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Optimization of Drying Temperature and Time for Enhancing Phytochemical Composition, Antioxidant Activity, and Sensory Properties of Selected Indigenous Spices in Nigeria

Sunday Ukwo [1,2,*], Blessing Etuk [1], Ekemini Ituen [2,3], Enobong Umoh [4] and Jaciane Ienczak [2]

[1] Department of Food Science and Technology, University of Uyo, Uyo 520261, Nigeria
[2] Department of Chemical and Food Engineering, Federal University of Santa Catarina, Florianópolis 88040-900, Brazil
[3] Department of Chemistry, University of Uyo, Uyo 520261, Nigeria
[4] Department of Agricultural Engineering, Akwa Ibom State University, Ikot Akpaden 532111, Nigeria
* Correspondence: sonipeter75@gmail.com

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Abstract: Drying is a critical postharvest operation that influences the composition and functional activity of bioactive compounds in spices. This study investigated the effects of drying temperature and time on phytochemical composition, antioxidant activity, and sensory quality of three indigenous spices (*Tetrapleura tetraptera*, *Xylopia aethiopica*, and *Monodora myristica*) using Response Surface Methodology (RSM). The study adopted a comparative multi-response optimization approach to identify species-specific drying conditions that simultaneously maximize phytochemical retention, antioxidant activity, and sensory quality. A Box–Behnken Design generated seventeen experimental runs, with drying temperature (50–70 °C) and time (24–36 h) as independent variables. Total phenolic, flavonoid, and terpenoid contents were quantified using validated spectrophotometric methods, while antioxidant activity was assessed through 1,1-diphenyl-2-picrylhydrazyl (DPPH) radical scavenging and ferric reducing antioxidant power (FRAP) assays. Drying conditions significantly ($p < 0.05$) influenced all responses, with pronounced species-dependent effects. *Xylopia aethiopica* dried at 70 °C for 30 h exhibited the highest total phenolic (13.12 mg GAE/100 g) and flavonoid contents (9.26 mg QE/100 g), while *Monodora myristica* recorded the highest terpenoid content (27.48 mg BSE/100 g) under the same conditions. The highest DPPH radical scavenging activity was also observed in *X. aethiopica* (16.24 µmol TE/g DW), whereas *Tetrapleura tetraptera* dried at 70 °C for 36 h exhibited the highest FRAP value (11.67 mg GAE/100 g). Sensory evaluation indicated that *T. tetraptera* dried at 70 °C for 36 h achieved the highest overall acceptability. The response surface models showed good fit and predictive reliability, with high coefficients of determination and non-significant lack of fit ($p > 0.05$). Drying temperature and spice type were identified as the major factors influencing the measured responses. These findings demonstrate that optimal drying conditions are species-specific and highlight the value of integrated multi-response optimization for enhancing the functional and sensory quality of indigenous spice powders.

Keywords: indigenous spices; phytochemical composition; process optimization; phenolic compounds; antioxidant activity

1. Introduction

Spices constitute an integral component of human diets, culinary practices, and complementary and alternative medicine owing to their abundance of bioactive compounds, distinctive flavour profiles, and inherent preservative properties [1]. In West Africa, *Tetrapleura tetraptera* (Aidan fruit), *Xylopia aethiopica* (African pepper), and *Monodora myristica* (calabash nutmeg) are widely recognized for their unique sensory attributes and broad spectrum of health-enhancing properties [2]. These indigenous spices are rich sources of phytochemicals and antimicrobials that can enhance preservative functions in foods [3]. Furthermore, they are known to contain antioxidants that support therapeutic functions, which have been associated with cholesterol-lowering effects and contribute to a reduced risk of cardiovascular diseases [4]. Although spices contain valuable bioactive constituents, their primary purpose in food systems is to enhance flavour and aroma rather than to serve as major contributors of essential nutrients [5].

The global spice market has experienced sustained growth over recent decades, reflecting its strong economic potential. Recent commercial data indicated that the market was valued at approximately USD 19.79 billion in 2024 and is projected to reach USD 29.87 billion by 2033, corresponding to an annual growth rate of about 4.7%. In Nigeria, the domestic spice market was estimated at USD 112.33 million in 2024 and is expected to increase to USD 165.07 million by 2033, representing a growth rate of 4.47% [6]. These figures highlight increasing global and local demand and underscore significant opportunities for value-added processing and commercialization of indigenous spices.

In many countries, rural households rely on spices primarily during periods of surplus because most spice species are seasonal, and only a small proportion undergo basic processing to extend availability during periods of scarcity [7]. To improve shelf life and maintain product stability, drying remains the most widely employed postharvest preservation technique [8]. However, drying temperature and time are critical factors that determine the quality of dried spices. Inadequate drying may result in high residual moisture content, which can promote fungal and bacterial proliferation, leading to quality deterioration, reduced shelf stability, and potential food safety risks during storage and processing into powdered forms. Conversely, excessive drying temperatures and prolonged exposure times can result in substantial nutrient losses, degradation of heat-sensitive bioactive compounds, and volatilization of aroma-active constituents, leading to reduced phytochemical integrity and antioxidant capacity. High-temperature conditions may further accelerate oxidative reactions and thermal degradation of sensitive compounds, thereby compromising texture, flavour, aroma, and overall sensory quality of the final product [9,10].

