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Comparative Evaluation of Drying Methods for Jerusalem Artichoke (Helianthus tuberosus L.) Flour Using FT-MIR and Chemometrics

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A B S T R A C T

Objective: This study evaluated how drying conditions influence the physicochemical, functional, and ATR-FT-MIR spectral characteristics of Jerusalem artichoke (*Helianthus tuberosus* L.) flour from three Moroccan locations, using exploratory chemometric analysis to identify treatment- and location-associated patterns.

Methods: Flour samples were prepared using microwave (90 and 500 W), conventional-oven (110 and 140°C), and low-temperature oven drying (40 and 80°C). The experimental design included 36 conditions (3 sampling locations × 3 drying methods × 2 power/temperature levels × 2 slice thicknesses), with triplicate technical measurements per experimental unit. ATR-FT-MIR spectra (4000–400 cm^{-1}; 4 cm^{-1} resolution) were analyzed using exploratory PCA.

Results: The ATR-FT-MIR spectra showed broadly similar profiles with treatment-associated differences in selected spectral regions. PCA showed visual grouping patterns associated with drying conditions and sampling locations; these patterns are interpreted as exploratory spectral differences rather than statistically validated class discrimination. Across the conditions reported in Table 3, pH ranged from 5.51 to 6.80, moisture from 3.28 to 7.76%, and ash from 1.47 to 5.00%. WAC ranged approximately from 140 to 450 g H_2O/100 g flour and WSI from approximately 15 to 35%. Microwave drying produced comparatively low residual moisture under several tested conditions, whereas the low-temperature laboratory-oven treatment showed comparatively less pronounced changes in some ATR-FT-MIR spectral profiles relative to the other dried samples. Because no untreated FT-MIR control or direct degradation markers were measured, these spectral observations are not interpreted as proof of preservation of native structure or chemical quality.

Conclusion: ATR-FT-MIR spectroscopy and PCA effectively differentiated Jerusalem artichoke flours dried under different conditions. Microwave drying promoted faster moisture removal and favorable functional properties, while low-temperature drying caused fewer spectral changes. Further validation with controls, replication, and compositional analyses is needed.

Keywords: Drying methods, *Helianthus tuberosus*, Flour, ATR-FT-MIR spectroscopy, Physicochemical properties

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Introduction

Jerusalem artichoke (*Helianthus tuberosus* L.) is an herbaceous, perennial plant that is native to North America and belongs to the Asteraceae family. It features an aerial stem that is branched and can be 2–3 m tall and an underground rhizome system giving rise to edible tubers. They store mainly fructo-oligosaccharides (FOS) and inulin as a source of carbohydrates [1]. Jerusalem artichoke tubers have been the target of significant attention in recent years due to their high inulin content; inulin has been used in a range of industrial applications and is also seen as a promising feedstock for bioethanol. The tubers of Jerusalem artichoke have been given a lot of attention in recent years as a source of inulin, which has a wide range of industrial applications and also has been suggested as a potential feedstock for bioethanol production [2, 3]. Jerusalem artichoke has several agronomic benefits over traditional crops, such as its fast growth, frost, drought and low fertility tolerance, and high pest and disease resistance [4,5]. These features allow it to be easily grown in marginal areas and are essential to the development of sustainable agricultural systems. Besides its agronomic use, this has increased the interest in the food sector, due to its nutritional, functional and medicinal potentials [7, 8]. However, the use of tubers of Jerusalem artichoke in industry has been limited due to their high moisture content (around 80%) [6]. The high moisture content significantly decreases their storage life; freshly harvested tubers start to deteriorate within two weeks of harvest [9]. Therefore, the process of converting tubers to flour is an effective preservation method which helps to store, transport and use the tubers in different food products, such as cookies, pancakes and porridge, and also extends the shelf life of the tubers. The quality and functional characteristics of Jerusalem artichoke flour have been found to be affected by several processing parameters, such as pre-cooking treatments [9], drying temperature, drying time and air space during the drying process [10]. Drying is one of the most crucial preservation methods in vegetable processing as it prevents the action of enzymes, restricts the microbial growth and postpones the deterioration of product [11]. However there are also undesirable physical and chemical changes that can be caused by drying which will impact the nutritional and functional quality of the final product. Thus, choosing an appropriate drying method is very important to remove water efficiently and maximize product quality. Microwave drying has been reported to give rapid volumetric heating and efficient water evaporation, significantly decreasing drying time [12]. However, long drying time leads to irregular temperature gradient and local over-heating caused by the distribution of electromagnetic field in the drying chamber is not uniform [13]. On the other hand, electric oven drying offers more uniform heat transfer, but usually takes longer processing time [14]. Analytical methods that can quickly characterize food composition are needed to make reliable assessment of changes caused by food drying. Fourier Transform Mid-Infrared (FT-MIR) spectroscopy has become a fast, non-destructive and inexpensive analytical method for the simultaneous identification of several food components without lengthy sample preparation [15]. FT-MIR spectroscopy, in conjunction with chemometric analysis tools like Principal Component Analysis (PCA), has been found to be useful for fast characterization, quality evaluation and process control of food. Aditionally, the effect of processing conditions on the quality of Jerusalem artichoke flour has been studied earlier but most studies have been limited to conventional quality parameters like moisture content, drying characteristics and physicochemical properties [9, 10]. However, PCA-based spectral differences alone do not establish changes in chemical composition or preservation of native structure. Accordingly, the present study combines drying-process optimization with ATR-FT-MIR/PCA exploration to (i) compare drying responses under the tested operating conditions, (ii) describe associated physicochemical and functional properties, and (iii) explore treatment- and sampling-location-associated spectral patterns. These two analytical components are interpreted as complementary rather than as direct validation of chemical preservation.

Materials and Methods

Experimental Material

Fresh Jerusalem artichoke tubers were collected from three sampling locations in the Béni Mellal-Khénifra region of Morocco: Béni Mellal, Fkih Ben Salah, and Ksiba. After collection, the tubers were washed with running water to remove adhering soil and stored at −10°C before processing. Cultivar/genotype, precise maturity criteria, harvest-to-freezing interval, storage duration, and thawing conditions were not documented. These raw-material and postharvest factors are therefore recognized as potential confounders, and differences among locations are interpreted as sampling-location-associated rather than as direct climatic effects.

The experimental design comprised 36 experimental conditions (3 sampling locations × 3 drying methods × 2 temperature/power levels × 2 slice thicknesses). Each condition represented one experimental unit (one physical sample). Physicochemical and functional measurements were performed in triplicate on the same experimental unit (n = 3 technical replicates). These repeated measurements estimate analytical repeatability and were not treated as independent biological or process replicates. Consequently, treatment- or location-level inferential ANOVA was not performed using the technical triplicates as independent observations.

Table 1: Jerusalem artichoke sampling locations included in the study.

Sampling location	Administrative region	Interpretation in this study
Béni Mellal	Béni Mellal-Khénifra, Morocco	Sampling-location-associated observations; no causal climatic inference.
Fkih Ben Salah	Béni Mellal-Khénifra, Morocco	Sampling-location-associated observations; no causal climatic inference.
Ksiba	Béni Mellal-Khénifra, Morocco	Sampling-location-associated observations; no causal climatic inference.

Preparation of Jerusalem artichoke flour

Jerusalem artichoke tubers from Béni Mellal, Fkih Ben Salah, and Ksiba were washed with tap water, peeled using the same preparation workflow, and sliced to nominal thicknesses of 0.1 and 1 cm. Three drying systems were evaluated: (i) microwave drying at 90 and 500 W using a Whirlpool MWP 304 M microwave oven (maximum power 900 W; chamber capacity 30 L); (ii) high-temperature conventional-oven drying at 110 and 140°C using an Itimat conventional oven, model I-08TTA13V (capacity 40 L; maximum temperature 300°C); and (iii) low-temperature laboratory-oven drying at 40 and 80°C using a BINDER laboratory drying oven (BINDER GmbH, Germany; exact model not documented). Air-circulation mode, temperature-control accuracy, tray loading, microwave frequency, and the precise drying-endpoint criterion were not documented and are acknowledged as reproducibility limitations. After drying, slices were milled, passed through a 500-µm sieve to standardize flour particle size, and stored at 5°C until analysis.

The study therefore distinguishes the two oven-based treatments by their operating temperature ranges and equipment: the Itimat high-temperature conventional oven (110–140°C) and

the BINDER low-temperature laboratory drying oven (40–80°C). The ambiguous term "electric oven" is not used as a scientific method label in the manuscript.

