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Research Article

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The Effect of Pretreatment and Hot-air Drying Parameters on the Drying Behavior and Quality Properties of Onion (*Allium cepa* L.)

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Abstract

Hot-air drying is widely applied for onion (*Allium cepa)* preservation, but processing conditions strongly influence the quality of the final powder. This study evaluated the effects of blanching time (0, 3, and 5 min), antibrowning treatments (sodium metabisulfite ($Na_2S_2O_5$) or sodium sulfite (Na_2SO_3); 0.05 - 0.2% w/v), and drying temperature (60 - 80 °C) on physicochemical, biochemical and sensory properties of onion powder. Optimal conditions (3 min blanching, 0.1% antibrowning agent, and 70 °C drying) minimized browning and maximized phenolic retention, achieving total phenolic content (TPC) of 25.42 ± 0.39 milligrams of gallic acid equivalents per gram (mg GAE/g) dry weight (DW). Gallic acid, caffeic acid, p-coumaric acid, and quercetin were identified as the major phenolic compounds. Sensory evaluation confirmed the desirable color, aroma, and overall acceptability of the optimized product. These findings support the production of high-quality onion powder while contributing to sustainable development goal (SDG) 2 (zero hunger) and SDG 12 (responsible for consumption and production) through improved food preservation, reduced postharvest losses and more efficient use of resources.

Keywords

Browning control, Hot-air drying, Onion powder, Phenolic retention, Process optimization

Introduction

Onion bulbs have been considered one of the most prominent vegetable crops worldwide for thousands of years. It can be used as vegetables, condiments, and medicines [1]. Onion is recognized for its high antioxidant capacity and its rich content of bioactive compounds, including phenolic compounds, flavonoids, and polysaccharides, which contribute to human health and well-being [2]. These bioactive compounds have been associated with several health-promoting properties, including antioxidant, anti-inflammatory, antimicrobial, and cardioprotective effects [3]. Fresh onions (FO) are highly perishable because of their high moisture content, resulting in limited shelf life and considerable postharvest losses during storage and transportation [4]. Depending on storage conditions, losses may reach 20 - 50%, mainly due to weight loss, decay, and sprouting [5, 6]. To prolong the shelf life of onions, it is important to reduce their water activity, which limits microbial growth and enzymatic reactions. This can be achieved by removing moisture via techniques such as freeze-drying, spray-drying, solar drying, or hot air drying [6]. Hot air drying is the most appropriate method. This process reduces the weight of onion bulbs, making bulk handling and transportation more efficient and thereby facilitating shipping [7]. It also

helps minimize waste by making onions available during the off-season at reasonable costs. However, a significant drawback of onion drying is the loss of original color and flavor [8], as well as the degradation of sensitive biochemical compounds such as polyphenols, which are vulnerable to deterioration at high temperatures [9]. To mitigate this drawback, blanching is commonly applied to inactivate enzymes such as polyphenol oxidase (PPO) and peroxidase (POD), which can cause undesirable sensory changes, including browning, off-flavors and odors, and nutrient degradation, such as vitamin loss during drying [10].

In the fruit and vegetable drying industry, sulfite soaking solutions are widely employed as pretreatments to achieve intense color retention, protection against pests and diseases, and extended shelf-life [11]. Na_2SO_3 and $Na_2S_2O_5$ are widely used as antibrowning agents because of their antioxidant, antimicrobial, and enzyme-inhibiting properties, which effectively limit enzymatic and non-enzymatic browning during drying [12]. However, excessive intake of sulfites disrupts human metabolic balance, resulting in various adverse effects, such as headaches, respiratory distress, allergic reactions, and potentially lung cancer [13]. Previous studies have demonstrated that drying conditions significantly influence the quality attributes of onion powders, highlighting the importance of process optimization for preserving product quality [6, 14].

Building on previous research, we hypothesized that blanching and sulfite pre-treatments would have a beneficial impact on the physicochemical and biochemical characteristics of dried red onion.

The present study aims to optimize the drying process by identifying the key parameters necessary to preserve the physicochemical, biochemical, and sensory properties of red onions. Unlike earlier studies that focused on single-factor effects or limited parameter ranges, this work investigates the combined and interactive effects of blanching duration, anti-browning agent type and concentration, and drying temperature. By adopting this multi-factorial optimization approach, the study aims to develop a drying technique that preserves the biochemical integrity, color, texture, and flavor of red onions while minimizing undesirable changes during processing, thereby establishing its novelty and contribution to the state of the art in onion drying and postharvest technology.

Materials and Methods

Chemicals

$Na_2S_2O_5$, Na_2SO_3, Folin–Ciocalteu reagent, aluminum chloride, sodium carbonate (Na_2CO_3), phosphorus pentoxide (P_2O_5), 3,5-dinitrosalicylic acid, sodium hydroxide, sodium potassium tartrate, phenol, gallic acid, caffeic acid, syringic acid, p-coumaric acid, and quercetin were purchased from Sigma-Aldrich (St. Louis, MO, USA).

Onion samples

Ten kilograms of onions in the province of Meknes, Morocco (33° 58' 39.396" N latitude and 5° 31' 29.856" W longitude), were purchased from a local market.

Sample preparation and treatment methods

Onion bulbs were sliced into 5 ± 0.2 mm-thick slices using a commercial slicer. 3 kg of onion slices were used as untreated controls, whereas the remaining 7 kg were subjected to the different pretreatments before drying.

Blanching

Different blanching durations (0, 3, and 5 min) in a hot water bath at 90 °C were tested to evaluate their impact on the color characteristics and biochemical properties of the onion samples compared with those of the control samples (Figure 1).

Anti-browning treatments

In addition to blanching, two commercial anti-browning agents, $Na_2S_2O_5$ and Na_2SO_3, were evaluated. Blanched and non-blanched onion slices were immersed for 15 min in $Na_2S_2O_5$ or Na_2SO_3 solutions (0.05, 0.1 and 0.2%, w/v). Untreated samples served as controls (Figure 1).

Drying process

After pretreatment, onion slices were placed on dryer trays and dried in a humidity chamber (HCP 153, Memmert, Germany) at temperatures ranging from 60 °C to 80 °C with a constant relative humidity of 30% (Figure 1).

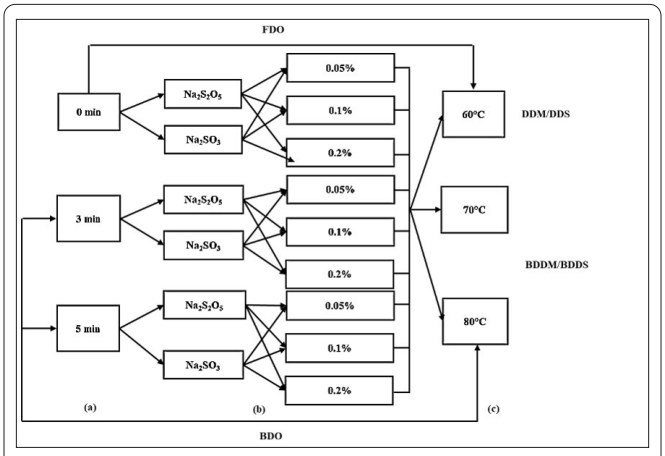


Figure 1: Optimization of the drying process through variations in the **(a)** blanching time, **(b)** antibrowning agent type and concentration, and **(c)** drying temperature. FDO: Fresh, undipped dried onion, BDO: Blanched, undipped dried onion, DDS: Onion samples subjected to sulfite dipping ($Na_2S_2O_5$/Na_2SO_3) followed by drying, and BDDS: Onion samples subjected to blanching, sulfite dipping ($Na_2S_2O_5$/Na_2SO_3), followed by drying.

