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Effect of Cooking Treatments on Drying Kinetics, Polyphenols Content and Antioxidant Activity of Orange-Fleshed Sweet Potato

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Abstract— *This study examines the effects of boiling, steaming, and microwaving on the drying kinetics, total polyphenol content (TPC), antioxidant activity, and total carotenoid content (TCC) of orange-fleshed sweet potatoes (OFSP), a vital source of beta-carotene for combating vitamin A deficiency. Results indicate that steaming preserved the highest TPC at 4.28 mg GAE/g DW, while microwaving yielded the highest TCC at 527.35 µg BCE/g DW. Antioxidant activity, measured via DPPH radical scavenging, was significantly enhanced by steaming (3.48 µmol TE/g DW) and microwaving (3.29 µmol TE/g DW) compared to boiling (1.40 µmol TE/g DW). The drying kinetics followed the Page model, demonstrating a strong fit ($R^2 > 0.9988$) across treatments, highlighting the complex moisture loss behaviors influenced by cooking methods. Boiling resulted in a 51% reduction in TPC due to leaching, while both steaming and microwaving significantly increased antioxidant activity despite some degradation of phenolic compounds during microwaving. These findings underscore the importance of cooking methods in optimizing the nutritional value of OFSP, providing practical recommendations for food preparation to enhance health benefits and address vitamin A deficiency in vulnerable populations.*

Keywords— ***Drying kinetics, Microwave cooking, Page model, Steam cooking, Sweet potatoes***

I. INTRODUCTION

Orange-fleshed sweet potato (OFSP) is a biofortified root crop that has gained significant attention due to its high beta-carotene content, which is converted to vitamin A in the body. OFSP has been recognized as an effective food-based approach to combat vitamin A deficiency, particularly in sub-Saharan Africa [1]. Beyond its vitamin A content, OFSP is also a good source of dietary fiber, complex carbohydrates, proteins, vitamins C and B, iron, and calcium [2]. Polyphenols and antioxidants in OFSP have become an emerging field of interest in nutrition research. These compounds contribute to the distinctive flesh color and are associated with numerous health benefits, including antioxidant and anti-inflammatory properties that could have preventive and therapeutic effects for various chronic diseases [1]. Recent scientific reports have concluded that the phenolic acid components in OFSP exhibit antioxidative and free radical scavenging activities with beneficial health-promoting effects [1].

Carotenoids, particularly β-carotene, are the primary bioactive compounds responsible for the distinctive orange color of OFSP and its potential to address vitamin A deficiency. OFSP varieties have been reported to contain significantly higher levels of carotenoids compared to other commonly consumed vegetables and fruits. [3] found that OFSP from Korea contained up to 570 µg/g (dry basis) of total carotenoids. The β-carotene content in OFSP can range from 100 to 1,600 µg/g (fresh weight), which is substantially higher than that found in carrots (43.5-88.4 µg/g), mangoes (10.9-12.1 µg/g), and tomatoes (2.17-2.83 µg/g) [1]. In addition to β-carotene, OFSP also contains other carotenoids such as α-carotene, β-cryptoxanthin,

lutein, and zeaxanthin, albeit in lower concentrations [4]. The carotenoid content in OFSP can vary significantly among cultivars, with some varieties like BARI SP-2 (Kamalasundari) showing exceptionally high levels in both raw and cooked forms. It's worth noting that cooking methods can affect carotenoid composition, with boiling associated with an increase in cis-β-carotene and a decrease in the trans isomer[5].

The rationale for studying cooking treatments such as boiling, steaming, and microwaving, as well as drying kinetics using models like the Page model, stems from the need to understand how these processes affect the nutritional and functional properties of OFSP. Cooking methods can significantly impact the bioavailability and retention of nutrients, including polyphenols and antioxidants [1]. Similarly, drying is an important preservation technique for OFSP, but the kinetics of moisture loss and its effects on nutrient content need to be carefully examined. By investigating these aspects, researchers can optimize processing methods to maintain or enhance the nutritional value of OFSP while improving its shelf life and versatility in various food applications.

