

Impact of Thermal and Solar Drying on the Bioactive Profiles, Color Parameters, and Antioxidant Capacity of calyx leaves (*Hibiscus sabdariffa* L.)

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Abstract

The study was conducted in January 2026 in the laboratories of the College of Education at Diyala University (Diyala/Baghdad, Iraq). Drying is a crucial post-harvest stage for hibiscus (*Hibiscus sabdariffa* L.) leaves, directly affecting the stability of their physicochemical and biologically active properties. This study investigated the comparative effects of conventional drying under direct sunlight and forced thermal drying via a temperature gradient (30°C, 40°C, and 50°C) on the chemical composition, CIELAB color parameters, and antioxidant performance of hibiscus cultivated in Diyala, Iraq. The experimental matrix evaluated moisture absorption, ash, crude fat, protein, and fiber dynamics, along with total phenolic content (TPC) and free radical scavenging capacity using DPPH and ABTS assays. The experimental results showed statistically significant differences ($p \leq 0.05$) between treatments. Convection drying at moderate temperatures (30–40°C), combined with drying under direct sunlight, optimally preserved the structural integrity of dietary fibers and nutrients, while achieving superior illumination (c^*) and balanced color coordinates. In contrast, raising the heat treatment temperature to 50°C resulted in severe thermal degradation of heat-sensitive polyphenols, leading to a significant decrease in antioxidant activity and undesirable surface browning due to non-enzymatic Maillard reactions and phenol oxidation. Pearson correlation analysis revealed a strong positive correlation between total phenolic content (TPC) and DPPH radical inhibition ($r = 0.812$), compared to a moderate correlation for the ABTS matrix ($r = 0.941$), confirming the essential role of mono-polyphenols in promoting plant bioactivity. These results underscore the need for precise thermodynamic regulation during post-harvest processing and recommend moderate temperatures (30–40°C) as the optimal technical basis for preserving the nutritional, aesthetic, and therapeutic value of hibiscus calyx in functional food and biopharmaceutical applications. Keywords: Antioxidant capacity; Polyphenols; Hibiscus (*Hibiscus sabdariffa*); Thermal drying; Color properties.

Keywords: Antioxidant capacity, Color parameters, Convective drying, Hibiscus sabdariffa, Proximate composition, Solar drying

Introduction

Hibiscus (*Hibiscus sabdariffa* L.) belongs to the Malvaceae family and is commonly known by its vernacular name "roselle" is commercially, cultivated in many tropical and subtropical countries, including India, Indonesia, Sudan, Egypt, and Mexico, as well as Malaysia [1], the hibiscus calyx

leaves are characterized by its bright red color, which is due to its anthocyanin content, such as cyanidin-3-sambubioside, cyanidin-3-glucoside, and delphinidin-3-glucoside[2].The calyx leaf is used to make jams, jellies, ice cream, pastries, preserves, and herbal drinks[3]. Drinking hibiscus tea is associated with numerous health

benefits, primarily due to its antioxidant properties. The anthocyanins present in the hibiscus calyx leaves are a key component of this plant [4].

Industrially, the quality of medicinal herbs depends primarily on post-harvest processes, particularly the drying stage [5]. Depending on the drying agents, the natural composition of certain substances, such as organic acids, alcohols, and phenolic compounds, is determined. Drying reduces the moisture content of hibiscus flowers to a safe level (approximately 7%), inhibiting microbial growth and stabilizing their chemical structure [6,7,8].

However, drying conditions and temperature can significantly affect the physical and chemical properties, impacting fat, protein, fiber, and mineral content, color, and storage stability[9] . Among the most common methods are sun-drying, widely adopted by producers due to its low cost, despite its dependence on weather conditions, and thermal drying, which uses hot air under controlled temperature and airflow, providing greater uniformity but carrying the risk of thermal degradation of heat-sensitive compounds such as polyphenols [10,11].

Understanding the effect of drying on the quality of dried herbs is essential for improving post-harvest processes and preserving their nutritional value and sensory characteristics. However, comparative information regarding the effects of conventional and thermal drying at different temperatures remains

limited, particularly in tropical regions [12]. Chemical changes are related to the temperature limits used; moderate temperatures (30°C–40°C) ensure the preservation of biochemical bonds, while excessively high temperatures (50°C and above) lead to heat stress that causes the destruction of the structural framework of proteins (denaturation), oxidation of lipids, and decomposition of heat-sensitive fibers, as well as the loss of water-soluble vitamins such as vitamins C and B-complex [13,14], and *H. sabdariffa* has lipid-lowering, antioxidant, and blood pressure-lowering properties. The effectiveness of the extracts varies depending on the drying temperature, and the therapeutic effect of the *hibiscus* is strongest when dried at 30°C [15,16]. Minerals (such as calcium, iron, and potassium) exhibit much higher thermal stability compared to organic compounds and vitamins. However, drying plants leads to an increase in their relative concentration in solid biomass due to the heavy loss of water, and their retention rate depends on the efficiency of the drying method and the surface area exposed to extraction [17,18].

