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Research Article

Effects of cooking techniques on phenolic content and sensory profiles of cauliflower

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ABSTRACT

In this study, the effects of the cooking methods (frying, stir-frying, air-frying, boiling, steaming, baking and sous-vide, and microwaving) on total phenolic content (TPC) and sensory profile of cauliflower have been investigated. Higher cooking temperatures have resulted in higher TPC values, which can be attributed to the generation of new phenolics by the Maillard reaction and cleavage of bound phenolics. The highest TPC and bitterness were obtained when steaming and baking (180°C for 20 min) were applied. While the boiling procedure results in low bitterness and sweetness due to the loss of related compounds in boiling water, the taste of cooked cauliflower was higher when steamed (12 min) and stir-fried (4.5 min). Overall acceptability of the boiled, steamed, and fried samples was higher than in baked and sous-vide treated samples. Steaming was determined as the best technique regarding TPC content and sensory properties.

Keywords: Cauliflower, Total phenolics, Cooking techniques, Sensory analysis, Steaming

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Introduction

Brassicaceae or *Cruciferae* is a family of vegetables in diets and is well known for its health-promoting compounds. Positive health effects of *Cruciferae* are mainly attributed to their high content of phenolic compounds (57.3-230 mg gallic acid equivalence (GAE)/100g) (Ramos dos Reis et al., 2015; Lafarga et al., 2018). Cauliflower (*Brassica oleracea L. var. botrytis*) and broccoli (*Brassica oleracea L. var. italica*) are the most frequently consumed species of Cruciferae, produced over 25 million tons worldwide (FAOSTAT, 2021). While the most predominant phenolic compounds present in cauliflower are protocatechuic acid, quercetin, pyrogallol, vanillic acid, coumaric acid, and kaempferol, other identified phenolic compounds in cauliflower include phenolic acids (gallic acid, 4- amino benzoic, stolleuropein, reversterol, caffein, catechol, alpha-coumaric acid, coumarin, 3-OH-tyrosol, chlorogenic, rosmarinic, caffeic, syringic acid, cinnamic acid, and sinapic acid), flavonoids (naringin, naringenin, 7-hydroxy flavonoid, rutin, quercetrin, apigenin, hespertin, hisperdin, rosmarinic acid, catechin) (Ramos dos Reis et al., 2015; Ahmed & Ali, 2013; Ali, 2015; Gratacós-Cubarsí et al., 2010).

Various kinds of cooking techniques could be evaluated based on their different heat transfer mechanism, such as boiling, frying, stir-frying, steaming, baking, *sous-vide* (SV), grilling, air-frying, and microwaving (MW) to increase the palatability and taste of vegetables and the retention of heat-labile compounds. Heat transfer mechanisms in these techniques depend on the design of the heating cabinet, food surface, contact material type, and fluid medium used (air, oil, water, steam). Cooking may positively or negatively affect total phenolic content (TPC) (Sharma et al., 2015). Some studies support that the TPC of vegetables decreases during boiling, steaming, baking, MW, and SV due to high temperatures (Ramos dos Reis et al., 2015; Lafarga et al., 2018; Sharma et al., 2015; Çubukçu et al., 2019). On the other hand, an increase in the TPC of freeze-dried vegetables has been observed in some studies due to comparing dry basis (d.b.) values (Turkmen et al., 2005; Girgin & El, 2015; Van Boekel, 2001; Cartea et al., 2011). In freeze drying, problems associated with high moisture content during solid mass extraction are reduced. Therefore, the variation in sample weight arising from differences in moisture content is eliminated (Maillard et al., 1996).

This study is a more comprehensive study on cauliflower concerning cooking techniques compared to previous studies mainly focusing on broccoli (Ramos dos Reis et al., 2015; Lafarga et al., 2018; Girgin & El, 2015; Engel et al., 2002; Wieczorek et al., 2018). The primary purpose of this study was to investigate the effects of cooking methods (frying, stir-frying, grilling, air-frying, boiling, steaming, baking and sous-vide, and microwaving) at various time and temperature conditions on TPC and sensory profile (appearance, odour, taste, and texture) of cauliflower, and to find the best cooking method accordingly.