The investigation aims to evaluate the effects of boiling, steaming, and microwaving on the drying kinetics, TPC, antioxidant activity, total carotenoid content, and color attributes of OFSP. This study will assess how these cooking methods influence the retention and bioavailability of nutrients and bioactive compounds in OFSP, which is recognized for its high beta-carotene content. Additionally, the research will analyze moisture loss kinetics using models such as the Page model to identify optimal processing techniques that enhance nutritional value and shelf life. The study will also explore the impact of cooking methods on color attributes, which are important for visual appeal and nutrient presence. Ultimately, the findings aim to provide practical recommendations for food preparation practices that maximize the health benefits of OFSP while addressing vitamin A deficiency.

II. MATERIALS AND METHODS

2.1 Materials

The OFSP (*Ipomoea batatas* L.) used in this study were sourced from a local market (With a moisture content of 74.29±2.20%). Analytical-grade solvents and chemicals, including ethanol, methanol, *n*-hexane, acetone, glacial acetic acid, sodium carbonate, Folin-Ciocalteu reagent, 2,2-diphenyl-1-picrylhydrazyl (DPPH), and 6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid (Trolox), were obtained from Sinopharm Chemical Reagent Co., Ltd. in Shanghai, China. Standard β-carotene (purity ≥ 99%) and gallic acid (purity ≥ 99%) were procured from Sigma (St. Louis, MO, USA). All reagents utilized in this study were of analytical grade or the highest available purity.

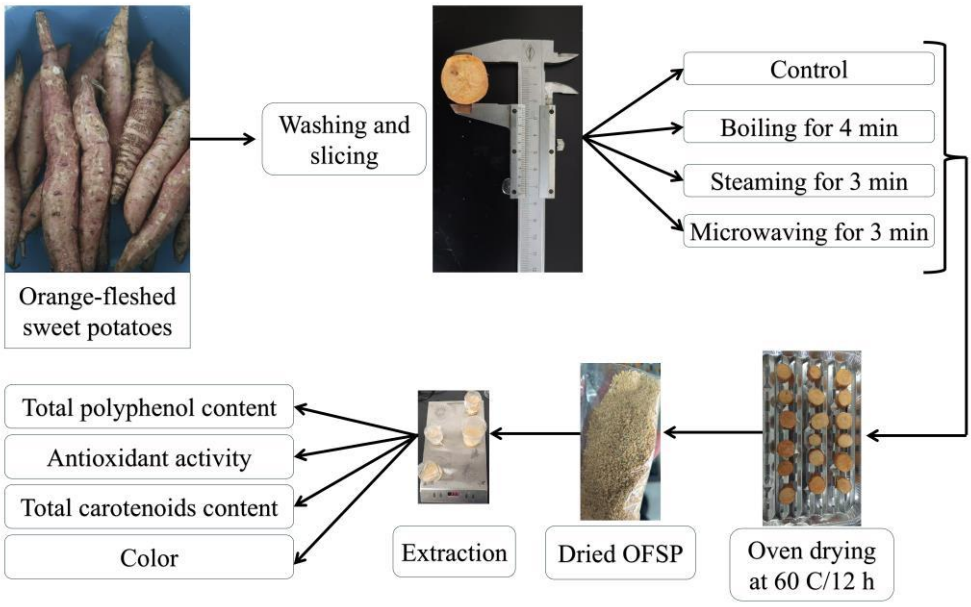

Fig. 1: Flow diagram of OFSP treatments, drying, and bioactivity evaluation.

2.2 Cooking Treatments

Prior to the application of cooking treatments, OFSP samples were thoroughly washed and uniformly sliced into pieces with diameters ranging from 2.3 to 2.8 cm and thicknesses of 1.0 to 1.2 cm (Fig. 1). This standardization ensured consistency across all treatments. For the boiling method, OFSP slices were immersed in boiling water for 4 min until thoroughly cooked. In the steaming treatment,

OFSP slices were steam-cooked for 3 min in a covered steamer. The microwave treatment involved cooking the OFSP slices for 3 min with a small amount of added water in a covered microwave-safe container using a Galanz microwave oven (Model MND-16, 550W, 220V, 50Hz). Following each cooking method, all samples were immediately transferred to perforated lightweight aluminum trays to enhance air circulation during the subsequent drying process. This preparation ensured uniform cooking and facilitated consistent drying conditions across all samples.

