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Optimization of Tunnel Drying Conditions and Moisture Properties of Six West African Mango Varieties Using Box-Behnken Design

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Abstract

Mango is a key export fruit in West Africa, but its short harvest season and high postharvest losses require efficient drying technologies to stabilize the product and meet international quality specifications for dried mango. This study aimed to optimize tunnel drying conditions to control the moisture properties of six mango varieties commonly processed in Burkina Faso (*Valencia, Lippens*, *Kent, Keitt, Brooks,* and *Amelie*). A Box-Behnken experimental design was applied with three independent factors (drying temperature, time, and relative humidity) to develop quadratic models describing the effects of these variables on final moisture content. The models showed that drying time and relative humidity were the most influential factors, while temperature had a secondary effect within the investigated range. Multi-response optimization using a desirability function identified a common set of operating conditions whose compliance with international moisture standards depends on the variety and on the standard considered. Under these conditions, predicted moisture contents ranged from 14.99% to 18.39% depending on the variety, with an overall desirability index close to 0.89. All six predictions are below the 25% limit for mango treated with preservatives and five of six lie within the 14% - 18% buyer range (Brooks, at 18.39%, exceeds it), but only Valencia and Lippens (14.99%) meet the 15% limit for untreated dried mango. Because lack of fit was significant for five varieties, these predictions require experimental confirmation. These results provide a predictive tool to control tunnel drying of mango and to better match buyer specifications on moisture content for export markets.

Keywords

Mango, Moisture Content, Box-Behnken Design, Optimization, Tunnel Drying Conditions

1. Introduction

The mango, the fruit of the mango tree (*Mangifera indica* L.), is one of the most widely produced fruits in West Africa in general and in Burkina Faso in particular. The harvesting period for this fruit (March to June) is relatively short and varies according to production regions. During the harvest season, large quantities of mangoes flood local markets, leading to poor sales and considerable post-harvest losses [1] [2]. These post-harvest losses are estimated at approximately 30% - 50% and are mainly attributed to the uneven distribution of marketing networks across the country, pest attacks, and the absence or inadequacy of appropriate post-harvest technologies for stabilizing fresh or processed mangoes [3] [4]. Fresh mangoes are indeed difficult to store at room temperature or by freezing and are also prone to browning reactions during prolonged refrigerated storage [5]. To address these preservation challenges, the development of appropriate processing technologies is essential.

Several mango processing technologies exist, including drying, purée production, nectars, jams, compotes, marmalades, vinegar, and other derived products [6]. Among these, drying remains the most widely used processing method, accounting for approximately 80% of processed mango products [7]. Previous studies have shown that mango drying is an effective alternative for reducing post-harvest losses [8]. Moreover, dried mango has been identified as a valuable food product for combating and preventing vitamin A deficiency, particularly during the dry season [8].

Drying is a dehydration process that reduces the amount of water available in fresh mangoes, thereby extending their shelf life [9] [10]. In Burkina Faso, favorable climatic conditions—such as high solar radiation, ambient temperature, and low relative humidity—facilitate drying operations. However, successful drying requires the rigorous modeling and control of technological parameters using robust scientific approaches, such as design of experiments (DoE). Experimental design methodologies enable the efficient organization of tests in scientific research and industrial studies, as described by Goupy [11], by allowing the simultaneous variation of multiple factors, rather than changing one parameter at a time through numerous trials [12].

To date, very few studies have focused on the optimization of dried mango production processes using mathematical modeling approaches. Such optimization is crucial for improving both the quality of dried mango and the economic profitability of mango drying activities. Therefore, the objective of this study is to contribute to the control and optimization of drying parameters for several mango

varieties from Burkina Faso using a tunnel dryer, through the application of design of experiments methodology, particularly the Box-Behnken design. This study provides novel insights into the optimization of mango drying processes in Burkina Faso by applying the Box-Behnken design of experiments to model and predict moisture content across multiple mango varieties. While previous research has largely focused on traditional drying methods or basic empirical studies, this work integrates mathematical modeling, multi-factor experimental design, and predictive optimization to identify the key parameters controlling moisture content. The findings contribute both scientifically and practically: they offer a predictive tool for stakeholders to control drying conditions, ensure compliance with international quality standards, and enhance the economic efficiency of mango processing activities. To our knowledge, this is the first systematic application of the Box-Behnken methodology to optimize tunnel drying of diverse mango varieties in Burkina Faso, providing a reference framework for similar tropical fruit processing studies.

2. Materials and Methods

2.1. Study Site

The study was conducted in a mango drying unit located in Bobo-Dioulasso (Latitude 11˚11'00"N, Longitude 4˚17'00"W), the capital of the Hauts-Bassins region, approximately 365 km from Ouagadougou, the capital city of Burkina Faso.

Bobo-Dioulasso is situated in the western part of Burkina Faso at an altitude of approximately 430 m above sea level. The city experiences a tropical climate, characterized by a dry season from November to March and a rainy season from late April to early October. Ambient temperatures are generally high throughout the year, with particularly elevated values between March and May, prior to the onset of the rainy season.

Annual rainfall in the area typically exceeds 1000 mm, indicating an intermediate rainfall level. Precipitation is lowest during the driest months (December and January), averaging about 1 mm, and reaches its maximum in August, with approximately 270 mm of rainfall [13].

2.2. Material and Product

The equipment used in this study included plant material**,** laboratory equipment**,** and drying equipment**.** The plant material consisted of six mango varieties: *Valencia, Lippens, Kent, Keitt, Brooks, and Amelie*. The mangoes were washed, peeled, and cut into slices with an average thickness of 1 cm prior to drying. Laboratory equipment included two Mettler Toledo halogen moisture analyzers, a digital balance and a laser thermometer. The drying equipment comprised a peeler**,** knives, cutting table, drip trays, cleaning equipment, and a tunnel-type dryer. The tunnel dryer is a gas-powered dryer mainly used for fruit and vegetable drying in Burkina Faso and is the most widely employed dryer in mango processing units across the country. The dryer has overall dimensions of 1.8 m × 1.8

m × 0.7 m and is installed on a masonry base. It consists of two compartments housing the gas burner. Each drying compartment contains two cells, each capable of holding 10 to 11 drying trays measuring 0.7 m × 1.2 m**.** The compartments are covered by a hood that channels moist air toward a chimney located at the top of the dryer. Gas consumption of the tunnel dryer ranges from 0.6 to 0.8 kg of gas per kilogram of dried mango produced [14].

Fruit source, ripeness and initial moisture. The fruits of the six varieties came from orchards located mainly in the Guiriko and Tannounyan regions of Burkina Faso and were processed during the 2024 mango season (March to August) following the same transport and processing flow. Ripeness at processing was not quantified beyond the selection of sound fruit at a maturity suitable for processing, and the initial moisture content of the fresh fruit of each variety was not measured. Differences between varieties therefore cannot be fully separated from differences in starting material (see Discussion).

2.3. Methodology

2.3.1. Experimental Objective

The majority of dried mango produced in Burkina Faso is intended for export and must therefore comply with international quality standards. According to the United Nations [15], the moisture content of dried mango should not exceed 15% for untreated products and 25% for mangoes treated with preservatives. In addition, some European Union countries require the residual moisture content of conventional dried mango to range between 14% and 18% [16]. The objective of this study was to model and optimize drying parameters using the design of experiments (DoE) approach, specifically the Box-Behnken design, in order to ensure that dried mango produced using tunnel dryers complies with international standards.

2.3.2. Experimental Domain

The Box-Behnken design is a response surface methodology that allows the direct development of quadratic models. One of its main advantages is its ability to study the influence of several factors simultaneously, while also allowing the inclusion of additional factors without compromising the results of previously conducted experiments [17].

The factor levels were defined following the methodology proposed by Bezerra *et al*. [17]. For all mango varieties studied, the selected ranges of variation for each factor are presented in **Table 1**.

2.3.3. Model Selection

In most cases, the exact mathematical model governing a physical or technological phenomenon is unknown. Consequently, when it is not feasible to establish a theoretical model requiring complete knowledge of all variable interdependencies, an empirical modeling approach is adopted [18]. Therefore, the second-order (quadratic) model described by Bezerra *et al*. [17], was selected to describe the relationship between the drying parameters and the response variable:

$$Y = a_0 + \sum a_i x_i + \sum a_{ij} x_i x_j + a_{ii} x_i^2 + \cdots$$

where

- Y is the water content of the dried mango,
- x_i represents a level of factor i,
- x_j represents a level of the factor j,
- a_0, a_i, a_{ij}, a_{ii} are the coefficients of the polynomial and reflect the effects of the factors.

