Received: 4 April 2017 | Accepted: 11 September 2017
DOI: 10.1111/jfpe.12632

ORIGINAL ARTICLE

WILEY Journal of Food Process Engineering

Kinetic modeling of hazelnut drying: Effects of different cultivars and drying parameters

A. Giraudo[1] | N. Valentini[2] | A. Venturello[1] | F. Savorani[1] | E. Bertone[1] | G. Bonazzola[2] | G. Zeppa[2] | F. Geobaldo[1]

[1]Department of Applied Science and Technology, Polytechnic of Turin, Corso Duca degli Abruzzi 24, Turin I-10129, Italy

[2]Department of Agricultural, Forestry and Food Sciences, University of Turin, Largo Paolo Braccini 2, Grugliasco (Turin) I-10095, Italy

Correspondence
F. Savorani, Department of Applied Science and Technology, Polytechnic of Turin, Corso Duca degli Abruzzi 24, Turin I-10129, Italy.
Email: francesco.savorani@polito.it

Abstract

In this study, for the first time, six different hazelnut cultivars, characterized by different carpological traits (diameter, volume, weight, density, shell thickness, shape index, empty volume between kernel and shell), were utilized for conducting 60 experiments in a lab-scale convective dryer, in which different drying air conditions (temperatures: 20 °C, 35 °C, 50 °C; relative humidity: 20%, 40%, 60%; airflow: 0.5 m/s) were explored with a Design of Experiment approach. The obtained drying curves where mathematically modeled and, among the tested kinetic models, the Fick's equation proved to best fit the drying data and was chosen to estimate the equilibrium moisture content (*Me*) and the drying rate (*k*) for each experiment, based on the studied variables. The *k* parameter was found to be greatly affected ($p < .01$) by the carpological traits related to the hazelnut dimension, by *T* and RH. Conversely, a weak correlation ($p \approx .05$) was found between the carpological traits and *Me* which, instead, resulted being greatly affected by *T* and RH ($p < .01$).

Practical applications

The precise definition of the complex dynamics involved in hazelnut drying process represents a crucial step toward an exhaustive comprehension and optimization of the drying process itself. The possibility of tailoring the process parameters to guarantee the best drying conditions for a specific lot of shelled hazelnuts represents an important goal eagerly pursued by the modern confectionary industry. During the last years, this topic has attracted a broad industrial interest, resulting in many research studies investigating the drying process. Our study takes into consideration not only the classical drying parameters but also the variability introduced by the carpological traits of different hazelnut cultivars and allows defining a mathematical model of general applicability, which describes the drying process and that could be potentially exploited to optimize the performance of the hazelnut drying at the industrial level.

1 | INTRODUCTION

Hazelnut (*Corylus avellana* L.) is worldwide one of the most important among nut crops and it accounts for a cultivated area of approximately 604,000 ha and a yearly production of about 840,000 tons of in-shell nuts. Over 65% of the hazelnut world production is supplied by Turkey, while Italy is the second hazelnut producer (13%) (average 2011–2013, FAOSTAT, 2015).

The largest part of the production is stored and used for several food preparations or products; only about 10% is directly consumed. Quality and organoleptic attributes of the final products are strongly dependent on the preprocessing treatments and the storage conditions of the seeds (Fontana, Somenzi, & Tesio, 2014).

Consequently, over the years, industries have regulated technological, chemical and organoleptic standards to define the hazelnut quality (Garrone & Vacchetti, 1992).

One of the most important factors affecting hazelnut quality is moisture content, since seeds are perishable in their fresh state and may deteriorate within a few days after harvest (Richardson, 1988). The water activity beyond certain limits promotes the development of molds, color changes, and rancidity. In Italy, nuts are traditionally harvested from the ground, picked up in one or two harvests, and sometimes the harvesting time can coincide with unfavorable weather conditions, such as summer storms, that can increase the nut moisture content above 20% wt (Tous et al., 2001). The kernel lipid content in hazelnuts is very high, up to 60% wt, with a considerable amount of unsaturated fatty acids (Amaral et al., 2006; Parcerisa, Richardson, Rafecas, Codony, & Boatella, 1998), which makes the kernel easily perishable due to rancidity.

For these reasons, to extend the storage life as long as possible while preserving the original quality, nuts must be dried immediately after harvest to reach a moisture content below 6% wt (Garrone & Vacchetti, 1992; Richardson, 1988).

Sun drying is a cheap method used by small producers. However, this method is not suitable for large productions (Lopez et al., 1998). For this reason, drying is carried out using forced air circulation driers with a slow stream of warm air (40–45 °C).

The dynamics involved in the hazelnut moisture exchange during drying need to be carefully understood for developing a drying model that will provide optimal solutions to be implemented at the industrial level.

Even though several studies dealing with drying kinetics and moisture transfer parameters are reported in literature, the complex structure and chemical composition of hazelnuts (Lopez et al., 1997, 1998) have not allowed obtaining a complete set of reliable information on the process yet. In the following, the principal studies dealing with the hazelnut drying process parameters are reported in chronological order.