2.3 Drying process and kinetics

All samples were weighed initially (t=0) and subsequently at 1-hour intervals for a total duration of 12 h using an analytical balance with a precision of ±0.01 g. The drying process for all treatments was conducted at a constant temperature of 60 ± 1°C in a Binder ED 56 oven equipped with a forced convection system. This setup ensured uniform heat distribution and efficient moisture removal throughout the drying period. The continuous 12-hour drying regime was implemented to comprehensively track moisture loss kinetics across all treatment groups under standardized conditions.

Moisture ratio is calculated as the ratio of the mass of water in a substance to the mass of dry matter, allowing for standardized comparisons between different samples. For OFSP, the moisture ratio at any given time can be expressed using the following equation.

$$MR = \frac{W_t - W_d}{W_0 - W_d} \text{ eq. (1)}$$

where W_t represents the mass of water in the OFSP sample at time (t), W_d is the mass of dry matter in the OFSP sample (constant throughout the drying process), and W_0 denotes the initial mass of water in the raw OFSP sample (at t=0).

The Page model was employed to analyze the drying kinetics of OFSP under various treatment conditions [6]. This empirical model is particularly useful for describing the moisture loss during drying processes and is mathematically defined as follows.

$$MR = \exp(-k.t^n) \text{ eq. (2)}$$

where MR represents the moisture ratio, k and n are constants; k reflects the rate of moisture loss, while n indicates the curvature of the drying curve, and t denotes time. To fit the model to the experimental data, non-linear regression techniques were utilized aimed at minimizing the difference between predicted and observed moisture ratio values.

2.4 Total polyphenol content analysis (TPC)

The Folin-Ciocalteu method was employed to determine the total phenolic content (TPC) of dried OFSP samples as described by Golshany, Yu and Fan [7]. For sample preparation, 5 g of powdered OFSP was extracted in 100 mL of 50% (v/v) aqueous ethanol. This mixture underwent sonication for 10 min using a 1200-watt probe sonicator at half intensity, followed by a 1-hour stirring period. Subsequently, the extract was centrifuged (8000 rpm, 10 min), filtered, and stored. Gallic acid solutions (0.1 – 1 mg/mL) were used as standards. The assay involved combining 0.5 mL of prepared sample or standard with 2.5 mL of 10% (v/v) Folin-Ciocalteu reagent, then adding 2 mL of 7.5% Na_2CO_3 solution. After mixing thoroughly, samples were incubated in darkness at 40°C for 15 min. A spectrophotometer (Model L8, INESA Co., Ltd., Shanghai, China) was used to measure absorbance at 765 nm. TPC was quantified using the standard curve equation ($y = 0.9766x + 0.0695$, $R^2 = 0.997$) and expressed as mg gallic acid equivalent per gram dry weight (mg GAE/g DW).

2.5 Antioxidant activity assays

The antiradical activity of dried OFSP samples was evaluated using the DPPH assay, following the protocol outlined by Golshany, Kamal, Yu and Fan [8]. OFSP dried samples were prepared as described in section 2.4. A calibration curve was established using Trolox standards ranging from 0 to 200 µg/mL. The assay procedure involved combining 200 µL of sample extract or Trolox standard with 2.8 mL of 0.2 mM DPPH solution in methanol, followed by thorough agitation. The reaction mixture was then incubated in darkness for 30 min at room temperature (25 ± 2°C). Absorbance was measured spectrophotometrically at 517 nm using a UV-visible spectrophotometer. Antiradical activity was quantified using the standard curve equation ($y = 156.02x + 6.7187$, $R^2 = 0.9953$) and expressed as micromoles of Trolox equivalent per gram of dry weight (µmol TE/g DW).