Therefore, this study aimed to evaluate the effect of conventional solar drying and thermal drying at different temperatures (30, 40, and 50°C) on the proximate composition, color characteristics, total polyphenol content, and antioxidant capacity, to determine the conditions that best preserve its nutritional, technological, and commercial quality.

N, 44°38'24.0" E) in January 2026. After the drying process was complete, Classification of plants in the Museum of Natural History/ University of Baghdad, the calyx leaves were divided into two groups for further drying to evaluate the effect of the drying method and temperature on their physical and

Materials and Methods

Plant Materials and Drying

Hibiscus calyx leaves (*Hibiscus sabdariffa*) were collected from a field in Diyala Governorate, Iraq (33°44'24.0"

chemical properties. Traditional sun drying was performed by spreading the flowers on wooden trays for 20 hours in direct sunlight, turning them every two hours to ensure even drying. Simultaneously, convection drying was carried out in a forced-air oven (DHG-9023A, Luzerne, China) at controlled temperatures of 30, 40, and 50°C for the same duration. In both cases, the process continued until a final moisture content

of 7% or less was achieved, a level suitable for preservation and storage according to ISO 2451. After drying, the calyx leaves were ground using a food mill (Hamilton Beach, model 80335R, China) and then sieved through a 150- μ m sieve to ensure uniform particle size. The samples were sealed in airtight polyethylene bags and stored at 4°C pending further analysis [19].

Physical, Chemical, and Tri-Catalytic Colorimetry Analysis

Approximate chemical composition analysis of the dried calyx leaves were performed according to the official methods of the Association of Official Analytical Chemists (AOAC): moisture (934.01), fat (920.39), ash (942.05), crude protein (954.01), and crude fiber (985.29). Colorimetry measurements were performed five times using a colorimeter (CR-300, Minolta, Osaka, Japan). Readings were recorded according to the CIELAB color space (a^* , b^* , c^*)[20].

Extraction of Phenolic Compounds

Phenolic compounds were extracted following the procedure described by [21]. Twenty grams of calyx leaves powder were mixed with 400 mL of 80% (v/v) methanol, and the mixture was stirred intermittently for 48 hours at room temperature. The resulting product was filtered, and the extraction process was repeated using an additional 200 mL of the same solvent. The extracts were collected and concentrated under reduced pressure using a rotary evaporator (Buchi R-300, Switzerland) at 40 °C until a dry concentrate was obtained. The concentrate was stored in tightly sealed amber bottles at 4 °C in a dark place.

The antioxidant capacity

The antioxidant capacity of the samples was evaluated using two spectrophotometric methods, 2,2-diphenyl-1-picrylhydrazyl (DPPH) and 2,2'-azino-bis [3-ethylbenzothiazoline-6-sulfonic acid] ($ABTS^+$). For the DPPH assay, an ethanolic solution (0.01 mM) was prepared and adjusted to an initial absorbance of 0.07 at 517 nm. For the

$ABTS^+$ assay, the cationic radical was generated by mixing 7.0 mM ABTS with 2.45mM $K_2S_2O_8$, the mixture was kept in darkness for 16 h for activation. It was then dilute with ethanol to an absorbance of 0.7 at 734 nm. The percentage of radical inhibition was calculated using the equation [22].

$$\text{Radical Scavenging Activity (\%)} = ((A_{\text{control}} - A_{\text{sample}}) / A_{\text{control}}) * 100$$

A_{control}

= the optical absorption (absorption) tests for the optical compressor (control)
 – reagent solution with solvent only, without the extract)

A_{sample} = the optical absorption tests for the
 hibiscus reconstituted sample after the
 reaction

Statistical analysis

All analyses were performed in triplicate and expressed as mean $\pm$ standard deviation (SD). The data was subjected to analysis of variance (ANOVA). The means were separated by Tukey's test ($p \leq 0.05$), using Statistical Minitab® 18.1 software (SCIENTEC, State College, Pennsylvania, USA). Pearson's correlation coefficient (r) was used to assess the relationship between total polyphenol content (TPC) and antioxidant capacity (ABTS and DPPH). Graphs and figures were generated using SigmaPlot® 14.5 software (Systat Software Inc., USA).