Minitab version 18 was used to estimate the model coefficients.

Table 1. Coded and actual levels of the independent variables used in the Box-Behnken experimental design.

Factors (Commodities)	Lower Limit	Upper Limit
(X_1) Temperature (T ˚C)	60	70
(X_2) Time (H)	15	24
(X_3) Relative humidity (%)	20	25

X_1: Drying temperature; X_3: Drying time; X_3: Relative humidity.

2.3.4. Experimental Matrix

The experimental matrix is a mathematical entity presented in tabular form, containing only the factors and as many rows as combinations of factor levels used in the experiments [17]. In this study, the experimental matrix was generated using Minitab® version 18, based on the Box-Behnken design described by Bezerra *et al.* [17]. A total of fifteen [15] experimental runs was generated by the software. In this design, the central level of each factor is combined with the lower and higher levels of the two remaining factors, allowing the evaluation of response variations as a function of factor levels. Table 2 presents the experimental matrix retained for the study.

Table 2. Experience matrix.

Test No.	Temperature (T ˚C)	Time (H)	Relative humidity (%)
1	60	15.0	22.5
2	70	15.0	22.5
3	60	24.0	22.5
4	70	24.0	22.5
5	60	19.5	20.0
6	70	19.5	20.0
7	60	19.5	25.0
8	70	19.5	25.0
9	65	15.0	20.0

Continued

10	65	24.0	20.0
11	65	15.0	25.0
12	65	24.0	25.0
13	65	19.5	22.5
14	65	19.5	22.5
15	65	19.5	22.5

2.3.5. Experimental Procedure and Response Measurement

Each of the fifteen experimental runs was performed once for each variety, following the experimental matrix and in accordance with the practical guide to mango drying developed by Snel *et al.* [14]. After each run, one sample of dried slices (100 g) per variety was collected and packaged in a sampling bag for laboratory analysis, giving 15 samples per variety and 90 samples for the tunnel dryer. The moisture analysis of each sample was repeated twice in succession; these repeats are repeated measurements of the same sample, not independent drying batches. The only independent estimate of pure error therefore comes from the three center-point runs [13]-[15] used in the lack-of-fit test.

Relative humidity control and monitoring. Only a laser thermometer is listed among the measuring equipment used for the drying trials; no humidity sensor, sensor position, logging interval or record of the humidity actually reached is reported. The three humidity levels (20%, 22.5% and 25%) should therefore be regarded as nominal set-points of the dryer rather than verified conditions, which limits the interpretation of the humidity effect.

For each experimental run, the response variable Y (moisture content) was determined by thermogravimetry with a Mettler Toledo halogen moisture analyzer (3 - 10 g of cut slices heated at 120˚C - 135˚C to constant weight, repeated twice in succession), using the AOAC method [19].

2.3.6. Model Validation

The adjusted or predicted moisture content values were calculated from the coefficients of the fitted model equation. Residuals were then obtained as the difference between observed and predicted values. These residuals were used to assess the predictive accuracy and validity of the model, in accordance with the criteria described by Bezerra *et al.* [17].

2.3.7. Model Optimization

Optimization was performed to establish a mathematical relationship between the drying parameters and the moisture content of the dried mango varieties under study. This approach involved identifying an optimal compromise among the response values (Y) to determine drying conditions that ensure compliance with international moisture standards for all mango varieties considered.

To identify the optimal drying parameters, multi-criteria optimization based on the approach developed by Derringer and Suich [20], was applied. The mathematical function used for optimization was the desirability function, as described by Lostado Lorza *et al*. [21]; Antony [22], Khuri and Mukhopadhyay [23]. This desirability function makes it possible to transform each response into dimensionless variables called desirability index (di). This index is in the range [0 and 1].

This function transforms each response into a dimensionless variable known as the individual desirability index (d_i), which ranges from 0 to 1.

In this study, for the response variable Y (moisture content), a target value of 15% was set for each variety in the Minitab response optimizer. The individual desirability equals 1 at the target and decreases as the predicted value moves away from it.

The overall desirability (D) was calculated as the geometric mean of the individual desirability indices. The quality of the optimized model was considered satisfactory when the overall desirability index (D) exceeded 50%, as reported by KY *et al*. [24].

3. Results

3.1. Evaluation of Moisture Content of the Six Mango Varieties

The results of the moisture content measurements obtained during the experiments are presented in Table 3. The results revealed considerable variation in moisture content depending on the mango variety and drying conditions. Moisture content ranged from 11.62% to 27.96% for the Amelie variety, 13.97% to 30.31% for *Brooks*, 12.30% to 22.87% for *Keitt*, 13.36% to 29.70% for *Kent*, 10.57% to 26.91% for *Lippens*, and 11.19% to 25.52% for *Valencia*. These variations were observed at drying temperatures between 60˚C and 70˚C, drying times ranging from 15 to 24 h, and relative humidity levels varying between 20% and 25%.

Table 3. Experimental design matrix and observed final moisture contents of the six mango varieties.

Test No.	Experience matrix			Moisture (%)					
	Temperature (˚C)	Time (h)	Relative humidity (%)	Kent	Valencia	Amelia	Brooks	Lippens	Keitt
1	60	15.0	22.5	29.70	25.52	27.96	30.31	26.91	20.54
2	70	15.0	22.5	26.66	22.48	24.92	27.27	23.87	19.89
3	60	24.0	22.5	14.91	12.73	13.17	15.52	12.12	14.67
4	70	24.0	22.5	13.36	12.18	11.62	13.97	10.57	12.30
5	60	19.5	20.0	22.06	17.88	20.32	22.67	19.27	19.68
6	70	19.5	20.0	19.79	15.61	18.05	20.40	17.00	16.90
7	60	19.5	25.0	18.67	16.49	16.93	19.28	15.88	19.09
8	70	19.5	25.0	16.74	12.56	15.00	17.35	13.95	17.18
9	65	15.0	20.0	21.80	17.62	20.06	22.41	19.01	21.09

Continued

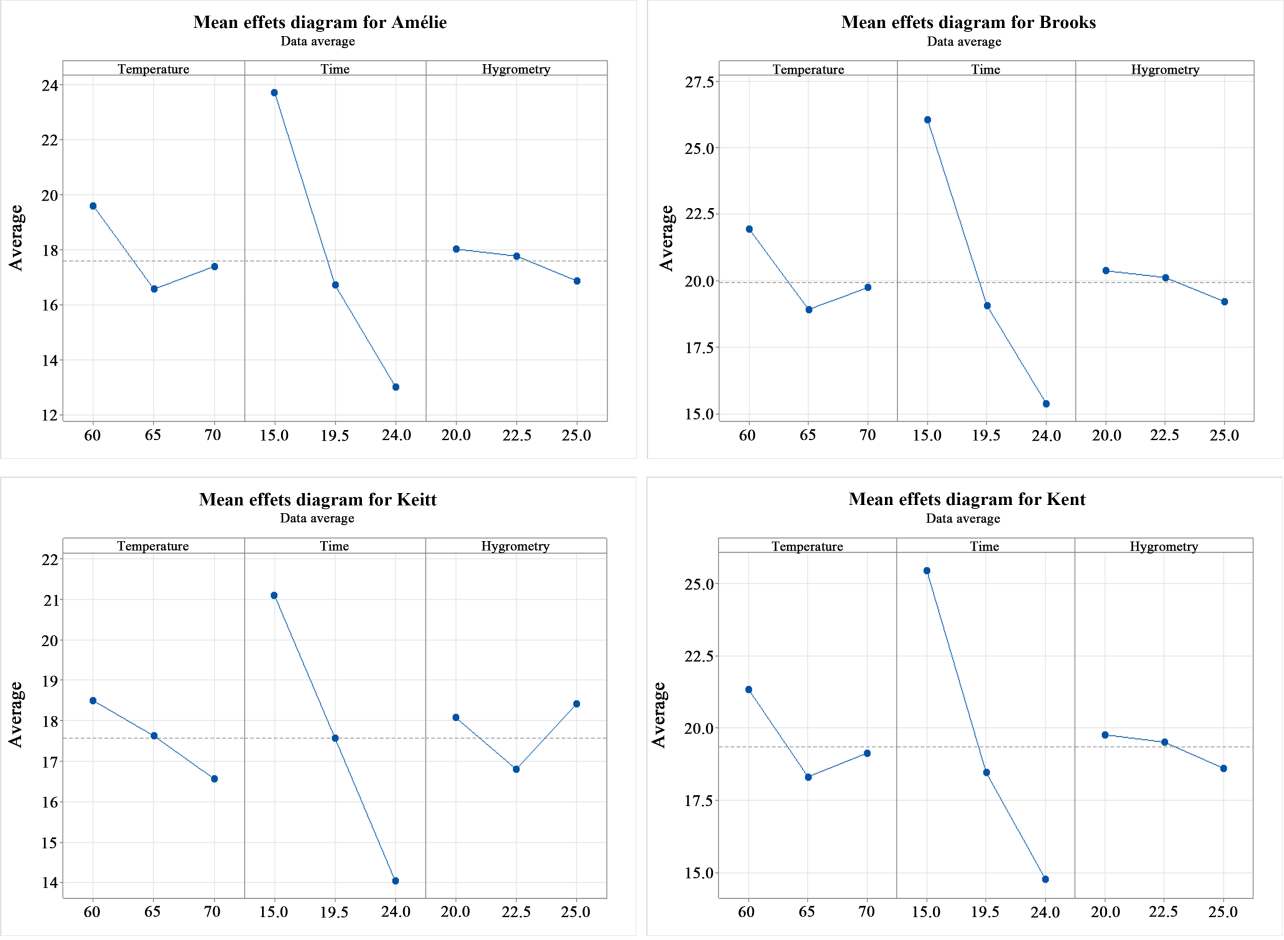
10	65	24.0	20.0	15.42	11.24	13.68	16.03	12.63	14.65
11	65	15.0	25.0	23.64	19.46	21.90	24.25	20.85	22.87
12	65	24.0	25.0	15.37	11.19	13.63	15.98	12.58	14.57
13	65	19.5	22.5	17.34	13.16	15.60	17.95	14.55	16.50
14	65	19.5	22.5	17.69	13.51	15.95	18.30	14.90	16.82
15	65	19.5	22.5	16.93	12.75	15.19	17.54	14.14	16.90