Materials and Methods

Approximately 7 kg of cauliflower (*Brassica oleracea L. var botrytis*) samples were purchased from local markets in Istanbul, Turkey, during September-October 2022. Samples were prepared in the same bite-sized pieces (inflorescences, 5 cm) to eliminate the enzymatic depletion of phenolic compounds due to cutting and slicing (Cartea et al., 2011). The mixed pieces were washed, wiped, and then divided into 200 g portions for processing.

Each of the cooked and raw samples was blended separately (Blendtec Classis 575, USA), then frozen immediately in aluminium bowls at -18°C and freeze-dried at -80°C, below 0.1 mbar for five days (Teknosem TOROS 4/4 DS, Istanbul, Turkey) and ground (IKA A11, China) and stored at -18°C until analysis. Therefore, extraction problems due to high moisture contents were eliminated, as defined by Maillard et al. (1996). Moisture loss was calculated by taking the weight into account.

Cooking Treatments

The cooking techniques and time-temperature parameters, given in Table 1, are determined in preliminary studies that acceptable palatability (bitable firmness and no burnt surface) has been obtained. The same portions (200 g) of cauliflower samples were:

(1) Boiled in 2 L drinking water (B8 and B10).
(2) Steamed 2 L of tap water (S10 and S12). The samples were suspended on a sieve with a lid above the boiling water level.
(3) Stir-fried in Teflon wok panes using 150 mL sunflower oil (F45 and F65).
(4) Baked using two preheated conventional ovens (Unox Cheftop Plus Combi Oven, Italy) (O20-150, O25-150, O20-180, and O25-180).
(5) Sous-vide (SV) cooked in preheated 4 L of tap water by a sous-vide cooker (Proficook pc-sv 1126, Germany) with a vacuum pump (Henkelman Mini Jumbo, Germany) (SV60 and SV70).

(6) Microwave-cooked (MW) using a microwave oven (Arçelik, MD823, Turkey) and sealed microwavable steam cooking bags (Koroplast).

(7) Air-fried (AF) by coating samples with sunflower oil in an air-fryer pan (Mi Smart Air Fryer 3.5 L, MAF02, China). At the 8th minute of each cooking, the air-fryer pan was shaken for 10-20 seconds to turn samples upside down.

Determination of TPC

Six grams of ground sample and 20 mL of 80% aqueous methanol (LC Grade) were added into a 50 mL Falcon centrifuge tube. The mixture was homogenised using an ultrasonic homogeniser (Banderin Sonopuls GM 2200.2) at room temperature and then centrifuged (Cryste Varispin 12R) at 10.000 x g at four °C for 20 minutes. After three extraction steps, supernatants were pooled in 50 mL centrifuge tubes and completed with 80% aqueous methanol to 50 mL in a volumetric flask and stored at -20°C. TPC was determined by the Folin-Ciocalteu method (Ainsworth & Gillespie, 2007) using Folin-Ciocalteu reagent (Sigma-Aldrich), sodium carbonate (ISOLAB Laborgeräte GmbH), gallic acid (Bio Basic) and microplate spectrophotometer (Thermo Scientific Multiskan SkyHigh). The results were reported as mg GAE/100 mg d.b.

Sensory Analysis

The sensory evaluation was performed by 15 semi-trained panellists (20-65 age) using sensorial attributes based on previous studies (Engel et al.,2002; Poelman & Delahunty, 2013) with modifications made according to the sensory panel results. Sensory analysis was conducted on five selected cooking methods, and the time-temperature combination resulted in relatively higher TPC values. MW and AF samples were excluded because they had significantly low TPC values (B8, S12, F45, O20-180, and SV70). About 20 g of floret with a stalk from each sample were placed on polystyrene tables, identified with random 3-digit numbers, and evaluated by a 9-point hedonic scale in an air-conditioned room (21 ±1°C) under white light. The odour of samples was described by odour impact, green odour, cooked cauliflower odour, and sulfur odour; appearance by uneven colour, stalk colour, floret colour, and moistness; taste by taste impact, green taste, cooked cauliflower taste, sweetness, bitterness, and sulfur taste, texture by firmness, moistness, chewing resistance, cohesiveness; finally general acceptability.