2.6 Total carotenoid content analysis (TCC)

Total carotenoid content of dried samples was determined according to the method described by Morsi, Morsy and Golshany [9], with modification. Approximately 0.5 g of finely ground dried sample was extracted with 10 mL of a hexane:acetone:ethanol mixture (50:25:25, v/v/v). The mixture was vortexed for 1 min and then sonicated for 15 min. Following centrifugation at 4000 rpm for 10 min, the supernatant was collected, and the extraction process was repeated twice with fresh solvent. The combined supernatants were then diluted to 25 mL with hexane. A standard curve was prepared using β-carotene (≥0.99 purity) dissolved in hexane at concentrations ranging from 0.5 to 10 µg/mL. Absorbance of both samples and standards was measured at 450 nm using a UV-visible spectrophotometer. Total carotenoid content was calculated using the β-carotene standard curve equation (y = 0.1207x

+ 0.1803, $R^2 = 0.9902$) and expressed as micrograms of β-carotene equivalent per gram of dry weight (µg BCE/g DW). All extractions and measurements were performed in triplicate under subdued light conditions to minimize carotenoid degradation.

2.7 Color analysis

The color of treated samples, before and after drying, was determined using a Minolta colorimeter. Color measurements were taken based on the CIELAB color space, which includes L* (luminosity), a* (red to green intensity), and b* (yellow to blue intensity). This method enabled precise quantification of color changes in OFSP samples due to different drying treatments, ensuring accurate and repeatable results for further analysis.

2.8 Statistical analysis

All experiments were performed in triplicate, and results are presented as mean ± standard deviation (SD). Statistical analysis was conducted using SPSS Statistics 27 (IBM Corp., Armonk, NY, USA) and OriginPro 2022 (OriginLab Corporation, Northampton, MA, USA). One-way analysis of variance (ANOVA) was employed to assess statistical significance among groups, followed by Tukey's post-hoc test for multiple comparisons. Differences were considered statistically significant at $P < 0.05$.

III. RESULTS AND DISCUSSION

3.1 Effects on Drying Kinetics

The analysis of MR data reveals distinct drying behaviors across different treatments and phases, aligning findings from other research while also presenting unique observations as shown in figure 2. The observed rapid initial moisture loss followed by slower drying rates is consistent with findings from other studies on sweet potato drying. Singh, Raina, Bawa and Saxena [10] reported that drying of sweet potato slices occurs entirely in the falling-rate period, indicating that diffusion is the dominant physical mechanism governing moisture movement. This aligns with our observations across all treatments. The phased approach (initial, middle, and final) provides a more detailed analysis compared to some other studies, allowing for a nuanced understanding of moisture loss patterns throughout the drying process. This approach could be valuable for optimizing drying protocols, as suggested by Kocabiyik and Tezer [11] for carrot slices. The effect of pre-treatments on drying rates presents a notable contrast to findings from previous research. While Falade, Olurin, Ike and Aworh [12] found that pre-treatments generally enhance drying rates, the results indicate that steam and boiling pre-treatments actually slowed the drying process compared to the control. This observation suggests that these pre-treatments may induce structural changes in the sweet potato tissue, leading to an increased water-holding capacity, which could ultimately benefit product quality. These findings underscore the necessity for further investigation into the impact of pre-treatments on the tissue structure of sweet potatoes. The behavior of microwave-treated samples in this study, which maintained the highest moist MR despite having lower initial moisture content, contrasts with typical observations reported in microwave drying studies. For instance, Rashid, Liu, Jatoi, Safdar, Lv and Li [13] found that microwave power significantly decreased drying time for sweet potato cubes. Our results suggest that microwave treatment may alter the sweet potato structure in ways that enhance moisture retention, warranting further investigation.

The Page model's exceptional performance in describing drying kinetics across all treatments is consistent with findings from other studies. Studies also found the Page model to be suitable for describing sweet potato drying kinetics [14, 15]. However, our study demonstrates even higher R-squared values (above 0.9988) compared to some previous studies, indicating particularly good model fit. These findings underscore the complex nature of the drying process and the importance of considering multiple factors when optimizing drying protocols for sweet potatoes. As suggested by recent research, future studies should focus on investigating the effects of these drying methods on product quality attributes [13], exploring the reasons behind the higher moisture retention in microwave-treated samples through microscopic analysis of tissue structure, and conducting sensory evaluations to determine consumer preferences for products dried using different methods [16].