Lopez et al. (1998) studied the effects of drying air conditions on the equilibrium moisture content for Spanish hazelnuts. Demirtas, Ayhan, and Kaygusuz (1998) solved a diffusion equation using implicit numerical methods to simulate the drying behavior of hazelnuts. Topuz, Gur, and Gul (2004) proposed a mathematical model for the simulation of simultaneous unsteady heat and mass transfer in nuts, using a fluidized bed drying. Kaya, Aydin, and Akgun (2011) investigated the sorption isotherms and the drying kinetics of hazelnuts under different temperature, relative humidity, and rate of drying air.

All these research studies provided useful piece of information about the drying process, suggesting that moisture removal could be described by means of few leading parameters.

In this work, we studied the drying trends of six hazelnut cultivars under different drying air conditions using a simple and rather practical approach. A novelty aspect of this research work with respect to the previous ones is the parallel investigation on six different hazelnut cultivars, characterized by different carpological traits. This provided a wider set of information that allowed us defining a mathematical model of general purpose for the hazelnut drying process, as it also takes into account the significant carpological traits.

2 | MATERIALS AND METHODS

2.1 | Hazelnut samples

"Camponica" (CA), "Nocchione" (NO), "Pauetet" (PA), "Ribet" (RI), "Tonda Gentile delle Langhe" (TGL) and UNITOL35 (L35) varieties were used as hazelnut cultivar for the study.

"**TGL**" was taken as the reference cultivar for Piedmont region and is commonly used in confectionery. "**L35**" selection was obtained from the crossing TGL × "Lansing" by the University of Turin (Valentini, Me, Vallania, & Zeppa, 2001; Valentini, Rolle, Stevigny, & Zeppa, 2006) and chosen for its very large size of the nut, very appreciated for direct consumption. "**Camponica**" was selected for the large nut size and medium shell thickness, while "**Nocchione**" was considered for its high shell thickness. "**Pauetet**" and "**Ribet**" (Spanish cultivars) were selected for their small nut size and thin shell thickness.

Samples of 5 kg for each cultivar were manually harvested from the ground just after the natural drop. The hazelnuts were collected in the period between 20 August and 6 September 2013, following the ripening time of each cultivar, in a germplasm hazelnut collection located in Chieri at 350 m a. s. l. (N 45°04', E 7°83', near Torino, Piedmont, Northwest Italy). Even though these cultivars where all harvested from the same restricted geographical area and at their commercial ripening, consistent differences in initial moisture content exist, ranging from 15% to 25% of relative humidity, that are of course relevant when considering a drying process.

On harvesting, samples were cold stored (6 °C, 55% RH) in vacuum bags (500 g) to preserve their moisture content until the beginning of the drying experiments.

Nuts were visually inspected to discard the damaged ones, according to the rules followed at the industrial level for the assessment of supply quality. Furthermore, a selection based on the mean weight was done, to eliminate empty shells ("blanks").

Before the beginning of the drying experiments, the samples, still under vacuum in their bags, were kept at room temperature for 24 hr to avoid changes of their moisture content.

2.2 | Carpological descriptors of fruits

To define the average carpological traits of each cultivar, three replicates of 30 raw hazelnuts for each variety were randomly selected and their carpological traits, represented by 13 different descriptors (Table 1), were analyzed. The measurements were accurately performed on each hazelnut, individually, for a total of 6 × 3 × 30 (540) nuts.

The weight of the nuts ($\boldsymbol{W_n}$) and of the kernels ($\boldsymbol{W_k}$) was measured using a precision balance (VWR 611–2602, ± 0.01 g; VWR, Radnor, PA). The nut volume (V_n^{mlL}) was measured by soaking the entire hazelnuts in 200 ml of water. Then, length (*L*), width (*w*), and depth (*d*) of both whole nut and kernel were measured using a caliper (VWR i819-0013, ± 0.01 mm).

The thickness of the shell ($\boldsymbol{T_s}$) was measured in two different positions using a caliper.

The density of the nut (D_n) was defined as the ratio W_n/V_n^{ml}.

The percentage of kernel by weight (**PKW**) was calculated as:

$$\mathbf{PKW} = \boldsymbol{W_k} / \boldsymbol{W_n} \times 100 \tag{1}$$

The nut volume (V_n^{mmc}) and the kernel volume (V_k^{mmc}) were estimated using the ellipsoid formula (Valentini et al., 2006):

TABLE 1 Carpological traits used to describe hazelnut cultivars

1	W_n	Nut weight (g)
2	V_n^{ml}	Nut volume (ml)
3	D_n	Nut density (g/ml)
4	W_k	Kernel weight (g)
5	PKW	Kernel by weight (%)
6	V_n^{mmc}	Nut volume (mmc)
7	V_k	Kernel volume (mmc)
8	Ve	Empty volume (%)
9	PKV	Kernel by volume (%)
10	SIR	Shape index ratio (%)
11	T_s	Shell thickness (mm)
12	Dp	Dp (mm)
13	T_s/Dp	Shell thickness/Dp (%)

$$\mathbf{V_n^{mmc}};\ \mathbf{V_k^{mmc}} = (4/3) \times \pi \times (\mathbf{L}/2)\times(\mathbf{w}/2)\times(\mathbf{d}/2) \quad (2)$$

The empty volume between kernel and shell (**Ve**) was defined as:

$$\mathbf{Ve} = \left[1-\left(\mathbf{V_k^{mmc}}/\mathbf{V_n^{mmc}}\right)\right] \times 100 \quad (3)$$

The percentage of kernel by volume (**PKV**) was calculated as:

$$\mathbf{PKV} = \left(\mathbf{V_k^{mmc}}/\mathbf{V_n^{mmc}}\right) \times 100 \quad (4)$$

The shape index of nut (SI_n) and kernel (SI_k) were estimated using the formula:

$$\mathbf{SI}_{(n,\ k)} = (\boldsymbol{w}+\boldsymbol{d})/2\boldsymbol{L} \quad (5)$$

Thus, the shape index ratio **(SIR)** was defined as the ratio between SI_n and SI_k.