Statistical Analysis

The averages and standard deviations were calculated from three measurements of the duplicate samples using Excel software (Microsoft Corporation, Redmond, WA, USA). One-way ANOVA and a post hoc Tukey test with a confidence interval of 95% were used to evaluate the statistical differences (Minitab® 16 Statistical Software, Minitab Inc. State College, Pennsylvania, USA). Correlation analyses were performed using Pearson’s correlation coefficient (r) (Excel 2016, Microsoft, Troy, NY).

Results and Discussion

Boiling and steaming processes increased the moisture content, which is expected. On the other hand, other processes decreased when partial steam escaped (Table 1). Stir-fried samples had the lowest moisture content. Moisture affected the appearance of the final cooked cauliflower (Figure 1).

TPC Evaluation

TPC of the processed samples (169.4-637.3 mg GAE/100g d.b.) were significantly higher than those of the raw samples (147.7-224.0 mg GAE/100g d.b., α=0.05) where TPC (mg GAE / 100 g ± SD) and % TPC increase of processed samples were given in Table 1 and Figure S1, which is inconsistent with the previous observations by Turkmen et al. (2005). Higher temperature applications significantly worsen this rise (O20-180, S12, and B8, α=0.05). The effect of higher temperature on TPC content could be explained by the cleavage of bound phenolic compounds: the degradation of the cell wall of the cauliflower and disruption of phenol-protein complexes, which resulted in the release of phenolic compounds, leading to a better extraction (Shahidi & Yeo, 2016). The Maillard reaction at high temperatures may also contribute to the production of some compounds, including phenolic compounds (Sharma et al., 2015; Maillard et al., 1996; Alves et al., 2021). It was declared that above 80°C, isomerisation and degradation reactions of sugar start to become appreciable, which is the initial stage of Maillard reactions (Van Boekel, 2001). Then, the amino group is regenerated, and brown pigments are formed at the intermediate and final stages. In our study, the inner temperature of processed samples was between 65-87ºC, which increased TPC. Application of SV70 cooking showed a significant increase in TPC. On the other hand, no significant change in TPC was observed when SV60 was applied because the sample's inner temperature was probably lower than 60°C, which is not enough for the reactions (Table 1, α=0.05). Because samples were packed during SV cooking for 60 minutes, the inner temperature could not be measured accurately at the end of the process.