3.2 Effect of cooking methods on TPC:

The data shows that steaming resulted in the highest TPC (4.28 mg GAE/g DW), followed by the control (3.92 mg GAE/g DW), microwaving (3.23 mg GAE/g DW), and boiling (1.92 mg GAE/g DW). This trend aligns with some recent studies but also presents some unique observations. Demirel Ozbek, Saral and Turker [17] found that microwave cooking, stir-frying, and sous vide increased TPC in *Trachystemon orientalis*, while steaming decreased it. In contrast, our results show steaming to be the most effective method for preserving and even increasing TPC in sweet potatoes. This difference could be attributed to the unique composition and structure of sweet potatoes compared to other vegetables. The significant decrease in TPC observed with boiling (51% reduction) is consistent with findings from Seal, Pillai and Chaudhuri [18], who reported that boiling caused the greatest reduction in TPC across various plants, with decreases ranging from 10.90%

to 25.66%. This reduction is likely due to the leaching of water-soluble phenolic compounds into the cooking water.

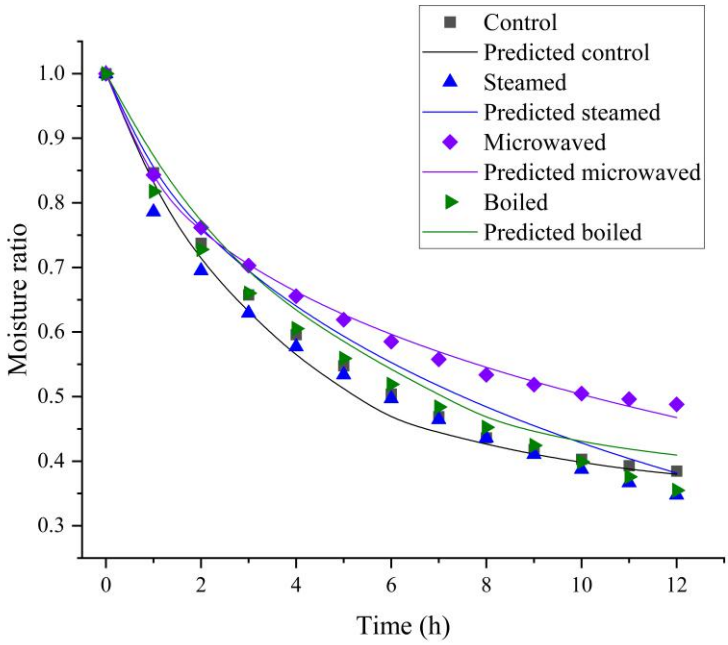

Fig. 2: Experimental and predicted MR values for drying of OFSP samples.

Table 1: Total polyphenol content, antioxidant activity, and total carotenoids content in OFSP samples.

Samples	TPC (mg GAE/g DW)	DPPH (µmol TE/g DW)	TCC (µg BCE/g DW)
Control	3.92 ± 0.04 ^{b}	0.65 ± 0.23 ^{c}	330.72 ± 12.08 ^{c}
Boiled	1.92 ± 0.07 ^{d}	1.40 ± 0.04 ^{b}	429.04 ± 23.93 ^{b}
Steamed	4.28 ± 0.08 ^{a}	3.48 ± 0.29 ^{a}	478.20 ± 30.07 ^{ab}
Microwaved	3.23 ± 0.08 ^{c}	3.29 ± 0.07 ^{a}	527.35 ± 36.26 ^{a}

All values are expressed as mean ± SD. Different superscripted letters within a column indicate significant differences (P<0.05).