Results and Discussion

Effect of Drying Temperature

Table 1 showed the main effects of drying temperature on moisture, ash, fat, protein, and crude fiber content. The results indicate that both conventional sun-drying and thermal drying are effective in reducing the moisture content of the flowers, with values ranging from 3.19% to 4.47% (on a dry weight basis). These values fall within the recommended limit of 7.5% according to international standards (8). Statistically, no statistically significant

differences ($p > 0.05$) were observed between the drying methods with respect to moisture content, indicating that all methods were equally effective in drying. When the moisture content falls below 7%, browning reactions occur, and color enhancing aromatic compounds begin to form (9). This decrease in moisture is also associated with a significant decrease in water activity, this ensures product stability by preventing thinning, mold and bacteria growth, and the breakdown of fatty compounds [23].

Table 1. Effect of different drying methods and temperatures on the proximate composition of *H. sabdariffa*.

Drying method	Moisture (%)	Ash (%)	Fat (%)	Crude protein (%)	Crude fiber (%)
Sun	3.81±0.17 ^a	1.11±0.34 ^b	3.27±1.50 ^a _b	2.83±0.25 ^{ba}	14.54±0.55 ^{ab}
30 °C	3.88±1.07 ^a	2.33±0.60 ^a _b	2.5±0.7 ^{bc}	3.39±0.24 ^b	12.27±1.88 ^b
40 °C	4.47±1.35 ^a	2.41±0.20 ^a	3.30±0.74 ^a	4.88±0.18 ^b	13.16±0.21 ^a
50 °C	3.19±0.09 ^a	1.22±0.51 ^a _b	2.6±1.1 ^b	5.32±0.60 ^a	12.32±0.24 ^b

*Values are expressed as mean ± standard deviation ($n=3$). Different letters within the same column indicate significant differences between treatments according to Tukey's test ($p \leq 0.05$).

The ash fraction represents the total mineral content in plant tissues. As shown in Table 1, significant differences ($p \leq 0.05$) were observed between the different drying protocols. Sun-dried hibiscus cups showed the lowest mineral concentration ($1.11 \pm 0.34\%$), which is statistically close to the mineral concentration in the 50°C treatment ($1.22 \pm 0.51\%$). In contrast, thermal drying at moderate temperatures enhanced the relative ash retention, with the 40°C treatment recording the highest statistically significant value ($2.41 \pm 0.20\%$). This distinctive mineral composition enhances the nutritional value of hibiscus cups (*Hibiscus sabdariffa*) as a rich source of essential dietary minerals necessary for human health. The crude fat content in the dried cups ranged from $2.5 \pm 0.7\%$ to 3.3% , showing statistically significant differences due to the drying methods and temperature gradients. Heat treatment at 40°C and 50°C resulted in the highest lipid concentrations ($3.30 \pm 0.74\%$ and $3.30 \pm 1.1\%$, respectively), indicating high thermal stability of the lipid components in the hibiscus matrix under these conditions. This low concentration is attributed to the prolonged drying dynamics required at lower temperatures, which may extend the activity period of the endogenous lipolytic enzymes before complete dehydration disrupts the system. Regarding crude protein content, significant differences were observed among the evaluated

treatments. The highest protein concentration ($5.32 \pm 0.60\%$) was recorded at 50°C , followed by treatment at 40°C ($4.88 \pm 0.18\%$), while solar drying and thermal drying at 30°C yielded the lowest values ($2.83 \pm 0.25\%$) and $3.39 \pm 0.24\%$, respectively. This upward trend, coinciding with the increase in thermal parameters, is primarily attributed to the relative concentration of nitrogenous solids resulting from accelerated moisture loss, or to heat-induced structural bonding within protein compounds, which altered their extractability during initial analysis. Crude fiber content ranged from 12.27% to 14.54% , demonstrating statistically significant differences between treatments.