Grinding

Dried onion slices were milled using a household blender.

Once all parameters were optimized, four samples were selected based on the optimal temperature to analyze moisture uptake characteristics, phenolic acids by high-performance liquid chromatography (HPLC), and sensory evaluation.

Physicochemical and biochemical analyses

Color measurements

The surface color of fresh and dried onions was measured via the CIELAB chromatic method using a CR:5 spectrophotometer (Konica Minolta, Japan). The lightness (L^*), redness (a^*), and yellowness (b^*) were measured. Saturation

(chroma, C*), browning index (BI), and whiteness index (WI) were calculated from L*, a*, and b* color coordinates via the following equations [6, 14]:

$$C^* = \sqrt{a^2 + b^2} \quad (1)$$

$$\frac{100\,(x-0.31)}{0.17}, \text{ where } x = \frac{a^* + 1{,}75L^*}{5{,}645L^* + a^* - 3{,}012b^*} \quad (2)$$

$$WI = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}} \quad (3)$$

Biomolecule extraction

Polyphenols, flavonoids and reducing sugars were extracted following the method described by Boudboud et al. [14], with slight modifications. The process consisted of homogenizing 1 g of the sample (fresh or dried onion) in 80% methanol (15 mL), followed by agitation at 270 × g for 90 min at room temperature. The mixture was subsequently centrifuged at 4500 r/min, and the supernatant was filtered through Whatman No. 4 paper.

TPC

TPC was determined using a modified Folin–Ciocalteu method based on Sidhu et al. [15]. 250 µL of onion extract was mixed with 250 µL of Folin–Ciocalteu solution × 10, followed by the addition of 0.5 mL of Na_2CO_3 solution (20% w/v), corresponding to an extract/Folin–Ciocalteu/Na_2CO_3 ratio of 1:1:2 (v/v/v). The reaction mixture was incubated for 30 min at room temperature in the dark. Absorbance was measured at 750 nm using an ultraviolet-visible (UV-Vis) spectrophotometer (V-630, JASCO). A calibration curve was prepared using gallic acid as the standard in the concentration range of 0.01 - 0.1 mg/mL. TPC were expressed as mg GAE/g of DW.

Total flavonoid content (TFC)

TFC was determined following Parthasarathi and Park [16] with some modifications. 1 mL of a 2% aluminum chloride solution diluted in methanol and 1 mL of the extract were mixed and incubated at room temperature for 10 min. A calibration curve was constructed using quercetin as the standard, in the concentration range of 0.02 - 0.08 mg/mL. The absorbance was measured at a wavelength of 415 nm. Results were expressed as milligrams of quercetin equivalent (mg QE/g DW).

Reducing sugar

Reducing sugars were determined according to the method of Miller [17]. 1 mL of onion extract was mixed with 3 mL of DNS reagent and 2 mL of distilled water. The mixture was heated in a boiling water bath for 5 min and cooled to room temperature. Absorbance was measured at 540 nm using a UV-Vis spectrophotometer (V-630, JASCO). A calibration curve was prepared using glucose (0.02 - 0.2 mg/mL), and the results were expressed as milligrams of glucose equivalents per gram of fresh weight (mg GE/g DW).

Application of the optimal drying conditions

Based on the optimized drying conditions, moisture uptake characteristics and sensory evaluation were performed on four samples: FDO, BDO, onion slices dipped in 0.1% Na_2SO_3 before drying (DDS 0.1%), and onion slices subjected to blanching followed by dipping in 0.1% Na_2SO_3 before drying (BDDS 0.1%). HPLC with diode-array detection (HPLC-DAD) analysis of phenolic acids was performed on FO, FDO, and BDDS 0.1%.

Determination of moisture uptake characteristics

The four onion powders were placed in a desiccator containing P_2O_5 at room temperature for one week to remove residual moisture. The powders were placed in open containers and subsequently transferred to a second desiccator (0.5 ± 0.03 g) containing a reservoir filled with distilled water to establish a high relative humidity environment. Samples were collected on the first, third, fifth, and seventh days over one week, with both water activity and water content measured in triplicate.

Water activity (a_w) was determined at 25 ± 1 °C via an AquaLab Pre CX-2 water activity meter (METER Group, Inc., USA), with three repetitions for each sample. The moisture content was measured via a ViBRA MD series moisture determination balance. Moisture uptake curves (water content vs water activity) were plotted from the collected data.

HPLC-DAD analysis of phenolic acids

To evaluate the effects of pretreatment and drying on the phenolic composition of onion, three samples were analyzed: FO, FDO, and BDO pretreated with 0.1% $Na_2S_2O_5$ (BDDS 0.1%). For each sample, 10 g of onion material was homogenized using a domestic blender and extracted with 20 mL of methanol/water (80:20, v/v). The mixture was shaken on a horizontal shaker for 10 min, followed by 15 min of ultrasonication in an ultrasonic bath to enhance phenolic extraction. The extracts were filtered through filter paper (Cordenons, Milan, Italy) to remove solid residues and concentrated under reduced pressure using a rotary evaporator (RE-100D, Phoenix Instrument, Germany). Prior to injection, all extracts were filtered through a 0.45 µm membrane filter, and an injection volume of 15 µL was used. The concentrated extracts were stored at -20 °C until chromatographic analysis. Phenolic compounds were analyzed using an HPLC-DAD system (Knauer, AS-1, DAD 6.1, Netherlands) equipped with a LUNA C18 reversed-phase column (250 × 4 mm i.e., 3 µm particle size) maintained at 4 °C. The mobile phase consisted of 1% (v/v) formic acid in ultrapure water (solvent A) and 100% methanol (solvent B), delivered at a constant flow rate of 1.0 mL min^{-1}. Separation was achieved using the gradient elution program presented in table 1. UV-Vis spectra were recorded between 190 and 600 nm, while chromatograms were monitored at 280 nm. Individual phenolic compounds were identified by comparing their retention times and UV spectra with those of authentic standards and quantified using external calibration curves prepared from five concentration levels ($R^2 \geq 0.998$). The phenolic profile was expressed as the concentration of each identified compound in the corresponding onion extract.

Sensory evaluation

The sensory evaluation was conducted in accordance with the ethical principles of the Declaration of Helsinki [18]. Participation was voluntary, and informed consent

Table 1: HPLC gradient conditions.

Time (min)	A (%)	B (%)	Flow rate (ml/min)
Initial	95	5	1
3	75	25	1
6	75	25	1
9	63	37	1
13	63	37	1
18	46	54	1
22	46	54	1
26	5	95	1
29	5	95	1

Note: A is the mobile phase consisting of 1% (v/v) formic acid in ultrapure water and B is the mobile phase consisting of 100% methanol.

was obtained from all participants prior to the study. Thirty healthy volunteers (18 - 40 years old), selected based on their willingness to participate, interest, and familiarity with onion products, took part in both descriptive and acceptance tests. The red onion powder samples, coded and consisting of four treatments (FDO, BDO, BDDS 0.1%, and DDS 0.1%) dried at the optimum temperature of 70 °C (3 g each), were randomly presented on separate plastic plates under controlled laboratory conditions with white incandescent lighting (Figure 2). Each panelist evaluated the predefined sensory attributes using the scale presented in table 2.

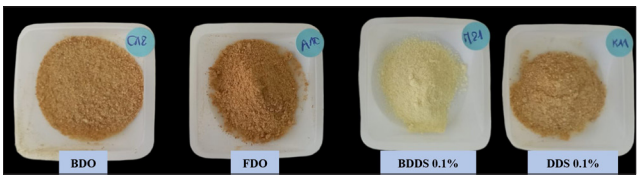


Figure 2: Sensory evaluation of dried and milled onion samples.