Despite increasing consumer demand, the processing of *Tetrapleura tetraptera, Xylopia aethiopica,* and *Monodora myristica* remains largely traditional and unstandardized. The conversion of these spices into powdered forms by small-scale processors frequently results in inconsistent product quality due to uncontrolled variations in drying temperature and time. Generating reliable data on the effects of drying conditions on nutrient retention is therefore essential to ensure that spices maintain their Phytochemical composition and antioxidant properties at levels comparable to their natural state [11,12]. Such evidence-based processing approaches can support healthier consumption patterns, improve agricultural productivity, and contribute to food security and household income generation in Nigeria and other developing countries [13,14]. Previous studies on some Nigerian spices have mainly focused on optimizing drying parameters for individual products, with greater emphasis on drying behaviour and moisture characteristics rather than comprehensive quality optimization [11]. Current literature reveals a paucity of studies employing integrated multi-response optimization to comparatively evaluate the effects of drying temperature and time on phytochemical composition, antioxidant activity, and sensory quality of indigenous Nigerian spices (*Tetrapleura tetraptera*, *Xylopia aethiopica*, and *Monodora myristica*) within a single experimental framework. Therefore, data-driven optimization of drying conditions is needed to support standardized processing practices and enhance the nutritional quality, functional properties, and market value of these indigenous spices.

Against this background, this study investigated the effects of drying temperature and time on the phytochemical composition, antioxidant activity, and sensory quality of *Tetrapleura tetraptera*, *Xylopia aethiopica*, and *Monodora myristica* using Response Surface Methodology. Specifically, it aimed to determine species-specific drying conditions that maximize phytochemical retention and antioxidant activity while enhancing the sensory quality of spice powders. Response Surface Methodology (RSM) is a robust statistical tool widely used in food processing for modelling and optimizing multivariable systems [9]. Through regression modelling, RSM establishes relationships between processing variables and product responses, enabling the identification of optimal processing conditions for improved product quality. Leveraging this capability, the present study adopts an integrated multi-response optimization approach to simultaneously evaluate phytochemical composition,

antioxidant activity, and sensory quality across three indigenous spices under comparable drying conditions. This approach provides a comprehensive framework for identifying species-specific drying parameters that maximize quality retention while generating scientific evidence to support the standardization of processing practices, enhance product quality, increase economic value, and promote value addition to indigenous Nigerian spices.

2. Materials and Methods

2.1. Collection and Preparation of Samples

Samples of local spices (Figure 1), including *Tetrapleura tetraptera* (Aidan fruit), *Xylopia aethiopica* (African pepper), and *Monodora myristica* (Calabash nutmeg) (Plates 1–3) were procured from Uyo main markets in Akwa Ibom, Nigeria, and transported to the Food Processing Laboratory, University of Uyo. Samples were manually cleaned to remove dirt and damaged portions, destalked, washed, and cut into uniform sizes. The initial moisture contents were determined as 14.12 ± 0.05%, 10.05 ± 0.01%, and 8.38 ± 0.02% (wet basis) for *T. tetraptera*, *X. aethiopica*, and *M. myristica*, respectively. Only samples of uniform physiological maturity, free from defects or mechanical damage, were selected. Slice thickness was standardized using a calibrated precision cutter, and all samples were subjected to identical pretreatment and handling conditions. Drying was carried out in a laboratory-scale hot-air dryer under controlled conditions. Drying temperature and time were defined as the independent variables according to the experimental design, while airflow velocity and chamber relative humidity were maintained constant throughout the experiments. This was to ensure that variations in drying kinetics, phytochemical retention, antioxidant capacity, and sensory properties were attributable solely to the applied temperature–time combinations, thereby enhancing experimental reproducibility and treatment comparability.

Samples were then pulverized using a mechanical grinder to produce fine powders. The powders were stored in an airtight container and taken to the Laboratory of Thermodynamics and Supercritical Technology (LATESC), Federal University of Santa Catarina (UFSC), Florianópolis, Brazil, for analysis. All chemicals and reagents used were of analytical grade and obtained from reputable suppliers.

Plate 1. *Tetrapleura tetraptera*

Plate 2. *Xylopia aethiopica*

Plate 3. *Monodora myristica*

Figure 1. Sample of spices.

2.2. Experimental Design and Process Optimization

A Box–Behnken Design (BBD) within the Response Surface Methodology (RSM) framework (Stat-Ease Inc., Minneapolis, MN, USA) was used to design the experiment and optimize the drying process parameters. Seventeen (17) experimental runs were generated based on the predefined factor domains for drying temperature (50, 60, and 70 °C) and drying time (24, 30, and 36 h) for *Tetrapleura tetraptera*, *Xylopia aethiopica*, and *Monodora myristica*. The BBD-RSM approach was applied to model and predict the optimal drying conditions. The study evaluated two independent variables, including drying temperature and drying time, while the dependent variables consisted of phytochemical constituents, antioxidant activity, and sensory attributes. These responses were used to assess the influence of the processing factors and to determine the optimal drying conditions for the selected spices.

2.3. Determination of Phytochemical Composition of Spices

The phytochemical composition of the spice extracts was evaluated by determining total phenolic, flavonoid, and terpenoid contents using validated spectrophotometric assays. Total phenolic content (TPC) was quantified using the Folin–Ciocalteu (F–C) method [15]. In this procedure, an aliquot of the extract was reacted with 10% (*v*/*v*) Folin–Ciocalteu reagent, followed by the addition of sodium carbonate to establish alkaline conditions needed for chromophore development. The reaction mixture was allowed to incubate, resulting in the formation of a characteristic blue molybdenum–tungsten complex. Absorbance was measured at 765 nm using a UV–VIS spectrophotometer (UV-1237 Labomed, Los Angeles, CA, USA), and TPC was calculated from a gallic acid standard calibration curve, with results expressed as mg gallic acid equivalent (GAE) per g of sample.

Total flavonoid content (TFC) was determined using the aluminium chloride colorimetric method, a widely accepted assay for quantifying flavonoid-type compounds [16]. The extract was sequentially treated with sodium nitrite, aluminium chloride, and sodium hydroxide, facilitating the formation of a stable flavonoid–$AlCl_3$ complex. The resulting chromophore exhibited maximum absorbance at 510 nm, and concentrations were obtained by reference to a quercetin standard curve, expressed as mg quercetin equivalent (QE) per g of sample.