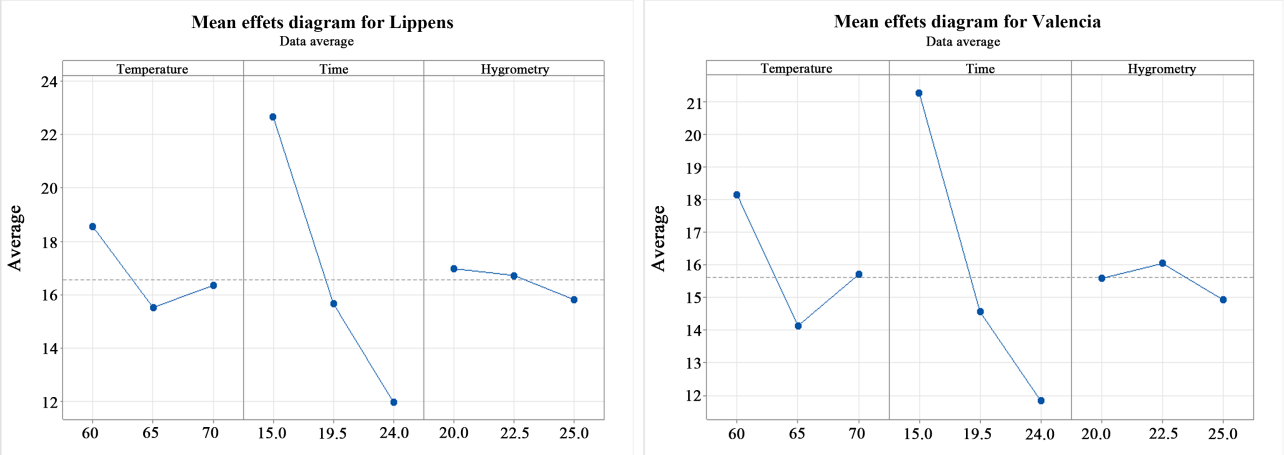
Values represent the observed final moisture contents (%) of the six mango varieties obtained under the experimental conditions defined by the Box-Behnken design. Moisture content is expressed as percentage of sample mass. Runs 13-15 are the three center-point replicates (65˚C, 19.5 h, 22.5% RH). Values for runs 12-15 were corrected to match the measured values reported in Table 5.

For all mango varieties, a decrease in moisture content was observed with increasing drying time. Conversely, an increase in moisture content was recorded at higher relative humidity levels.

3.2. Main Effects Plots and Contour, Surface, and Pareto Charts of Moisture Content

The main effects plots (Figure 1) indicated that drying time, relative humidity,





Note: The plots show the main effects of drying temperature, drying time, and relative humidity on final moisture content for each mango variety.

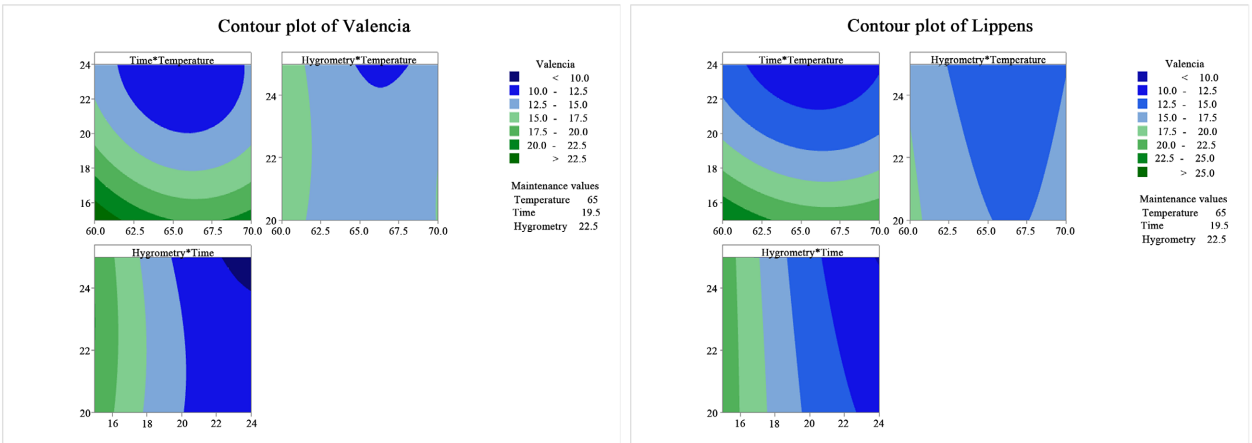
Figure 1. Main-effects plots showing the influence of drying temperature, drying time, and relative humidity on final moisture content in the six mango varieties.

and temperature exerted a pronounced influence on the moisture content of the *Valencia, Lippens, Kent, Keitt, Brooks*, and *Amelie* varieties. In general, these factors exhibited a negative effect on moisture content, indicating that increasing their levels resulted in reduced moisture content.

However, an exception was observed for the Keitt variety, for which relative humidity initially exerted a negative effect on moisture content, followed by a positive effect at higher humidity levels.

The overlaid contour plots (**Figure 2**) indicated that, in order to achieve moisture contents compliant with international standards [25], a minimum relative humidity of approximately 22.5%, a drying time between 19 and 24 h, and a drying temperature between 60˚C and 70˚C are required for all mango varieties studied.

The response surface plots (**Figure 3**) showed that moisture content decreases with increasing drying time (from 15 to 22.5 h) and increasing temperature (from 60˚C to 70˚C) until an optimum point is reached, beyond which the effect stabilizes, while moisture content increases with increasing relative humidity.