Statistical analysis

A full factorial design was used to evaluate the effects of blanching time, antibrowning agent type, antibrowning agent concentration, and drying temperature on the quality attributes of dried onion. The experimental factors and their corresponding levels are presented in table 3. The response variables evaluated were chromaticity (C), BI, WI, TPC, TFC, and reducing sugar content.

The statistical software Minitab 8 (Minitab Inc., State College, PA, USA) were used to conduct these experiments. The effect of each factor was determined via a complete factorial analysis of variance (ANOVA), where the statistical significance ($p < 0.05$) of the main effects of each factor was evaluated. Optimum conditions were determined using the response optimizer. The criteria for the optimum conditions were to minimize the BI, maximize the WI, TPC, TFC, and reducing sugars.

Table 3: Operational parameters for the drying optimization of *A. cepa L.*

Blanching time (min)	Anti-browning agent		Drying temperature (°C)
	Type	Concentration (%)	
0	$Na_2S_2O_5$	0.05	60
3	Na_2SO_3	0.1	70
5	-	0.2	80

Results and Discussion

Optimization of the physicochemical and biochemical properties of dried onions (*A. cepa L.*)

The physicochemical and biochemical characteristics of the FO samples were evaluated (Table 4). This comparison aimed to understand how drying processes affect the nutritional and physicochemical properties of red onion. The high moisture content found in FO bulbs (91.93 g/100 g) could explain their rapid deterioration during storage, which is within the range mentioned by Brahimi et al. [19] for 11 Moroccan onion ecotypes (87.80 - 92.30 g/100 g).

The FO exhibited a chromaticity value of 23.4 ± 4.62, comparable to the 25.63 reported by Paul et al. [20]. In contrast, Sarkar et al. [5] reported a substantially lower value (6.44 ± 0.09). These differences may be attributed to variations in cultivar, agricultural practices, and the combined effects of genetic and environmental factors on color intensity [21].

The TPC of the FO reached 9.4 ± 0.12 mg GAE/g DW, which is close to the 8.2 ± 0.16 mg GAE/g DW reported by Brahimi et al. [19]. Sidhu et al. [15] reported a higher value (11.6 ± 0.10 mg GAE/g DW). Similarly, the TFC of the FO was 3.62 ± 0.12 mg QE/g DW, which is higher than the range reported by Brahimi et al. [19]. In contrast, the reducing sugar content of the FO (18.13 ± 1.12 mg QE/g DW) was lower than the range of 22.01 - 34.73 mg QE/g DW reported by the same authors. These variations may be attributed to differences in cultivar, maturity stage, environmental conditions, postharvest handling, and extraction procedures [15].

Table 2: Descriptive attributes for sensory evaluation of onion powders.

Color	Odor	Pungency	Sweet taste	Onion flavor	Overall acceptability
1 = Brown	1 = Low	1 = Low	1 = Low	L = low	1 (dislike extremely) to 9 (like extremely)
2 = Orange	2 = Average	2 = Average	2 = Average	2 = Average	
3 = Yellow	3 = Strong	3= Extremely	3= Extremely	3 = Strong	
4 = Other	-	-	-	-	

Table 4: Analysis of various ecotypes of FO (*A. cepa. L*) before drying.

FO	Moisture content (g/100 g)	Chromaticity (C*)	TPC (mg GAE/g DW)	TFC (mg QE/g DW)	Reducing sugars (mg GE/g DW)
	91.93 ± 0.30	23.4 ± 4.62	9.4 ± 0.12	3.62 ± 0.12	18.13 ± 1.12

Color measurements

Factorial ANOVA was performed to evaluate the effects of blanching time, antibrowning agent type, concentration, drying temperature, and their interactions on the measured quality parameters. The analysis indicated that blanching time ($F = 5.67$, $p = 0.009$) and drying temperature ($F = 8.01$, $p = 0.002$) were the main factors significantly influencing the quality attributes. A significant interaction between blanching time and drying temperature was also observed ($F = 3.43$, $p = 0.021$), whereas the effects of antibrowning agent type ($F = 0.63$, $p = 0.436$), concentration ($F = 0.03$, $p = 0.968$), and the remaining interaction terms were not statistically significant ($p > 0.05$). The blanching time, antibrowning agent, and drying temperature increased onion color stability. In contrast, the choice of antibrowning agent had no significant effect on the measured parameters, as all tested agents yielded similar results ($p > 0.05$). Chromaticity increased with increasing blanching duration and drying temperature, peaking at 70 ˚C after 5 min of blanching (Figure 3 and supplementary table S1 and S2). According to the legend, red/orange areas represent high response values, green indicates intermediate levels, and blue corresponds to low values. $Na_2S_2O_5$ and Na_2SO_3 exhibited comparable effects, particularly at relatively high concentrations and moderate blanching times, significantly improving color retention [22]. However, increasing both the concentration (>0.14%) and temperature (>74 ˚C) resulted in higher chromaticity values (23 - 24), reflecting more pronounced color shifts (Supplementary figure S1). $Na_2S_2O_5$ and Na_2SO_3 are chemically related sulfur-containing compounds that both release sulfite ions (SO_3^{2-}) when dissolved in solution. These sulfite ions are primarily responsible for their antioxidant and anti-browning properties. Because both compounds ultimately generate the same active species, they exhibit similar mechanisms of action. Specifically, sulfite ions inhibit PPO, the enzyme responsible for enzymatic browning, and act as reducing agents that prevent the oxidation of phenolic compounds [23]. In addition to their effectiveness as antibrowning agents, sulfites are progressively depleted during thermal processing. Sulfur dioxide can be lost through volatilization during drying, while sulfite ions are also consumed through reactions with oxidized compounds and other food constituents. Consequently, the residual sulfite content in dried products is generally lower than the amount initially applied. In the present study, the optimized pretreatment employed a 0.1% sulfite solution, selected to achieve effective quality preservation while minimizing sulfite usage. According to the Codex Alimentarius Commission [24], the maximum permitted residual sulfite content in dried vegetables is 500 mg SO_2 kg^{-1} DW. Although residual sulfite levels were not measured in the present study, future investigations should quantify them to verify compliance with regulatory limits and further assess consumer safety.

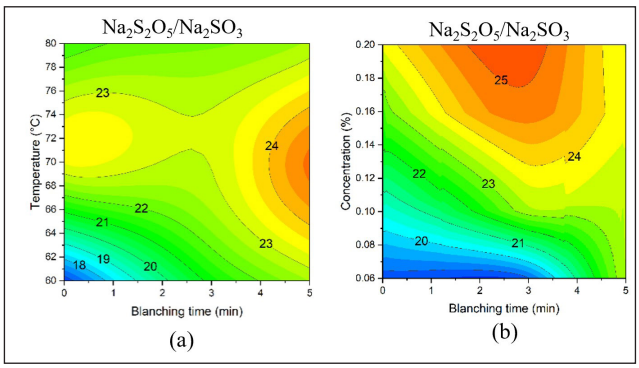


Figure 3: Contour plots of the combined effects of **(a)** temperature and blanching time, **(b)** antibrowning agent ($Na_2S_2O_5/Na_2SO_3$) concentration and blanching time on chromaticity.

Figure 4 shows that browning intensifies with increasing temperature and longer blanching times. Compared with 5 min, 3 min of blanching effectively lowered the BI because of PPO inactivation, which is consistent with the findings of Paul et al. [20]. However, extending the duration of blanching to 5 min did not further reduce BI and may have promoted phenolic oxidation due to tissue degradation.

