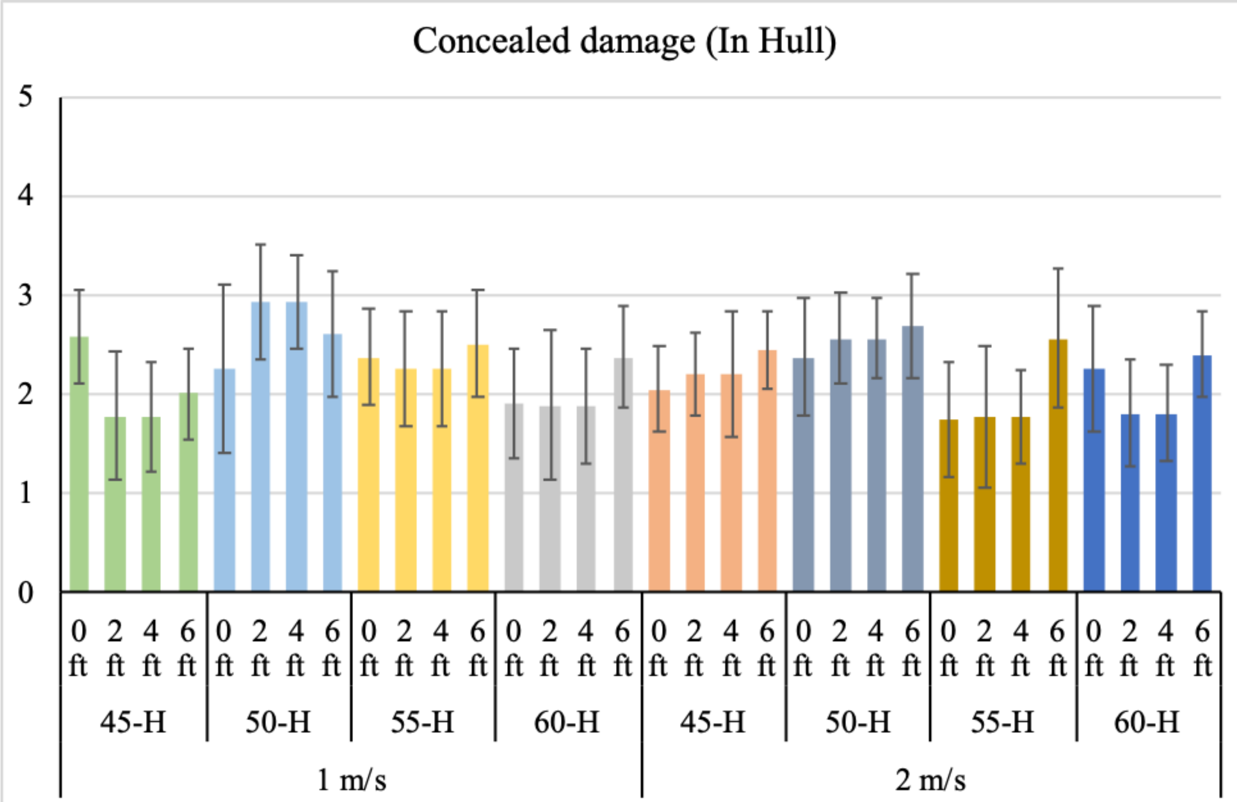


Figure AB.55 Color development score of in-shell almonds for Monterey variety

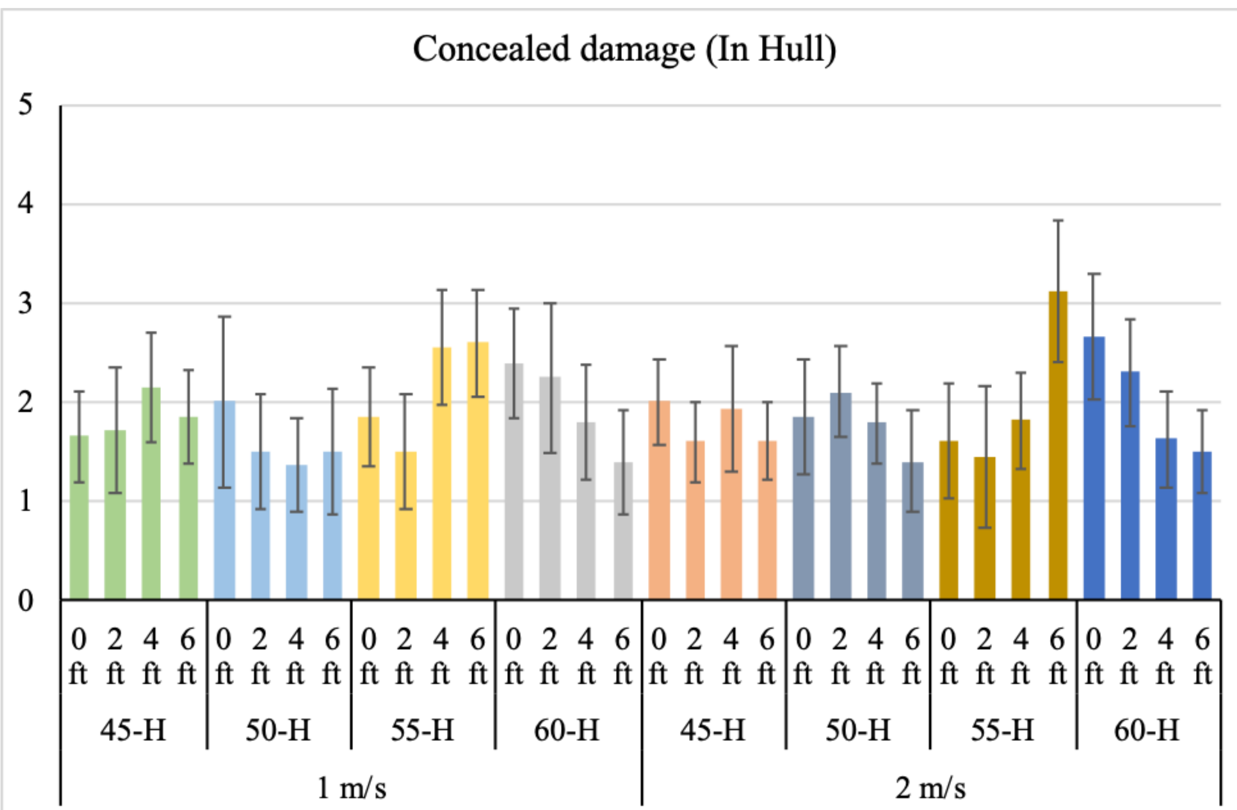