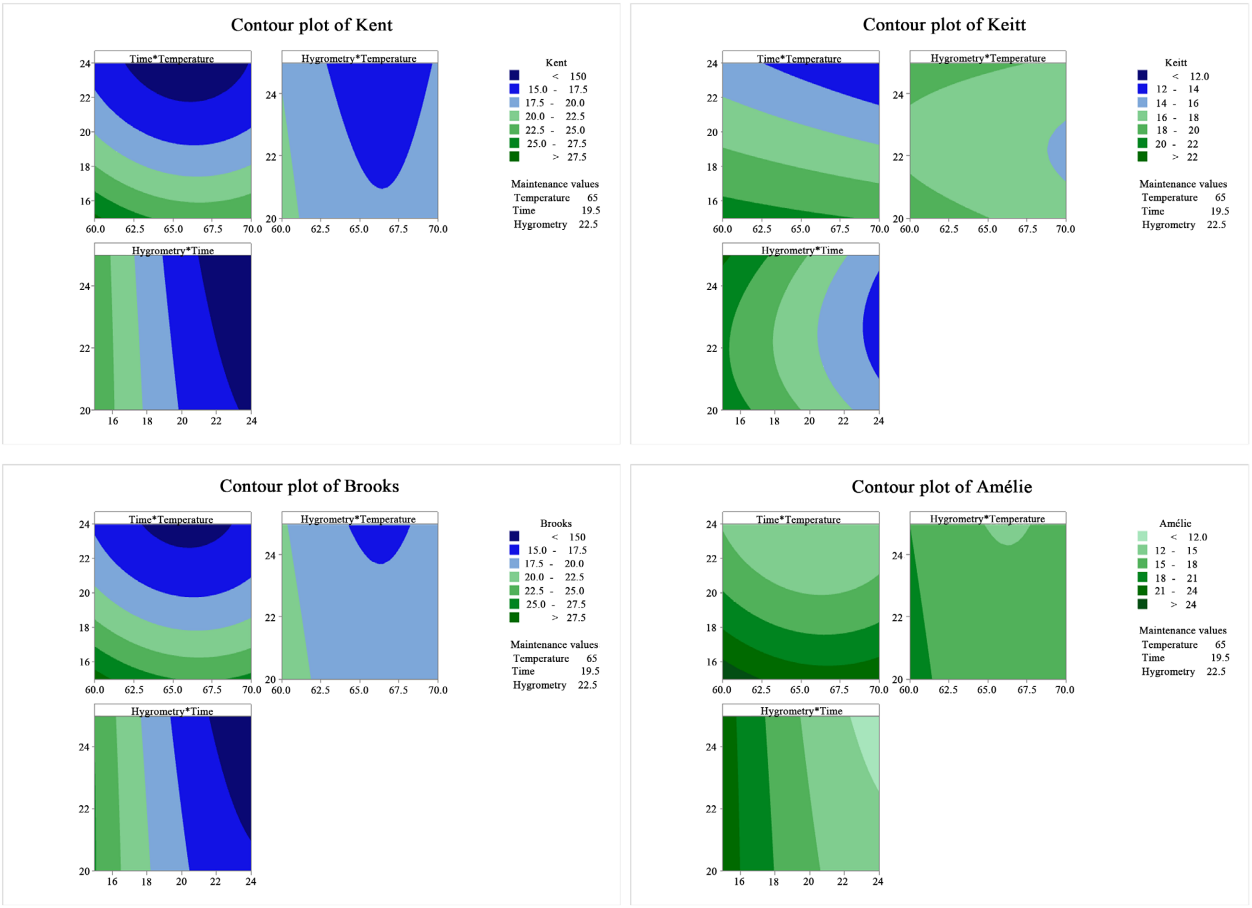
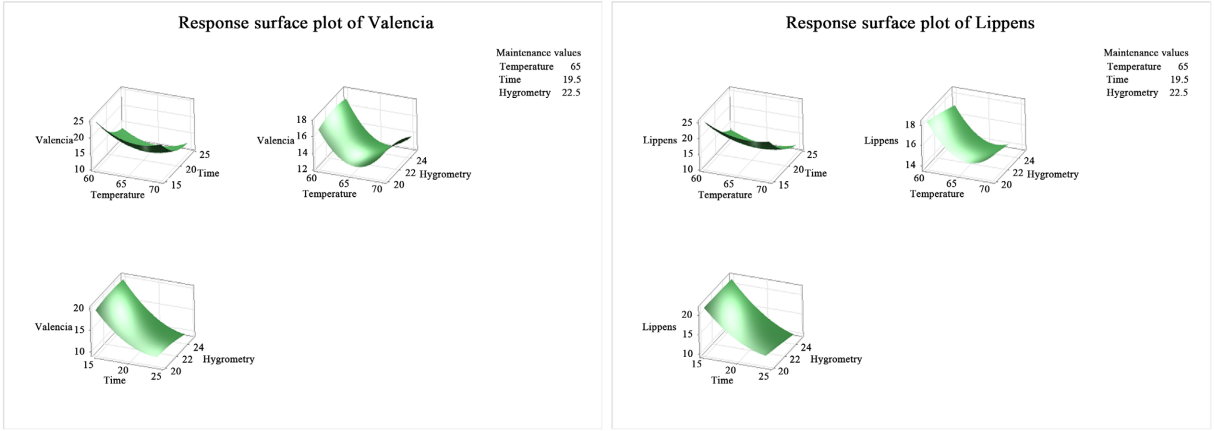
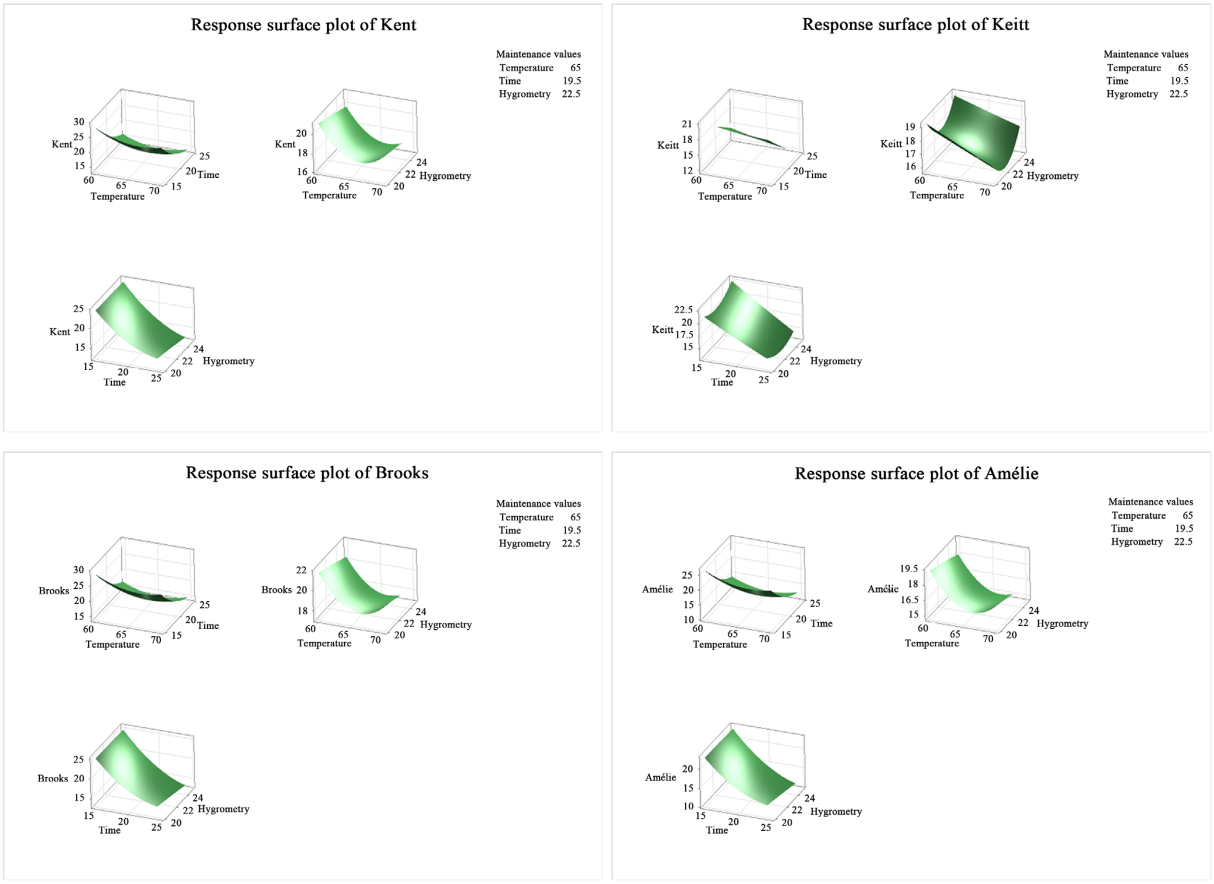


Figure 2. Humidity contour graph (%) of mango varieties as a function of humidity and time.