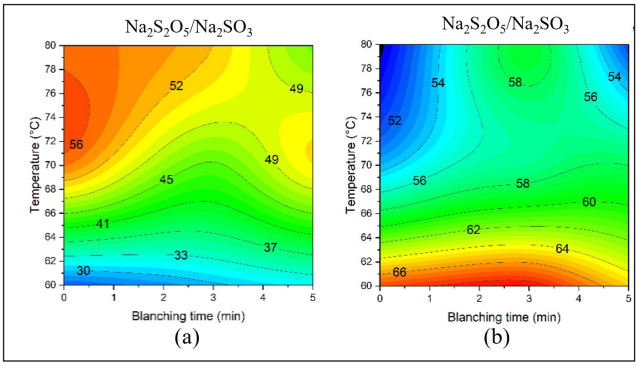


Figure 4: Contour plots of the combined effects of temperature and blanching time on the **(a)** BI and **(b)** whitening index.

The highest WI values (66.03 ± 0.23) were observed at 60 ˚C, whereas the WI decreased to 53.37 ± 0.21 at 80 ˚C (Figure 5 and supplementary table S1), suggesting that intermediate drying temperatures better preserve color [5]. Increasing blanching time up to approximately 3 min and higher concentrations (0.16 - 0.20%) enhanced whitening, whereas prolonged times (5 min) beyond this point slightly reduced the effect. Similarly, moderate blanching temperatures (65 - 68 ˚C) combined with higher concentrations favored higher whitening values, while elevated temperatures (>75 ˚C) led to a decline (Supplementary figure S3). Moreover, the BI decreased as the antibrowning agent concentration increased from 47.8 ± 0.70 at 0.05% to 37.62 ± 0.82 at 0.2% (Supplementary figure

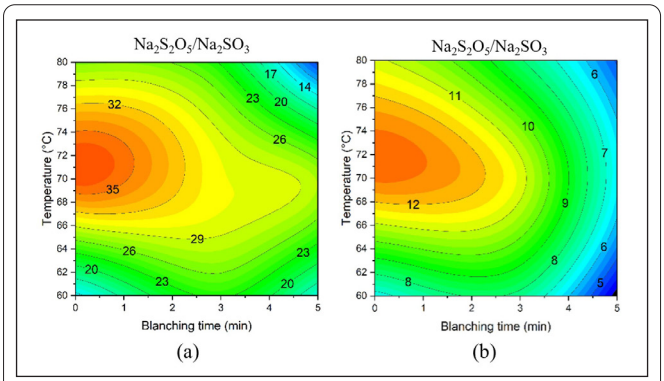


Figure 5: Contour plots of the combined effects of temperature and blanching time on the **(a)** TPC and **(b)** TFC.

S2). While browning phenomena during drying have been extensively studied in other fruits and vegetables, comparable data for onion remains scarce. Therefore, relevant findings reported for other plant matrices are discussed for contextual interpretation. These findings are consistent with those of Boudboud et al. [14], who reported that higher concentrations of anti-browning agents effectively inhibit enzymatic oxidation and reduce browning in dried grapes. Similar results have also been observed in apple [25]. Additionally, BI showed a strong positive correlation with temperature, confirming that both enzymatic browning and nonenzymatic browning intensify at relatively high temperatures. Similar temperature-dependent browning effects have been reported in dried pineapple slices [26], and the effects of pretreatment and drying on color retention were emphasized by Sarkar et al. [5].

Total phenolic and flavonoid contents

TPC remain stable between 0 and 3 min (25.63 ± 0.50 to 25.42 ± 0.39 mg GAE/g DW) at 70 °C but decreased significantly above this temperature (16.79 ± 0.37 mg GAE/g DW), confirming the heat sensitivity of the phenolic compounds (Figure 5 and supplementary table S1). The highest TPC (29 ± 0.25 mg GAE/g) was recorded at 2 - 3 min of blanching with an antibrowning agent concentration of 0.6 - 0.7% (Supplementary figure S4). The stability of TPC observed during short blanching periods may be attributed to the rapid inactivation of oxidative enzymes, particularly PPO and POD, which limits enzymatic oxidation of phenolic compounds during subsequent drying. In addition, moderate heat treatment may disrupt cell walls and weaken phenolic–cell wall interactions, thereby improving the extractability of bound phenolics without causing significant thermal degradation [27]. Conversely, prolonged blanching and higher drying temperatures promote thermal degradation and diffusion of water-soluble phenolics into the blanching medium, resulting in lower TPC values, as also observed in samples blanched for 5 min [28].

In contrast, Zhang et al. [27] reported a progressive increase in the TPC from 60 to 80 °C, which they attributed to complete PPO inactivation and enhanced release of phenolic compounds from plant tissues. Similar increases in phenolic content following moderate thermal treatment have also been reported in recent studies on fruits and vegetables, where structural disruption facilitated solvent access to intracellular phenolic compounds [29]. However, when thermal exposure becomes excessive, degradation of thermolabile phenolics, oxidation reactions, and polymerization become predominant, resulting in a net reduction of TPC [30]. Similar polyphenol losses have been documented in dried pineapple slices [26], attributed to lignin breakdown and thermal degradation [31].

TFC followed a similar pattern, increasing at 68 - 78 °C from 0 - 3 min (10 ± 0.52 to 12 ± 1.20 mg QE/g DW) (Figure 5) but decreasing at 5 min (5.01 ± 0.25 mg QE/g DW). This decline is mainly attributed to the high susceptibility of flavonoids to prolonged thermal treatment, which promotes oxidation, hydrolysis of glycosidic bonds, and structural rearrangements, thereby reducing their stability and increasing leaching into the blanching medium [28]. This finding aligns with that of Xanthopoulos et al. [32], who attributed TFC preservation after drying to enzyme inactivation.

The optimal conditions for TPC and TFC retention were short blanching times (0 - 1 min) combined with a low anti-browning agent concentration (0 - 0.06%) (Supplementary figure S5). Moreover, $Na_2S_2O_5$ likely contributed to phenolic preservation by scavenging reactive oxygen species and inhibiting enzymatic browning reactions, thereby reducing oxidative degradation during drying [33]. Furthermore, Zzaman et al. [26] reported that rising temperatures degrade cell walls, activating oxidative and hydrolytic enzymes that reduce antioxidant levels in foods. Drying methods and pretreatments also play critical roles in phenolic retention [9]. Compared with FO, the optimized drying treatment (BDDS) exhibited significantly higher TPC and TFC, whereas reducing sugar values were significantly lower ($p < 0.05$).