Figure AB.56 Color development score of in-hull almonds for Fritz variety

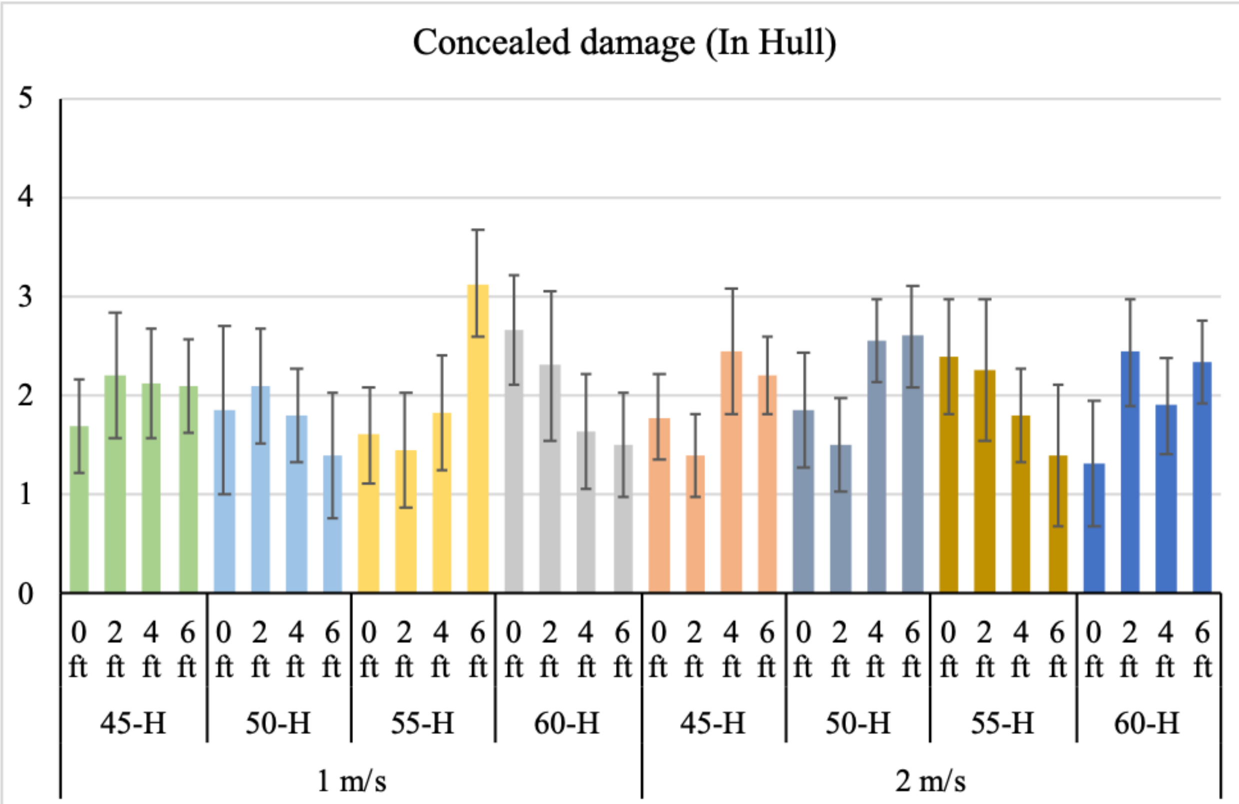


Figure AB.57 Color development score of in-shell almonds for Fritz variety