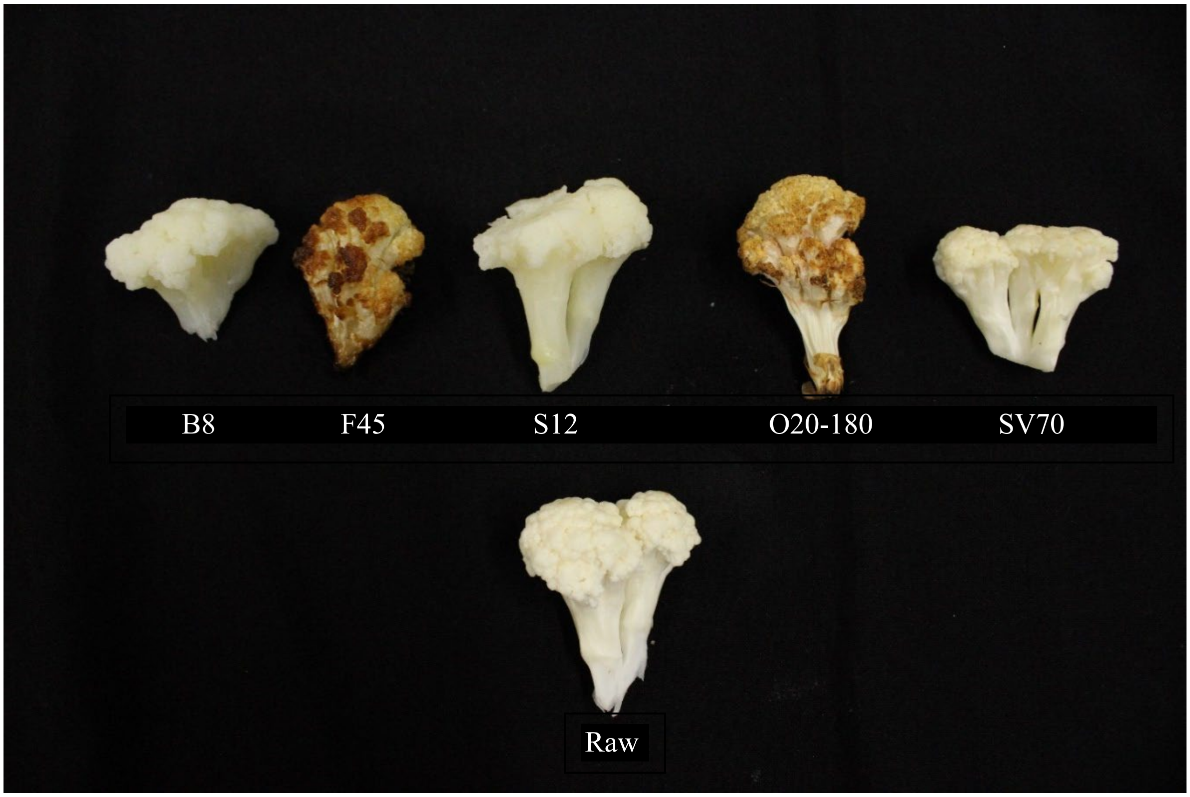

Figure 1. Picture of cooked (top) (B8; F45; S12; O20-180; SV70 from left to right, respectively) and raw (bottom) cauliflowers (B8, boiling for 8 min; F45, stir-frying for 4.5 min, S12, steaming for 12 min, O20-180, Oven cooking at 180°C for 20 min, at 70°C)

Table 1. Moisture content (%), TPC of cauliflower (mg GAE / 100 g ± SD), and % TPC increase of processed samples (% ± SD*)

Conventional Techniques	Sample codes	Moisture Content, %	Final T$_{inner}$ ºC	% TPC increase, db. (%, ±SD)	TPC (mg GAE/100 g ±SD)	Rapid high-tech Techniques	Sample codes	Moisture Content, %	Final T$_{inner}$ ºC	% TPC increase, db. (%, ±SD)	TPC (mg GAE/100 g ±SD)
Raw sample		93.2	-	-	224.0 ±5.5a	Raw sample		91.6		-	147.7 ±2.1^{a}
Oven baking						Microwave					
20 min – 150°C	O20-150	88.3	70	112.2±1.79^{bcd}	475.2 ±4.0^{b}	250 W – 8 min	MW250-8	91.4	85	120.5±8.62^{bcd}	325.7 ±12.7^{b}
25 min – 150°C	O25-150	87.1	76	107.0±0.53^{cd}	463.5 ±1.2^{b}	250 W –10 min	MW250-10	90.3	81	54.4±3.71^{ef}	228.1 ±5.5^{c}
20 min – 180°C	O20-180	88.8	71	**155.0±1.05^{ab}**	571,0 ±2.4^{c}	350 W – 6 min	MW350-6	90.5	80	47.7±1.32^{ef}	218.2 ±1.9^{c}
25 min – 180°C	O25-180	81.1	76	105.4±8.05^{cd}	459.8 ±18.0^{b}	350 W – 8 min	MW350-8	90.5	75	57.9±13.12^{ef}	233.2 ±19.4^{c}
						500 W – 5 min	MW500-5	90.7	85	118.6±4.23^{bcd}	322.9 ±6.2^{b}
Steaming						500 W – 6 min	MW500-6	90.0	81	105.4±11.57^{cd}	303.4 ±17.1^{b}
10 min	S10	92.2	86	117.6±1.95^{bcd}	487.3 ±4.4^{b}	700 W – 3 min	MW700-3	90.4	81	59.2±8.18^{ef}	235.1 ±12.1^{c}
12 min	S12	91.4	87	**164.3±28.7^{a}**	591.8 ±64.3^{b}	700 W – 5 min	MW700-5	89.9	70	56.0±3.99^{ef}	230,4 ±5.9^{c}
Boiling**						Air-frying					
8 min	B8	93.4	75	**133.4±13.26^{abc}**	522.7 ±29.7^{b}	150°C – 10 min	AF150-10	81.8	71	22.9±11.57^{fg}	181.5 ±17.1^{b}
10 min	B10	94.1	85	56.8±5.37^{ef}	351.2 ±12,0^{c}	150°C – 15 min	AF150-15	77.1	78	40.1±2.87^{fg}	206.9 ±4.2^{b}
						180°C – 10 min	AF180-10	77.5	80	37.1±1.16^{fg}	202.5 ±1.7^{b}
Stir-frying***						180°C – 15 min	AF180-15	74.2	65	52.5±1.48^{ef}	225.3 ±2.2^{bc}
4.5 min	F45	79.3	83	55.2±6.42^{ef}	347.7 ±4,4^{b}						
6.5 min	F65	75.3	86	46.5±29.0^{ef}	328.1 ±64,9^{b}						
Sous-vide											
60°C - 60 min	SV60	91.6	-	1.4±0.79^{g}	227.0 ±1.8^{a}						
70°C - 60 min	SV70	92.5	-	87.9±8.79^{de}	420.8 ± 9.7^{b}						