The geometric mean diameter (***Dp***) of the nut was obtained as (Mohsenin, 1970):

$$\boldsymbol{Dp} = (\boldsymbol{L}\times\boldsymbol{w}\times\boldsymbol{d})/3 \quad (6)$$

Eventually, the ratio $\boldsymbol{T_s/Dp}$ was calculated.

The Tukey's test was used to evaluate the differences among the six nut cultivars according to each carpological descriptor, using the software "SPSS Statistics 21.0" (IBM, New York).

2.3 | Drying experiments

The drying tests were conducted on the six cultivars using a 2^2 full factorial design, with validation of the central point, by spanning from high to low air *T* and RH values (Table 2), according to the main works found in literature (Demirtas et al., 1998; Kaya et al., 2011; Lopez et al., 1998). Experiments were performed in duplicate for each experimental condition defined by the design, producing data for an overall set of 5 conditions x 6 cultivars x 2 replicates = 60 drying tests.

The drying experiments were performed using an in-house made, pilot convective dryer (Figure 1), mimicking the industrial process.

For each drying test, approximately 500 g of hazelnuts per cultivar were placed in separate plastic net baskets (that allowed the air to freely flow through) and put inside the drying chamber, which was a stainless steel cubic box with 30 cm internal length, insulated with spray rubber coating in the inner walls. The chamber was accessible for sample transportation from the upper part of the box that could be opened. The *T* and the RH of the air inside the drying chamber were constantly monitored by means of a RH/*T* sensor (EE07, E + E Elektronik Ges.m.b.H., Austria) interfaced to a personal computer.

TABLE 2 Experimental design planned for the drying tests

Drying *T* (°C)	Drying RH (%)	Cultivar
20	20	Nocchione
20	60	
50	20	
50	60	
35	40	
20	20	Pauetet
20	60	
50	20	
50	60	
35	40	
20	20	L35
20	60	
50	20	
50	60	
35	40	
20	20	Camponica
20	60	
50	20	
50	60	
35	40	
20	20	Ribet
20	60	
50	20	
50	60	
35	40	
20	20	TGL
20	60	
50	20	
50	60	
35	40	

The drying air inside the chamber was heated by a Peltier cell that was connected to a P.I.D. regulation system (E5CN Digital Controller, Omron Europe B.V., Netherlands) to keep the air temperature constant. To control the air moisture (RH), a flow of dry compressed air was split into two pipelines. One flow was bubbled through the water filling the

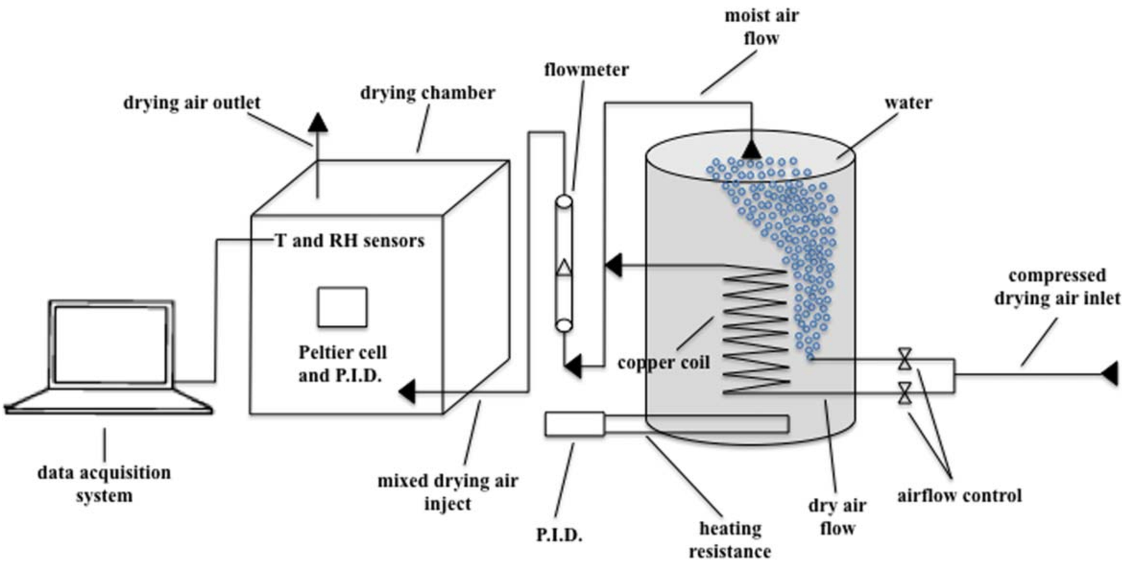

FIGURE 1 Scheme of the lab-scale drying system adopted for the experiments

tank, resulting in moist air, while the second stream was kept dried and heated by passing through a copper coil. The water temperature was controlled using a second P.I.D. regulation system (E5CN Digital Controller, Omron Europe B.V., Netherlands), and set at the same values of the drying air inside the chamber.