Total terpenoid content (TTC) was determined using the vanillin–sulfuric acid colorimetric assay as previously described [17], with minor modifications. 0.5 mL of the extract was mixed with 0.5 mL of 5% (*w*/*v*) vanillin solution prepared in glacial acetic acid, followed by the addition of 2.5 mL of concentrated sulfuric acid. The reaction mixture was vortexed and incubated at 60 °C for 10 min to allow chromophore development, then rapidly cooled in an ice bath to stabilize the red–pink complex. Absorbance was measured at 548 nm against a reagent blank using a UV–Visible spectrophotometer. β-Sitosterol was used as the reference standard. β-Sitosterol was selected due to its classification as a phytosterol (a triterpenoid derivative) possessing structural features that enable a stable chromogenic reaction with the vanillin–sulfuric acid reagent. Its application as a calibration standard in vanillin-based total terpenoid assays has been widely reported in phytochemical analyses of plant matrices, thereby supporting its suitability for relative quantification of terpenoid-reactive compounds in this study**.** Standard β-sitosterol solutions were prepared and subjected to identical reaction conditions to construct a calibration curve, which exhibited satisfactory linearity within the tested concentration range. Total terpenoid content was calculated from the linear regression equation of the calibration curve and expressed as milligrams of β-sitosterol equivalent per gram of extract (mg BSE/g extract). The values obtained represent relative total terpenoid content of the spices.

2.4. Antioxidant Activity Assays

The antioxidant potential of the spice extracts was assessed using the DPPH free radical scavenging assay and the ferric reducing antioxidant power (FRAP) assay, following established protocols. The free radical scavenging capacity of the extracts was evaluated using the 1,1-diphenyl-2-picrylhydrazyl (DPPH) assay [18]. An aliquot (1.0 mL) of the extract was mixed with 1.0 mL of 0.4 mM DPPH solution prepared in methanol. The reaction mixture was incubated in the dark for 30 min to allow complete interaction between the antioxidants present in the extract and the DPPH radicals. The decrease in absorbance, corresponding to DPPH radical reduction, was recorded at 517 nm using a UV–Vis spectrophotometer (UV-1237, Labomed, Los Angeles, CA, USA). Radical scavenging activity was calculated relative to a control solution containing all reagents.

The ferric reducing antioxidant power of the extracts was determined using varying concentrations (100–500 μg/mL) of the extract, which were mixed with 2.5 mL of phosphate buffer (0.2 M, pH 6.6) and 2.5 mL of 1% potassium ferricyanide. The resulting mixture was incubated at 50 °C for 20 min, rapidly cooled, and treated with 2.5 mL of 10% trichloroacetic acid. The mixture was then centrifuged at 3000 rpm for 10 min, and 2.5 mL of the supernatant was combined with 2.5 mL of distilled water and 0.5 mL of 0.1% ferric chloride. After standing for 10 min, the formation of the Prussian blue complex was measured at 700 nm using a UV–Vis spectrophotometer (UV-1237, Labomed, Los Angeles, CA, USA). Increased absorbance indicated greater reducing power of the extracts [19].

2.5. Sensory Evaluation

The sensory characteristics of the dried spice samples were evaluated by twenty (20) semi-trained panelists using a 9-point hedonic scale (9 = like extremely; 5 = neither like nor dislike; 1 = dislike extremely). Panelists were selected based on prior familiarity with sensory evaluation procedures and absence of known allergies to spice products**.** Samples were coded with random three-digit numbers and presented in a randomized order on white ceramic plates under controlled laboratory conditions (well-lit and quiet environment).

Panelists assessed appearance, aroma, texture, and general acceptability. To minimize bias and carry-over effects, potable water and spit cups were provided for palate cleansing between samples, and panelists were instructed to refrain from discussion during the evaluation session. The sample presentation order was balanced to reduce positional bias**.** Additional comments were recorded on structured evaluation forms provided to each panelist [20]. All evaluations were conducted in a single session under standardized environmental conditions to ensure consistency of assessment.

2.6. Statistical Analysis

All experimental determinations were conducted in triplicate, and results were expressed as mean ± standard deviation. Statistical analyses were performed using IBM SPSS Statistics version 23.0 (IBM Corp., Armonk, NY,

USA). One-way analysis of variance (ANOVA) was applied to evaluate significant differences among treatment means, and mean separation was carried out using Duncan's Multiple Range Test (DMRT) at a significance level of $P < 0.05$. Experimental design, optimization, and generation of treatment combinations were performed using Response Surface Methodology (RSM), based on the Box–Behnken Design (BBD), which was employed using Design-Expert® software (Stat-Ease Inc., Minneapolis, MN, USA).

3. Results and Discussion

3.1. Effect of Drying Temperature and Time on the Phytochemical Composition of the Spices

The effects of drying temperature and time on the phytochemical composition of the three spices are presented in Table 1. The results indicate that drying conditions significantly influenced the total phenolic, flavonoid, and terpenoid contents of *Tetrapleura tetraptera* (T), Xylopia *aethiopica* (X), and *Monodora myristica* (M). Among the evaluated treatments, *Xylopia aethiopica* dried at 70 °C for 30 min ($X_{70:30}$) exhibited the highest total phenolic content (13.12 mg GAE/100 g) and flavonoid content (9.26 mg QE/100 g). Under the same drying condition ($M_{70:30}$), *Monodora myristica* recorded the highest terpenoid content (27.48 mg BSE/100 g). In contrast, *Tetrapleura tetraptera* generally showed comparatively lower phytochemical levels across most of the drying conditions investigated. For instance, at 50 °C for 24 min ($T_{50:24}$), it exhibited the lowest flavonoid content (2.57 mg QE/100 g).

Table 1. Effect of drying temperature and time on the phytochemical composition of the spices.