Reducing sugar

For reducing sugars (Supplementary table S1), figure 6 shows that short blanching times (1 - 2 min) and temperatures ranging from 65 - 75 °C increased the reducing sugar content. However, as Zhang et al. [34] noted, prolonged blanching reduces reducing sugar levels due to leaching. Since these sugars

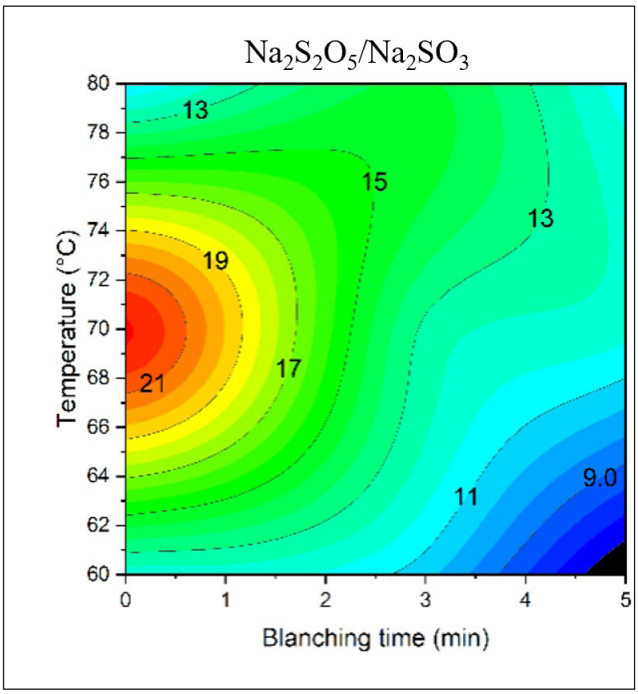


Figure 6: Contour plots of the combined effects of temperature and blanching time on reducing sugars.

are water-soluble, extended exposure to hot water facilitates their diffusion from the cellular structure into the blanching medium [35]. This finding contrasts with that of Xanthopoulos et al. [32], who reported a decrease in sugar content as the temperature increased. However, at short blanching times (≤2 min) with low concentrations (≤0.10%), higher sugar levels were preserved, whereas prolonged blanching (>6 min) caused a marked decline (Supplementary figure S6a). This loss can be attributed to increased tissue permeability, which facilitates sugar leaching into the blanching medium, as well as thermal degradation or the participation of sugars in early Maillard

reactions. A similar pattern was observed for the temperature–concentration interaction (Supplementary figure S6b). Moderate temperatures (60 - 66 °C) combined with higher concentrations (≥0.14%) favored sugar preservation, while higher temperatures (>70 °C) led to progressive reductions [36]. This is likely due to enhanced solubility and diffusion of sugars at elevated temperatures, couple with heat-induced degradation.

Based on our findings, the optimal processing conditions include blanching for 0 - 3 min, immersing samples in a 0.1% solution of any tested antibrowning agent (as they exhibit similar effects), and drying at 70 °C.

Application of optimal conditions for enhancing red onion quality

Moisture uptake

As expected, the moisture content increased with increasing water activity. FDO consistently presented the highest equilibrium moisture content across the measured water activity range. At a water activity of 0.75, the moisture content was recorded at 35% (Figure 7).

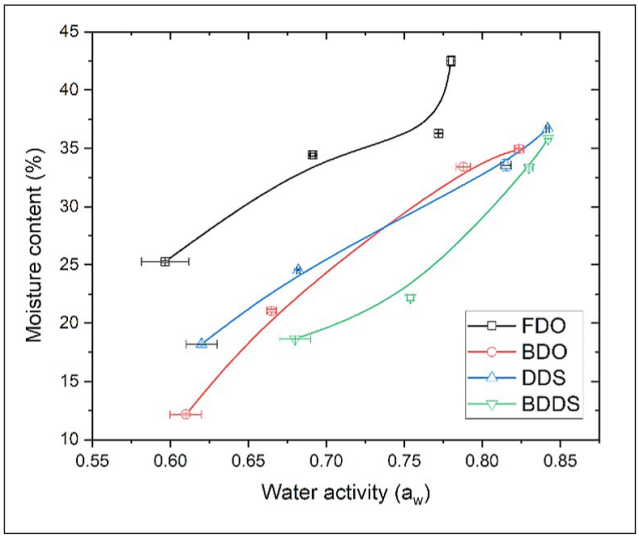


Figure 7: Moisture uptake characteristics of onion samples.

In contrast, BDO results in a moderate reduction in moisture content (27%), indicating that blanching partially removes or alters water-binding components, leading to a lower overall water-holding capacity [37]. The DDS 0.1% sample demonstrates an even further decrease in adsorbed water (26%), implying that sulfite treatment modifies or diminishes hydrophilic sites through chemical interactions with onion tissues, thus reducing the ability to retain moisture [12]. Finally, BDDS 0.1% has the lowest equilibrium moisture content at every water activity level, revealing that the combination of both blanching and sulfite dipping has the most pronounced effect on minimizing hygroscopicity. These trends have significant practical implications. BDDS 0.1% samples that have lower moisture contents at a given water activity generally boast increased microbial stability and potentially longer shelf times, although they may rehydrate more slowly. Conversely, FDO samples that yield higher moisture contents can be advantageous for faster rehydration but may be more susceptible to quality deterioration during storage.

HPLC-DAD analysis of phenolic acids

Three sample extracts, FO, FDO, and blanched onion treated with 0.1% Na_2SO_3 before drying (BDDS 0.1%), prepared under the optimized conditions, were analyzed by HPLC-DAD to characterize their phenolic profiles. Six phenolic compounds were identified in FO, four in FDO, and five in BDDS 0.1% (Table 5). Gallic acid, caffeic acid, p-coumaric acid, and quercetin were the predominant compounds. FO contained higher concentrations of most phenolic compounds than the dried samples. Among the dried samples, BDDS 0.1% exhibited higher concentrations of gallic acid (0.86 ± 0.28 mg/g DW), caffeic acid (0.59 ± 0.12 mg/g DW), p-coumaric acid (1.05 ± 0.18 mg/g DW), quercetin (1.03 ± 0.33 mg/g DW), and syringic acid (0.35 ± 0.13 mg/g DW) than FDO. Catechin was detected only in FO, whereas syringic acid was absent from FDO but remained detectable in BDDS 0.1%. These results are consistent with the thermal sensitivity of phenolic compounds during drying and with the protective effect of blanching and sulfite pretreatment reported in previous studies [31].

Table 5: List of phenolic compounds identified in onion extracts by HPLC-UV-Vis.

Samples	T_R (min)	Identification	Concentration (mg/g DW)
FO	3.61	Gallic acid	1.06 ± 0.25
	5.23	Catechin	0.72 ± 0.05
	5.76	Caffeic acid	0.89 ± 0.37
	6.81	P-coumaric acid	1.38 ± 0.33
	11.55	Quercetin	1.25 ± 0.15
	15.93	Syringic acid	0.42 ± 0.02
FDO	3.54	Gallic acid	0.66 ± 0.17
	5.80	Caffeic acid	0.26 ± 0.12
	6.92	P-coumaric acid	0.33 ± 0.07
	11.52	Quercetin	0.26 ± 0.10
BDDS 0.1%	3.58	Gallic acid	0.86 ± 0.28
	5.86	Caffeic acid	0.59 ± 0.12
	6.76	P-coumaric acid	1.05 ± 0.18
	11.43	Quercetin	1.03 ± 0.33
	15.91	Syringic acid	0.35 ± 0.13

Sensory evaluation

The sociocultural traits of the panel used in this research are shown in table 6. The dietary patterns of the panelists revealed that the majority consumed fresh raw onion, followed by sautéed onions, whereas others preferred them pickled or cooked in traditional Moroccan dishes such as tajines. Moreover, most of the panelists were familiar with onion powder, unlike those in the study by Edith et al. [38], where all participants were unfamiliar with this product. The descriptive sensory analysis of onion powders dried at 70 °C (Figure 8) revealed clear differences among the treatments. In agreement with the instrumental color measurements, BDDS 0.1% exhibited a yellow color, whereas DDS 0.1%, BDO, and FDO showed a cinnamon color, reflecting the better color preservation achieved under the optimized pretreatment conditions. This improved appearance was accompanied by favorable sensory characteristics, as BDDS 0.1% presented the lowest pungency, the highest sweet taste,

Table 6: Sociocultural traits of the sensory analysis panel.