Chemical analysis

Moisture content

Moisture content was determined gravimetrically by drying the flour at 105 ± 2°C to constant mass. Measurements were performed in triplicate on the same experimental unit and are reported as mean ± SD. The retained laboratory documentation identifies the procedure as AOAC-based, but the exact AOAC method number was not available; therefore, no unverified method number is assigned [16].

pH measurement

The pH was measured potentiometrically with a pH probe, consistent with electrode-based determination of pH in fruit and vegetable products [17]. Measurements were performed in triplicate on the same experimental unit and are reported as mean ± SD. Instrument-model, calibration-buffer, sample-to-water ratio, equilibration, and measurement-temperature details were not available in the retained laboratory documentation and are acknowledged as reproducibility limitations.

Ash content

Ash content was determined by gravimetric incineration following the laboratory's AOAC [16] based procedure. Measurements were performed in triplicate on the same experimental unit and are reported as mean ± SD. The exact AOAC method number and furnace time/temperature were not available in the retained laboratory documentation and are therefore not specified.

$$Ash(\%) = \frac{Massofash}{Massofsample} \times 100$$

Water absorption capacity (WAC) and water solubility index (WSI)

For WAC and WSI determination, 0.5 g of flour was mixed with 10 mL of distilled water and incubated for 15 min in a stirred water bath at 40 or 80°C. The mixture was centrifuged at 5000 rpm for 30 min. The hydrated sediment was weighed for WAC determination, and the separated supernatant was dried at 105°C for 12 h to determine recovered soluble solids for WSI. Measurements were performed in triplicate on the same experimental unit. The calculation basis is reported explicitly below so that the units are unambiguous [3, 18].

Water absorption capacity (WAC) was calculated using the following equation:

$$WAC\ (g\ H_2O/100\ g\ flour) = [(W_2 - W_1) / W_1] \times 100$$

Where:

W_1 = weight of the dry flour sample (g)

W_2 = weight of the hydrated sediment after centrifugation (g)

Water solubility index (WSI) was calculated using the following equation:

$$WSI\ (\%) = (W_3 / W_1) \times 100$$

Where:

W_1 = initial weight of the dry flour sample (g)

W_3 = weight of the dried soluble solids recovered from the supernatant (g)

Thus, WAC is expressed consistently as g H_2O/100 g flour and WSI as g soluble solids/100 g initial dry flour (%, on this calculation basis). Measurements were performed at both 40 and 80°C.

Attenuated Total Reflectance Fourier Transform Mid-Infrared (ATR-FT-MIR) Spectroscopy

ATR-FT-MIR spectra were acquired using a Bruker Vector 22 FT-IR spectrophotometer equipped with an attenuated total reflectance accessory, DTGS

detector, MIR source, and diamond crystal (45° incidence; Pike Miracle, Pike Technologies, Madison, USA). Spectra were recorded in absorbance mode over 4000–400 cm^{-1} at 4 cm^{-1} resolution. Each recorded spectrum was generated from 90 co-added scans [19]. The available method record does not document additional independent spectral acquisitions per physical sample; accordingly, the 90 scans are treated as co-added instrumental scans rather than independent replicates.

No fresh/undried ATR-FT-MIR control was included in the documented experiment. Consequently, all statements that a drying method "preserved native structure" have been removed and replaced by comparisons of relative spectral-profile changes among the dried samples.

The retained chemometric documentation does not provide a reproducible record of baseline correction, normalization, smoothing, derivatives, SNV/MSC, mean-centering, or scaling beyond the stated spectral acquisition conditions. Accordingly, PCA findings are presented strictly as exploratory visual summaries, and no validated classification-performance claim is made.

Chemometrics methods

Principal component analysis (PCA) was used as an exploratory unsupervised method to summarize variation in the ATR-FT-MIR data and visualize treatment- and sampling-location-associated spectral patterns. PCA score-plot grouping is not interpreted as statistically validated class discrimination. A supervised classifier (e.g., PLS-DA) was not added because the experiment lacks documented independent biological/process replication suitable for robust validation; applying such a model to technical or non-independent observations could produce optimistic performance estimates [20].

The PCA figures and reported explained-variance values are therefore interpreted as descriptive outputs from the available analysis. Because the exact data-matrix dimensions, preprocessing sequence, and software/version were not documented, no additional processing details are inferred. Future validation should archive the complete spectral matrix, preprocessing sequence, software/version, and an independent validation design.

Statistical analysis. Descriptive results from physicochemical and functional measurements are reported as mean ± SD of three technical replicate measurements on the same experimental unit. Because these replicates are not independent biological/process replicates, they were not used as independent observations for treatment- or location-level ANOVA. The 2^2 factorial model for each drying method and sampling location contains four design points and four fitted coefficients (intercept, two main effects, and one interaction), making it saturated when no independent repeated process runs are available. Accordingly, regression coefficients, response profiles, and desirability outputs are interpreted as descriptive/exploratory model summaries; inferential coefficient p-values, lack-of-fit tests, predictive R^2, and claims of statistically validated optimization are not reported [20].

Design of Experiments (DOE)

A two-factor, two-level full factorial design (2^2) was used within each drying approach to examine the effects of slice thickness (X_1) and drying temperature or microwave power (X_2). The coded factor levels were −1 and +1, with the corresponding physical settings listed in Table 2.

For each drying approach, four factor combinations were defined by the 2^2 design. Because a model containing an intercept, two main effects, and their interaction is saturated if each combination is run only once, independent replication is required to estimate experimental error and support inferential model statistics.

The 2^2 factorial design comprised four factor combinations for each drying method within each geographical location. Each factor combination corresponded to one experimental unit. Analytical

measurements were performed in triplicate on the same experimental unit; therefore, these triplicate measurements are technical replicates and do not constitute independent experimental replication for estimating pure experimental error. Accordingly, the fitted first-order interaction models are treated as saturated descriptive models unless independent repeated experimental runs or additional validation data are available. Inferential claims concerning coefficient significance, lack-of-fit, or predictive reliability are therefore not made from the technical replicates alone.

Table 1: Experimental areas of the factors studied

Microwave			High-temperature oven			Low-temperature oven		
Test number	**Thicknesses (cm)**	**Drying power**	**Test number**	**Thicknesses (cm)**	**Temperature (°C)**	**Test number**	**Thicknesses (cm)**	**Temperature (°C)**
1	-1	-1	1	-1	-1	1	-1	-1
2	+1	-1	2	+1	-1	2	+1	-1
3	-1	+1	3	-1	+1	3	-1	+1
4	+1	+1	4	+1	+1	4	+1	+1

Three drying methods were evaluated: microwave drying, high-temperature oven drying, and low-temperature oven drying. For each drying method, two experimental levels were tested. At Level −1, samples were sliced to a thickness of 0.1 cm and dried at 90 W by microwave, 110 °C in a high-temperature oven, or 40 °C in a low-temperature oven. At Level +1, the slice thickness was 1 cm, with drying conditions of 500 W by microwave, 140 °C in a high-temperature oven, or 80 °C in a low-temperature oven.

Results

Chemical analysis

Table 3 summarizes pH, moisture content, and ash content for the three sampling locations and drying conditions. The reported values are means ± SD of three technical replicate measurements (n = 3) performed on the same physical sample for each experimental condition. The observed pH values ranged from 5.51 to 6.80. Because the triplicates are technical rather than independent biological or process replicates, the differences among drying treatments and geographical locations are interpreted descriptively and are not presented as inferentially significant treatment effects [21].

Moisture content ranged from 3.28 to 7.76% in Table 3. The highest value (7.76%) was observed for the Fkih Ben Salah sample dried in the low-temperature laboratory oven at 40°C. The lowest reported value (3.28%) occurred for the Fkih Ben Salah sample under high-temperature conventional-oven drying at 140°C and for the Ksiba sample under microwave drying at 500 W.

Ash content ranged from 1.47 to 5.00% in Table 3. The observed variation may reflect both processing conditions and differences among the sampled raw materials; without a factorial

inferential analysis and controlled raw-material covariates, these differences should not be attributed uniquely to drying method or geographical/climatic origin.