Solar drying maintained the highest structural fiber yield ($14.54 \pm 0.55\%$), while thermal drying at 30°C and 50°C resulted in the lowest retention values ($12.27 \pm 1.88\%$ and $12.32 \pm 0.24\%$, respectively). This suggests that the gradual, outdoor solar drying mechanism may preserve the structural integrity of the plant cell wall sugars. In contrast, rapid convection thermal drying can lead to localized thermal stress, resulting in partial thermal degradation or melting of the fragile hemicellulosic or pectin fiber fragments. Overall, the rough analysis indicates that convection drying at 40°C provides an optimal thermodynamic balance for preserving the essential macronutrients

(ash, fat, and protein) in hibiscus flowers, while solar drying is beneficial exclusively for maximizing crude fiber retention. Previous studies have clearly shown that variations in drying conditions alter the overall mass transfer and solids concentration, directly affecting total lipids, structural fibers, and mineral ash composition. Furthermore, the significant shifts in protein content observed across all treatments are consistent with established research indicating that drying parameters are the primary determinants of protein stability[24,25]. While low temperatures or exposure to open air can prolong enzyme-mediated proteolysis, optimal thermal drying alters protein retrieval and structural bonding, thereby changing the detectable crude protein content within the residual dry matter Mahmood *et al.*, 2025; Yang *et al.*,2026).

Effect of drying temperature on the color properties of *H. sabdariffa*

Table 2 shows the color properties of the dried and ground hibiscus cups. The results showed significant differences ($p < 0.05$) between the different treatments. The redness values (a^*) ranged from 24.03 to 34.09, with a sharp and noticeable decrease in red intensity at 50 °C (24.03) compared to the other temperatures. This loss of redness in

This darkening can be attributed to non-enzymatic browning reactions (Maillard reaction) and the oxidation of

the heat-dried samples, especially at 50 °C, is attributed to the thermal decomposition of anthocyanins—the primary pigments responsible for the red color of hibiscus—as well as non-enzymatic tanning reactions (Maillard reaction) and polyphenol oxidation. These processes are accelerated at high temperatures, changing the visible appearance of the product from a bright crimson red to a dull, dark reddish-brown (6). Regarding the yellowness value (b^*), the highest retention was recorded in sun-dried samples ($6.61 \pm 0.35a$), followed closely by treatment at 40°C ($5.40 \pm 0.67a$). Treatment at 50°C resulted in a significant decrease to 3.68, reflecting thermal stress on the co-pigment matrix. Furthermore, the color saturation values (c^*), representing color intensity and purity, varied considerably among the treatments. Treatment at 40°C recorded the highest positive color saturation value ($1.57 \pm 0.82a$), indicating a more vivid and stable color, while the other treatments (sun, 30°C, 50°C) showed negative or near-zero values. This shift suggests the interplay of blue-yellow tones in the final powder appearance, largely dependent on the degradation or stabilization of the basic pigment compounds under different thermal conditions.

polyphenols, processes that intensify at higher temperatures and alter the visual appearance of the product [26].

Table 2. Effect of drying temperature on the CIELAB color parameters (a^* , b^* , c^*) of and dried *H. sabdariffa*

Drying method	a^* (Redness)	b^* (Yellowness)	c^* (Chroma)
Sun	33.27 ± 0.26^a	6.61 ± 0.35^{ab}	-0.32 ± 0.56^{ab}
30 °C	32.36 ± 0.17^{bc}	3.98 ± 0.36^{bc}	-1.14 ± 0.15^b
40 °C	34.09 ± 0.13^{ab}	5.40 ± 0.67^a	1.57 ± 0.82^a
50 °C	24.03 ± 0.46^d	3.68 ± 0.20^c	-0.11 ± 0.31^{ab}

*Values are expressed as mean $\pm$ standard deviation ($n= 3$). Different superscript letters within the

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same column indicate significant differences among treatments according to Tukey's test ($p \leq 0.05$).