Appendix C.1 Sorting of almonds

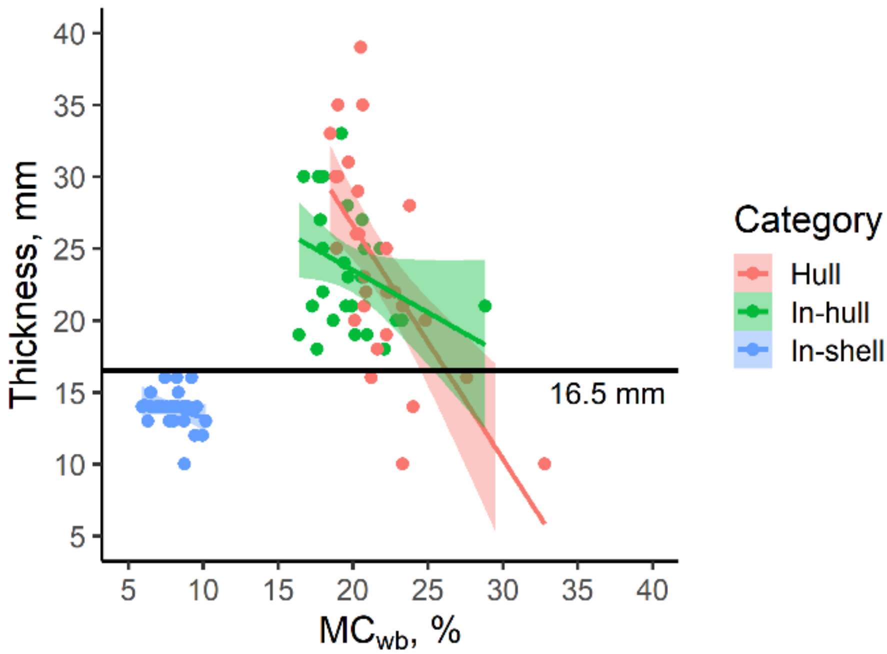


Figure AC.1 Separation of in-shell almonds from hulls and in-hull almonds based on thickness for the Nonpareil variety