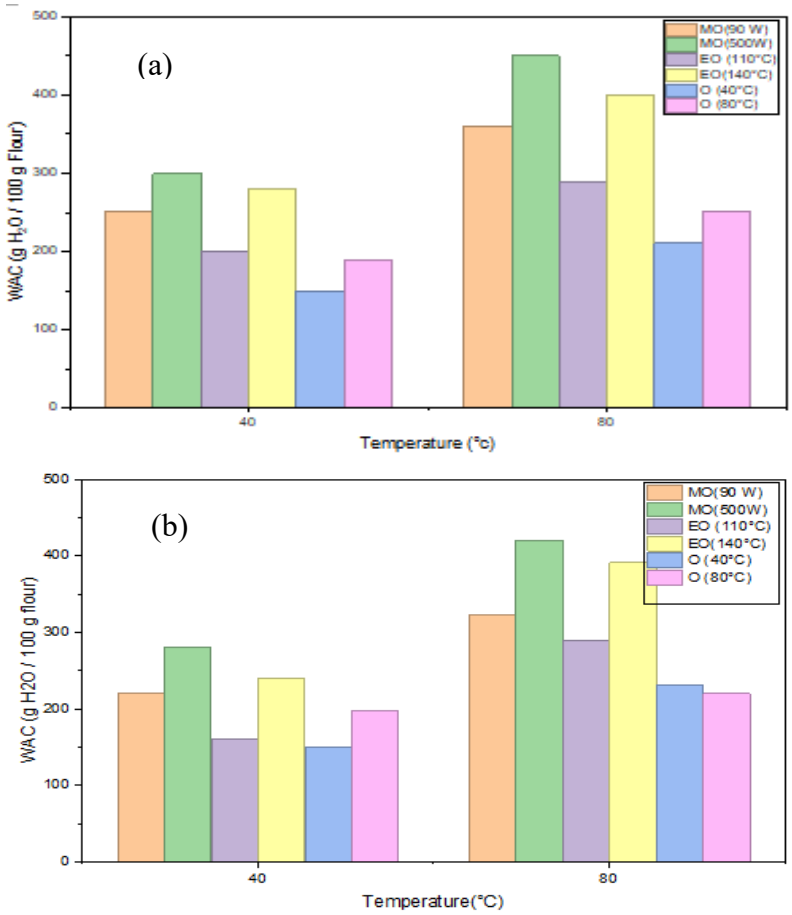
Table 3: pH, moisture content, and ash content of Jerusalem artichoke flours from the three sampling locations. Values are mean ± SD, n = 3 technical replicate measurements per experimental unit

Sampling location	Drying mode and characteristics		pH	Moisture content (%)	Ash content (%)
Béni Mellal	**Microwave power (W)**	P = 90 W	5.7 ± 0.1	5.34 ± 0.3	2.17 ± 0.4
		P = 500 W	6.14 ± 0.1	3.96 ± 0.12	3.93 ± 0.09
	High-temperature oven Temperature	T = 110 °C	6.8 ± 0.05	5.79 ± 0.5	4.86 ± 0.06
		T = 140 °C	5.94 ± 0.02	4.27 ± 0.17	4.75 ± 0.21
	Low-temperature oven Temperature	T = 40 °C	6.31 ± 0.04	6.61 ± 0.3	2.57 ± 0.15
		T = 80°C	6.24 ± 0.1	4.81 ± 0.22	5 ± 0.31
Fkih Ben Salah	**Microwave power (W)**	P = 90W	6.1 ± 0.1	5.16 ± 0.28	2.87 ± 0.19
		P = 500W	6.12 ± 0.08	3.76 ± 0.13	4.38 ± 0.21
	High-temperature oven Temperature	T = 110 °C	6.8 ± 0.03	5.87 ± 0.24	5 ± 0.31
		T = 140 °C	6.08 ± 0.07	3.28 ± 0.31	4.26 ± 0.18
	Low-temperature oven Temperature	T = 40 °C	6.37 ± 0.01	7.76 ± 0.62	2.99 ± 0.13
		T = 80 °C	6.37 ± 0.16	5.08 ± 0.26	4.93 ± 0.27
Ksiba	**Microwave power (W)**	P = 90 W	6.09 ± 0.04	5.8 ± 0.2	1.47 ± 0.2
		P = 500 W	6.5 ± 0.06	3.28 ± 0.33	4.22 ± 0.28

	High-temperature oven Temperature	T = 110 °C	6.7 ± 0.21	6.53 ±0.34	4.69 ± 0.19
		T = 140 °C	5.51 ± 0.07	3.91 ± 0.14	4.86 ± 0.22
	Low-temperature oven Temperature	T = 40 °C	6.3 ± 0.03	7.17 ± 0.21	2.62 ± 0.19
		T = 80 °C	6.57 ± 0.14	5.44 ± 0.28	4.53 ± 0.22

Functional properties: WAC and WSI

Figure 1 presents the water absorption capacity (WAC) of Jerusalem artichoke flours obtained from the three sampling locations under the tested drying conditions. For consistency with the Abstract, WAC is expressed as g H_2O/100 g flour; the values corresponding to 1.4–4.5 g/g are therefore approximately 140–450 g H_2O/100 g flour [22]. The observed differences among treatments and locations should be interpreted descriptively unless supported by an appropriate inferential analysis.



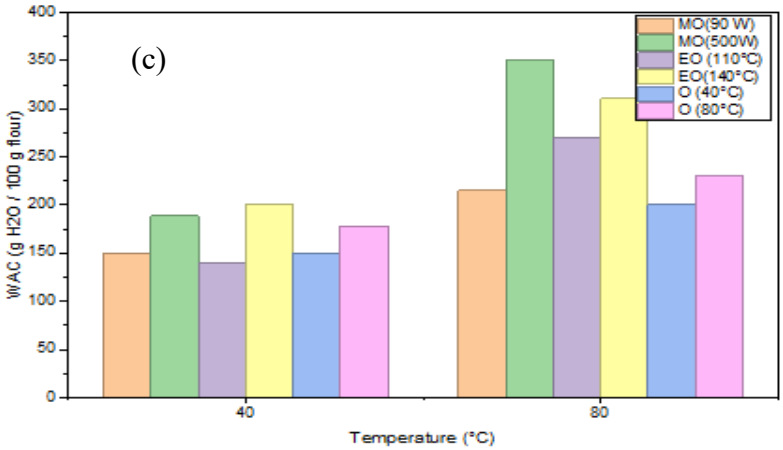
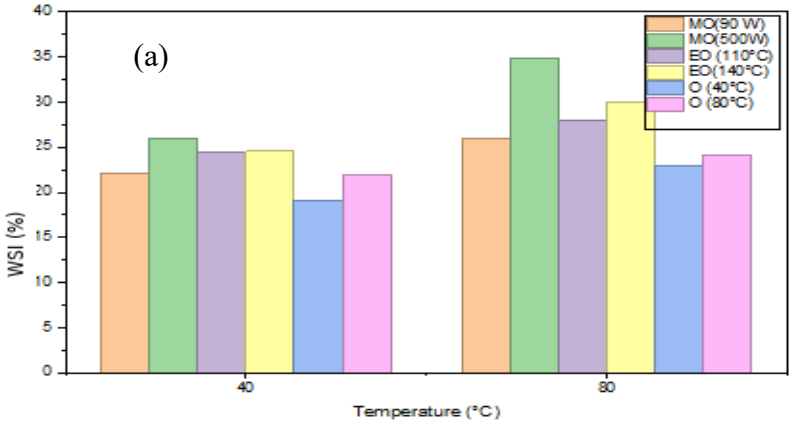


Figure 1: Water absorption capacity (WAC; g H_2O/100 g flour) of Jerusalem artichoke flour from (a) Béni Mellal, (b) Fkih Ben Salah, and (c) Ksiba

The water absorption capacity of Jerusalem artichoke flour as affected by temperature is shown in the results of figure 2. The higher temperatures induced increased water absorption due to the disruption of starch granules, exposure of the hydrophilic groups, and increased solubilisation of the amylose molecules [22]. The response prediction profiles for the three drying methods (without pre-treatment) obtained from the response surface curves and desirability functions showed that the effect of the operating factors depended on the drying method and on the geographical origin of the samples, which were analyzed separately for the three study zones. The power density of the microwave beam (or temperature) and the thickness of the sample were the most significant variables, while the drying time and final moisture content had relatively minor effects. This finding is in line with the earlier investigations of thermal and electromagnetic drying processes [23, 24]. In microwave drying, Figures 2a to 3c demonstrate a pronounced and almost linear decrease in drying time and moisture content for the different microwave drying power densities. This behavior is due to volumetric heating caused by the dielectric losses, that increases the migration of water inside the material and the extraction of water, [18, 24]. While differences in overall desirability were noted across the three study zones the overall results are not interpreted as solely an effect of the drying process.