Frequency of FO consumption	Number of panelists
Everyday	20
3 times/week	5
2 times/week	2
1 time/week	1
1 or 2 times/week	2
Never	0
FO consumption	-
Raw (in salads or other dishes)	15
Sauteed	8
Pickled	2
Other	5
Onion powder consumption	-
Yes	25
No	5

the least burnt flavor, and the greatest overall acceptability. The reduced burnt flavor is consistent with the lower BI and higher WI observed for the optimized treatment, indicating that blanching combined with sulfite pretreatment effectively limited browning during drying. In contrast, BDO exhibited the strongest odor and onion flavor, while FDO presented intermediate scores without particularly excelling in any sensory attribute. Except for sweetness, which did not differ significantly among the samples, all other sensory attributes showed significant variation. Similar sweetness scores are consistent with the comparable reducing sugar contents

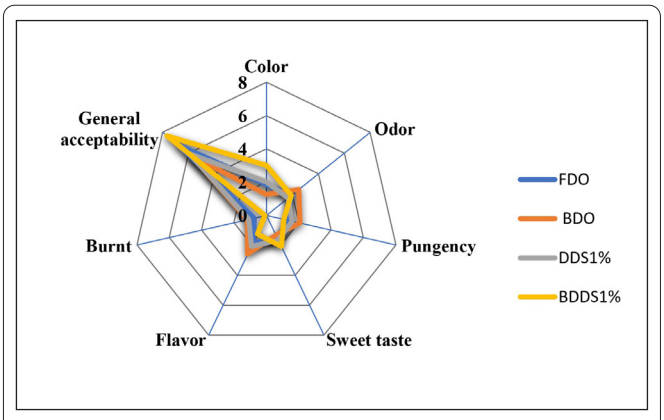


Figure 8: Descriptive sensory analysis of onion powder dried under different conditions.

obtained under the optimized drying conditions, whereas the superior overall acceptability of BDDS 0.1% can be explained by the combined preservation of color, reduced browning, and improved biochemical quality. These findings demonstrate that optimizing pretreatment and drying conditions enhanced not only the physicochemical characteristics of onion powder but also its sensory quality and consumer acceptance.

Conclusion

Blanching, antibrowning pretreatments, and drying temperature significantly influenced the drying behavior and quality of red onion powder. Among the investigated conditions, blanching for 3 min, immersion in a 0.1% antibrowning solution, and drying at 70 ˚C provided the best balance between physicochemical, biochemical, and sensory quality by minimizing browning while preserving phenolic compounds, flavonoids, reducing sugars, and overall acceptability. These findings demonstrate the importance of optimizing pretreatment and drying parameters to improve the quality and shelf life of dried onion products. The optimized process provides a practical and sustainable approach for producing high-quality onion powder with potential industrial applications. Future research should focus on improving aroma retention through encapsulation technologies, particularly by incorporating suitable wall materials and emulsion-based delivery systems using spray-drying or freeze-drying techniques to protect volatile sulfur compounds during processing and storage. Such approaches could further enhance the sensory quality, stability, and commercial value of dried onion products.

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Conflict of Interest

None.

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Supplementary Content

Table S1: Impact of blanching time, anti-browning agent Na_2SO_3, their concentrations, and temperature on physicochemical and biochemical parameters of dried onions.

Run order	Blanching time (min)	Anti-browning agents		Temperature (˚C)	C*	BI	WI	TPC (mg GAE/g)	TFC (mg QE/g)	Reducing sugar (%)
		Type	Concentration (%)							
1	0	Na_2SO_3	0.05	60	12.96 ± 0.11	23.27 ± 0.20	65.90 ± 0.02	15.03 ± 0.13	9.63 ± 0.30	18.43 ± 0.18
2	0	Na_2SO_3	0.05	70	23.14 ± 0.08	52.43 ± 0.06	55.06 ± 0.09	24.24 ± 0.03	13.45 ± 0.06	23.01 ± 0.02
3	0	Na_2SO_3	0.05	80	16.84 ± 0.37	47.50 ± 0.85	45.96 ± 0.71	35.02 ± 0.16	17.96 ± 0.08	11.75 ± 0.04
4	0	Na_2SO_3	0.1	60	15.73 ± 0.26	26.23 ± 0.38	62.30 ± 0.29	9.02 ± 0.02	4.67 ± 0.11	11.42 ± 0.07
5	0	Na_2SO_3	0.1	70	23.76 ± 0.03	59.96 ± 0.02	50.59 ± 0.04	36.06 ± 0.10	13.5 ± 0.03	24.45 ± 0.03
6	0	Na_2SO_3	0.1	80	20.81 ± 0.36	65.68 ± 0.32	42.49 ± 0.82	27.21 ± 0.02	7.66 ± 0.04	13.38 ± 0.02
7	0	Na_2SO_3	0.2	60	23.36 ± 0.33	34.33 ± 0.55	68.30 ± 0.14	15.71 ± 0.02	5.63 ± 0.03	8.43 ± 0.07
8	0	Na_2SO_3	0.2	70	22.75 ± 0.03	52.39 ± 0.01	54.59 ± 0.06	32.34 ± 0.03	11.98 ± 0.02	22.37 ± 0.10
9	0	Na_2SO_3	0.2	80	24.19 ± 0.45	53.15 ± 0.48	55.16 ± 0.77	21.45 ± 1.24	8.53 ± 0.24	9.73 ± 1.85
10	3	Na_2SO_3	0.05	80	12.63 ± 0.14	66.58 ± 0.14	54.58 ± 0.01	17.02 ± 0.03	7.84 ± 0.05	9.35 ± 0.06
11	3	Na_2SO_3	0.05	70	16.43 ± 0.02	51.60 ± 0.14	53.83 ± 0.03	32.00 ± 0.90	8.48 ± 0.18	21.12 ± 0.05
12	3	Na_2SO_3	0.05	60	20.28 ± 0.01	29.92 ± 0.20	67.60 ± 0.01	29.04 ± 0.08	8.41 ± 0.02	12.4 ± 0.10
13	3	Na_2SO_3	0.1	60	19.17 ± 0.46	28.06 ± 0.48	68.03 ± 0.00	22.68 ± 0.02	8.32 ± 0.02	4.36 ± 0.04
14	3	Na_2SO_3	0.1	70	23.55 ± 5.43	40.42 ± 0.11	55.91 ± 0.19	40.45 ± 0.06	19.62 ± 0.20	17.91 ± 0.04
15	3	Na_2SO_3	0.1	80	27.24 ± 0.01	43.40 ± 1.21	55.34 ± 0.02	43.65 ± 0.15	8.20 ± 0.01	18.28 ± 0.15
16	3	Na_2SO_3	0.2	60	20.96 ± 0.14	25.22 ± 0.83	68.82 ± 0.01	20.97 ± 1.48	7.32 ± 0.01	6.20 ± 0.01
17	3	Na_2SO_3	0.2	70	25.35 ± 0.02	32.36 ± 0.03	58.22 ± 09	24.44 ± 0.05	10.34 ± 0.05	6.88 ± 0.09
18	3	Na_2SO_3	0.2	80	24.69 ± 0.48	40.58 ± 0.73	64.91 ± 0.79	18.04 ± 0.04	8.85 ± 0.04	11.61 ± 0.10
19	5	Na_2SO_3	0.05	60	23.12 ± 0.01	33.78 ± 0.02	61.50 ± 0.07	15.06 ± 0.05	3.16 ± 0.01	5.88 ± 0.02
20	5	Na_2SO_3	0.05	70	24.68 ± 0.17	54.24 ± 0.17	50.88 ± 0.14	24.74 ± 0.06	8.78 ± 0.02	20.08 ± 0.02
21	5	Na_2SO_3	0.05	80	21.53 ± 0.01	52.03 ± 0.15	40.51 ± 0.49	13.16 ± 0.17	6.43 ± 0.03	3.22 ± 0.16
22	5	Na_2SO_3	0.1	60	20.53 ± 0.01	30.71 ± 0.01	64.08 ± 0.28	17.88 ± 0.07	7.48 ± 0.05	6.35 ± 0.07
23	5	Na_2SO_3	0.1	80	23.05 ± 0.08	49.72 ± 0.03	51.28 ± 0.07	2.39 ± 0.08	6.22 ± 0.07	14.04 ± 0.0
24	5	Na_2SO_3	0.1	70	23.26 ± 0.08	53.68 ± 0.54	59.86 ± 0.06	21.22 ± 0.07	7.30 ± 0.05	8.10 ± 0.04
25	5	Na_2SO_3	0.2	60	20.40 ± 0.01	29.79 ± 0.02	64.44 ± 0.58	13.78 ± 0.02	3.23 ± 0.03	5.68 ± 0.23
26	5	Na_2SO_3	0.2	70	23.90 ± 0.07	45.83 ± 0.19	60.60 ± 0.03	34.82 ± 0.06	5.71 ± 0.03	13.17 ± 0.03
27	5	Na_2SO_3	0.2	80	22.71 ± 0.66	37.05 ± 1.58	60.84 ± 0.86	3.02 ± 0.04	2.97 ± 0.01	22.75 ± 0.13