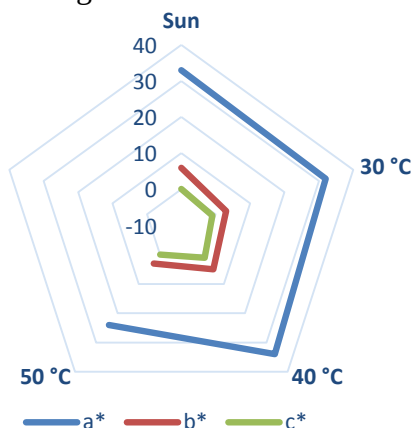
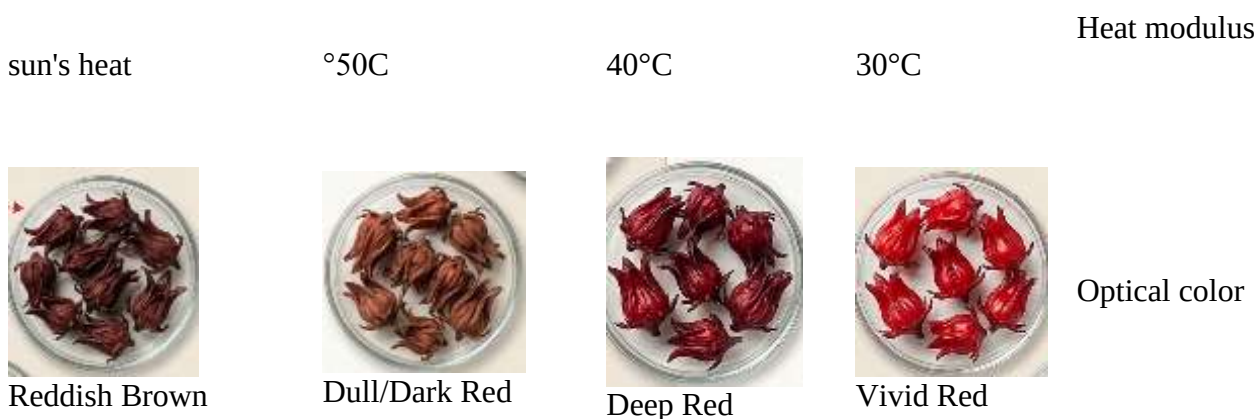


Figure 1 . Effect of drying temperature on the CIELAB color parameters (a*, b*, c*) of and dried *H. sabdariffa*

The results in figure 1 show that drying temperature and method have a significant and decisive impact on the qualitative and color characteristics of *Hibiscus sabdariffa* sepals. Comparative analysis of the four treatments (30°C, 40°C, 50°C, and sunlight) reveals that the observed variation in red color stability can be attributed to physicochemical changes in the anthocyanin pigment, the primary component responsible for the plant's market and nutritional value.

The results indicate that convective drying at a moderate temperature of 40°C was the most efficient in preserving the bright red crimson color of the calyces, as evidenced by the significantly higher a* value (34.09 \pm

0.13) compared to other treatments. However, when the drying temperature was further raised to 50°C, a gradual shift towards a dull, dark red color was observed. This degradation can be scientifically attributed to the thermal instability of anthocyanins, the primary pigments responsible for the red color in roselle, which undergo structural transformation and cleavage under prolonged or higher heat exposure. Additionally, the accelerated non-enzymatic browning (Maillard reactions) and phenol oxidation at 50°C contribute significantly to the formation of brown melanoidins, masking the desirable red hue and reducing the overall color. This is scientifically explained by the fact that lower temperatures preserve the chemically stable flavylium cation structure, the

form responsible for the red color in the acidic environment of the sepals. Furthermore, the gradual and steady decrease in humidity at this temperature inhibits the activity of oxidation enzymes such as polyphenol oxidase (PPO) before they begin to oxidize phenols and form dark brown chalcones or brown compounds resulting from the Maillard reaction between reducing sugars and amino acids available in the sepal tissue [27].

The sun-drying treatment resulted in the lowest levels of color quality, with the samples tending towards a reddish-brown color. This color failure can be explained by the synergistic effect between uneven heat stress and photo-oxidation. Ultraviolet (UV) radiation acts as a chemical catalyst, accelerating the breakdown of the chemical bonds in plant pigments in a process. Furthermore, the slower rate at which tissues reach complete drying under sunlight, compared to ventilated ovens, allows for a longer period of enzymatic activity, thus promoting enzymatic browning [28].

Based on the results shown in the table, it can be concluded that the color stability of dried (*H. sabdariffa*) is closely related to the degree of control over drying conditions. This study confirms that using a hot air stream at moderate temperatures not exceeding 30–40°C provides an ideal environment for protecting the pigment content from thermal and photochemical degradation, thus ensuring the preservation of the sensory and biochemical properties of the calyx. These results are consistent with several previous studies indicating the high sensitivity of anthocyanin pigments to heat stress conditions during food processing and drying. The a^* coefficient (responsible for the reddening index) showed high stability and suitability at 40°C, registering its

complexes, a gradual shift towards a dull, dark red color is observed. This color deterioration is attributed to the thermal degradation of anthocyanins; excess heat breaks the glycosidic bonds and opens the central ring of the pigment molecule, transforming them into colorless