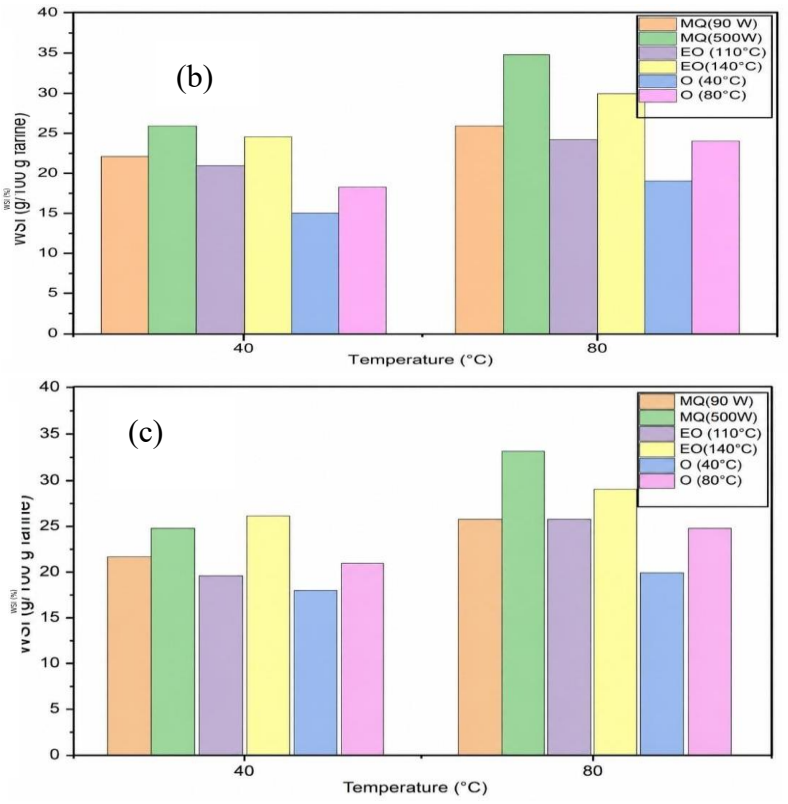


Figure 2: Water solubility index (WSI; %) of Jerusalem artichoke flour from (a) Béni Mellal, (b) Fkih Ben Salah, and (c) Ksiba, measured at 40 and 80°C

Abbreviations: MO = microwave drying; HTO = high-temperature oven drying (originally "electric oven"); LTO = low-temperature oven/incubator drying (originally "oven drying").

Optimization of Jerusalem artichoke drying parameters

The aim of this study was to optimize the parameters influencing Jerusalem artichoke drying across the three zones and to compare the three drying modes.

Mathematical model

Table 4 shows mathematical response models depending on drying mode and characteristics, and the sample thickness:

Table 2: The mathematical models for the responses

	Drying mode	Mathematical model
Béni Mellal	**Microwave**	Y1=7.7825+0.2325X1-7.1675X2-0.2675X1X2
		Y2=20.75-0.895X1-1.4X2-0.305X1X2
		Y3=2.755-0.0685X1-0.81X2+0.76X1X2
	High-temperature oven	Y1=19.165-1.44X1-3.31X2-6.415X1X2
		Y2=22.1625-0.1475X1+0.6521X2-0.7475X1X2
		Y3= 5.065+0.46X1 -0.81X2 -0.215X1X2
	Low-temperature oven	Y1= 33.62+1.875X1 -12.625X2 +0.125X1X2
		Y2= 18.12-0.97X1 -1.22X2 +0.9X1X2
		Y3= 5.77+0.625X1 -0.925X2 +0.0475X1X2
Fkih Ben Salah	**Microwave**	Y1= 6.9+0.89X1-6.325X2 -0.885X1X2
		Y2= 19.7875-0.5125X1-1.8175X2 -0.2675X1X2
		Y3=4.3325-0.2575X1-1.2925X2 +0.3175X1X2
	High-temperature oven	Y1= 15.1125+2.3625X1-8.3625X2 -1.6125X1X2
		Y2= 22.49+0.05X1 -0.155X2 -0.015X1X2
		Y3= 5.035+0.08X1 -1.985X2 +0.07X1X2
	Low-temperature oven	Y1= 34.15+2.1X1 -13.4X2 -0.35X1X2
		Y2= 19.235+0.705X1 -1.985X2 -0.455X1X2
		Y3= 6.565+0.575X1 -1.285X2-0.075X1X2
Ksiba	**Microwave**	Y1=6.98+1.6 X1 -6.27X2-1.65X1X2
		Y2=20.2975-0.1575 X1 -1.3875X2 +0.6575X1X2

		Y3= 5+0.21X1 -1.95X2 +0.06X1X2
	High-temperature oven	Y1= 17.0375+2.7875X1 -6.7875X2 +0.4625X1X2
		Y2= 21.685-0.28X1 +0.46X2 -0.755X1X2
		Y3= 5.0825+0.4625X1 -1.3375X2 +0.0525X1X2
	Low-temperature oven	Y1=34.025+1.725X1 -13.775X2 -0.975X1X2
		Y2= 23.1575+0.6125X1 -2.1725X2+0.6225X1X2
		Y3=6.4075+0.3525X1 -0.8375X2 +0.0975X1X2

With:

Y_1: drying time (h) in the fitted factorial equations; Table 5 reports the corresponding optimizer output in minutes.

Y_2: yield (%)

Y_3: moisture content (%)

X_1: coded slice-thickness factor (−1 = 0.1 cm; +1 = 1 cm)

X_2: coded drying-condition factor (−1/+1 corresponding to the physical temperature or microwave-power levels reported in Table 2)

Exploratory response profiling and composite desirability

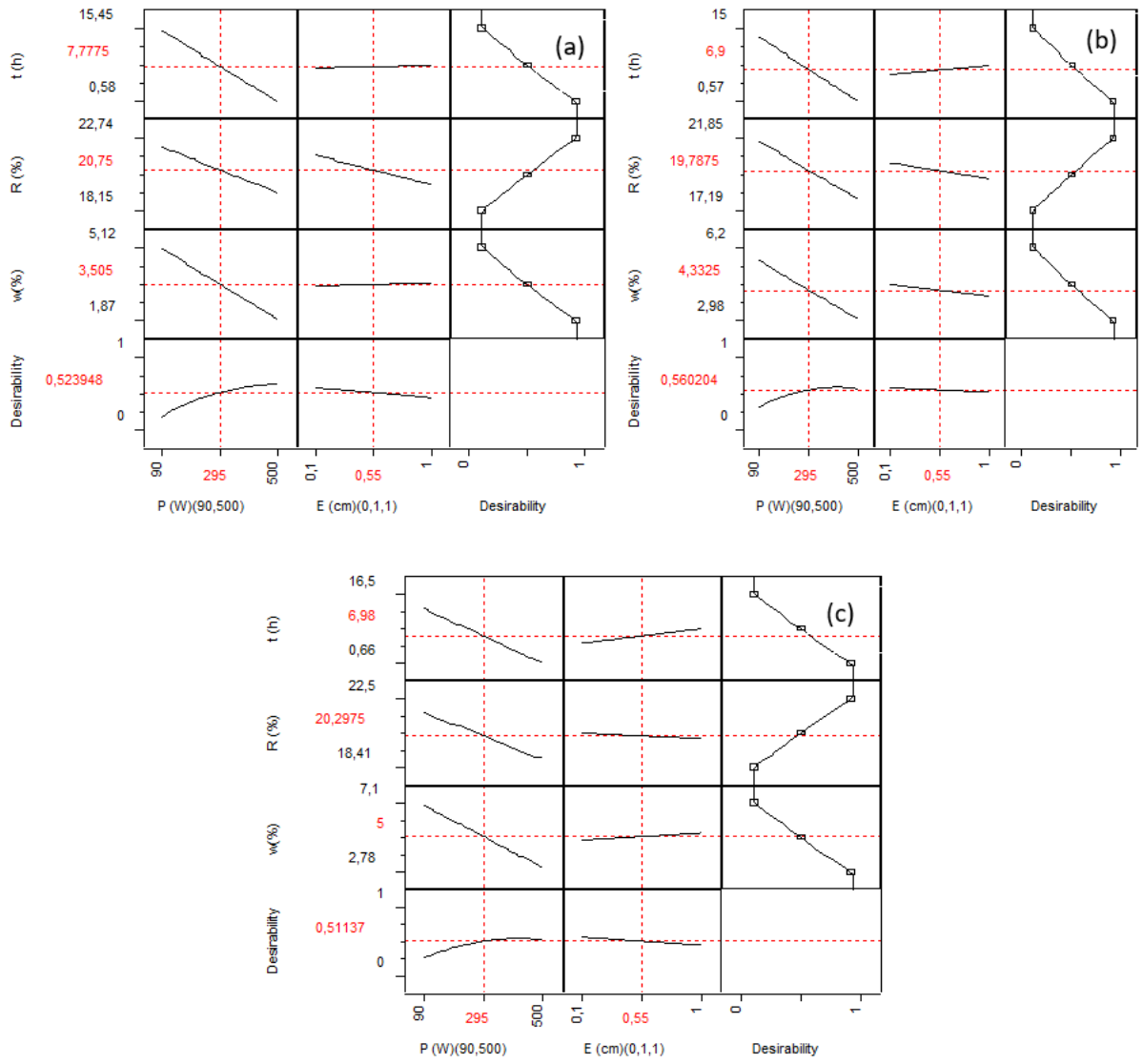


Figure 3: Response profiles for microwave drying for (a) Béni Mellal, (b) Fkih Ben Salah, and (c) Ksiba