Table S2: Impact of blanching time, anti-browning agent $Na_2S_2O_5$, their concentrations, and temperature on physicochemical and biochemical parameters of dried onions.

Run order	Blanching time (min)	Anti-browning agents		Temperature (˚C)	C*	BI	WI	TPC (mg GAE/g)	TFC (mg QE/g)	Reducing sugars (%)
		Type	Concentration (%)							
1	0	$Na_2S_2O_5$	0.05	60	14.88 ± 0.01	24.41 ± 0.03	69.00 ± 0.03	18.82 ± 0.03	8.15 ± 0.12	6.52 ± 0.17
2	0	$Na_2S_2O_5$	0.05	70	22.85 ± 0.02	52.26 ± 0.02	54.71 ± 0.02	43.75 ± 0.27	18.02 ± 0.02	20.08 ± 0.13
3	0	$Na_2S_2O_5$	0.05	80	19.54 ± 0.03	52.95 ± 0.11	47.75 ± 0.02	34.44 ± 0.07	15.36 ± 0.04	9.23 ± 0.06
4	0	$Na_2S_2O_5$	0.1	60	16.05 ± 0.20	26.61 ± 0.31	68.58 ± 0.02	13.01 ± 0.20	6.41 ± 0.11	13.19 ± 0.05
5	0	$Na_2S_2O_5$	0.1	70	21.72 ± 0.08	52.34 ± 0.20	52.77 ± 0.03	47.34 ± 0.09	7.48 ± 0.08	17.91 ± 0.06
6	0	$Na_2S_2O_5$	0.1	80	24.44 ± 0.04	60.71 ± 0.09	51.17 ± 0.01	20.58 ± 0.36	7.91 ± 0.03	9.39 ± 0.56
7	0	$Na_2S_2O_5$	0.2	60	21.95 ± 0.01	27.05 ± 0.02	70.83 ± 0.01	10.34 ± 0.07	5.23 ± 0.09	11.60 ± 0.07
8	0	$Na_2S_2O_5$	0.2	70	26.02 ± 0.02	61.14 ± 0.69	53.24 ± 0.87	35.64 ± 0.08	12.00 ± 0.07	26.90 ± 0.09
9	0	$Na_2S_2O_5$	0.2	80	24.12 ± 0.34	53.66 ± 0.13	55.64 ± 0.36	21.33 ± 0.49	9.40 ± 0.17	12.97 ± 0.03
10	3	$Na_2S_2O_5$	0.05	60	13.50 ± 0.15	38.62 ± 0.17	68.06 ± 0.01	19.10 ± 0.00	10.14 ± 0.01	9.61 ± 0.01
11	3	$Na_2S_2O_5$	0.05	70	25.25 ± 0.02	49.94 ± 0.14	54.79 ± 0.09	45.72 ± 0.17	10.62 ± 0.02	17.15 ± 0.07
12	3	$Na_2S_2O_5$	0.05	80	20.03 ± 0.47	50.11 ± 0.33	53.42 ± 0.07	17.33 ± 0.07	4.84 ± 0.04	15.55 ± 0.13
13	3	$Na_2S_2O_5$	0.1	60	26.28 ± 0.05	30.79 ± 0.04	69.01 ± 0.03	24.27 ± 0.13	4.37 ± 0.03	11.04 ± 0.02
14	3	$Na_2S_2O_5$	0.1	70	21.45 ± 0.30	46.08 ± 0.57	57.03 ± 0.05	22.57 ± 0.05	11.87 ± 0.15	9.68 ± 0.02
15	3	$Na_2S_2O_5$	0.1	80	21.62 ± 0.16	54.24 ± 0.34	58.49 ± 0.06	21.24 ± 0.05	10.95 ± 0.04	19.22 ± 0.02
16	3	$Na_2S_2O_5$	0.2	60	26.88 ± 0.07	22.23 ± 0.19	69.76 ± 0.01	24.53 ± 0.07	7.87 ± 0.05	19.67 ± 0.03
17	3	$Na_2S_2O_5$	0.2	70	26.07 ± 0.22	46.05 ± 0.60	61.82 ± 0.06	15.72 ± 0.01	6.47 ± 0.03	4.16 ± 0.20
18	3	$Na_2S_2O_5$	0.2	80	27.35 ± 0.06	59.30 ± 0.19	66.38 ± 0.23	18.82 ± 0.07	7.86 ± 0.02	12.61 ± 0.08
19	5	$Na_2S_2O_5$	0.05	60	22.64 ± 0.04	31.14 ± 0.09	65.24 ± 0.06	18.53 ± 0.04	3.06 ± 0.01	6.18 ± 0.02
20	5	$Na_2S_2O_5$	0.05	70	24.61 ± 0.09	55.77 ± 0.25	57.14 ± 0.01	27.66 ± 0.05	5.85 ± 0.01	7.68 ± 0.08
21	5	$Na_2S_2O_5$	0.05	80	22.60 ± 0.04	53.54 ± 0.17	50.19 ± 0.02	10.37 ± 0.11	4.94 ± 0.10	9.79 ± 0.02
22	5	$Na_2S_2O_5$	0.1	60	24.11 ± 0.01	31.61 ± 0.02	67.09 ± 0.02	16.75 ± 0.06	3.41 ± 0.02	6.77 ± 0.09
23	5	$Na_2S_2O_5$	0.1	70	27.01 ± 0.05	56.66 ± 0.11	58.99 ± 0.14	27.74 ± 0.08	3.47 ± 0.05	11.05 ± 0.02
24	5	$Na_2S_2O_5$	0.1	80	22.02 ± 0.16	46.14 ± 0.41	51.07 ± 0.06	5.76 ± 0.11	6.64 ± 0.07	3.78 ± 0.17
25	5	$Na_2S_2O_5$	0.2	70	25.11 ± 0.12	40.31 ± 0.25	60.41 ± 0.06	30.98 ± 0.04	7.36 ± 0.04	10.99 ± 0.06
26	5	$Na_2S_2O_5$	0.2	60	25.24 ± 0.01	31.93 ± 0.02	68.01 ± 0.07	8.27 ± 0.12	2.07 ± 0.03	6.11 ± 0.05
27	5	$Na_2S_2O_5$	0.2	80	24.50 ± 0.29	35.90 ± 0.51	55.55 ± 0.05	10.19 ± 0.06	2.20 ± 0.03	14.17 ± 0.12