Samples	Total Phenol (GAE/100g)	Total Flavonoid (mg QE/100g)	Total Terpenoid (mg BSE/100 g)
$X_{50:30}$	11.37 ^{e} ± 0.10	5.47 ^{f} ± 0.03	18.81 ^{f} ± 0.10
$M_{50:30}$	9.32 ^{f,g} ± 0.00	6.21 ^{e} ± 0.12	22.14 ^{d} ± 0.11
$X_{70:30}$	13.12 ^{a} ± 0.11	9.26 ^{a} ± 0.01	22.44 ^{d} ± 0.02
$M_{70:30}$	12.03 ^{d} ± 0.01	8.36 ^{b} ± 0.04	27.48 ^{a} ± 0.03
$X_{60:24}$	12.66 ^{c} ± 0.03	7.21 ^{d} ± 0.02	19.26 ^{e} ± 0.03
$M_{60:24}$	11.09 ^{e,f} ± 0.12	7.32 ^{c,d} ± 0.01	24.30 ^{c} ± 0.02
$X_{60:36}$	12.93 ^{b} ± 0.02	7.52 ^{c} ± 0.01	19.32 ^{e} ± 0.02
$M_{60:36}$	12.04 ^{d} ± 0.13	7.63 ^{c} ± 0.11	24.86 ^{b} ± 0.12
$T_{50:24}$	7.92 ^{c,d} ± 0.04	2.57 ^{i} ± 0.04	12.43 ^{h,i} ± 0.01
$T_{70:24}$	10.82 ^{f} ± 0.11	6.33 ^{e} ± 0.02	17.36 ^{f,g} ± 0.10
$T_{50:36}$	8.31 ^{h} ± 0.19	3.28 ^{h} ± 0.03	13.27 ^{h} ± 0.03
$T_{70:36}$	11.27 ^{e} ± 0.13	6.73 ^{d,e} ± 0.10	17.69 ^{f,g} ± 0.00
$T_{60:30}$	9.26 ^{f,g} ± 0.10	5.21 ^{g} ± 0.01	16.42 ^{g} ± 0.11
$T_{60:30}$	9.26 ^{f,g} ± 0.10	5.21 ^{g} ± 0.01	16.42 ^{g} ± 0.11
$T_{60:30}$	9.26 ^{f,g} ± 0.10	5.21 ^{g} ± 0.01	16.42 ^{g} ± 0.11
$T_{60:30}$	9.26 ^{f,g} ± 0.10	5.21 ^{g} ± 0.01	16.42 ^{g} ± 0.11
$T_{60:30}$	9.26 ^{f,g} ± 0.10	5.21 ^{g} ± 0.01	16.42 ^{g} ± 0.11

Values are expressed as mean ± standard deviation of triplicate determinations. Means within the same column with different superscript letters (a–i) differ significantly ($p < 0.05$), whereas means with the same superscript letter are not significantly different.

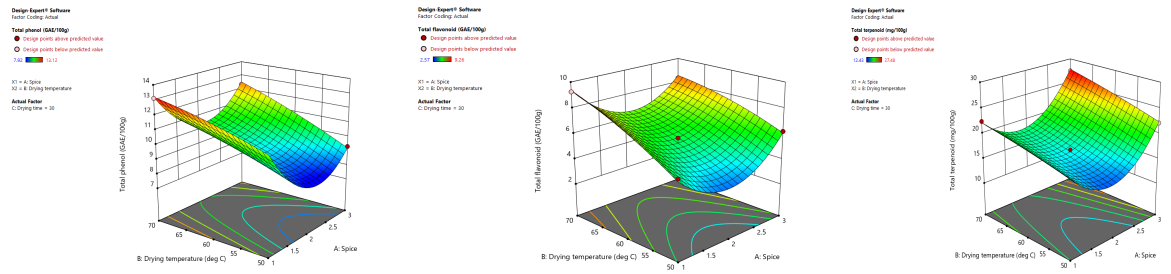
Also, *Xylopia aethiopica* dried at 70 °C for 30 min ($X_{70:30}$) exhibited the highest total phenolic and flavonoid contents, with values of 13.12 mg GAE/100 g and 9.26 mg QE/100 g, respectively**.** This observation is consistent with previous reports indicating that moderately elevated drying temperatures applied for shorter durations can improve the retention of polyphenols and flavonoids. Rapid moisture removal under these conditions may minimize enzymatic oxidation and limit prolonged exposure to heat, thereby reducing thermal degradation [10,21]. A rapid reduction in water activity can also suppress oxidative enzymes such as polyphenol oxidase, which catalyze the degradation of phenolic compounds during post-harvest processing. Since phenolics and flavonoids are major contributors to antioxidant activity, the optimization of drying parameters is critical for preserving the functional quality of spices.

The findings obtained for *Xylopia aethiopica* support this mechanism, as higher phytochemical retention was generally observed under moderately elevated drying temperatures and shorter drying periods. Similarly, *Monodora myristica* dried at 70 °C for 30 min ($M_{70:30}$) exhibited the highest terpenoid concentration (27.48 mg BSE/100 g), which was significantly greater than the values obtained under other drying treatments. Terpenoids are major contributors to the characteristic aroma and bio-functional properties of spices, including antimicrobial, antioxidant, and anti-inflammatory activities [21]. The elevated terpenoid content observed at higher drying temperatures may be attributed to enhanced disruption of the cellular matrix and the thermal cleavage of bound or

precursor compounds. Furthermore, rapid moisture reduction at elevated temperatures may accelerate enzyme inactivation and limit oxidative degradation, thereby contributing to higher measurable terpenoid levels [22].