Finally, the mixture of wet and dry air entered from the bottom part of the drying chamber to ensure the wanted RH value for the drying experiments.

With the help of some little fans that were also placed at the bottom of the drying chamber, the air was circulating evenly and getting through the above-located hazelnuts to eventually exit the drying chamber from its upper part. For each experimental point of the defined design, the RH of the drying air was adjusted by manually regulating the moist and the dried airflows, according to the monitored RH values inside the chamber. Furthermore, the velocity of the drying air was set at 0.5 m/s and controlled using a flowmeter (Platon NGX, RM&C Ltd, UK).

2.4 | Hazelnut moisture measurement

When the air inside the drying chamber was at the set conditions for the current experiment, the experiments started loading the chamber with samples corresponding to 500 g of whole nuts for each of the six cultivars. Approximately once an hour (excluding the evening and night hours), the samples of each cultivar were temporarily taken out from the drying chamber and separately weighted (VWR 611–2602 balance, ± 0.01 g; VWR, Radnor). Three analytical replicates of measurement were performed and the mean $W_{n(t)}$ was calculated. The drying experiment was then continued until the next weighting occurrence. When the weight difference with respect to the previous measurement for all the cultivars was less than ± 0.05 g, it was assumed that the equilibrium moisture content between the hazelnuts and the surrounding drying air was reached. After measuring the final weight $W_{n(f)}$ of each cultivar sample, the shelled hazelnuts were ground using a grinder (DPA141, Moulinex) and the moisture analysis was carried out by means of a thermobalance (RADWAG MAC 210/NH; Radom, Poland). The temperature inside the thermobalance was set at 120 °C and the determination of the hazelnut moisture content occurred every 120 s and considered complete when the values obtained from two consecutive measurements did not change. Three analytical replicates for each measurement were performed and their mean was calculated and used as the final moisture content [$M_{n(f)}$] of each cultivar in each experimental condition. Finally, Equation 7 was applied to calculate the total hazelnuts moisture content for each measurement point [$M_{n(t)}$] during the drying experiments for each cultivar.

$$M_{n(t)} = 1 - \left(W_{n(f)}/W_{n(t)}\right) \times \left(1 - M_{n(f)}\right) \tag{7}$$

2.5 | Data processing

The moisture removal processes and their dependence on the process variables are commonly expressed in term of drying kinetics (Correia, Andrade, & Guiné, 2013; Krokida, Karathanos, Maroulis, & Marinos-Kouris, 2003) and, in this research work, the first order kinetics, the second-order kinetics and a diffusion kinetics derived from the Fick's diffusion equation in a sphere (Crank, 1975; Cussler, 2009) were considered and solved (Table 3) to fit the experimental data (i.e., the hazelnut moisture values during drying). The term C was replaced by the

TABLE 3 Kinetic equations and their analytical solutions

Kinetics	Raw equation	Analytical solution
1st order	$\partial C/\partial t = k \times [C]$	$C = C_0\ e^{-kt} + M_e$
2nd order	$\partial C/\partial t = k \times [C]^2$	$C = \frac{(M_e\ k\ t + C_0)}{1 + k\ t}$
Diffusion in a sphere	$\partial C/\partial t = D \times \left(\partial^2 C/\partial r^2\right)$	$\frac{C - M_e}{C_0 - M_e} = 1 - \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-Dn^2\ \pi^2 t\right)/r^2$

The analytical solution to diffusion in a sphere can be found in (Crank, 1975). The term n refers to the number of layers in the sphere, while r is the sphere radius.

TABLE 4 Carpological descriptors (from 1 to 6) of nut samples (mean value and SE). Means within a column followed by the same letter are not significantly different (p ≤ .05; Tukey test). Hazelnut cultivar: CA = "Camponica"; NO = "Nocchione"; PA = "Pauetet"; RI = "Ribet"; TGL = "Tonda Gentile delle Langhe"; L35 = "UNITOL35"

Cv	W_n (g)	V_n (ml)	D_n (g/ml)	W_k (g)	PKW (%)	V_n (mmc)
CA	3.06 ± 0.10 b	4.22 ± 0.06 b	0.72 ± 0.01 b	1.35 ± 0.06 b	44.24 ± 0.86 c	4,358.6 ± 86.2 b
NO	2.32 ± 0.04 cd	3.26 ± 0.05 c	0.71 ± 0.02 b	0.84 ± 0.03 c	36.27 ± 0.55 d	3,042.2 ± 170.4 c
PA	1.97 ± 0.05 d	2.59 ± 0.05 d	0.76 ± 0.01 b	0.93 ± 0.03 c	47.35 ± 0.64 b	2,711.6 ± 4.0 c
RI	2.00 ± 0.04 d	2.62 ± 0.02 d	0.76 ± 0.02 b	0.98 ± 0.03 c	48.97 ± 0.69 ab	2,791.0 ± 4.5 c
TGL	2.57 ± 0.04 c	2.78 ± 0.11 d	0.93 ± 0.02 a	1.32 ± 0.02 b	51.45 ± 0.22 a	2,934.1 ± 8.9 c
L35	5.18 ± 0.15 a	8.39 ± 0.15 a	0.62 ± 0.01 c	1.97 ± 0.08 a	38.01 ± 0.62 d	7,909.3 ± 69.1 a

measured $M_{n(t)}$ values and three parameters were estimated by the kinetic models: C_0, M_e, and k.