The standardized Pareto charts of effects (**Figure 4**) revealed that drying time is the most influential factor to be controlled for optimizing moisture content across all mango varieties studied. Temperature was identified as a significant factor for the *Valencia* and *Keitt* varieties, whereas relative humidity was significant only for the *Valencia* variety. In addition, significant interaction effects were observed between time and relative humidity for the *Valencia* variety, and between time and temperature for the *Valencia* and *Keitt* varieties ($\alpha = 0.15$).



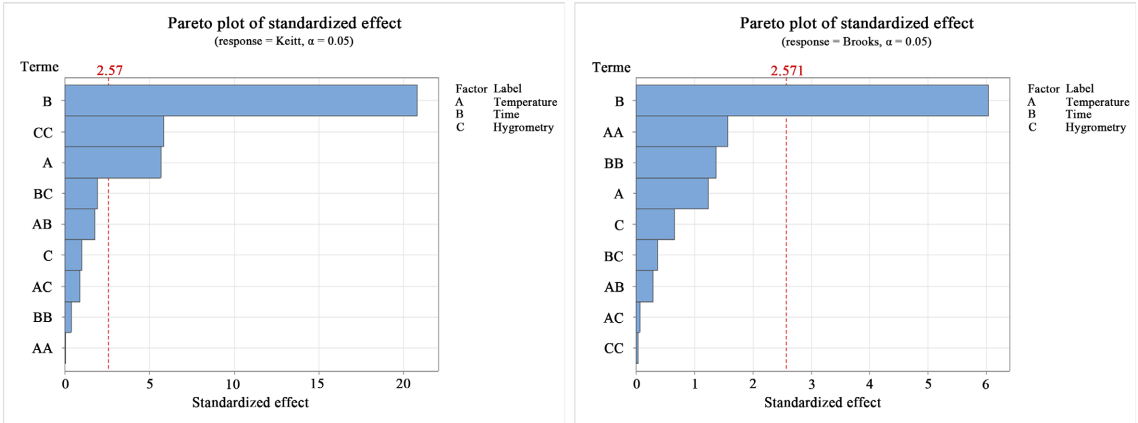


Note: Each response-surface plot shows the combined effect of two drying variables on final moisture content. while the third variable was kept at its central level.

Figure 3. Response-surface plots illustrating the combined effects of drying conditions on final moisture content in the six mango varieties.

3.3. Model Equations

The results of the estimated regression coefficients for moisture content (%) of the mango varieties studied (**Table 4**) indicated that drying time and temperature exert a negative effect, whereas relative humidity has a positive effect on the moisture content across all varieties.



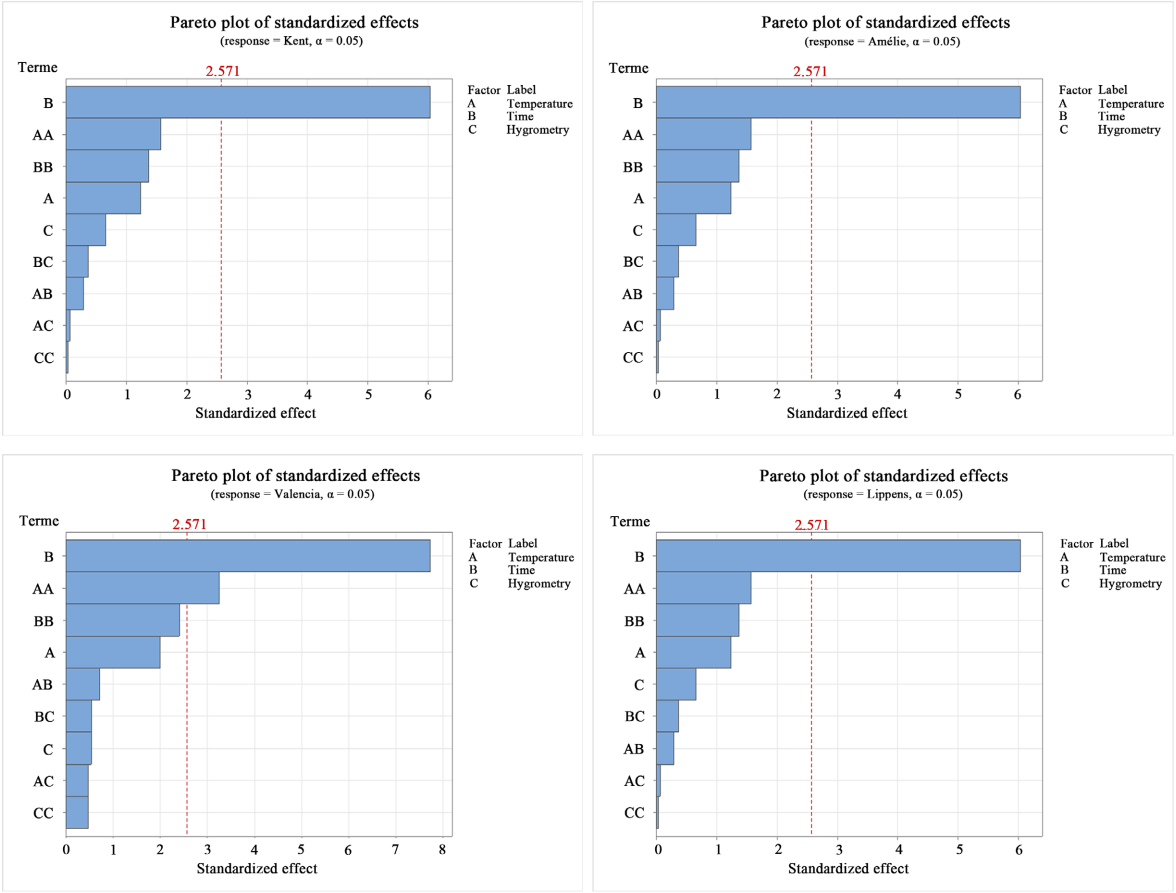


Figure 4. Pareto plot of standardized effects (Mango *var. Brooks. Amelie. Valence. Kent. Keit* and *Lippens*).

Table 4. Estimated regression coefficients of the fitted moisture-content models for the six mango varieties.

	Term	Coeff	Coef ErT	T Value	P value	IVF
Keitt	Constant	16.740	0.277	60.51	0.000	
	Temperature	−0.964	0.169	−5.69	0.002	1.00
	Time	−3.525	0.169	−20.81	0.000	1.00
	Hygrometry	0.174	0.169	1.03	0.352	1.00
	Temperature * Temperature	0.014	0.249	0.06	0.958	1.01
	Time * Time	0.096	0.249	0.39	0.715	1.01
	Relative Humidity * Relative Humidity	1.459	0.249	5.85	0.002	1.01
	Temperature * Time	−0.430	0.240	−1.79	0.133	1.00
	Temperature * Relative humidity	0.218	0.240	0.91	0.406	1.00
	Time * Relative Humidity	−0.465	0.240	−1.94	0.110	1.00
Kent	Constant	17.32	1.45	11.98	0.000	
	Temperature	−1.099	0.885	−1.24	0.270	1.00

Continued

	Time	−5.343	0.885	−6.03	0.002	1.00
	Hygrometry	−0.581	0.885	−0.66	0.541	1.00
	Temperature * Temperature	2.05	1.30	1.57	0.177	1.01
	Time * Time	1.79	1.30	1.37	0.228	1.01
	Relative Humidity * Relative Humidity	−0.05	1.30	−0.04	0.969	1.01
	Temperature * Time	0.37	1.25	0.30	0.778	1.00
	Temperature * Relative humidity	0.08	1.25	0.07	0.949	1.00
	Time * Relative Humidity	−0.47	1.25	−0.38	0.721	1.00
Valencia	Constant	13.140	0.997	13.19	0.000	
	Temperature	−1.224	0.610	−2.01	0.101	1.00
	Time	−4.718	0.610	−7.73	0.001	1.00
	Hygrometry	−0.331	0.610	−0.54	0.611	1.00
	Temperature * Temperature	2.922	0.898	3.25	0.023	1.01
	Time * Time	2.165	0.898	2.41	0.061	1.01
	Relative Humidity * Relative Humidity	−0.427	0.898	−0.48	0.654	1.01
	Temperature * Time	0.622	0.863	0.72	0.503	1.00
	Temperature * Relative humidity	−0.415	0.863	−0.48	0.651	1.00
	Time * Relative Humidity	−0.472	0.863	−0.55	0.608	1.00
Lippens	Constant	14.53	1.45	10.05	0.000	
	Temperature	−1.099	0.885	−1.24	0.270	1.00
	Time	−5.343	0.885	−6.03	0.002	1.00
	Hygrometry	−0.581	0.885	−0.66	0.541	1.00
	Temperature * Temperature	2.05	1.30	1.57	0.177	1.01
	Time * Time	1.79	1.30	1.37	0.228	1.01
	Relative Humidity * Relative Humidity	−0.05	1.30	−0.04	0.969	1.01
	Temperature * Time	0.37	1.25	0.30	0.778	1.00
	Temperature * Relative humidity	0.08	1.25	0.07	0.949	1.00
	Time * Relative Humidity	−0.47	1.25	−0.38	0.721	1.00
Amelia	Constant	15.58	1.45	10.78	0.000	
	Temperature	−1.099	0.885	−1.24	0.270	1.00
	Time	−5.343	0.885	−6.03	0.002	1.00