In contrast, *Tetrapleura tetraptera* consistently exhibited comparatively lower phytochemical concentrations across most drying treatments. The lowest flavonoid content (2.57 mg QE/100 g) was recorded at 50 °C for 24 min ($T_{50:24}$). This pattern suggests that *T. tetraptera* may be more sensitive to suboptimal drying conditions, particularly prolonged exposure to moderate temperatures. Extended drying durations under such conditions may permit continued residual enzymatic activity, especially polyphenol oxidase-mediated oxidation, resulting in progressive degradation of heat-labile phenolic compounds [23]. The lower retention of phenolics and flavonoids in this species, compared with terpenoids, highlights the importance of species-specific physiological and biochemical characteristics, including enzyme distribution, matrix composition, and cellular microstructure, in determining phytochemical stability during thermal processing [24].

Further evidence of the influence of drying conditions is provided by intermediate treatments such as $X_{60:24}$ and $M_{60:36}$, which demonstrated partial preservation of phenolic and flavonoid compounds and a more balanced phytochemical retention profile. This observation agrees with reports that controlled drying at moderate temperatures can reduce oxidative stress, limit excessive thermal exposure, and promote gradual enzyme inactivation, thereby minimizing phytochemical losses [25]. However, terpenoid concentrations under these intermediate treatments remained lower than those observed at higher-temperature treatments. This suggests a potential trade-off between the preservation of heat-sensitive polyphenols and the enhanced liberation or extractability of terpenoids under more intensive drying conditions [26]. These results indicate that optimal drying conditions are species-dependent and require a balance between phytochemical preservation and the enhancement of desirable bioactive compounds. The three-dimensional (3D) response surface plots illustrating the interactive effects of spice variety and drying temperature on total phenolic, flavonoid, and terpenoid contents are presented in Figure 2a–c, respectively.



(**a**) (**b**) (**c**)

Figure 2. 3D response surface plots showing the interactive effects of spice variety and drying temperature on (**a**) total phenolic content; (**b**) total flavonoid content; and (**c**) total terpenoid content.

The response surface models showed high predictive accuracy and reliability of the total variation in phenolic, flavonoid, and terpenoid contents. Drying temperature consistently emerged as the most influential processing factor affecting phytochemical retention, while spice type also contributed significantly to variations in the responses. Although drying time showed a smaller effect, it significantly influenced terpenoid content, suggesting that both shorter and longer drying durations can affect its retention. The presence of significant spice–temperature interaction effects across responses further confirms the species-dependent nature of thermal responses during drying. These findings are consistent with previous reports emphasizing the critical role of temperature and temperature–time interactions in modulating enzymatic inactivation, oxidative reactions, structural breakdown, and volatilization of bioactive compounds [26].

3.2. Effect of Drying Temperature and Time on the Antioxidant Activity of the Spices

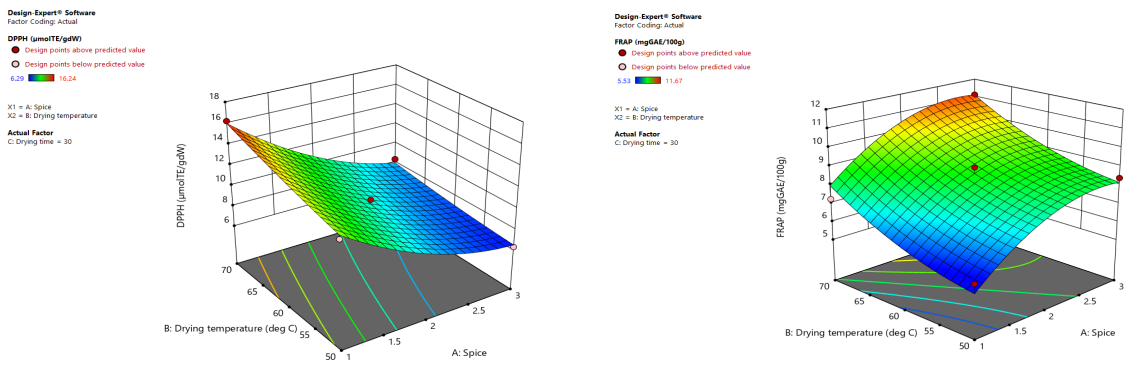
The effect of drying temperature and time on the antioxidant activity of the three spices is shown in Table 2. The results showed that drying conditions significantly ($p < 0.05$) influenced the antioxidant properties of *Tetrapleura tetraptera*, *Xylopia aethiopica*, and *Monodora myristica*, as measured by DPPH and FRAP assays. *Xylopia aethiopica* exhibited the highest DPPH radical scavenging activity, particularly under the condition of 70 °C for 30 h ($X_{70:30}$), which yielded 16.24 µmol TE/g DW. In contrast, *Monodora myristica* generally recorded the lowest DPPH values. The $M_{50:30}$ sample showed the lowest value (6.29 µmol TE/g DW). This indicates weaker free radical scavenging activity compared with the other samples. For FRAP values, which reflect reducing power, *Tetrapleura tetraptera* showed the best performance at higher drying temperatures. $T_{70:36}$ and $T_{70:24}$ recorded the highest values (11.67 and 11.26 mg GAE/100 g, respectively). This was followed by $M_{70:30}$, which recorded 11.11 mg GAE/100 g.

Table 2. Effect of drying conditions on the antioxidant activity of the spices.