C_0 refers to the initial moisture content of the hazelnuts (M_i), while M_e estimates the equilibrium moisture content between the hazelnuts and the drying air. Finally, the kinetic constant term k (which is D, in the diffusion equation) gives information about the drying rate wherewith the hazelnut moisture is varying from their initial content (M_i) to the equilibrium content (M_e). The main reason for using this type of kinetics was to reduce the number of parameters for defining the model, that is, the risk of overfitting. The root mean square error (RMSE) was considered to estimate the goodness of fit achieved by each kind of kinetics: the smaller the error, the better the model fitted the experimental data.

Afterwards, a three-way Analysis of Variance (ANOVA) test was performed for each kinetic model obtained to single out relations of M_e and k with T (X_1), RH (X_2), and the hazelnut cultivar (X_3).

As the hazelnut cultivar is a discrete variable, which did not allow sorting for further calibration modeling, the Factor Analysis (FA) (Basilevsky, 1994) was performed to represent the different cultivars through the nut descriptors values (Tables 4 and 5) and using a lower number of variables.

Eventually, Multiple Linear Regression (MLR) analysis (Grafen & Hails, 2002) was performed to predict the M_e and k drying parameters as a function of the drying air conditions (T and RH) and the carpological traits measured on hazelnuts belonging to each cultivar.

All the above described steps for data processing were performed using the Curve Fitting toolbox of MATLAB (The MathWorks Inc., Natick, MA) and some in-house written scripts.

3 | RESULTS AND DISCUSSION

3.1 | Carpological descriptors of hazelnuts

Significant differences between the cultivars were found according to all the carpological descriptors, as it can be seen in Tables 4 and 5.

"L35" was the biggest in terms of W_k, V_k, W_n, V_n^{mmc}, and V_n^{ml}. The highest and the lowest T_s were found in "Nocchione" (1.80 mm) and in "Ribet" (1.07 mm), respectively.

"Pauetet" and "Ribet" had nuts with elongated shape, while nuts of the remaining cultivars had approximately roundish shape ($SI_n > 0.93$, data not shown).

"TGL" showed the highest values for D_n, PKW and the lowest Ve. "Nocchione" and "L35" had the lowest PKW and the highest Ve at the same time, which differ significantly from the remaining cultivars. The T_s/Dp ratio was significantly different in "Nocchione" hazelnuts, due to their high T_s, while "L35" ones had the highest Dp values.

3.2 | Data fitting of drying tests measures by different kinetics

The experimental data obtained for every cultivar and every experimental condition were fitted using the three kinetic models described above (Table 3). A RMSE of 0.30 and 0.21 was achieved by the first and the second-order kinetic models, respectively, while the diffusion model based on the Fick's equation showed the lowest RMSE (0.18).

These results confirmed that the most important parameter during drying is the moisture diffusivity, as was already reported by Kaya et al.

TABLE 5 Carpological descriptors (from 7 to 13) of nut samples (mean value and SE). Means within a column followed by the same letter are not significantly different (p ≤ .05; Tukey test). Hazelnut cultivar: CA = "Camponica"; NO = "Nocchione"; PA = "Pauetet"; RI = "Ribet"; TGL = "Tonda Gentile delle Langhe"; L35 = "UNITOL35"

Cv	V_k (mmc)	Ve (%)	PKV (%)	SIR (%)	T_s (mm)	Dp (mm)	T_s/Dp (%)
CA	1,620.5 ± 41.03 b	62.82 ± 0.48 b	37.18 ± 0.48 b	0.90 ± 0.01 bc	1.40 ± 0.04 bc	20.27 ± 0.13 b	6.89 ± 0.16 b
NO	876.6 ± 67.2 d	71.21 ± 1.13 a	28.79 ± 1.13 c	0.85 ± 0.02 cd	1.80 ± 0.14 a	18.52 ± 0.29 c	9.73 ± 0.88 a
PA	1,195.0 ± 11.45 c	55.93 ± 0.43 c	44.07 ± 0.43 a	0.97 ± 0.01 a	1.14 ± 0.03 cd	17.30 ± 0.01 d	6.59 ± 0.15 b
RI	1,121.3 ± 44.6 cd	59.83 ± 1.59 bc	40.17 ± 1.59 ab	0.95 ± 0.01 ab	1.07 ± 0.02 d	17.47 ± 0.01 d	6.12 ± 0.09 b
TGL	1,343.3 ± 66.0 c	54.20 ± 2.38 c	45.80 ± 2.38 a	0.95 ± 0.02 ab	1.21 ± 0.02 cd	17.77 ± 0.02 d	6.80 ± 0.13 b
L35	2,251.1 ± 66.4 a	71.54 ± 0.80 a	28.46 ± 0.80 c	0.82 ± 0.01 d	1.58 ± 0.04 ab	24.72 ± 0.07 a	6.38 ± 0.18 b