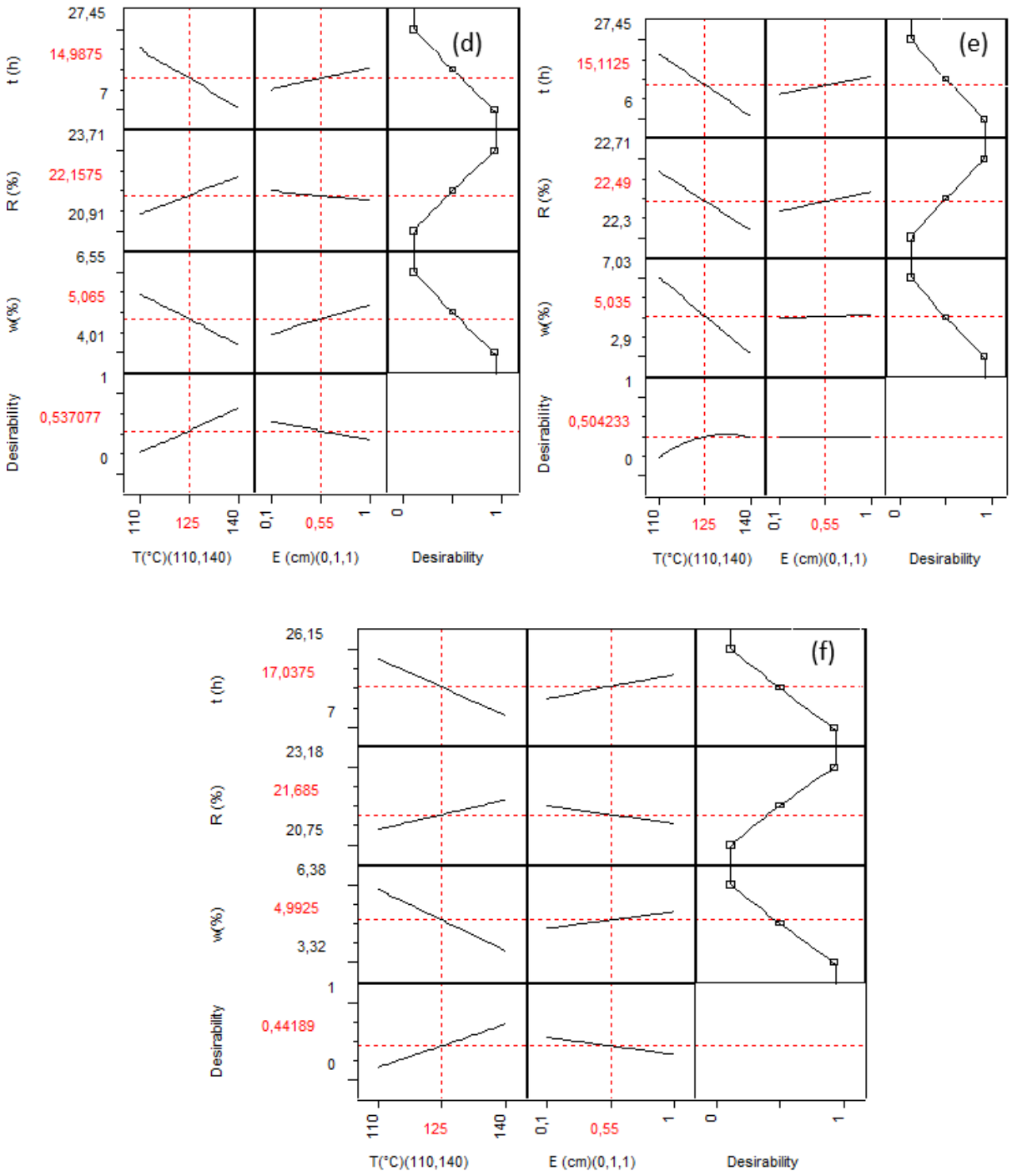


Figure 4: Response profiles for high-temperature conventional-oven drying for (d) Béni Mellal, (e) Fkih Ben Salah, and (f) Ksiba

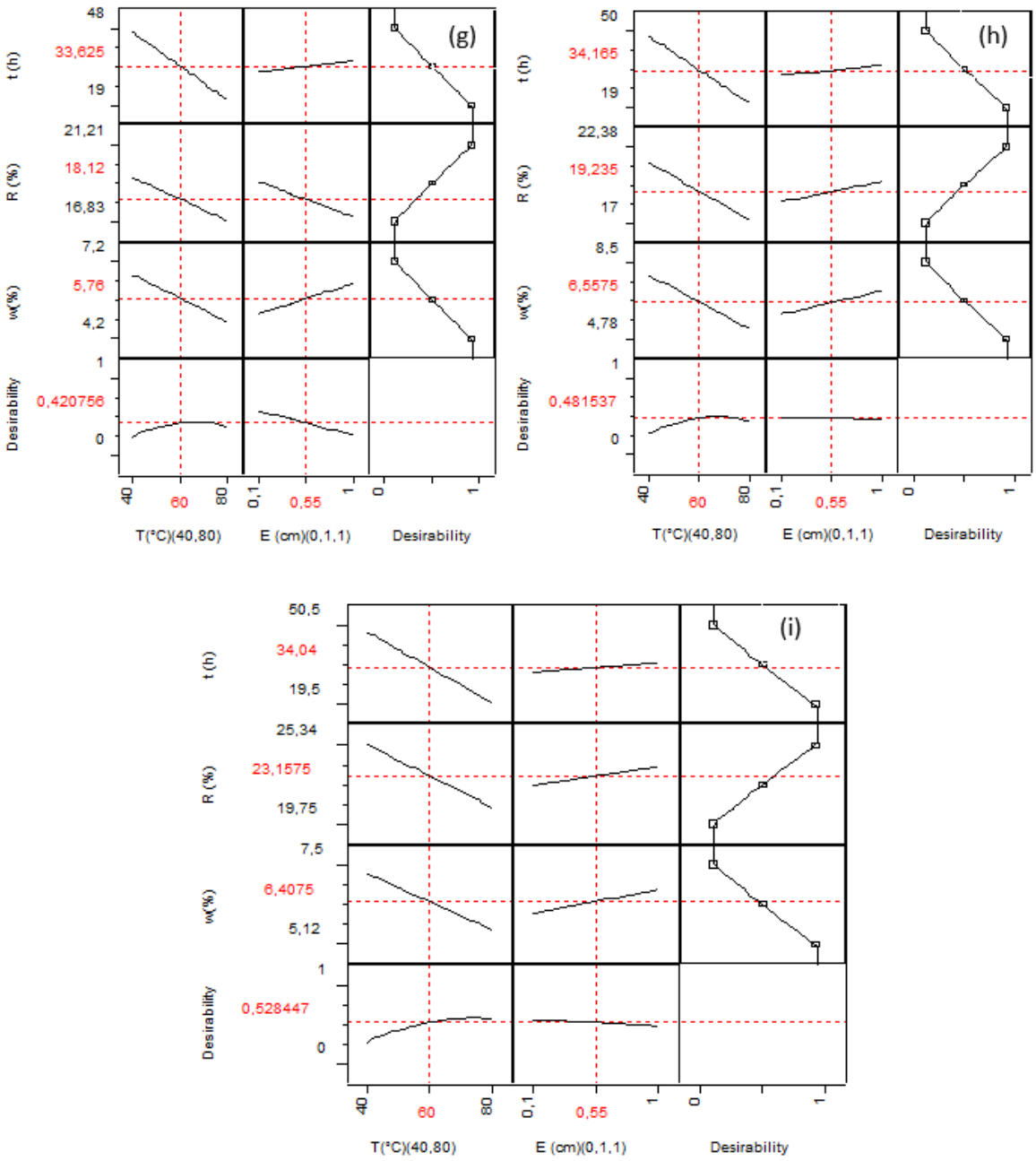


Figure 5: Response profiles for low-temperature laboratory-oven drying for (g) Béni Mellal, (h) Fkih Ben Salah, and (i) Ksiba