*SD, standard deviation; $p < 0.05$

** Total phenolic contents (TPC) of boiling water were 0.90 and 0.79 mg Gallic acid equivalents (GAE)/mL dry basis (d.b.) for 8 and 10 min, respectively

*** The temperature of the oil was approximately 180°C

****T$_{inner}$, cauliflower's centre temperature at the process's end

TPC increase of 10-minute boiled samples was significantly less than steamed ones due to the leaching of phenolics into water (0.90-0.79 mg GAE/mL), which can be explained by osmosis and water solubility of phenolic compounds (Table 1, α=0.05). In addition, the loss of TPC was significantly higher when processing time in boiling was increased (α=0.05). Significant losses of bioactive compounds due to boiling cauliflower were observed in contrast to steaming in literature (Girgin & El, 2015). Despite high-temperature application, a significantly lower increase in TPC was observed in stir-frying and air-frying. This can be explained by higher water loss during cooking and, consequently, heat and mass transfer mechanism due to the impact of water content on the thermophysical properties of foods (density, specific heat, enthalpy, thermal conductivity, and thermal diffusivity). The specific heat of high-moisture foods is primarily dominated by water content (Sahin & Sumnu, 2006a). Air-frying uses a combination of radiation, conduction, and convection heat transfer mechanisms and a narrow cooking chamber, creating a very intense heat transfer medium, which results in more rapid drying than baking. During stir-frying, as soon as the cauliflower is placed in the pan, it encounters both the high heat from the pan through heat conduction and the oil, which is at a much higher temperature than the boiling point of water. Steam, generated into the food pores, moves further and out into the oil. As a result, outward steam pressure prevents oil uptake and increases moisture loss simultaneously. This mechanism explains why the stir-fried samples had the lowest moisture content (Chen et al., 2021).

The TPC of the samples was also increased in MW and AF samples; however, not as much as in baking and steaming (α=0.05). This phenomenon might be due to the rapid drying on the sample's surface during AF, which leads to low thermal diffusivity and lowers the Maillard reaction rate (Van Boekel, 2001).