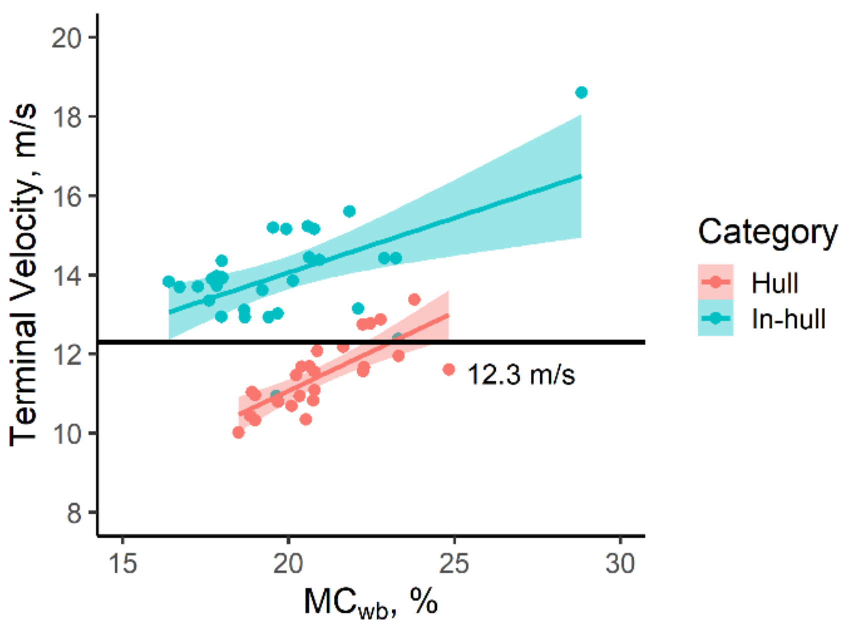


Figure AC.2 Separation of hulls and in-hull almonds based on terminal velocity for the Nonpareil variety

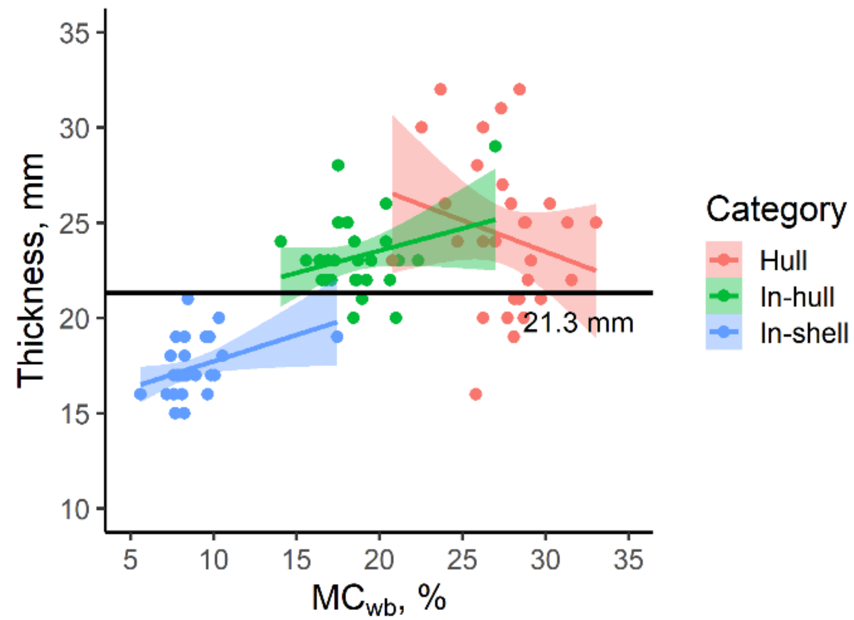


Figure AC.3 Separation of in-shell almonds from hulls and in-hull almonds based on thickness for the Monterey variety

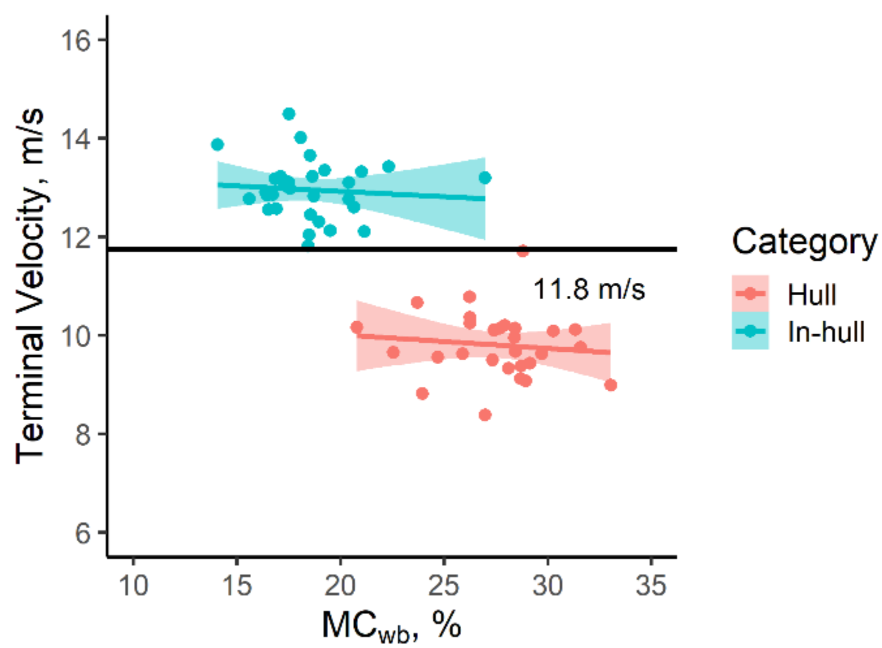


Figure AC.4 Separation of hulls and in-hull almonds based on terminal velocity for the Monterey variety