Table 5: Reported exploratory composite-desirability solutions from the saturated factorial response models. Drying time is reported in minutes; these outputs are not independently validated optima

Drying method	Sampling location	Optimal condition	Drying time (min)	Yield (%)	Moisture content (%)	Desirability
Microwave	Béni Mellal	500 W; 0.1 cm	37.8	20.55	1.87	0.79
Microwave	Fkih Ben Salah	500 W; 0.1 cm	34.2	18.75	2.98	0.69
Microwave	Ksiba	500 W; 1 cm	39.6	19.41	3.32	0.60
High-temperature oven	Béni Mellal	140 °C; 0.1 cm	420	23.71	4.01	0.98
High-temperature oven	Fkih Ben Salah	135.345 °C; 0.1 cm	1635.71	22.42	3.79	0.56
High-temperature oven	Ksiba	140 °C; 0.1 cm	420	23.18	3.32	0.98
Low-temperature oven	Béni Mellal	64.0779 °C; 0.1 cm	1749.01	18.6577	4.97	0.57
Low-temperature oven	Fkih Ben Salah	67.4887 °C; 0.56405 cm	1741.21	18.50	6.09	0.49
Low-temperature oven	Ksiba	80 °C; 0.1 cm	1260	22.22	6.02	0.63

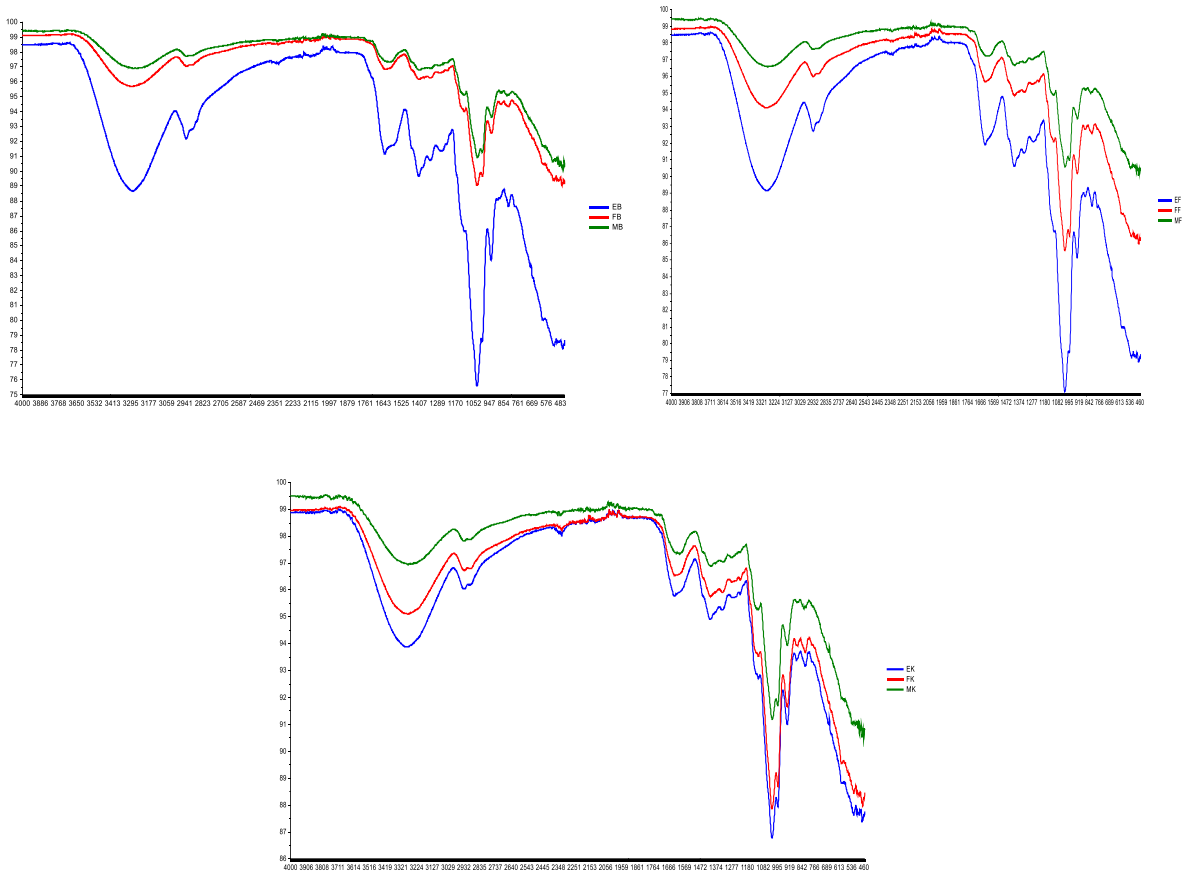


Figure 6: ATR-FT-MIR spectra of Jerusalem artichoke flour samples from (a) Béni Mellal, (b) Fkih Ben Salah, and (c) Ksiba, acquired over 4000–400 cm^{-1}. EB/FB/MB denote the low-temperature oven, high-temperature oven, and microwave treatments for Béni Mellal; EF/FF/MF denote the corresponding treatments for Fkih Ben Salah; and EK/FK/MK denote the corresponding treatments for Ksiba

Figure 6 shows treatment-associated differences in ATR-FT-MIR band shapes and intensities within each sampling location. In Béni Mellal, the low-temperature laboratory-oven spectrum shows comparatively strong features near 3200, 1590, 1350, 1000, and 940 cm^{-1}. In Fkih Ben Salah, differences are visible near 984, 962, and 887 cm^{-1}; in Ksiba, the spectra are more similar visually, with smaller intensity differences in the carbohydrate-rich fingerprint region. Jerusalem artichoke/inulin-rich powders have been reported to show broad O–H bands near 3300–3400 cm^{-1}, C–H stretching near 2930 cm^{-1}, and strong polysaccharide-related C–O/C–O–C features in the 1200–900 cm^{-1} region [34,35]. These assignments support interpretation of spectral fingerprints but do not establish quantitative compositional change or preservation of native structure.

