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Research Article

Thermally Induced Physicochemical and Volatile Transformations in Three Shallot Cultivars of Different Origins after Deep Frying and Their Sensory Implications

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Abstract
Shallot (*Allium cepa* L. var. *aggregatum*) is widely used as a culinary spice; however, information on cultivar-dependent responses to deep frying remains limited. This study comparatively evaluated three Indonesian cultivars of different origins – Palasa (PL) and Lembah Palu (LP) from Donggala, and Bima Brebes (BB) from Brebes – in raw and fried forms. Physicochemical properties, total phenolic content (TPC), antioxidant activity (AA), volatile compounds (HS-SPME–GC–MS), and sensory attributes were analyzed, and multivariate analysis was applied to assess variation among samples. The result showed that deep frying significantly reduced moisture content (2.56–3.84%) and antioxidant activity, while measured TPC increased after frying. A total of 33 volatile compounds were identified in raw samples and 23 in fried samples. Frying altered volatile composition, shifting from sulfur-containing compounds (disulfides, trisulfides, thiophenes) in raw shallots to thermally generated compounds such as pyrazines, strecker aldehydes, and furans in fried samples. Principal component analysis (PCA) clearly separated raw and fried, distinguishing cultivar-specific differences. Raw PL and LP exhibited sulfur-rich volatile profiles, whereas BB was characterized by a higher proportion of dipropyl disulfide. Sensory evaluation revealed distinct cultivar×environment-dependent quality attributes, with fried PL and LP preferred for crispness and structural integrity, whereas fried BB received higher scores for taste and overall acceptance. These findings demonstrate that deep frying induces significant physicochemical and volatile transformations in shallots, with cultivar-specific responses influencing sensory quality. The results provide a scientific basis for selecting appropriate cultivars and optimizing processing conditions to improve product quality and consistency in fried shallot production.

Keywords: Antioxidant activity, Bima brebes, Lembah palu, Palasa, Sensory evaluation, Volatile compounds

1 Introduction

Shallots (*Allium cepa* L. var. *aggregatum*) are a popular flavoring spice commonly used for various cuisines. They are used for their distinct pungent taste and aroma [1]. Shallots are mostly used in raw conditions during food preparation. However, the diversification of shallot-based products (puree, paste and fried shallot) is currently gaining more interest. This is due to their improved practical application, shelf-life, and added value. Fried shallots are one of the popular shallot-based products due to their distinct taste. It is usually produced by deep-frying sliced shallots until golden brown and crispy [2].

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This can be used as a complementary garnish, adding flavor to various dishes. Central Sulawesi is one of the major producers of fried shallot products in Indonesia. The products have been acknowledged for their flavor, texture and consistency. This was mostly contributed by the use of specific cultivars, specifically Lembah Palu and Palasa cultivars. However, these cultivars are specifically adapted to the unique soil and environmental conditions of Central Sulawesi, which limits their successful cultivation in other regions [3], [4]. This geographic restriction creates a significant supply-demand gap. Therefore, it is necessary to identify alternative shallot cultivars that can match the quality standards of those varieties while offering better geographical adaptability and higher production volumes.

Bima Brebes, Lembah Palu, and Palasa are among the popular shallot cultivars currently cultivated by farmers. These cultivars were released by the Indonesian Agency for Research and Development due to their superior characteristics. Shallot cultivars vary in their morphological, biochemical [5], physicochemical [1], [6], and chemical composition [7]. These quality parameters need to be considered by farmers to choose the cultivars with high consumer preference. The study on the quality aspects of shallots obtained from various cultivars has been extensively carried out. However, further study with more comparative analysis is still needed to strengthen the body of knowledge in this aspect. In this context, it is essential to evaluate the potential of the Bima Brebes cultivar as a substitute for Palasa and Lembah Palu. Furthermore, this information is important for the industries to develop diversified shallot-based products for special purposes and meet consumer preferences.

Shallots contain various chemicals related to their quality and beneficial health effects. They have antioxidants [8], [9], vitamin C [10], and some essential minerals that have beneficial effects on human health [5]. Previous studies have found that shallots have high total phenolic content and antioxidant activity [11]. They also contain various volatiles significantly related to the sensory quality. Dipropyl disulfide, methyl propyl disulfide, (Z)-1-(Prop-1-en-1-yl)-2- propyldisulfane (or cis-Propenyl propyl disulfide), (E)-1-(Prop-1-en-1-yl)-2-propyldisulfane, 2-methyl-2-pentenal, and 2,4-dimethyl-thiopene are among the major volatile compounds in raw shallots [9]. The cooking process affects the shallots' physicochemical composition and volatile compounds significantly affect their sensory quality. The boiling process could reduce the shallot's phenolic content, but its antioxidant activity was unchanged [12]. Frying, on the other hand, reduced organosulfur compounds while forming various nitrogen-containing compounds such as pyrazines [13]. The deep-frying process is a complex reaction involving the Maillard reaction, lipid oxidation, hydrolysis, and amino acid degradation [14], [15]. The deep-frying process was known to be affected by the frying medium [16]. The performance was also significantly related to the cultivars used [17]. Due to this complexity, the effect of deep-frying on the quality of shallots and the chemical changes that occur, specific to the cultivars used, should be studied. This is important for choosing the right cultivar to be used to produce fried shallots with desired characteristics.

Deep-fried shallots have a brown color, fragrant sulfury aroma, sweet aroma, rancid aroma, savory, sweet, salty, and bitter taste [18]. Building on this pioneering work, [19] determined that the main volatiles in fresh shallots were allylpropyl and dipropyl disulfide, whereas thiopropane S-oxide distinguished shallots from onions. By identifying 93 volatile chemicals in fried shallot oil, a more recent study by [20] expanded on this paradigm and showed how thermal processing significantly changes the volatile profile through lipid oxidation and Maillard reactions.