Samples	DPPH (µmolTE/g DW)	FRAP (mgGAE/100 g)
X_{50}:30	12.31 ^{d} ± 0.01	5.53 ^{g} ± 0.10
M_{50}:30	6.29 ^{i} ± 0.01	8.39 ^{e} ± 0.10
X_{70}:30	16.24 ^{a} ± 0.03	7.24 ^{e,f} ± 0.11
M_{70}:30	8.33 ^{h} ± 0.02	11.11 ^{b} ± 0.12
X_{60}:24	14.01 ^{c} ± 0.02	6.47 ^{f,g} ± 0.13
M_{60}:24	7.21 ^{h,i} ± 0.04	9.24 ^{c,d} ± 0.13
X_{60}:36	15.13 ^{b} ± 0.02	6.89 ^{f} ± 0.13
M_{60}:36	7.36 ^{h,i} ± 0.04	9.86 ^{c} ± 0.10
T_{50}:24	8.78 ^{g,h} ± 0.01	7.73 ^{e,f} ± 0.10
T_{70}:24	10.24 ^{f} ± 0.01	11.26 ^{a,b} ± 0.10
T_{50}:36	8.97 ^{g} ± 0.03	7.88 ^{e,f} ± 0.12
T_{70}:36	11.12 ^{e} ± 0.03	11.67 ^{a} ± 0.11
T_{60}:30	9.33 ^{f,g} ± 0.01	8.60 ^{d} ± 0.12
T_{60}:30	9.33 ^{f,g} ± 0.01	8.60 ^{d} ± 0.12
T_{60}:30	9.33 ^{f,g} ± 0.01	8.60 ^{d} ± 0.12
T_{60}:30	9.33 ^{f,g} ± 0.01	8.60 ^{d} ± 0.12
T_{60}:30	9.33 ^{f,g} ± 0.01	8.60 ^{d} ± 0.12

Values are expressed as mean ± standard deviation of triplicate determinations. Means within the same column with different superscript letters (a–i) differ significantly ($p < 0.05$), whereas means with the same superscript letter are not significantly different.

The results showed that the interaction between spice type and drying temperature significantly influenced antioxidant activity, indicating that the effect of drying temperature varied depending on the spice type. This suggests that changes in drying temperature did not affect all spices uniformly, highlighting the importance of considering spice-specific responses during processing. Similarly, the reduced response model used to evaluate the effects of spice type, drying temperature, and drying time on FRAP antioxidant activity was highly significant, indicating a good fit of the model to the experimental data. Among the factors studied, spice type exerted the greatest influence on FRAP activity, followed by drying temperature, whereas drying time had little significant effect on the response. *X. aethiopica* exhibited the highest DPPH activity, particularly at high drying temperature (70 °C for 30 h), indicating that elevated temperatures enhance radical scavenging capacity, likely through the thermal liberation of bound phenolic compounds. This observation agrees with the findings, which reported increased phenolic content and antioxidant activity in thermally processed *X. aethiopica* [27]. However, *M. myristica* consistently showed lower DPPH values but relatively higher FRAP responses under high-temperature drying conditions, indicating stronger reducing power rather than radical scavenging ability. This differential behavior underscores the complexity of antioxidant mechanisms and supports the need for multiple analytical assays when characterizing antioxidant activity in spices [28]. *T. tetraptera* demonstrated a balanced antioxidant profile, with moderate DPPH and high FRAP values, particularly at elevated drying temperatures, confirming its functional and medicinal relevance [29]. The 3D response surface plot illustrating these effects are presented in Figure 3a, b for FRAP and DPPH, respectively.



(**a**) (**b**)

Figure 3. 3D response surface plots showing the interactive effects of spice variety and drying temperature on (**a**) DPPH radical scavenging activity and (**b**) ferric reducing antioxidant power (FRAP).

Response surface analysis revealed that spice variety and drying temperature significantly influenced both DPPH and FRAP responses. A significant antagonistic interaction between spice variety and drying temperature was observed for DPPH activity, indicating that the effects of temperature varied across spice species [29]. Spice variety was the most significant factor influencing both antioxidant assays, indicating that antioxidant responses differed among the spice types. The response models showed good reliability and predictive ability, with high coefficients of determination, non-significant lack of fit, acceptable coefficients of variation, and strong predictive performance. The coefficient estimates further confirmed that spice variety had the greatest influence on antioxidant properties. The results demonstrate that antioxidant activity in these local spices is primarily governed by intrinsic spice characteristics and drying temperature, highlighting the importance of species-specific optimization of drying conditions. Antioxidant activity in complex plant systems is generally not attributable to a single predominant compound but rather to synergistic and additive interactions among multiple phytochemical constituents. Phenolic compounds, flavonoids, terpenoids, and other secondary metabolites may act through complementary mechanisms [13]. Consequently, the overall antioxidant capacity measured by assays such as DPPH and FRAP reflects the integrated effect of these interacting compounds. This complexity may partly explain the variability observed under different drying conditions and underscores the multifactorial nature of antioxidant responses in spice matrices

3.3. Effect of Drying Conditions on the Sensory Properties of Spices

The sensory properties of *Tetrapleura tetraptera*, *Xylopia aethiopica*, and *Monodora myristica* dried under various temperatures and time, were rated on appearance, aroma, texture, and general acceptability. The results indicated that *Tetrapleura tetraptera* dried at 70 °C for 36 h ($T_{70:36}$) achieved the highest scores across all attributes, including appearance (7.77), aroma (7.43), texture (7.48), and general acceptability (7.46). This shows a superior sensory quality under these conditions. Conversely, *Xylopia aethiopica* dried at 50 °C for 30 h ($X_{50:30}$) recorded the lowest scores for appearance (5.44), general acceptability (5.86), and texture (5.72), suggesting less favorable sensory characteristics at lower drying temperatures and shorter times. *Monodora myristica* showed variable results; while the sample dried at 70 °C for 30 h ($M_{70:30}$) had a high aroma score (6.73) and good general acceptability (7.33), its texture was relatively poor (5.66), though the $M_{60:36}$ sample demonstrated a good score across all attributes. Notably, *T. tetraptera* samples dried at 60 °C for 30 h ($T_{60:30}$) showed reproducible high scores across multiple replicates, with minimal variation in appearance (7.28–7.41), aroma (7.09–7.22), and texture (6.87–6.98). Significant differences ($p < 0.05$) existed among most samples, except for the replicated $T_{60:30}$ samples of *T. tetraptera*, highlighting the impact of drying conditions on sensory qualities.

Table 3. Effect of drying conditions on the sensory properties of the spices.