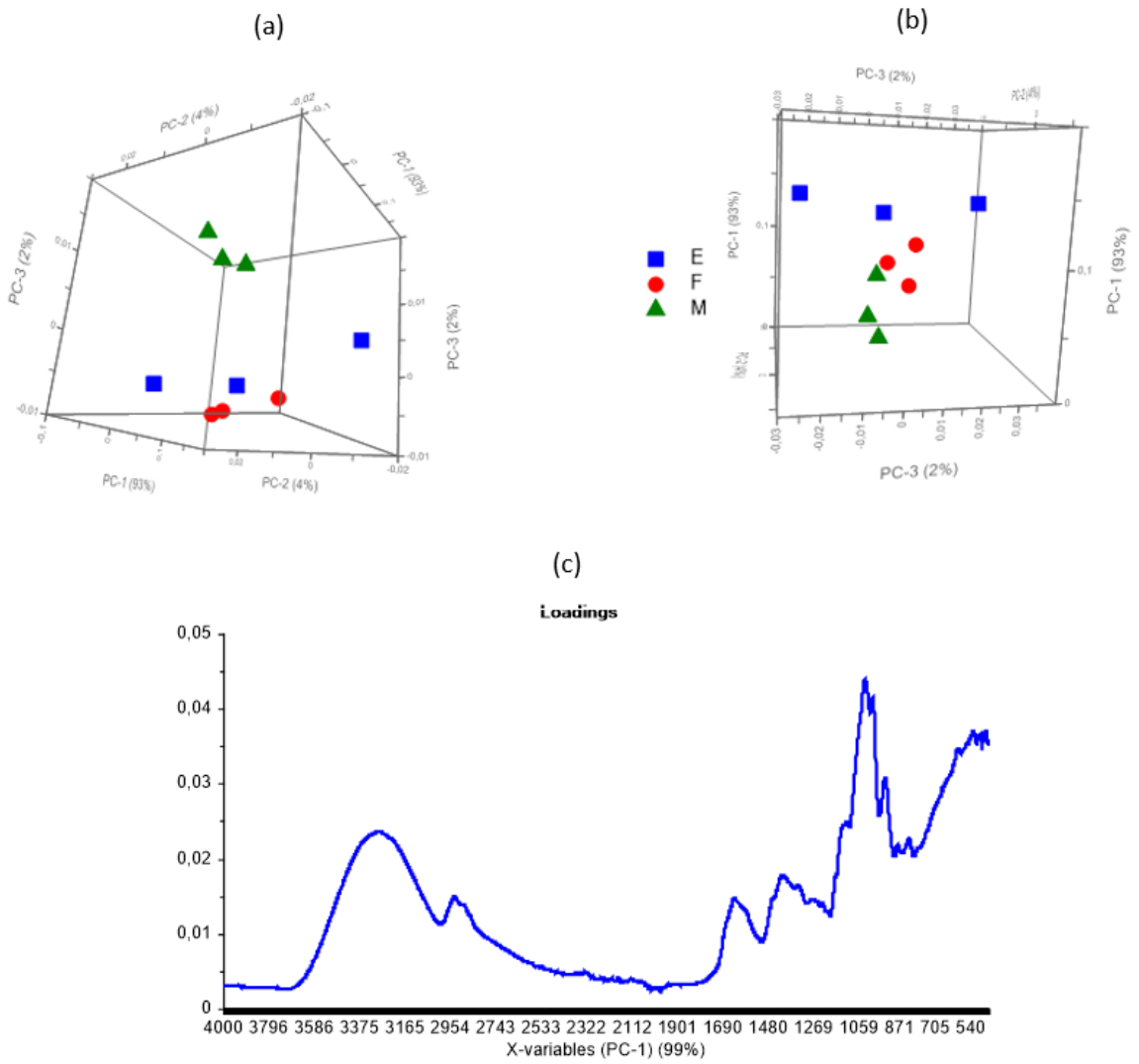


Figure 7: Exploratory PCA outputs from the location-specific ATR-FT-MIR analysis: (a) Béni Mellal score plot, (b) Fkih Ben Salah score plot, and (c) PC1 loading plot. Panel (c) is a loading plot, not a Ksiba score plot

For the Béni Mellal and Fkih Ben Salah PCA score plots shown in Figures 7a and 7b, PC1 was reported to account for approximately 93% of the variance, with PC2 and PC3 accounting for approximately 4% and 2%, respectively. Panel 7c is a PC1 loading plot from a selected spectral dataset in which PC1 accounts for approximately 99% of the reported variance. These percentages refer to different PCA outputs and are therefore not combined as if they arose from a single model. The available figure set does not contain an equivalent Ksiba score plot for Figure 7.

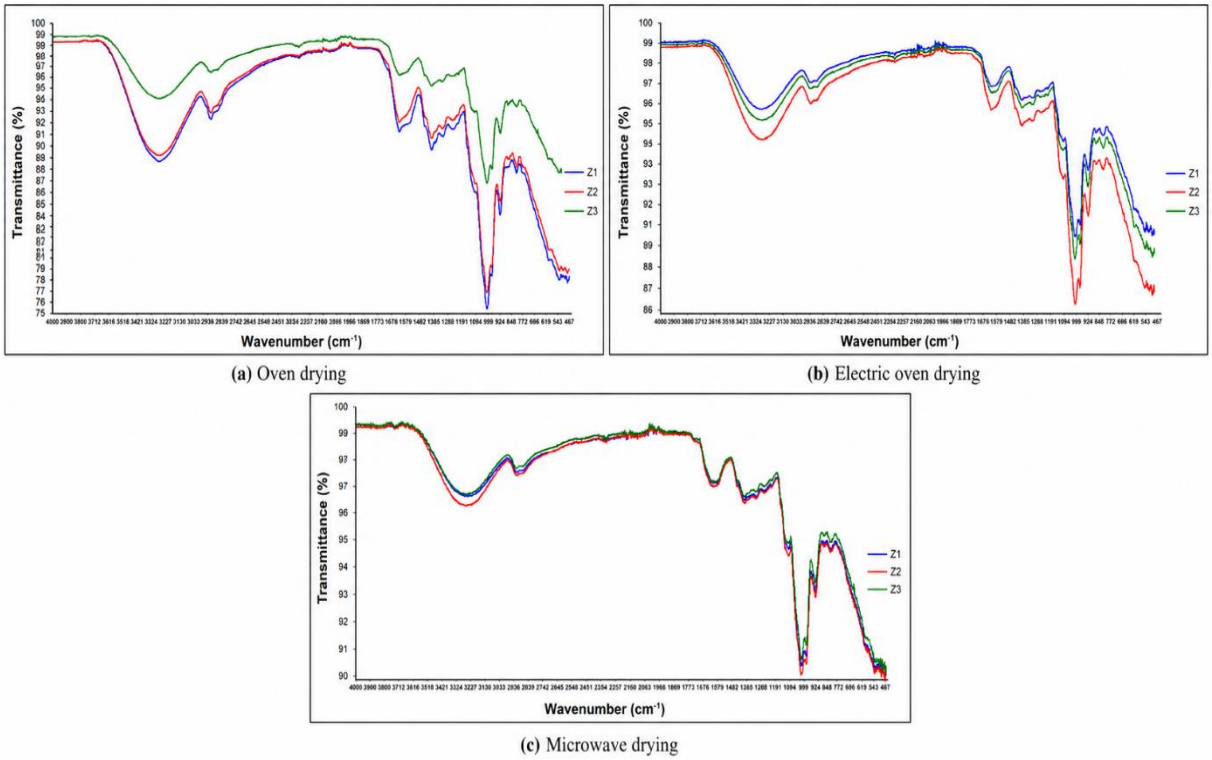


Figure 8: ATR-FT-MIR spectra of Jerusalem artichoke flour obtained using (a) low-temperature oven/incubator drying, (b) high-temperature oven drying, and (c) microwave drying, with samples from Béni Mellal, Fkih Ben Salah, and Ksiba

The second spectral comparison evaluates each drying approach across the three sampling locations (Figure 8). This comparison is intended to describe sampling-location-associated spectral variation within a common processing treatment; it does not isolate climatic effects because raw-material characteristics were not experimentally controlled.

For the low-temperature oven/incubator treatment (Fig. 8a), the spectra from the three sampling locations are broadly similar but show subtle differences in the fingerprint region. Such differences may be associated with raw-material composition, maturity, agronomic history, or other uncontrolled sampling factors; they should not be attributed specifically to geography or climate.

For microwave drying (Fig. 8c), only modest spectral differences are visible among the three sampling locations. The O–H stretching region near 3280 cm^{-1} differs slightly in the Fkih Ben Salah spectrum, which may reflect differences in residual moisture and/or hydrogen-bonding environments. This interpretation remains tentative without targeted compositional analysis.