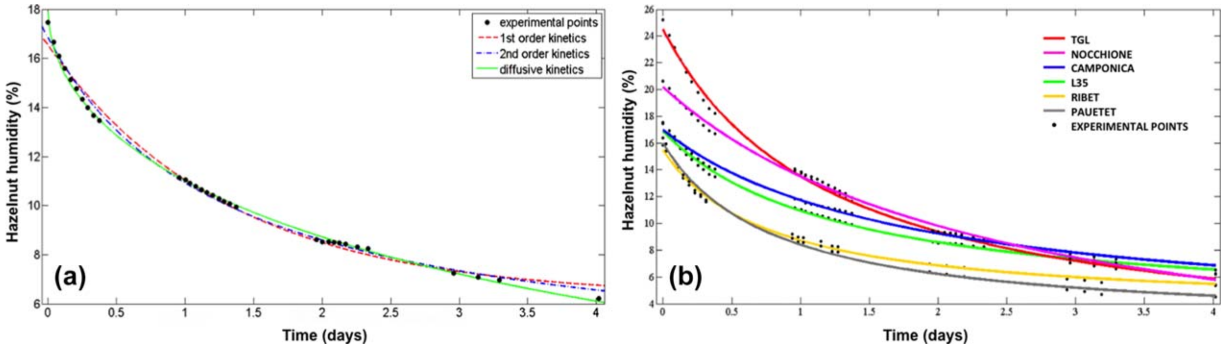

FIGURE 2 Drying curves. (a) Comparison among fitting curves corresponding to the 1st order kinetics (dash line), the 2nd order kinetics (dash-dot line) and the diffusion kinetics based on the Fick's 2nd law (solid line) for the same cultivar [L35; T 20 °C; RH 20%];
(b) Comparison among the changes of moisture content during drying of hazelnuts belonging to the six hazelnut cultivars at the same experimental condition [T 20 °C; RH 20%]

(2011); Mrkic et al. (2007); Dincer and Hussain (2004); Demirtas et al. (1998); Lopez et al. (1998).

Figure 2a depicts a representative comparison among the three kinetics applied to a single drying test and a single cultivar (T 20 °C; RH 20%, cv L35). It is made clear that the diffusion model (derived from Fick's equation) is fitting the data the best but also that the simpler first and second-order kinetics are adequate in describing the occurring drying phenomenon even if with limitations on the initial and final experimental points.

Therefore, only the M_e and k values obtained by the diffusion model were considered for the subsequent data treatment.

A complete overview of the experimental condition [T 20 °C; RH 20%] considering all the hazelnut cultivars is also reported in Figure 2b. The drying kinetics of the different cultivars show quite different drying rates, as it can be seen by the slope of the curves. Despite having the highest M_i, the cultivar TGL reached a lower M_e with respect to Camponica and L35. Nocchione had lower M_i than TGL but they reached approximately the same M_e. Ribet and Pauetet showed to have both the lowest Mi and lowest M_e at the end of the drying process. These findings confirm how an initial rather higher moisture content does not mean a slower drying process or a different [$M_{e(f)}$] and how the cultivar features also play a role on the overall drying process.

As a matter of fact, the results of a three-way ANOVA test showed that all the considered variables [air temperature (X_1), relative humidity (X_2), and hazelnut cultivar (X_3)] were statistically significant for $p < .01$ with respect to the k values (Table 6). Similarly, the air temperature and relative humidity were significant for $p < .01$ with respect to M_e values (Table 6), while the hazelnut cultivar was only weakly significant with a $p \approx .05$. The ANOVA results seem to agree with the drying behavior reported in Figure 2b, confirming that in all the experimental conditions both the drying rate and, to a lesser extent, the M_e can be affected using different hazelnut cultivars.

3.3 | Factor analysis of the carpological descriptors

The results of the FA performed on the 13 nut descriptors are shown in Figures 3 and 4. Figure 3 shows the loadings plot using the first three FA components, representing the descriptors in a three-dimensional space: the closer the descriptors, the more similar they are with respect to the provided information. Since W_n, V_n, W_k, V_k, and Dp are associated to dimensional parameters and they correlated among

TABLE 6 Three-way ANOVA test performed on the k values (a) and on the M_e values (b)

Source	Sum Sq.	*df*	Mean Sq.	*F*	Prob > *F*
(a) *k* values					
X_1	0.02776	1	0.02776	89.12	0
X_2	0.00293	1	0.00293	9.39	.0059
X_3	0.01168	5	0.00234	7.5	.0004
Error	0.00654	21	0.00031		
Total	0.04956	29			
(b) Me					
X_1	36.703	1	36.703	21.56	.0001
X_2	194.966	1	194.966	114.53	0
X_3	23.823	5	4.765	2.8	.0434
Error	35.747	21	1.702		
Total	297.697	29			