3.3 Effect of cooking methods on antioxidant activity (DPPH):

The DPPH radical scavenging activity results show that both steaming (3.48 µmol TE/g DW) and microwaving (3.29 µmol TE/g DW) significantly increased antioxidant activity compared to the control (0.65 µmol TE/g DW). Boiling also increased antioxidant activity (1.40 µmol TE/g DW) but to a lesser extent. These findings partially align with Seal, Pillai and Chaudhuri [18], who found that microwave cooking led to an increase in DPPH radical scavenging activities by 9.39% to 46.32% across various plants. However, our results show a much more dramatic increase in antioxidant activity for both steaming and microwaving (over 400% increase). The increase in antioxidant activity despite the decrease in TPC for microwaved samples is particularly interesting. This suggests that while some phenolic compounds may be degraded during microwaving, the process might be enhancing the antioxidant capacity of the remaining compounds or generating new antioxidant compounds through chemical reactions. It's noteworthy that while steaming resulted in the highest TPC, it did not significantly differ from microwaving in terms of DPPH radical scavenging activity. This suggests that the relationship between TPC and antioxidant activity is not always linear, and different cooking methods may affect these parameters in complex ways. This observation is supported by a study by Zhang, Qu, Xie, Shi, Shi and Yu [19], which found that different cooking methods had varying effects on phenol content and antioxidant activity in peanut sprouts. They

reported that microwaving retained the highest levels of both TPC and antioxidant activity, which partially aligns with our findings for antioxidant activity but differs for TPC.

3.4 Effect of cooking methods on total carotenoids content

The results of total carotenoids content in OFSP reveal significant differences across various cooking methods, with microwave treatment yielding the highest carotenoid levels (527.35 µg BCE/g DW), followed by steaming (478.20 µg BCE/g DW), boiling (429.04 µg BCE/g DW), and control (330.72 µg BCE/g DW). These findings align with previous research indicating that microwave cooking effectively retains carotenoids compared to boiling and steaming. For example, a study by Buratti, Cappa, Benedetti and Giovanelli [20] demonstrated that microwaving preserved carotenoids in vegetables due to shorter cooking times and reduced exposure to heat, which minimizes degradation. Similarly, Vimala, Nambisan and Hariprakash [21] found that thermal processing can disrupt the food matrix, facilitating carotenoid extraction; however, prolonged exposure to heat can degrade these sensitive compounds. The superior retention of carotenoids observed in microwaved samples may be attributed to rapid cooking times that prevent excessive thermal damage, thus preserving nutrient integrity. In contrast, while boiling showed an increase in carotenoid content compared to control, it was less effective than microwaving and steaming. This observation is consistent with findings from Demirel Ozbek, Saral and Turker [17], who reported that boiling can enhance carotenoid levels in certain vegetables but cautioned about nutrient loss through leaching. Overall, these results underscore the importance of selecting appropriate cooking methods to maximize the nutritional benefits of sweet potatoes and other vegetables, suggesting that microwaving is particularly effective for enhancing carotenoid retention while minimizing nutrient loss during preparation.