highest value ($34.09 \mu\text{M} \pm 0.13$), followed by sun-drying ($33.27 \mu\text{M} \pm 0.26$), with no statistically significant difference between them according to Tukey's test ($p > 0.05$). This high value reflects the stability of anthocyanin pigments and phenolic compounds under moderate thermal conditions. Conversely, raising the drying temperature to 50°C resulted in a sharp and significant decrease in the a^* values, reaching (24.03 ± 0.46), confirming the thermal decomposition and structural warping of the anthocyanin pigments responsible for the characteristic red color of hibiscus. As for the yellowness index b^* , the sun-drying treatment achieved the highest observed value (6.61 ± 0.35), followed by the 40°C treatment (5.40 ± 0.67). Regarding the color saturation index c^* , the 40°C drying treatment stood out, registering the only significant positive value (1.57 ± 0.82), while the other treatments (sun-drying, 30°C, and 50°C) registered negative and sub-zero values. This trend at 40°C reflects the emergence of a more balanced and pure color of the red pigments, resulting from a reduction in non-enzymatic browning reactions and polyphenol oxidation. These reactions typically lead to the formation of dark brown pigments that obscure the original color characteristics of the flowers at higher temperatures (50°C). In general, moderate temperatures (30–40°C) and sun-drying contributed to preserving the freshness and color balance of the hibiscus flowers, while drying at 50°C resulted in a significant decrease in color intensity and the

appearance of darker and paler samples, a clear indicator of exposure to high heat stress. These results confirm that precise control of drying temperatures is crucial for maintaining the visual appearance of the final product, a key element for quality assessment and consumer acceptance in the food and pharmaceutical industries that rely on

Influence of drying temperature on total polyphenol content (TPC)

Figure 2 shows the total phenolic content (TPC) in extracts of dried hibiscus calyx under different conditions, measured in gallic acid equivalents (mg GAE/g dry sample). The results showed statistically significant differences ($p \leq 0.05$) between the different drying treatments;

A clear upward trend in TPC values was observed with increasing thermal drying temperature compared to solar drying. The convection drying treatment at 50°C recorded the highest total phenol content (approximately 5.5 mg GAE/g), followed by the treatment at 40°C (approximately 5.3 mg GAE/g). This increase is attributed to the fact that relatively high temperatures (up to 50°C) contribute to the rapid inhibition of phenol-oxidizing enzymes such as polyphenol oxidase (PPO), thus limiting the enzymatic degradation of phenolic compounds during the process. Furthermore, thermal energy can rupture the cellular tissue of the calyx, facilitating the extraction and release of bound phenols and binding processes within the plant matrix. In contrast, solar drying showed the lowest total phenol content (approximately 3.6 mg GAE/g).

H. sabdariffa is well known for its high concentration of antioxidant compounds, mainly polyphenols and tocopherols, which neutralized free radical and protect against oxidative damage, consumption of these compounds contributes to the prevention

hibiscus. These observed color changes are closely related to the chemical transformations of phenomena, which are simultaneously responsible for both color and antioxidant activity[29]. In this context, the total phenolic content (TPC) and its relationship to total antioxidant capacity were assessed using ABTS and DPPH tests.

of chronic diseases such as cardiovascular disease, cancer, and neurodegenerative disorders, highlighting the importance of evaluating antioxidant capacity (CA) under different processing conditions to preserve functional value [30]. Extracts of *H. sabdariffa* calyx leaves are characterized by their rich content of antioxidant compounds, particularly phenols and anthocyanins, which play a vital role in scavenging free radicals and reducing oxidative stress. Consuming these bioactive compounds contributes to the prevention of many chronic diseases such as cardiovascular diseases and degenerative disorders, which underscores the importance of evaluating the antioxidant capacity under different drying conditions to preserve the functional and therapeutic value of the flowers. This significant decrease is attributed to the long period of time spent in sun-drying and direct exposure to ultraviolet radiation and oxygen, conditions that provide an ideal environment for the continuation of enzymatic activity and the activation of non-enzymatic oxidative reactions, leading to the degradation of light- and air-sensitive phenolic compounds and the loss of part of the total antioxidant content. These changes in total phenolic content (TPC) are closely related to the overall antioxidant capacity of the flowers; therefore, this correlation was assessed by measuring the antioxidant capacity using ABTS and DPPH assays to verify the efficiency of this extracted compound [31].