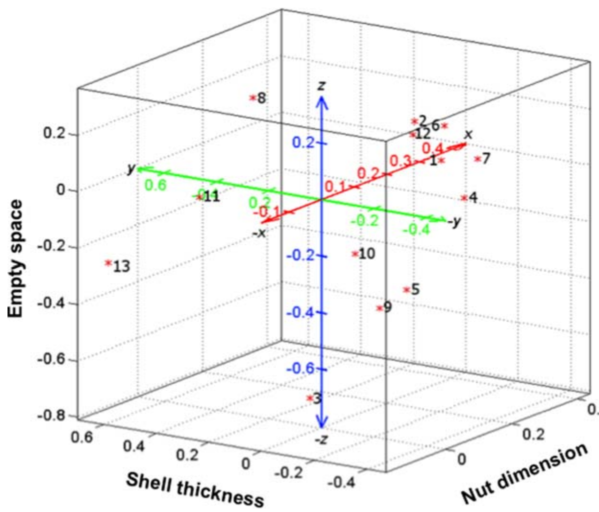

FIGURE 3 3D-loadings plot of the FA using the first three factor components. Numbers 1–13 refer to the carpological descriptors of the hazelnuts. Vector x is called the "nut dimension," vector y the "shell thickness" and vector z the "empty space" between the nut kernel and shell

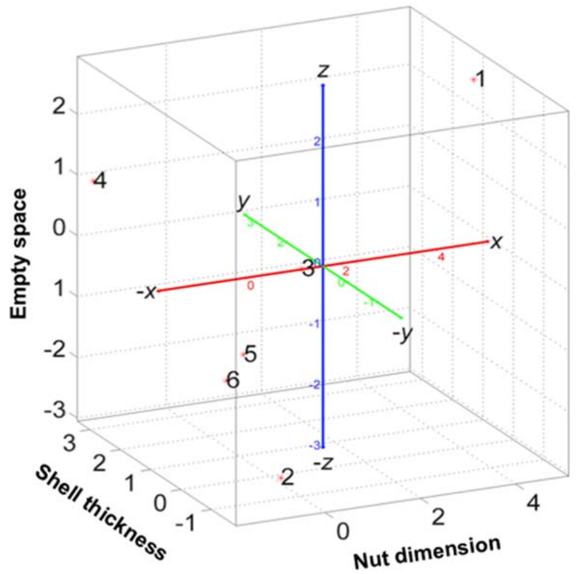

FIGURE 4 3D-scores plot of the FA using the first three factor components. Numbers 1–6 refer to the hazelnut cultivars. 1 = "L35," 2 = "TGT," 3 = "Camponica," 4 = "Nocchione," 5 = "Ribet," 6 = "Pauetet"

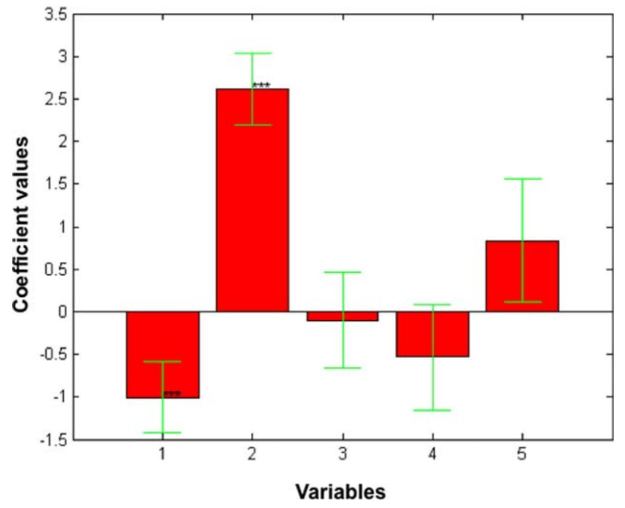

FIGURE 5 Coefficients plot of the variables for the MLR model on M_e. 1. Temperature, 2. Relative humidity, 3. Nut dimension, 4. Shell thickness, 5. Empty space. ***($p < .001$) **($p < .01$) *($p < .05$)

each other around the first component (vector x), this component was considered to be referring to the "nut dimension." Similarly, the second component (vector y) refers to the "shell thickness" (T_s) and the third one (vector z) refers to the "empty space" between nut shell and kernel since it is inversely related to D_n and directly related to Ve.

The scores plot in Figure 4 shows the projection of each nut variety on the same three *FA* components renamed according to their meaning as inferred from the loadings plot inspection. "L35" was the biggest, but also had a considerable empty space between kernel and shell. "TGL" had the smallest empty space. "Nocchione" showed to have high values of shell thickness and small nut dimension at the same time.

"Camponica" was found to be approximately in the intersection of the three components, while "Pauetet" and "Ribet" were close to each other, with a small nut dimension and a small empty space.

3.4 | MLR models

Five independent variables (T, RH, and scores of the three first components of the FA previously performed on the carpological traits: nut dimension, shell thickness and empty space) were used to build the models based on MLR analysis to study their behavior with respect to *Me* and *k*. The results are shown in Figures 5 and 6, respectively.

Both T and RH coefficients were highly significant ($p < .001$) on the M_e model (Figure 5) while no significant correlation was instead found between M_e and the nut descriptors obtained through FA.

M_e decreases with increasing T (inverse relationship), showing the opposite behavior with increasing RH, in full agreement with data reported by Kaya et al. (2011) and Lopez et al. (1998). Therefore, if hazelnuts of any cultivar are placed at the same RH in two separated drying rooms at different T, in average the higher M_e will be found in hazelnuts dried using a lower T.