Samples	Appearance	Aroma	Texture	General Acceptability
$X_{50:30}$	5.44 ^{f} ± 0.01	6.42 ^{b,c} ± 0.10	5.72 ^{d} ± 0.03	5.86 ^{e,f} ± 0.01
$M_{50:30}$	6.43 ^{d,e} ± 0.02	7.21 ^{a} ± 0.12	5.93 ^{c} ± 0.03	6.52 ^{d,e} ± 0.04
$X_{70:30}$	6.33 ^{d,e} ± 0.03	7.27 ^{a} ± 0.10	6.37 ^{b} ± 0.01	6.73 ^{d} ± 0.03
$M_{70:30}$	7.14 ^{c} ± 0.01	6.73 ^{c} ± 0.01	5.66 ^{d} ± 0.02	7.33 ^{c} ± 0.04
$X_{60:24}$	5.82 ^{f} ± 0.03	7.03 ^{a,b} ± 0.13	6.12 ^{b,c} ± 0.04	5.99 ^{e} ± 0.01
$M_{60:24}$	6.74 ^{d} ± 0.10	6.83 ^{b} ± 0.11	5.83 ^{c,d} ± 0.01	6.86 ^{d} ± 0.04
$X_{60:36}$	6.13 ^{e} ± 0.01	7.18 ^{a} ± 0.10	6.20 ^{a} ± 0.02	6.07 ^{d,e} ± 0.01
$M_{60:36}$	6.86 ^{d} ± 0.01	6.62 ^{b} ± 0.10	5.87 ^{c,d} ± 0.11	6.94 ^{d} ± 0.10
$T_{50:24}$	7.14 ^{c,d} ± 0.10	6.34 ^{c} ± 0.12	6.58 ^{b} ± 0.02	6.78 ^{c,d} ± 0.02
$T_{70:24}$	7.59 ^{b} ± 0.01	7.33 ^{a} ± 0.11	7.33 ^{a} ± 0.03	7.76 ^{a} ± 0.02
$T_{50:36}$	7.22 ^{c,d} ± 0.02	6.52 ^{b,c} ± 0.04	6.67 ^{a,b} ± 0.01	6.69 ^{d} ± 0.02
$T_{70:36}$	7.77 ^{a} ± 0.01	7.43 ^{a} ± 0.113	7.48 ^{a} ± 0.03	7.46 ^{b} ± 0.04
$T_{60:30}$	7.36 ^{c} ± 0.02	7.20 ^{a} ± 0.12	6.93 ^{a,b} ± 0.03	6.83 ^{d} ± 0.03
$T_{60:30}$	7.40 ^{c} ± 0.01	7.11 ^{a,b} ± 0.10	6.89 ^{a,b} ± 0.02	6.76 ^{d} ± 0.02
$T_{60:30}$	7.28 ^{c} ± 0.04	7.09 ^{a,b} ± 0.10	6.98 ^{a,b} ± 0.04	6.88 ^{d} ± 0.03
$T_{60:30}$	7.34 ^{c} ± 0.03	7.22 ^{a} ± 0.11	6.87 ^{a,b} ± 0.02	6.92 ^{d} ± 0.04
$T_{60:30}$	7.41 ^{c} ± 0.02	7.19 ^{a} ± 0.01	6.93 ^{a,b} ± 0.03	6.90 ^{d} ± 0.04

Values are expressed as mean ± standard deviation of triplicate determinations. Means within the same column with different superscript letters (a–i) differ significantly ($p < 0.05$), whereas means with the same superscript letter are not significantly different.

Drying temperature and time significantly influenced the appearance, aroma, texture, and general acceptability of samples dried at 70 °C for 36 h recorded the highest sensory scores, indicating that higher temperatures and extended drying enhanced the desirable sensory characteristics in some spices. This agrees with

reports that indicated improved sensory acceptability of dried onion varieties at elevated drying temperatures [30]. In contrast, *X. aethiopica* dried at a lower temperature (50 °C for 30 h) recorded the lowest appearance and acceptability scores, suggesting inadequate moisture removal and suboptimal sensory development [31]. *Monodora myristica* showed variable sensory responses depending on drying conditions, with high aroma scores at 70 °C but reduced texture acceptability. These results highlight the need for spice-specific drying optimization. Similar effects of drying conditions on sensory quality have been reported for tropical fruits and spices [32].

Results revealed that spice variety, drying temperature, and drying time significantly ($p < 0.05$) affected appearance, while aroma was influenced primarily by drying time and its interaction with spice variety. Texture and general acceptability were significantly affected by spice variety and drying temperature, with significant antagonistic interactions between spice variety and temperature for aroma and texture, indicating opposite response trends with simultaneous increases in these factors [33,34]. The results indicate that higher drying temperatures and longer drying times improve appearance, texture, and overall acceptability by producing drier, crisper, and visually appealing spices, while suboptimal drying yields damp and less acceptable products. Given that appearance strongly drives consumer purchase decisions [35].

The 3D response surface plots illustrating the combined effect of spice variety and drying temperature on appearance, aroma, texture, and general acceptability of spices are shown in Figure 4a–d.