Continued

	Hygrometry	−0.581	0.885	−0.66	0.541	1.00
	Temperature * Temperature	2.05	1.30	1.57	0.177	1.01
	Time * Time	1.79	1.30	1.37	0.228	1.01
	Relative Humidity * Relative Humidity	−0.05	1.30	−0.04	0.969	1.01
	Temperature * Time	0.37	1.25	0.30	0.778	1.00
	Temperature * Relative humidity	0.08	1.25	0.07	0.949	1.00
	Time * Relative Humidity	−0.47	1.25	−0.38	0.721	1.00
Brooks	Constant	17.93	1.45	12.40	0.000	
	Temperature	−1.099	0.885	−1.24	0.270	1.00
	Time	−5.343	0.885	−6.03	0.002	1.00
	Hygrometry	−0.581	0.885	−0.66	0.541	1.00
	Temperature * Temperature	2.05	1.30	1.57	0.177	1.01
	Time * Time	1.79	1.30	1.37	0.228	1.01
	Relative Humidity * Relative Humidity	−0.05	1.30	−0.04	0.969	1.01
	Temperature * Time	0.37	1.25	0.30	0.778	1.00
	Temperature * Relative humidity	0.09	1.25	0.07	0.949	1.00
	Time * Relative Humidity	−0.47	1.25	−0.38	0.721	1.00

Coeff = estimated regression coefficient; SE Coeff = standard error of the estimated coefficient; VIF = variance inflation factor. Positive coefficients indicate an increase in final moisture content. whereas negative coefficients indicate a decrease.

For the *Valencia* variety, the coefficients of the moisture content model were as follows:

temperature = −15.23, time = −6.07, humidity = 5.92, temperature^2 = 0.1169, time^2 = 0.1069, humidity^2 = −0.068, temperature × time = 0.0277, temperature × humidity = −0.0332, and time × humidity = −0.47, with a constant term of 520.

Thus, the water content model for the *Valencia* variety can be expressed as:

$$Y = 520 - 15.23T - 6.07t + 5.92H + 0.1169T^2 + 0.1069t^2 - 0.068H^2 + 0.0277T \cdot t - 0.0332T \cdot H - 0.47t \cdot H$$

where:

- Y = moisture content (%)
- T = drying temperature (˚C)
- t = drying time (h)
- H = relative humidity (%)

For the *Kent* variety, the coefficients of the moisture content model were:

temperature = −11.34, time = −4.77, humidity = 0.5, temperature^2 = 0.0819, time^2 = 0.0884, humidity^2 = −0.008, temperature × time = 0.0166, temperature ×

humidity = 0.007, and time × humidity = −0.042, with a constant term of 448.

Thus, the moisture content model for the *Kent* variety can be expressed as:

$$Y = 448 - 11.34T - 4.77t + 0.5H + 0.0819T^2 + 0.0884t^2 - 0.008H^2 + 0.0166T \cdot t - 0.007T \cdot H - 0.042t \cdot H$$

where:

- Y = moisture content (%)
- T = drying temperature (˚C)
- t = drying time (h)
- H = relative humidity (%)

For the *Brooks* variety, the coefficients of the moisture content model were:

temperature = −11.34, time = −4.77, humidity = 0.5, temperature^2 = 0.0819, time^2 = 0.0884, humidity^2 = −0.008, temperature × time = 0.0166, temperature × humidity = 0.007, and time × humidity = −0.042, with a constant term of 448.

Thus, the moisture content model for the *Brooks* variety can be expressed as:

$$Y = 448 - 11.34T - 4.77t + 0.5H + 0.0819T^2 + 0.0884t^2 - 0.008H^2 + 0.0166T \cdot t - 0.007T \cdot H - 0.042t \cdot H$$

where:

- Y = moisture content (%)
- T = drying temperature (˚C)
- t = drying time (h)
- H = relative humidity (%)

For the *Amelie* variety, the coefficients of the moisture content model were:

temperature = −11.34, time = −4.77, humidity = 0.5, temperature^2 = 0.0819, time^2 = 0.0884, humidity^2 = -0.008, temperature × time = 0.0166, temperature × humidity = 0.007, and time × humidity = −0.042, with a constant term of 446.

Thus, the moisture content model for the *Amelie* variety can be expressed as:

$$Y = 446 - 11.34T - 4.77t + 0.5H + 0.0819T^2 + 0.0884t^2 - 0.008H^2 + 0.0166T \cdot t - 0.007T \cdot H - 0.042t \cdot H$$

where:

- Y = moisture content (%)
- T = drying temperature (˚C)
- t = drying time (h)
- H = relative humidity (%)

For the *Lippens* variety, the coefficients of the moisture content model were:

temperature = −11.34, time = −4.77, humidity = 0.5, temperature^2 = 0.0819, time^2 = 0.0884, humidity^2 = −0.008, temperature × time = 0.0166, temperature × humidity = 0.007, and time × humidity = −0.042, with a constant term of 445.

Thus, the moisture content model for the *Lippens* variety can be expressed as:

$$Y = 445 - 11.34T - 4.77t + 0.5H + 0.0819T^2 + 0.0884t^2 - 0.008H^2 + 0.0166T \cdot t - 0.007T \cdot H - 0.042t \cdot H$$

where:

- Y = moisture content (%)
- T = drying temperature (˚C)
- t = drying time (h)
- H = relative humidity (%)

For the *Keitt* variety, the coefficients of the moisture content model were: temperature = −0.28, time = 1.204, humidity = −10.76, temperature^2 = 0.00055, time^2 = 0.0048, humidity^2 = 0.2334, temperature × time = −0.0191, temperature × humidity = 0.0174, and time × humidity = −0.0413, with a constant term of 148.4.

Thus, the moisture content model for the *Keitt* variety can be expressed as:

$$Y = 148.4 - 0.28T - 1.204t - 10.76H + 0.0055T^2 + 0.0048t^2 + 0.2334H^2 - 0.0191T \cdot t - 0.0174T \cdot H - 0.0413t \cdot H$$

where:

- Y = moisture content (%)
- T = drying temperature (˚C)
- t = drying time (h)
- H = relative humidity (%)

Model adequacy was further assessed through analysis of variance and a lack-of-fit test based on the three center-point replicates (runs 13-15). Using the observed and predicted values reported in Table 5, the quadratic models explained 89.5% - 99.0% of the variance (R^2) across the six mango varieties (Table 6), with adjusted R^2 ranging from 70.6% (Amelie, Lippens) to 97.3% (Keitt). The lack-of-fit test was significant for five varieties—Kent (F = 71.56, p = 0.014), Valencia (F = 33.58, p = 0.029), Amelie (F = 71.61, p = 0.014), Brooks (F = 71.56, p = 0.014), and Lippens (F = 71.61, p = 0.014) indicating residual curvature not fully captured by the quadratic terms. In contrast, the test was non-significant for Keitt (F = 7.81, p = 0.116), confirming full model adequacy for this variety alone. This limitation is attributable to the reduced residual degrees of freedom [5] inherent to the 15-run Box-Behnken design, which constrains the statistical power of the lack-of-fit test for the other varieties (Table 6).

Table 5. Observed and predicted moisture contents and residual values for validation of the fitted models.