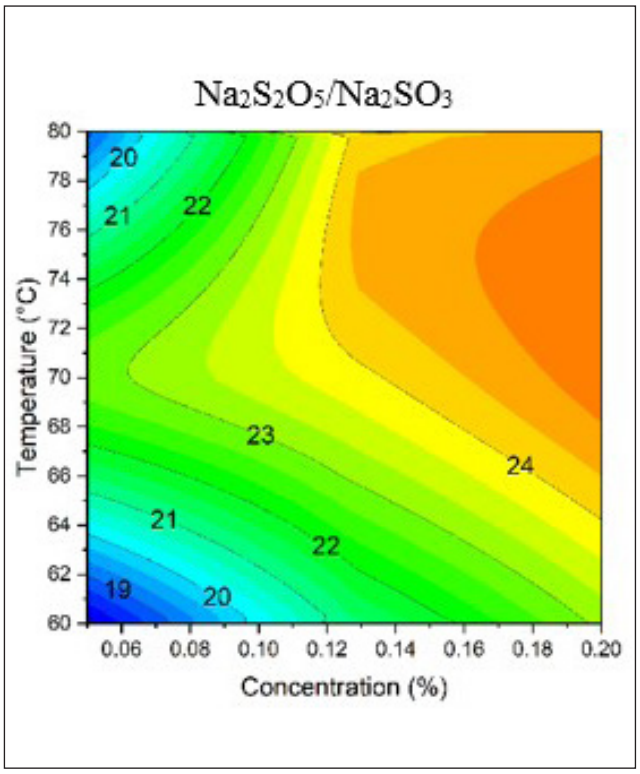


Figure S1: Contour plots illustrating the combined effects of temperature and anti-browning agent concentrations on chromaticity.

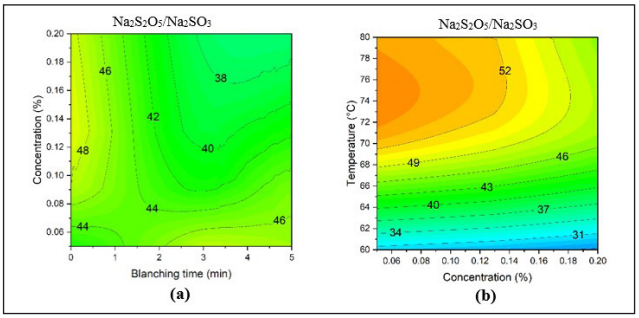


Figure S2: Contour plots illustrate the combined effects of anti-browning agent concentrations and blanching time **(a)**, temperature and anti-browning agent concentrations **(b)** on browning index.

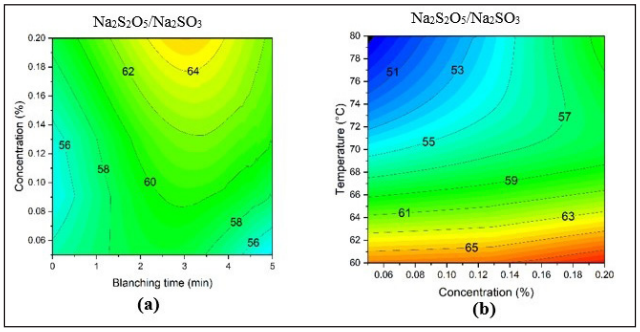


Figure S3: Contour plots illustrating the combined effects of anti-browning agent concentrations, and blanching time **(a)**, temperature and anti-browning agent concentrations **(b)** on whitening index.

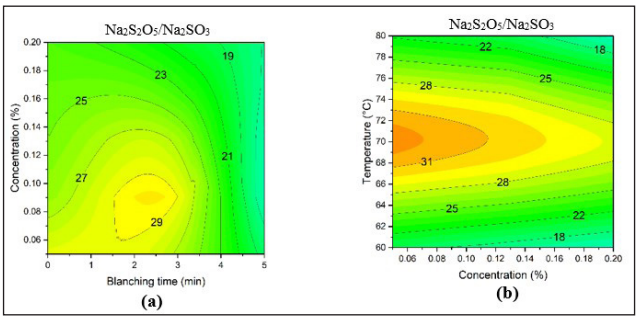


Figure S4: Contour plots illustrating the combined effects of anti-browning agent concentrations, and blanching time **(a)**, temperature and anti-browning agent concentrations **(b)** on TPC.

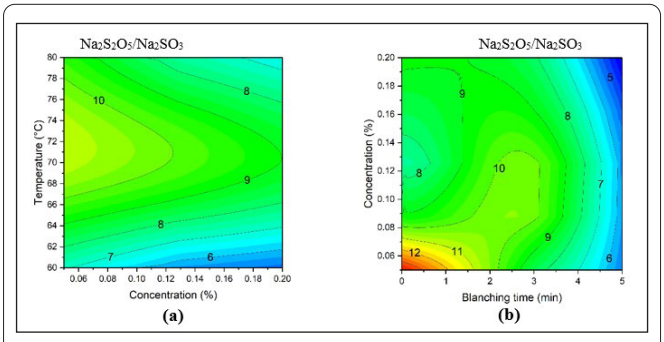


Figure S5: Contour plots illustrating the combined effects of anti-browning agent concentrations, and blanching time **(a)**, temperature, and anti-browning agent concentrations **(b)** on TFC.

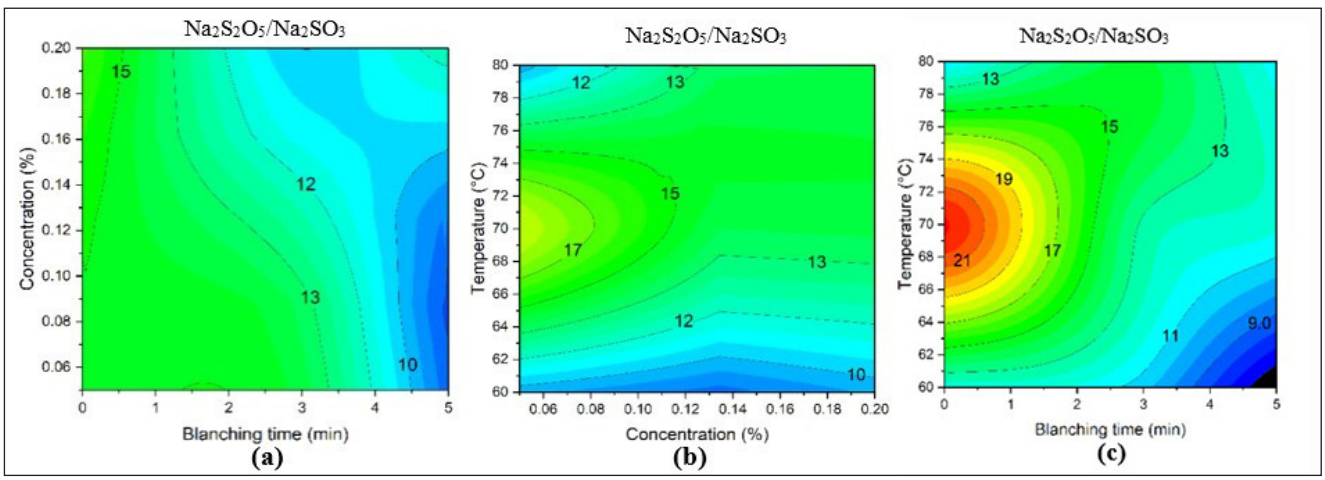


Figure S6: Contour plots illustrating the combined effects of **(a)** anti-browning agent concentrations and blanching time, **(b)** temperature, and anti-browning agent concentrations, and **(c)** temperature and blanching time on reducing sugars.