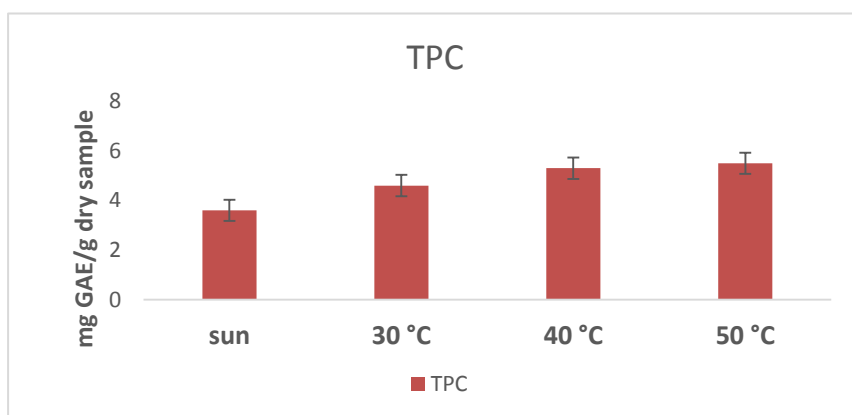


Figure 2. Effect of different drying temperatures on the total polyphenol content (TPC) mg GAE/g dry sample in *H. sabdariffa*, *Values are expressed as mean $\pm$ standard deviation ($n=3$). Different superscript letters within the same column indicate significant differences among drying treatments according to Tukey's test ($p \leq 0.05$).

Influence of antioxidant capacity in H. sabdariffa

The antioxidant capacity (AC) of *Hibiscus* in figure 3, assessed using ABTS and DPPH radicals in fig. 3, revealed contrasting trends reflecting the nature and mechanism of action of each assay and their statistical correlation with total phenolic content (TPC).

Heat-dried hibiscus calyx samples at 30°C and 40°C exhibited the highest free radical inhibition rates in the DPPH assay (approximately 54% and 51.5%, respectively), indicating the high stability of antioxidant molecules

and sensitive pigments such as anthocyanins under these moderate drying conditions. Conversely, raising the temperature to 50°C, as well as the solar drying treatment, resulted in a significant decrease in DPPH radical scavenging activity (reaching approximately 44% and 40%, respectively). This decline at 50°C is attributed to the partial thermal decomposition of the phenolic hydroxyl groups responsible for the reducing activity, or their transformation into less active polymers due to increased heat stress[32].

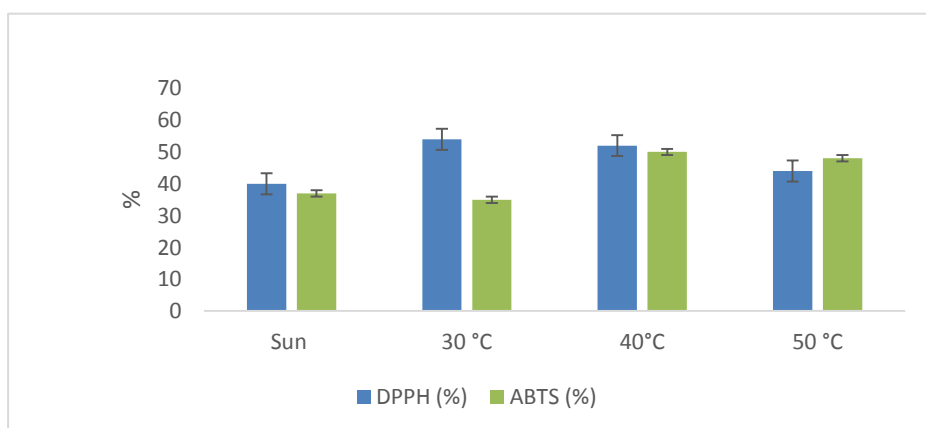


Figure 3: antioxidant capacity of hibiscus flowers determined by ABTS and DPPH assays.

Meanwhile, the ABTS assay showed a consistent upward trend, largely reflecting the accumulation of total phenolic compounds (TPCs). Free radical scavenging activity increased significantly upon heat treatment at 40 and 50 °C, peaking at approximately 49.5% and 47.5%, respectively. In contrast, solar drying and treatment at a lower temperature (30 °C) resulted in the lowest inhibition rates (37% and 35%, respectively). This perfectly synchronized behavior demonstrates the extremely strong statistical correlation between TPCs and the ABTS assay ($r = 0.941$), confirming that thermally released phenolic compounds are the primary driver of antioxidant capacity in the aqueous system. The marked increase in ABTS radical inhibition at elevated temperatures is directly attributed to the thermal decomposition of the cellular matrix, which facilitates the release of bound polyphenols, along with the potential formation of new reducing agents from non-enzymatic Maillard reactions. These results structurally confirm that optimizing the drying kinetics of hibiscus (*H. sabdariffa*) Calyx requires a delicate thermodynamic balance. While drying at moderate temperatures (30–40 °C)