	Experience matrix			*Kent*				*Valencia*				*Amelia*			
	Temperature (˚C)	Time (h)	Relative humidity (%)	Measured Moisture (%)	Predicted Humidity (%)	Residue		Measured Moisture (%)	Predicted Humidity (%)	Residue		Measured Moisture (%)	Predicted Humidity (%)	Residue	
						Value	Rate (%)			Value	Rate (%)			Value	Rate (%)
1	60	15.0	22.50	29.70	27.97	1.73	5.82	25.52	24.79	0.73	2.86	27.96	26.23	1.73	6.19
2	70	15.0	22.50	26.66	25.03	1.63	6.11	22.48	21.10	1.38	6.14	24.92	23.29	1.63	6.54
3	60	24.0	22.50	14.91	16.54	−1.63	−10.93	12.73	14.11	−1.38	−10.84	13.17	14.80	−1.63	−12.37
4	70	24.0	22.50	13.36	15.09	−1.73	−12.95	12.18	12.91	−0.73	−5.99	11.62	13.35	−1.73	−14.88
5	60	19.50	20.0	22.06	21.08	0.98	4.44	17.88	16.77	1.10	6.15	20.32	19.34	0.98	4.82
6	70	19.50	20.0	19.79	18.71	1.08	5.46	15.61	15.16	0.45	2.88	18.05	16.97	1.08	5.98
7	60	19.50	25.0	18.67	19.74	−1.08	−5.78	16.49	16.94	−0.45	−2.73	16.93	18.01	−1.08	−6.38

Continued

8	70	19.50	25.0	16.74	17.72	−0.98	−5.85	12.56	13.66	−1.10	−8.76	15.00	15.98	−0.98	−6.53
9	65	15.0	20.0	21.80	24.51	−2.71	−12.43	17.62	19.45	−1.83	−10.38	20.06	22.77	−2.71	−13.51
10	65	24.0	20.0	15.42	14.77	0.65	4.21	11.24	10.96	0.28	2.49	13.68	13.03	0.65	4.75
11	65	15.0	25.0	23.64	24.29	−0.65	−2.75	19.46	19.74	−0.27	−1.39	21.90	22.55	−0.65	−2.97
12	65	24.0	25.0	15.37	12.66	2.71	17.63	11.19	9.36	1.84	16.44	13.63	10.92	2.71	19.88
13	65	19.5	22.5	17.34	17.32	0.02	0.11	13.16	13.14	0.02	0.15	15.60	15.58	0.02	0.13
14	65	19.5	22.5	17.69	17.32	0.37	2.09	13.51	13.14	0.37	2.74	15.95	15.58	0.37	2.32
15	65	19.5	22.5	16.93	17.32	−0.39	−2.30	12.75	13.14	−0.39	−3.06	15.19	15.58	−0.39	−2.57

Experience matrix				*Brooks*				*Lippens*				*Keitt*			
	Temperature (˚C)	Time (h)	Relative humidity (%)	Measured Moisture (%)	Predicted Humidity (%)	Residue		Measured Moisture (%)	Predicted Humidity (%)	Residue		Measured Moisture (%)	Predicted Humidity (%)	Residue	
						Value	Rate (%)			Value	Rate (%)			Value	Rate (%)
1	60	15.0	22.5	30.31	28.58	1.73	5.70	26.91	25.18	1.73	6.43	20.54	20.90	−0.37	−1.79
2	70	15.0	22.5	27.27	25.64	1.63	5.98	23.87	22.24	1.63	6.83	19.89	19.84	0.05	0.25
3	60	24.0	22.5	15.52	17.15	−1.63	−10.50	12.12	13.75	−1.63	−13.45	14.67	14.72	−0.05	−0.34
4	70	24.0	22.5	13.97	15.70	−1.73	−12.38	10.57	12.30	−1.73	−16.37	12.30	11.93	0.37	3.01
5	60	19.5	20.0	22.67	21.69	0.98	4.32	19.27	18.29	0.98	5.08	19.68	19.22	0.46	2.34
6	70	19.5	20.0	20.40	19.32	1.08	5.29	17.00	15.92	1.08	6.35	16.90	16.86	0.04	0.24
7	60	19.5	25.0	19.28	20.35	−1.08	−5.60	15.88	16.96	−1.08	−6.80	19.09	19.13	−0.04	−0.21
8	70	19.5	25.0	17.35	18.33	−0.98	−5.65	13.95	14.93	−0.98	−7.02	17.18	17.64	−0.46	−2.68
9	65	15.0	20.0	22.41	25.12	−2.71	−12.09	19.01	21.72	−2.71	−14.26	21.09	21.18	−0.09	−0.43
10	65	24.0	20.0	16.03	15.38	0.65	4.05	12.63	11.98	0.65	5.15	14.65	15.06	−0.41	−2.80
11	65	15.0	25.0	24.25	24.90	−0.65	−2.68	20.85	21.50	−0.65	−3.12	22.87	22.46	0.41	1.79
12	65	24.0	25.0	15.98	13.27	2.71	16.96	12.58	9.87	2.71	21.54	14.57	14.48	0.09	0.62
13	65	19.5	22.5	17.95	17.93	0.02	0.11	14.55	14.53	0.02	0.14	16.50	16.74	−0.24	−1.45
14	65	19.5	22.5	18.30	17.93	0.37	2.02	14.90	14.53	0.37	2.48	16.82	16.74	0.08	0.47
15	65	19.5	22.5	17.54	17.93	−0.39	−2.22	14.14	14.53	−0.39	−2.76	16.90	16.74	0.16	0.95

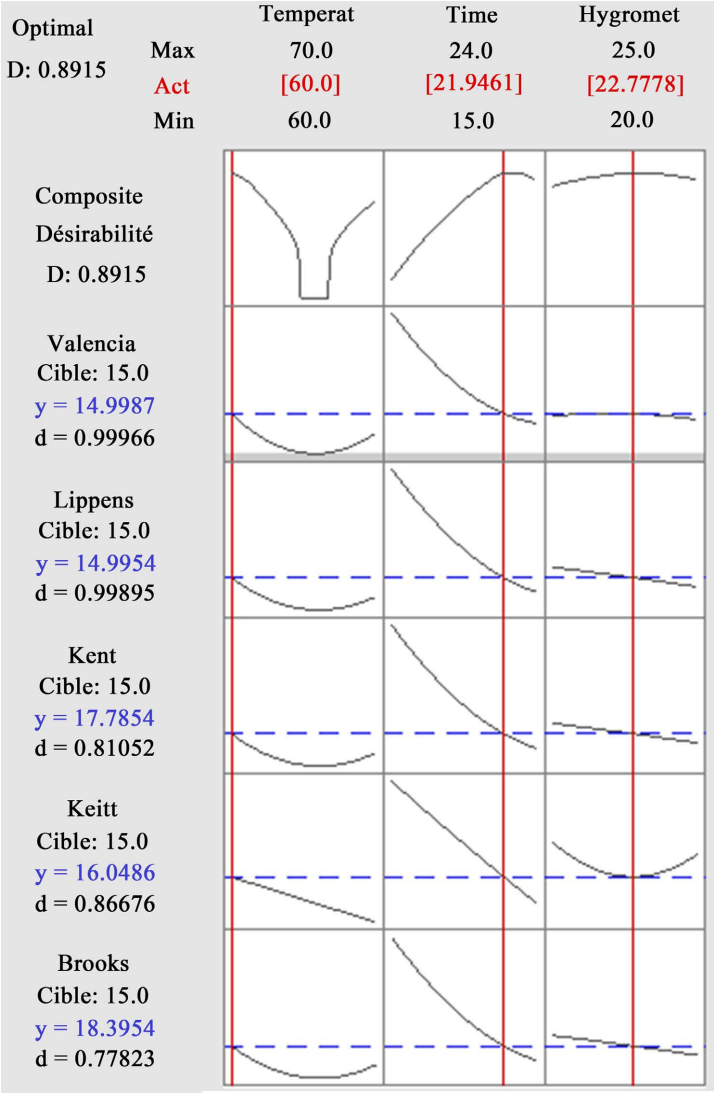
Residual = observed value minus predicted value; residual rate (%) = residual value expressed as percentage of the predicted moisture content.

Table 6. Coefficients of determination (R^2) and lack-of-fit test results for the quadratic moisture-content models of the six mango varieties.

Varieties	R^2	R^2 adjusted	F (lack-of-fit)	P
Kent	89.5%	70.7%	71.56%	0.014
Valencia	94.2%	83.8%	33.58%	0.029
Amelia	89.5%	70.6%	71.61%	0.014
Brooks	89.5%	70.7%	71.56%	0.014
Lippens	89.5%	70.6%	71.61%	0.014
Keitt	99.0%	97.3%	7.81%	0.116

3.4. Model Optimization

The results of the optimization allowed the determination of the optimal drying time and relative humidity, which were identified as the two most influential factors on the moisture content of the six mango varieties studied, with the drying temperature at the lower level of the domain. The optimum shown in Figure 5 corresponds to 60˚C, 21.95 h (21 h 56 min 46 s) of drying and 22.78% relative humidity.