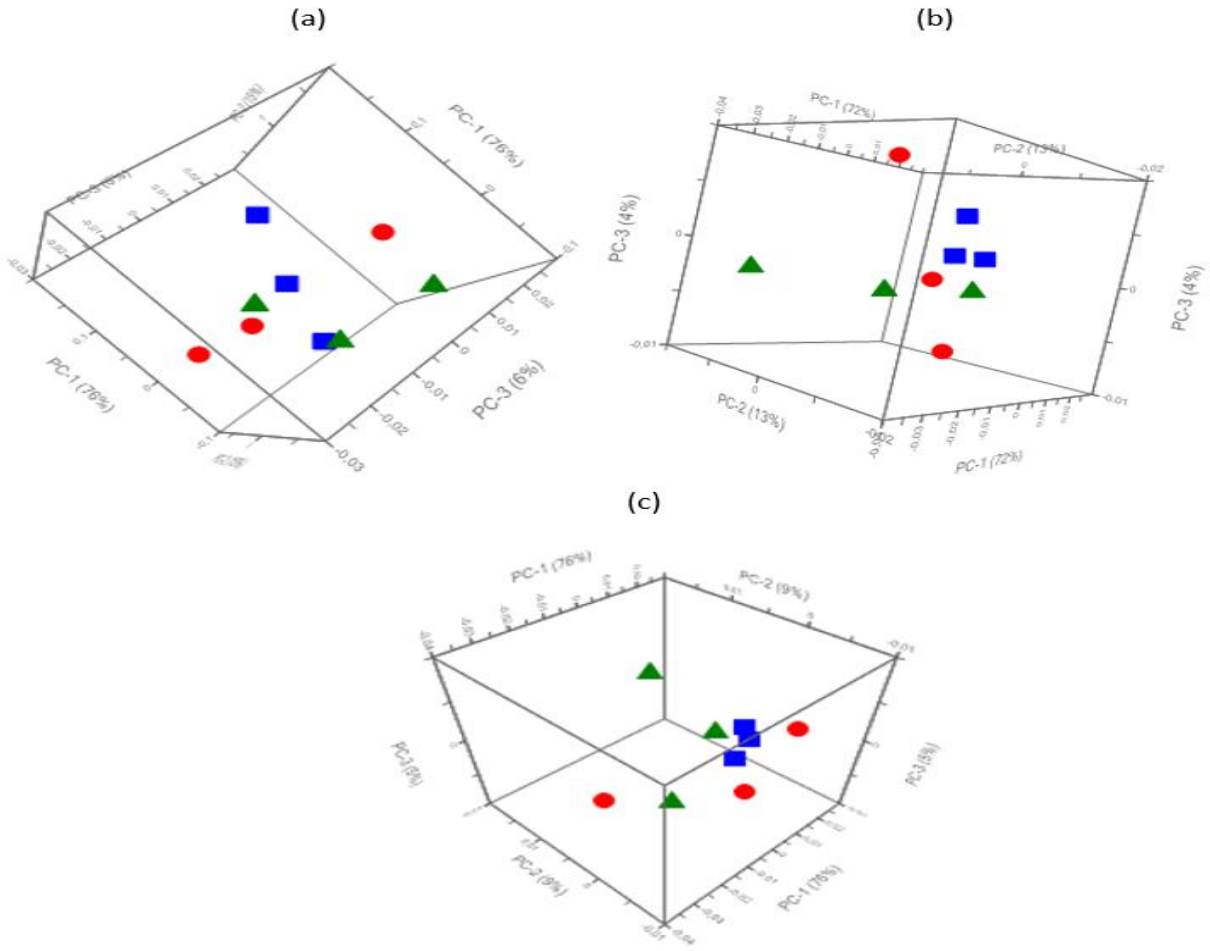


Figure 9: PCA score plots for (a) low-temperature oven/incubator drying, (b) high-temperature oven drying, and (c) microwave drying across the three sampling locations

Figure 9 illustrates exploratory PCA grouping patterns for samples processed by each drying approach. For the low-temperature oven/incubator dataset, PC1, PC2, and PC3 were reported to explain 76%, 18%, and 6% of the variance, respectively. For the high-temperature oven dataset, the corresponding reported values were 72%, 13%, and 4%. For the microwave dataset, most variance was reported on PC1. The plots suggest sampling-location-associated spectral patterns, but visual grouping alone does not establish statistically significant discrimination. Any claim of classification performance would require an appropriately validated supervised model and independent or cross-validated performance metrics.

Discussion

The response prediction profile for the three drying methods, obtained from the response surface models and desirability functions, indicated that the effect of the operating factors for each method was dependent on the geographical origin of the samples and the geographical origin of the samples was analyzed separately for each of the three study zones. The microwave power (or temperature) was the main factor affecting the drying responses, drying time and residual moisture content were mainly influenced by these

two factors, and sample thickness was a secondary but significant factor. Such behaviour is in line with other previous studies of thermal and electromagnetic drying technologies [23, 24]. In Figure 3a–c, the drying time and residual moisture content decreases almost linearly with the increase of microwave power for microwave drying. This phenomenon is considered to be caused by the volumetric heating of the material due to the dielectric losses, which increases water migration within the material and promotes the evaporation of water, thus increasing the overall desirability [18, 24]. The differences in desirability between the different zones must be interpreted as due to the characteristics of the samples collected from each geographical area as well as to the effect of microwave drying. Figure 3d–f show that the temperature applied during electric oven drying exerted a more gradual influence on the process responses and in some instances the influence was not linear. In general, the maximum desirability was found near the middle of the experimental domain indicating a moderate balance between moisture removal and product quality. This is a typical characteristic of the quadratic response surface models that are frequently employed in process optimization [25]. Figures 3g–i indicate that, for conventional oven (incubator) drying, the temperature was the predominant drying parameter and had similar slopes of response to the drying process as those recorded for microwave drying, but they were not as strong. This behavior is consistent with heat convection and moisture diffusion being the main mechanisms controlling the drying process, and lead to longer drying times along with slower changes in product properties [23]. Overall, the response profiles, along with the quasi-linear/quadratic trends, and the local maxima in the desirability confirm that response surface methodology with multi-response optimization is suitable for modeling and optimization of the drying process [25]. Each drying method, each study area each sample was analyzed independently to give a different set of optimal operating conditions for the predictive optimization. The best solutions are the compromise solutions that minimize drying time, maximize process performance, and minimize residual moisture content [26]. In the microwave drying, the optimal parameters in each zone were achieved with the maximum microwave power used (500 W). The sample thickness of 0.1 cm was found to be optimum for both Zones 1 and 2, providing a minimum drying time (0.57–0.66 h), and moisture content after drying. The best desirability value was achieved for Zone 1, meaning that the samples taken from Zone 1 showed better response during the microwave drying process under the conditions investigated. This is consistent with the mechanisms of fast internal heating and vapor formation that were reported for the microwave drying of plant materials [24]. The optimum conditions for electric oven drying were near 140°C and low sample thickness, which obtained high values of desirability for Zones 1 and 3. The results for the optimum obtained in the present study was at approximately 135°C and had a lower desirability value for Zone 2 which suggested different response of the samples from this geographical area to the drying conditions investigated as opposed to indicating greater thermal sensitivity. These observations are similar to observations made in heat and mass transfer models for convective drying processes [27]. Conventional oven (incubator) drying showed the best drying results between 64 and 80°C and drying time and residual moisture content were very high compared to the drying results achieved by microwave and electric oven drying (21–29 h and 9–16% respectively). The results are similar to diffusion-controlled drying kinetics, which is typical of conventional hot-air drying systems. However, the overall desirability was moderate due to the compromise made between the processing time and drying performance [23]. The FT-MIR spectra of samples from Zones 1, 2 and 3, respectively, of Jerusalem artichoke flour dried by the three processes are shown in Figures 6a–c. Each geographical zone's samples were analyzed separately. The mid-infrared region of a spectrum contains a number of characteristic regions, such as the X–H stretching region, the triple-bond region, the double-bond region, and what is known as the fingerprint region [28]. The band between 3650 and 3000 cm^{-1} was attributed to the O–H

stretching vibrations of moisture, while the band at ~ 2930 cm^{-1} was assigned to the C–H stretching vibrations [30, 31]. The band at 1590 cm^{-1} was assigned to changes in protein secondary structure, and C–N stretching and C–H deform vibrations were assigned to the bands at 1280, 1350 and 1407 cm^{-1}, respectively [32]. The absorbances of the functional groups at 940, 990, 1100, 1360, 1407, 1631, 2930 and 3200 cm^{-1} indicated that the major functional groups in Jerusalem artichoke flour were carbohydrate-related, which was consistent with the findings of Aboubakar et al. [32]. The spectral data were mostly clustered within the fingerprint region (1700–900 cm^{-1}), in which the absorption bands of carbohydrates, moisture, proteins and lipids were detected [33].

For high-temperature conventional-oven drying, the reported optimizer output favored high temperatures and thin slices for the Béni Mellal and Ksiba datasets, while the Fkih Ben Salah output showed a lower composite desirability and a much longer predicted drying time. Because the factorial models are saturated and the exact desirability limits/weights are not recoverable from the archived record, these results are interpreted only as exploratory model-based compromises and not as validated operating optima or evidence of thermal sensitivity.

PCA was used to summarize these spectral differences. Score plots are interpreted as exploratory visualization of multivariate spectral variation rather than proof of statistically significant class separation or direct change in chemical composition. Loading contributions in the carbohydrate-rich fingerprint region (approximately 1200–900 cm^{-1}) are chemically plausible for fructan/inulin-rich matrices [34,35], while contributions in the O–H stretching region may reflect residual water and hydrogen-bonding environments. Because preprocessing details and independent spectral replication were not completely preserved, the PCA is not presented as a validated classification model.

Conclusion

This study combined exploratory drying-process modeling with ATR-FT-MIR spectroscopy and PCA to compare Jerusalem artichoke flours obtained under different processing conditions and from three Moroccan sampling locations. Microwave drying was associated with comparatively rapid moisture removal under several tested conditions, while the low-temperature laboratory-oven treatment showed comparatively less pronounced changes in selected ATR-FT-MIR spectral features among the dried samples. No single drying method is designated as universally “best,” because the methods differed in moisture removal, functional properties, and spectral behavior and were not compared at equivalent energy input or a common endpoint. The study does not demonstrate preservation of native structural integrity, shelf-life extension, or climatic causation because no fresh ATR-FT-MIR control, storage study, direct degradation markers, or controlled raw-material replication was available. The saturated DOE models and PCA are therefore interpreted as exploratory. Future work should include independent process replicates, validated model diagnostics, archived chemometric preprocessing, fresh controls, and targeted measurements such as inulin/FOS, sugars, HMF, color, antioxidant properties, DSC/XRD, or microscopy.

Declaration

Conflict of Interest

The author declares no conflict of interest related to the publication of this article.

Consent for Publication

The author confirms that the final version of the manuscript has been reviewed and approved for publication.

Conflict of Interest

No conflict of interest has been declared by the authors.

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AI Declaration

None.

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