Heat transfer direction in MW is opposite of that in conventional cooking (Araszkiewicz et al., 2007) (Figure 2). In conventional heating, a hard, heat-resistant surface layer reduces heat transfer and mass transfer of the water in the centre through the surface, requiring longer cooking time. However, in MW, the food material absorbs MW energy. It converts MW energy into the heat generated throughout the product at a rate that depends on the water content of food related to its dielectric properties (ε', ε'') (Sahin & Sumnu, 2006b). As a result, the highest temperature is observed at the centre of the food rather than the surface, and the core and base temperatures drop due to the rapid evaporation of the water (Araszkiewicz et al., 2007). Because the rate of microwave drying is much faster than traditional hot air drying, which is highest at the beginning of the process, rapid drying lowers the rate of Maillard reaction, as described above.

When we examine the effects of MW parameters, lower power and lower process time (250 W—8 min and 500 W—5 min) seem better for microwave-cooking vegetables, resulting in a significantly higher increase of TPC (α=0.05) compared to other techniques.

Finally, O20-180 and S12 were the best cooking techniques for TPC in cauliflower samples.

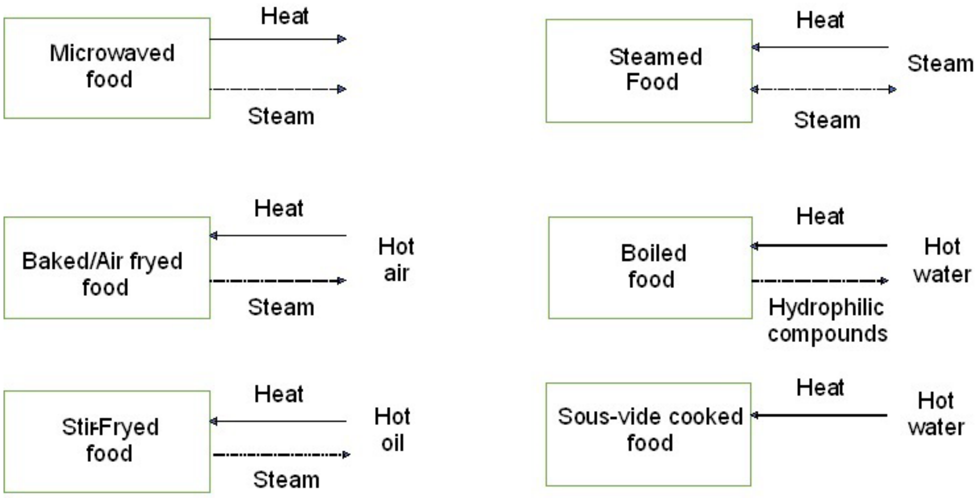

Figure 2 Schematic representation of the heat and mass transfer mechanism of different cooking methods (Araszkiewicz et al., 2007) where the heat transfer direction in microwaved cooking and conventional cooking is opposite

Sensory Analysis

The cooking method affected the samples' appearance, odour, taste, and texture, and these attributes are shown in Figure 3 and Table S1-S5. Both odour impact and cooked cauliflower odour were highest in B8. Similarly, Araya et al. (2009) compared the quality criteria and sensory perception of raw, high-pressure processed, sous-vide cooked, and boiled carrots. They reported that the highest cooked taste and odour impact was obtained in boiled carrots. However, no statistical difference ($p > 0.05$) in odour impact between B8 and F45 existed. Statistical difference in CCO between B8 and S12 was also not observed. There was a high correlation between odour impact and CCO ($r=0.89$), which can be interpreted as the CCO being much more effective than the green odour in the overall odour of the samples. Application of SV resulted in the highest green odour and the lowest CCO. The cellular microstructure of samples obtained by cryo-SEM has shown that SV causes less tissue damage than boiling (Araya et al., 2009). A sulfur odour was found in the O20-180 and F45 samples, with fried samples having the highest score. Compounds such as dimethyl disulfide and trisulfide, minor volatile breakdown products arising from S-methylcysteine sulfoxide, cause sulfur odour at a significant level in processes such as frying and baking, where the water content decreases significantly (Kubec et al., 1998; Marcinkowska & Helen, 2022).