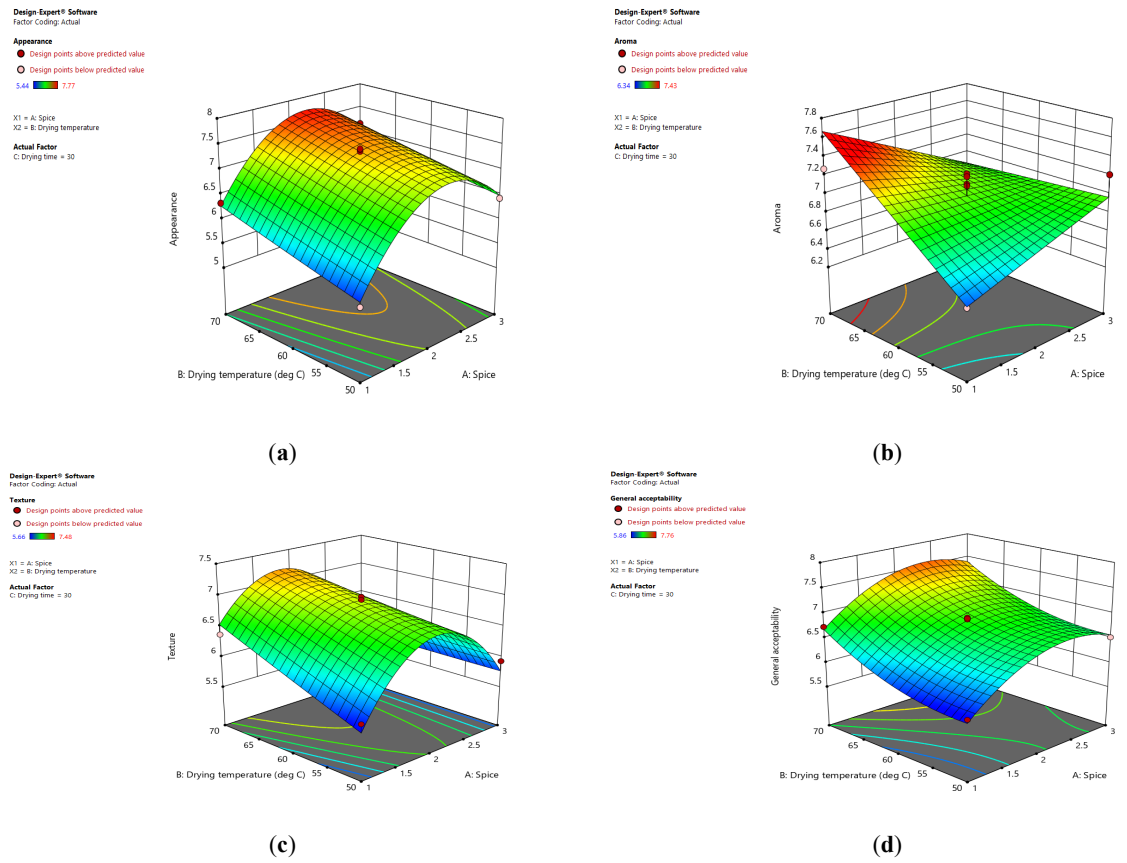


Figure 4. 3D response surface plots showing the interactive effects of spice variety and drying temperature on (**a**) appearance; (**b**) aroma; (**c**) texture; and (**d**) general acceptability of the spice samples.

The RSM analysis showed that spice type had an important influence on the sensory attributes of the dried spices. For appearance, spice type significantly affected the response, indicating that changes in spice type caused noticeable variations in appearance scores. No similar pattern was observed for aroma because no additional response trend was detected in the model. For texture, spice type also had a significant influence, showing that textural characteristics varied among the different spices. For general acceptability, both spice type and drying temperature significantly influenced consumer preference, suggesting that variations in these factors affected the overall acceptance of the products. Overall, spice type had the greatest influence on the sensory properties of the dried spices, while drying temperature mainly affected general acceptability.

Despite the robust optimization achieved through Response Surface Methodology, this study did not include fresh (undried) samples as reference controls for absolute retention analysis. Previous reports have highlighted that processing conditions can influence the stability and variability of plant bioactive compounds [36,37], which is

consistent with the present findings showing that drying temperature and time significantly affected phytochemical content and antioxidant activity. Consequently, the results primarily reflect the influence of drying parameters within the experimental domain rather than the precise quantification of bioactive losses from the fresh state. Nonetheless, the optimization framework remains appropriate for identifying processing conditions that maximize functional quality attributes. Future investigations incorporating fresh baselines could further elucidate retention dynamics and complement the present results.

4. Conclusions

This study provides robust and comprehensive evidence that drying temperature and time are critical determinants of phytochemical integrity, antioxidant capacity, and sensory quality in the underutilized African spices *Tetrapleura tetraptera*, *Xylopia aethiopica*, and *Monodora myristica*. Thermal processing at elevated temperatures, particularly 70 °C, markedly enhanced the availability of key bioactive compounds, including phenolics and terpenoids, and significantly improved antioxidant activity, with pronounced species-specific responses. *Monodora myristica* demonstrated superior performance under high-temperature drying in terms of terpenoid enrichment.

A clear processing trade-off was established between the enhancement of antioxidant functionality and the stability of heat-labile phytochemicals. Higher drying temperatures promoted terpenoid release and antioxidant capacity. This is most noted in *X. aethiopica* and *T. tetraptera* but resulted in measurable reductions in flavonoids and alkaloids, particularly in *T. tetraptera*. Sensory evaluation demonstrated that optimized drying significantly improves appearance, aroma, texture, and overall consumer acceptability, with *T. tetraptera* dried at 70 °C for 36 h ($T_{70:36}$) achieving the highest sensory scores. In contrast, suboptimal low-temperature drying impaired flavor development in *X. aethiopica*, underscoring the necessity of adequate thermal input for sensory quality formation. The findings clearly demonstrate that a one-size-fits-all drying approach is inadequate; rather, spice-specific and evidence-based drying protocols are essential for maximizing functional value and consumer appeal. The research establishes controlled thermal drying as a scientifically validated, sustainable postharvest strategy for enhancing shelf stability, phytochemical quality, and market value of indigenous spices.

Author Contributions

S.U. and B.E.: contributed to conceptualization, methodology, investigation, data curation, and drafting of the original manuscript; E.I.: was responsible for supervision, validation, and manuscript review and editing; E.U. and J.I.: contributed to supervision, methodology, and data curation; S.U. and J.I.: also handled visualization, review, and editing. All authors have read and agreed to the published version of the manuscript.

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Data supporting the findings of this study are available from the corresponding author on a reasonable request.

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Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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