The drying air parameters and the nut dimension were both significant on the k MLR model, with ($p < .001$) and ($p < .01$), respectively, as shown in Figure 6. Conversely, negligible correlations were found on k with respect to the other nut descriptors, shell thickness and the empty space.

Increasing T, k increases, as expected. However, a direct relationship between k and RH was also demonstrated. This last result, which represents a new important finding for the optimization of the drying process of shelled nuts, is not straightforward intuitive, but it can be explained as follows: the shell, which is the outer part of the hazelnut, is made by of a material quite similar to wood; the water permeability through the wood is promoted by a high

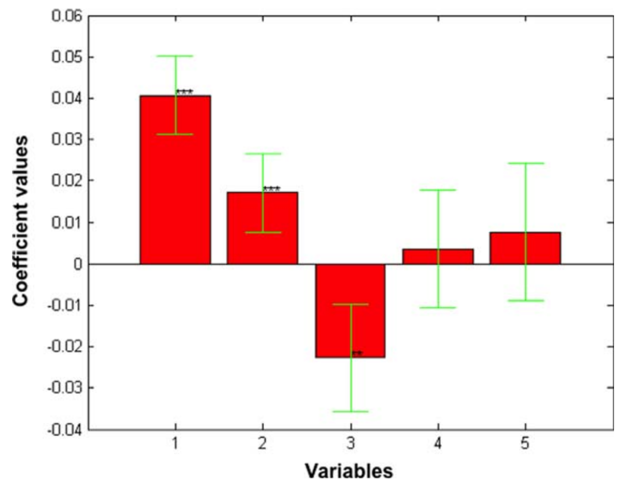

FIGURE 6 Coefficients plot of the variables for the MLR model on k. 1. Temperature, 2. Relative humidity, 3. Nut dimension, 4. Shell thickness, 5. Empty space. ***($p < .001$) **($p < .01$) *($p < .05$).

moisture content in the wood itself, as it was demonstrated by Jinman, Rui, and Guangxue (1994). This explains why the moisture diffusion from the nut kernel through the shell is enhanced using a higher RH air during drying.

Furthermore, increasing the nut dimension decreases k. The bigger the nut dimension, the smaller is the area/volume ratio and in this case, the cultivar features can play a significant role. This is the reason why a slower drying speed could be observed for the cultivars having a bigger volume, that is, Camponica and L35.

4 | CONCLUSIONS

The drying behavior of six hazelnuts cultivars, representative of different carpological traits, was analyzed under different drying air conditions. It was concluded that the mechanism of moisture diffusion during drying could be easily described by two physical parameters, M_e and k, if the drying air conditions are kept under control. Moreover, it was demonstrated that, using different hazelnut cultivars, significantly different drying rates (k) and, to a lesser extent, moisture content at the end of the process (M_e) can be obtained.

The FA applied on the studied carpological traits resulted in a good method to explore the variability of the different nut cultivars, which were well represented by means of just three factors: the nut dimension, the shell thickness and the empty space between nut kernel and shell.

Two MLR models were performed to evaluate the role of the hazelnut traits and the drying air conditions on (a) k and (b) M_e separately. According to the first model, it was clearly demonstrated that the T, the RH and all the carpological traits related to the nut dimension greatly affect the k values. According to the second model, it was shown that, being constant the air RH, the M_e will be higher with decreasing air T, while increasing the air RH increases both the k and M_e values. Despite the hazelnut cultivar slightly affects M_e, as it was demonstrated from the ANOVA test, no significant correlation was found instead between the hazelnut traits and M_e values in the MLR model. In this context, some assumptions can be done. It can be inferred that the effect of the traits considered in this work is too slight to be measured, or that further traits should be considered to describe the cultivar thoroughly. Moreover, it can be possible that the cultivar may not be completely described just by looking at the carpological traits and those additional parameters, that is, the initial moisture content, might play an important role to explain the relation between cultivar and M_e.

The information gathered in the study may lead to an optimized storage life of the dried nuts but all the presented aspects have to be carefully taken into account when considering the industrial needs to define a drying model of general applicability.

The work here presented represents a preliminary study toward the real application for online drying process monitoring and control at industrial level. However, in this context a larger set of experimental data should be produced to increase the model robustness.

NOMENCLATURE

M	Moisture content (g g^{-1}, dry basis)
W	Weight (g)
k	Kinetics constant term (s^{-1})
t	Time (s)
D	Diffusivity (mm^2 s^{-1})
C,	Concentration (mol/m^3)
r	Radius (mm)
RH	Air relative humidity (%)
T	Air temperature (°C)
$\boldsymbol{p}$	Significance level value

Subscripts

$_n$	Whole hazelnut
$_k$	Kernel
$_s$	Shell
$_i$	Initial
$_f$	Final
$_e$	Equilibrium

ORCID

A. Giraudo http://orcid.org/0000-0002-8514-1085

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How to cite this article: Giraudo A, Valentini N, Venturello A, et al. Kinetic modeling of hazelnut drying: Effects of different cultivars and drying parameters. *J Food Process Eng*. 2018;41:e12632. https://doi.org/10.1111/jfpe.12632