A very high level of uniform colour was observed in B8, S12, and SV70, with B8 being the highest. However, occasional brown spots were observed in O20-180 and F45; thus, the score for uniform colour was lower. Therefore, O20-180 and F45 were also selected as the darkest colour due to Maillard reactions at high temperatures ($p > 0.05$). Navajas-Porras et al. (2022) applied various cooking processes to different foods, including cauliflower, and observed an increase in Maillard reaction products with frying and baking. As expected, according to the water loss, the B8 had the moistest appearance, while the O20-180 had the driest appearance ($p > 0.05$). The lowest moisture content was observed in F45, which O20-180 follows. The discrepancy between moisture values and sensorial perceived moistness may be due to the oiliness of F45, masking the dryness of the sample by coating the mouth and oil droplets on the sample.

The most intense and the highest cooked cauliflower taste was found in F45 and S12 ($p > 0.05$). The lower taste impact of B8, O20-180, and SV70 coincided with less intense cooked vegetable notes. The green taste of O20-180 and SV70 was also intense. Both bitterness and sweetness had the lowest score in B8 due to the transition of soluble sugars and glucosinolates to boiling water. S12 and O20-180 were the most bitter samples ($p > 0.05$). TPC was also highest for S12 and O20-180 and lowest for B8, proving that TPC highly affected the bitterness. Previous studies have also reported that the increase in bitterness is due to the glucosinate level in cauliflowers (Engel et al., 2002; Wieczorek et al., 2022). In a survey of Brussels sprouts, high concentrations of sinigrin and progoitrin were associated with consumer rejection and poor taste (Van Doorn et al., 1998; Wieczorek et al., 2022). In turnip, it was also observed that the higher the glucosinolate level, the higher the bitterness (Nor et al., 2020). There was no difference in sweetness scores of S12, F45, O20-180, and SV70 ($p > 0.05$). Although sulfur taste (2.60 for F45 and 2.00 for O20-180) was rated lower than sulfur odour (4.33 for F45, 3.47 for O20-180), both were higher in samples F45 and O20-180 than in the other samples.

O20-180 and SV70 were very firm, resistant to chewing, and cohesive, meaning that the samples break down into small particles in the mouth that do not combine with saliva and are difficult to swallow. Similar results were observed in B8, S12, and F45 regarding firmness, chewing resistance, and cohesiveness, making them easier to eat.

The general acceptability of the samples prepared was highly affected by cooking methods, as were other sensorial attributes. The highest acceptability value was observed in S12, whereas the lowest was in O20-180 and SV70. Bitterness and sulfur odour/taste did not affect the general acceptance. However, it should be noted that sulfur odour was generally not high in most of the samples. Green taste notes were higher in samples with high firmness and chewing resistance, as well as low cohesiveness and general acceptability. Panellists highly rated samples with high CCO/taste and taste impact with a moist appearance for general acceptability.