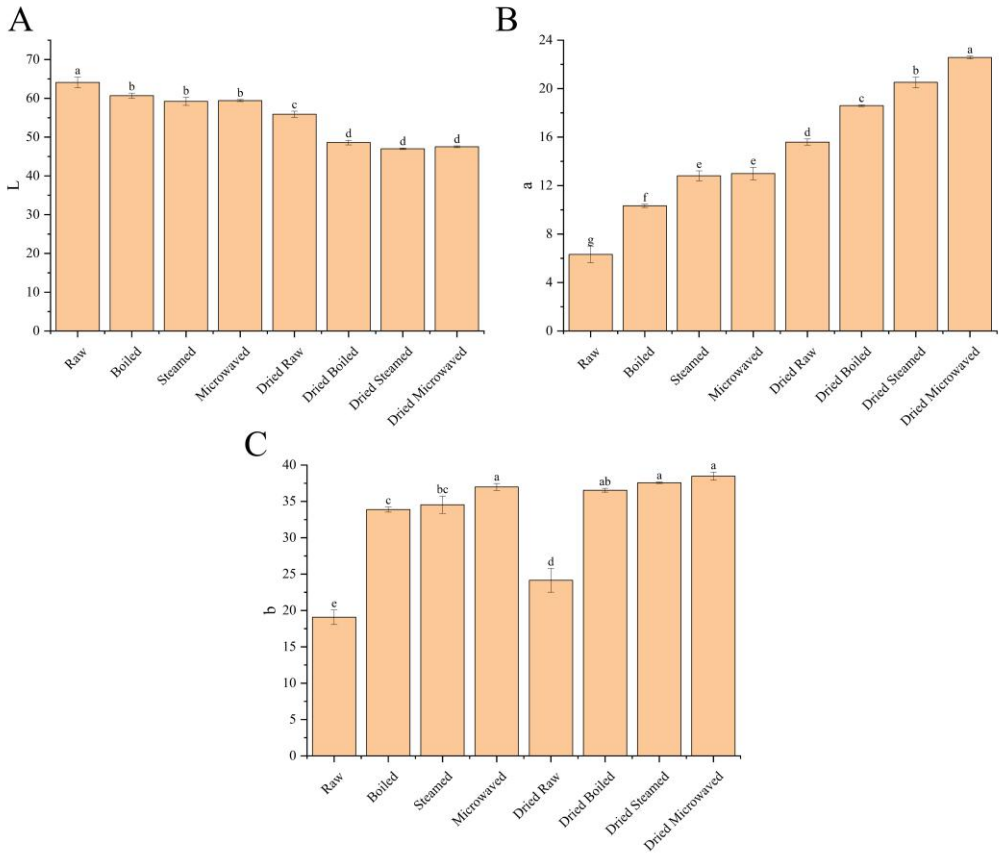

Fig. 3: Color analysis results of different samples, lightness (A), yellowness (B), and redness (C).

3.5 Effect of cooking methods on color

The analysis of color parameters (L*, a*, b*) in sweet potatoes reveals significant changes across various cooking methods (Fig. 3). The raw samples exhibited the highest lightness (L* = 64.11), followed by boiled (60.68) and steamed (59.21) samples, with microwaved samples showing a similar value (59.43). These findings align with research by Buratti, Cappa, Benedetti and Giovanelli [20], who noted that cooking methods significantly affect the color attributes of vegetables, with boiling typically

resulting in darker colors due to cell wall breakdown and pigment release. Additionally, the increase in redness (a*) and yellowness (b*) observed in boiled, steamed, and microwaved samples suggests that these cooking methods may enhance the visibility of carotenoids. The results indicate that boiling increased a* to 10.33 and b* to 33.88, supporting findings from Islam, Nusrat, Begum and Ahsan [5] that boiling can enhance carotenoid accessibility while potentially causing some nutrient losses. In contrast, dried samples exhibited lower lightness values, particularly for dried boiled (48.60) and dried steamed (46.98) sweet potatoes, indicating a significant loss of brightness compared to their raw counterparts. This reduction is consistent with findings from Akissoé, Hounhouigan, Mestres and Nago [22], which reported that drying processes can lead to color degradation due to oxidative reactions and pigment breakdown. Interestingly, dried microwaved samples maintained a relatively higher yellowness (38.48) compared to other dried treatments, suggesting that microwaving may help preserve some carotenoid content even after drying. This observation is supported by research from Yadav, Guha, Tharanathan and Ramteke [23], who highlighted that microwave cooking can enhance the retention of bioactive compounds while minimizing color degradation compared to traditional drying methods. Overall, these results emphasize the importance of selecting appropriate cooking methods not only for nutrient retention but also for preserving the visual appeal of sweet potatoes, which is crucial for consumer acceptance.

IV. CONCLUSION

This study provides compelling evidence regarding the impact of various cooking methods on the nutritional and functional properties of OFSP. The findings indicate that steaming is the most effective method for preserving total phenolic content, while microwaving significantly enhances carotenoid retention. Notably, both steaming and microwaving demonstrated a marked increase in antioxidant activity compared to boiling, which resulted in substantial nutrient loss. These results emphasize the critical role of cooking techniques in maximizing the health benefits of OFSP, a key food source for combating vitamin A deficiency. By optimizing cooking methods, we can enhance the nutritional value of OFSP, thus contributing to better dietary practices and health outcomes in populations at risk of vitamin A deficiency. Future research should continue to explore the intricate relationships between cooking processes and nutrient bioavailability to further refine food preparation practices that support public health initiatives.

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