variety

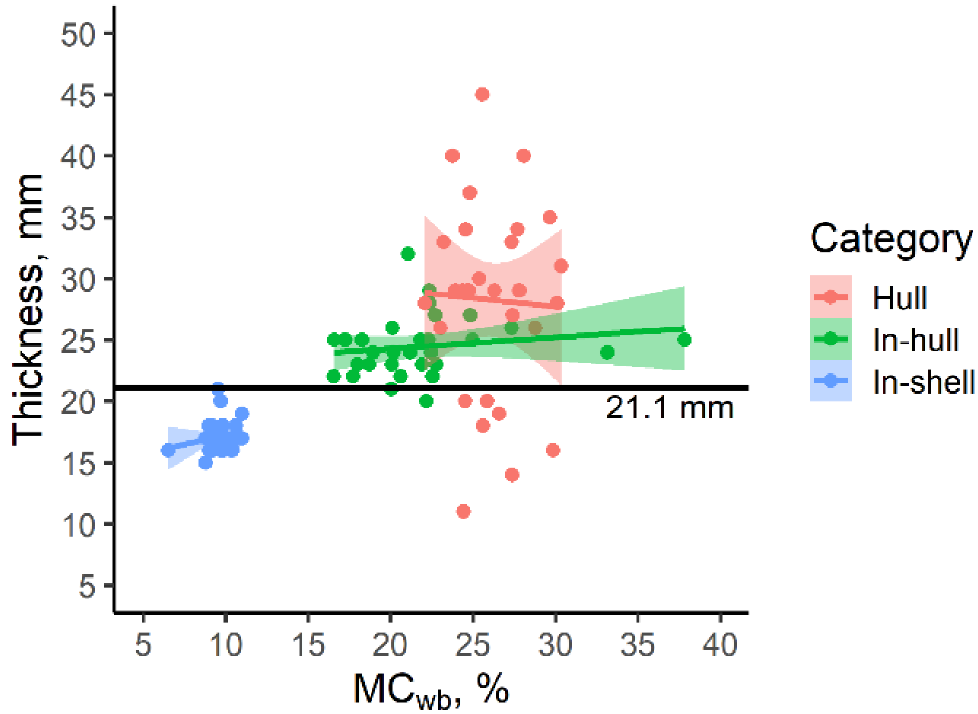


Figure AC.5 Separation of in-shell almonds from hulls and in-hull almonds based on thickness for the Fritz variety

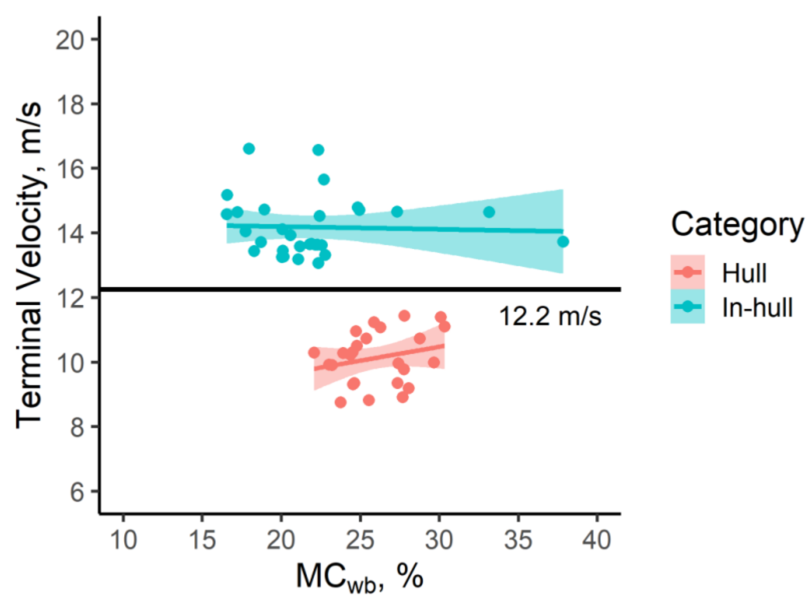


Figure AC.6 Separation of hulls and in-hull almonds based on terminal velocity for the Fritz variety