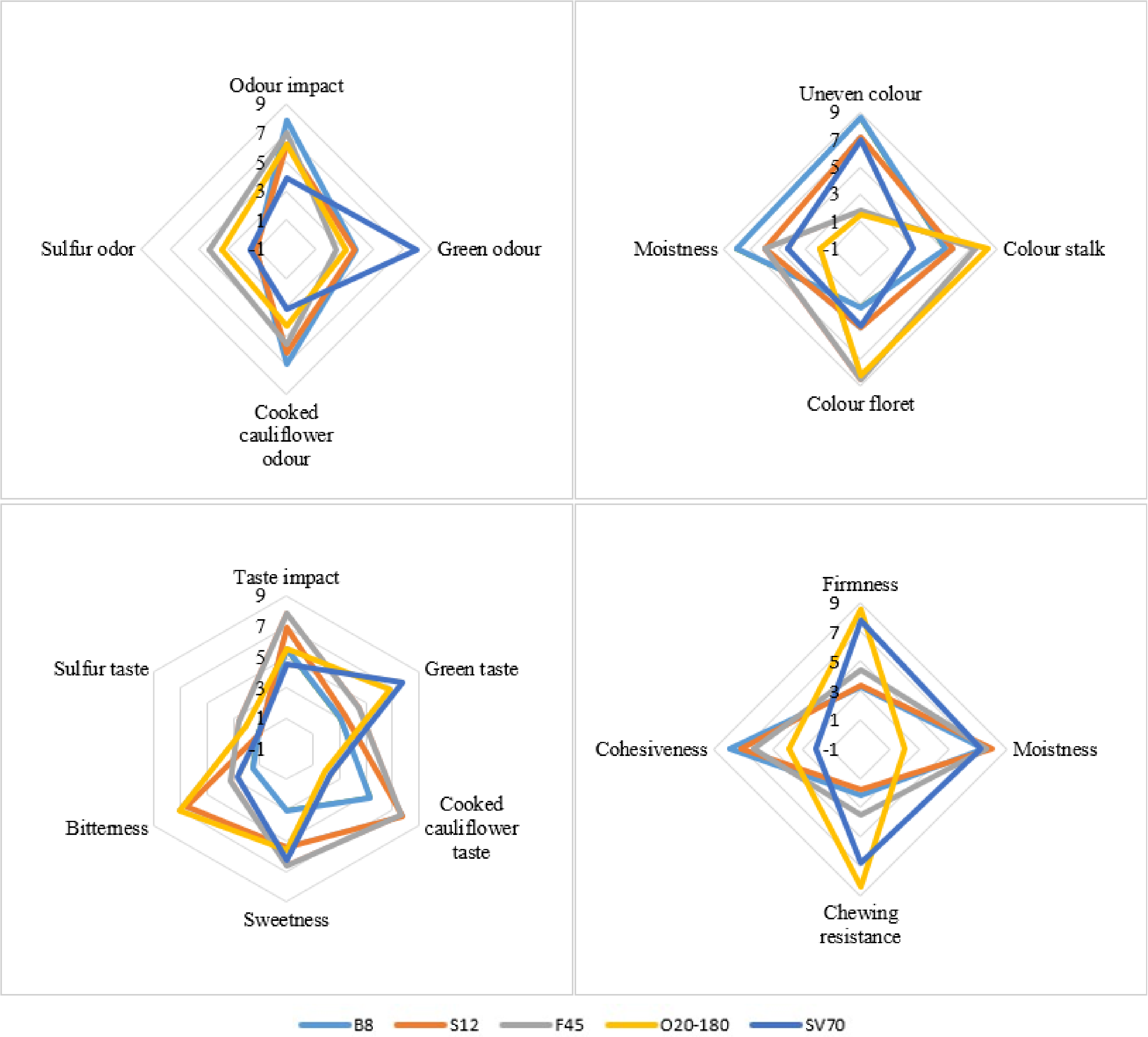

Figure 3. The effect of cooking methods on sensorial properties of cauliflowers (B8, Boiling for 8 min; F45, Stir-frying for 4.5 min, S12, Steaming for 12 min, O20-180, Oven cooking at 180°C for 20 min, SV70, Sous-vide cooking at 70°C)

Conclusions

The highest TPCs were observed in the O20-180 and S12 samples. On the other hand, steamed cauliflower was the most acceptable sample in terms of sensory properties such as higher moistness, chewability, intense and high CCO, and taste. As a heating medium, the change in water amount during cooking treatment was critical for effective heat transfer, sensory properties, and TPC content due to Maillard reactions and the release of bound phenolics by cell wall disruption. In further studies, the changes in certain dominant phenolic compounds and their derivatives of samples could be determined by more sensitive methods. HMF content and colour properties could be measured, and narrower steaming process parameter intervals could be applied to optimise the steaming process. Additionally, thermal probes and flow meters placed in the heating chamber can help track the movement of water, elucidating heat and mass transfer mechanisms. Integrated ovens could also be improved, or different coating formulations could be applied to prevent surface hardening.

Compliance with Ethical Standards

Conflict of interest: The author(s) declares that they have no actual, potential, or perceived conflict of interest for this article.

Ethics committee approval: The authors declare that this study does not include experiments with human or animal subjects, so ethics committee approval is not required.

Data availability: Data will be made available on request.

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