ensures optimal preservation of specific free mono-molecule anthocyanins—as structurally demonstrated by the maximum DPPH radical removal capacity at 30 °C (54%) and the visible retention of the red color (a^* value)—exceeding these temperature thresholds (up to 50 °C) leads to a slight decrease in the DPPH fraction ($r = 0.812$). However, these higher temperature limits simultaneously promote the extraction of macromolecule-bound phenolic compounds, thus maintaining a generally strong antioxidant capacity.

Statistical analysis in table 4 revealed a very strong positive correlation between the total phenolic content (TPC) and the radical-reducing capacity of ABTS, with a correlation coefficient of 0.941. This result provides conclusive scientific evidence that the polyphenolic compounds extracted from hibiscus calyces are the primary and dominant contributors to the antioxidant activity in the aqueous reaction environment of the ABTS treatment. This upward trend is consistent with the observations in the graphs. The peak in total phenol production at elevated temperatures (40°C and 50°C) coincided with a significant increase in ABTS radical inhibition [33,34].

Table 4 .Pearson's correlation between total polyphenol content (TPC) and antioxidant capacity determined by the ABTS and DPPH assays

Variables	DPPH	ABTS	TPC
TPC	-	0.466	1
ABTS	-	1	0.941
DPPH	1	0.635	0.812

This is attributed to the efficiency of thermally released polyphenols (such as flavonoids and phenolic acids) in electron transport (SET mechanism) and neutralization of this stable radical. Furthermore, the results demonstrated a strong positive correlation between total phenol (TPC) content and DPPH radical scavenging activity, with a correlation coefficient of 0.812. This strong correlation confirms that phenols play a key role in the hydrogen atom transport (HAT) mechanism characteristic of the DPPH assay in organic media. However, the fact that this correlation ($r = 0.812$) is relatively lower than that of ABTS ($r = 0.941$) suggests that some highly specialized phenolic compounds (such as heat-sensitive mono-anthocyanin pigments) underwent structural changes or partial decomposition at 50°C. This resulted in a slight decrease in DPPH radical scavenging efficiency, while the total phenolic content (TPC) remained high or stable due to the release of other phenolic compounds that do not possess the same specific reactivity in the DPPH medium. On the other hand, a moderate positive correlation ($r = 0.635$) was recorded between the ABTS and DPPH antioxidant assays. This modest correlation explains the lack of perfect alignment between the two assay curves; the scientific reasons for this difference lie in the different natures of the free radicals used and the solubility medium for each. While the aqueous ABTS system responds to hydrophilic compounds and heat-soluble non-enzymatic browning reaction products, the DPPH system tends to measure lipophilic compounds and heat-sensitive free pigments in an alcoholic medium. These complementary correlations confirm that total phenolic content is the strongest biochemical predictor of the total reducing capacity of hibiscus extract. However, it is important to note that the thermal drying conditions

(between 30°C and 50°C) reshape the product's phenolic profile and pigment structure, which is reflected differently in the pathways and efficiency of antioxidant systems.

Conclusions

The results of this study confirm that drying conditions and temperature decisively affect the physical, chemical, color, and biological properties of *H. sabdariffa*. Traditional sun-drying and controlled thermal drying between 30 and 50°C helped preserve fats, fibers, and phenolic compounds, resulting in higher brightness and color stability, as well as high antioxidant capacity, which is primarily linked to the total polyphenol content. Conversely, thermal drying at 50°C caused a significant decrease in total polyphenol content and free radical scavenging capacity (DPPH and ABTS), accompanied by a marked change in product color—evidence of the thermal degradation of bioactive compounds and phenolic pigments. Pearson correlation analysis revealed a strong positive relationship between phenolic content and antioxidant activity ($r = 0.812$ for DPPH), confirming that polyphenols are the main contributors to the antioxidant function in *H. sabdariffa*. These results collectively highlight the importance of precise temperature control during drying as a key strategy for preserving the nutritional, sensory, and technical value of hibiscus as a medicinal herb. They also provide scientific evidence supporting the development of sustainable post-harvest technologies, and further studies on energy efficiency and sensory enhancement are recommended to further develop the technical applications of these findings.

Conflict of interest

The authors declare no conflict of interest related to this publication.

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