Note: The optimum conditions were identified by maximizing the overall desirability function for final moisture content across the six mango varieties.

Figure 5. Optimization plot showing the combination of drying temperature. drying time. and relative humidity that maximized overall desirability for the six mango varieties.

Under these conditions, the predicted minimum moisture contents for each variety were: *Valencia*: 14.99%, *Lippens*: 14.99%, *Kent*: 17.78%, *Keitt*: 16.04%, *Brooks*: 18.39%, and *Amelie*: 16.05%, as illustrated in Figure 5. Compliance with

the moisture limits must be judged separately for each applicable standard: i) all six predicted values are below the 25% limit for mango treated with preservatives [15]; ii) Valencia, Lippens, Keitt, Amelie and Kent (14.99% - 17.78%) fall within the 14% - 18% range required by some European buyers [16], whereas Brooks (18.39%) exceeds the upper bound of 18%; and iii) only Valencia and Lippens (14.99% each) are below the 15% maximum for untreated dried mango [15], while Kent, Keitt, Brooks and Amelie (16.04% - 18.39%) exceed it.

The overall desirability index (D) was calculated as 89.15% (**Figure 5**), which is higher than the satisfaction index reported by Ky *et al*. [24] (88%) and well above the threshold of 50% indicated by Derringer [20] [26], indicating a favorable compromise among the six responses. This index is computed from model predictions, however, and the significant lack of fit reported above for five of the six varieties means that it should not be read as confirmation of the optimum; validation runs at the optimal conditions are needed.

4. Discussion

4.1. Moisture Content Validation and Comparative Analysis

The moisture contents predicted for the six mango varieties (14.99% - 18.39%) under optimized tunnel drying conditions must be compared with each applicable standard separately. Five varieties (*Valencia*, *Lippens*, *Keitt*, *Amelie* and *Kent*; 14.99% - 17.78%) fall within the 14-18% range required by some European buyers [16], but *Brooks* (18.39%) exceeds its upper limit, so the optimized range cannot be described as 14% - 18% for all six varieties. Only *Valencia* and *Lippens* (14.99% each) meet the 15% maximum for untreated dried mango [15]; the other four varieties (16.04% - 18.39%) satisfy only the 25% limit applicable to mango treated with preservatives, or would require longer drying or lower humidity than the shared optimum. These results are consistent with Nduhiu *et al*. [1], who reported final moisture contents of 16.52% - 23.86% for Cameroon mango varieties using electric convective drying, and lower than values obtained by Doymaz [5] for mushroom slices under similar temperature ranges. The observed variation across varieties may reflect differences in initial tissue structure and water binding capacity, as moisture reduction is primarily governed by free water evaporation during the initial drying phase. Because ripeness and initial moisture content of the fruit were not measured (see Materials and Methods), cultivar effects cannot be fully separated from differences in starting material.

4.2. Key Drying Parameter Hierarchy

Within the 60˚C - 70˚C temperature range, drying time emerged as the dominant factor influencing final moisture content across all varieties, followed by relative humidity, with temperature showing a secondary effect. This parameter hierarchy aligns with findings from Mugodo and Workneh [27], who demonstrated that drying duration primarily controls moisture removal in convective systems operating at moderate temperatures, where mass transfer becomes the rate-limiting

step rather than thermal activation. The positive effect of relative humidity on final moisture content corroborates the mass transfer principles outlined by Mujumdar [10], where increased air humidity reduces the driving force for water vapor diffusion from the product surface.

4.3. Model Robustness and Predictive Performance

The quadratic models explained 89.5% - 99.0% of the variance, but their predictive accuracy was uneven: residuals exceeded 5% of the predicted value in several runs (up to 21.5% for *Lippens* in run 12; **Table 5**), and the lack-of-fit test was significant for five of the six varieties. Given the significant lack of fit, these models should be treated as approximate guides within the tested domain (60˚C - 70˚C, 15 - 24 h, 20% - 25% RH); comparison with the pineapple drying models reported by Chokngam and Suvanjumrat [28] remains indicative only and does not by itself establish the suitability of Box-Behnken designs for non-linear drying behavior. The interaction effects observed between drying time and relative humidity for the Valencia variety indicate coupled mass transfer phenomena that require multivariate experimental approaches rather than single-factor optimization.

4.4. Theoretical Contributions to Convective Drying

These findings challenge the traditional temperature-centric approach to convective drying control. Within industrial tunnel dryer operating ranges (60˚C - 70˚C), the study demonstrates a temperature saturation zone where further temperature increases yield marginal moisture reduction benefits while increasing energy costs. This supports a paradigm shift toward time-humidity dominated process control, as mass transfer gradients become the primary limitation. The significant time × humidity interactions observed validate the need for response surface methodologies to capture non-linear moisture migration patterns in high-water-content tropical fruits.

4.5. Practical Implications for Industrial Drying

From a process engineering perspective, prioritizing accurate time control over temperature adjustments offers substantial energy savings without compromising product quality. The identified robust drying window (15 - 24 h, 20% - 23% RH, 60˚C - 70˚C) accommodates natural fluctuations in ambient conditions although compliance with the applicable moisture standards must be verified for each variety (see above) and confirmed by validation runs [25]. This operational flexibility is particularly valuable for small-to-medium scale processors in developing countries facing variable raw material quality and environmental conditions.

4.6. Transferability and Scalability

The modeling framework developed is directly applicable to other tropical fruits with comparable tissue structure and water content (pineapple, papaya, banana), requiring only adaptation of factor ranges. The global desirability index (D =

0.8915) indicates a favorable compromise among the six varieties, but it is based on model predictions with significant lack of fit for five varieties and has not been confirmed by validation runs; scale-up to industrial tunnel drying therefore requires confirmation. The optimized parameters may help West African processors approach European moisture specifications (14% - 18%), although Brooks is predicted to exceed this range and only Valencia and Lippens are predicted to meet the 15% limit for untreated product.

5. Conclusions

The socio-economic importance of mango for actors in the mango sector in Burkina Faso including producers, processors, and traders motivated this study on the drying process using the design of experiments (DoE) approach. The study aimed to contribute to the professionalization of the drying system, improve the quality of dried mango from Burkina Faso, and, consequently, enhance the economic profitability of mango drying activities.

Beyond process optimization, the outcomes of this study open new perspectives for both drying theory and industrial application. The results demonstrated that the DoE methodology allows the development of mathematical models capable of predicting the moisture content of mangoes. Specifically, the study revealed that, at a drying temperature of 60˚C, a drying time of 21.95 h (21 h 56 min 46 s) and a relative humidity of 22.78% are predicted to give minimum moisture contents ranging from 14.99% for the *Lippens* variety to 18.39% for the *Brooks* variety. Compliance depends on the standard: only Valencia and Lippens (14.99%) are below the 15% maximum for untreated dried mango; five of the six varieties fall within the 14% - 18% buyer range (Brooks, at 18.39%, does not); and all six are below the 25% limit for treated mango. These predictions should be confirmed by validation runs at the optimum.

These findings provide valuable information for stakeholders in the mango drying sector, enabling them to meet customer specifications regarding moisture content. Furthermore, the results contribute new knowledge on the drying of mango varieties from Burkina Faso, supporting efforts to optimize drying processes and improve product quality.

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Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Highlights

- Box-Behnken design optimized tunnel drying of six West African mango vari-

eties.

- Drying time and relative humidity were the main determinants of final moisture content.
- Quadratic models explained 89.5% - 99.0% of moisture variance, with significant lack of fit for five of six varieties.
- The predicted optimum (≈60˚C, ~22 h, ~22.8% RH) were predicted to give 15% - 18.4% moisture; compliance varies by variety and by standard.
- A global desirability index ≈0.90 provides a robust tool for industrial tunnel-drying control.

Author Contributions

Inoussa KY: investigation, supervision, validation, visualization, data conservation, methodology, writing-proofreading and editing. Jean Axel T. KABORE: conceptualization, methodology, data conservation and writing-original version. Hyacinthe KANTE-TRAORE: methodology, data conservation and writing-original version. Lucien BAMBARA: conceptualization, methodology, data conservation and writing-original version. Roland Nag-Tiero MEDA: writing-proofreading and editing.

Conflicts of Interest

The authors declare that they have no relevant financial or non-financial interests to disclose.

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