From a customer perspective, this flavor/aroma quality should also be accompanied by the texture, crispness, color and the shape/form of the fried shallot. Furthermore, with the increasing interest of consumers towards products with health benefits, the occurrence of bioactive compounds in food products is currently sought after. Comprehensive information on these aspects is essential. However, there is still limited study on the direct comparison of fresh and deep-fried shallots' physicochemical and flavor properties. This study aimed to compare the physicochemical, volatile, and sensory properties of fresh and deep-fried shallots from the most popular Indonesian improved shallot cultivars. The result will be beneficial for farmers and industries to choose the correct cultivars for consumption to meet the current demand and the preferences of the market.

2 Materials and Methods

2.1. *Materials*

Three shallot cultivars, namely Palasa (PL), Lembah Palu (LP), and Bima Brebes (BB), were collected from Donggala, Central Sulawesi Province (for PL and LP) (regosol soil in the lowlands of 0-400 above sea level) and Brebes, Central Java Province (for BB) (alluvial or latosol soil at an altitude of 0-1000 above sea level).

The shallots were carefully sorted by size and condition. Only healthy and undamaged shallots were used in this study. Refined, bleached and deodorized (RBD) palm oil was obtained from the local market. SPME fibers (50/30 µm DVB/CAR/PDMS) for volatile analysis were obtained from Supelco (Supelco Inc., PA, USA). All chemical reagents were obtained from Merck (Jakarta, Indonesia). The chemicals used were of analytical grade.

2.2 *Preparation of raw and deep-fried shallots*

Shallots were peeled and washed with running water until clean. Drained shallots were then sliced to 1-2 mm thickness using a commercial mandoline (Tupperware, SC, USA). These sliced shallots were referred to as "raw shallots". The frying procedure was based on local practices. It was conducted using 2 L of palm oil, preheated to an initial temperature of 107 °C. Upon the addition of sliced shallots, the thermal profile was monitored from a median temperature of 110 °C to a final temperature of 140 °C with a total duration of 10 to 14 minutes. Fresh oil was used in every batch and replication of the frying treatment. The deep-fried shallots were drained and cooled at room temperature to obtain "fried shallots".

The raw and deep-fried samples were packed in sealed airtight plastic bags of high-density polyethylene (HDPE) and kept at 10°C before analysis. Fresh samples were analyzed for their color and texture. Raw and fried shallots were analyzed for moisture content, antioxidant activity, total phenolic contents, and volatile compounds. The hedonic and ranking test was done only for the fried samples.

2.3 *Preparation of methanolic extract*

The methanolic extract was prepared by mixing 0.2 g of ground shallot samples with 5 ml methanol (80%). The mixture was shaken at 150 rpm for 12 h. The supernatant obtained by centrifugation was then used for analysis.

2.4 *Moisture content*

Moisture content was measured using a Toluene distillation method based on Apriyantono *et al.,* [21]. The sample (5 g) was added with 200 mL of saturated toluene in a dry flask. The flask was then connected to the apparatus (cooler, reservoir and the receiving tube). The flask was carefully heated for 15 mins. When the toluene started to boil, the speed of the distillation was reduced to less than two drops per second. When most of the water was distilled off, the distillation speed was raised to 4 drops per second. The distillation was continued for another 5 mins. The receiving tube was then chilled until it reached room temperature. Following the complete separation of the water and toluene, the volume of water was measured, and the water content was obtained as a percentage.

2.5 *Texture and color*

The texture of raw shallot was determined using the method of Arambula *et al.,* [22] with slight modification. The samples (1mm of thickness and cm diameter) were subjected to a texture meter (Texture Analyzer, Zwick Z 0.5, ZwickRoell GmbH & Co. KG, Ulm, Germany). The test was carried out at two mm/s and 15 mm clamp openings until the samples were crushed. Color analysis was determined using the Hunter Hutching method (Konika Minolta CR 400, Konica Minolta, Japan). The color was presented as (lightness), (red - green), and (blue - yellow) values.

2.6 *Total phenolic content*

Total phenolic content (TPC) was determined using the method described by Chumark *et al.,* [23]. The methanolic extract (0.5 ml) was mixed with 0.5 ml of distilled water and 5 ml of 10% Folin-Ciocalteu reagent and vortexed (Labnet International Inc., Mod. S0200). The reaction continued for 5 mins. Around 4 mL of 7.5% sodium carbonate solution was then added and vortexed. The solution was then kept for two hours. The absorbance was measured by using a spectrophotometer (Mod. Lambda 25, Perkin Elmer, Germany). Gallic acid was used as a standard. TPC was presented as gallic acid equivalent in milligrams per 100 g of the sample on a dry basis (mg GAE/100 g DB) and wet basis (mg GAE/100 g WB).

2.7 *Antioxidant activity*

Antioxidant activity (AA) was determined following the method of Kunyanga *et al.,* [24]. The DPPH assay was selected as a benchmark and widely accepted method in *Allium* research, enabling direct comparison with existing literature data [25], [26]. The methanolic extract (0.1 ml) was reacted with 3.9 ml of 0.1 mM DPPH solution. The mixture was kept at ambient conditions (25 °C) for 30 minutes.

The absorbance was measured at 517 nm using a spectrophotometer (Mod. Lambda 25, Perkin Elmer, Germany). DPPH radical scavenging activity was calculated and displayed on a percentage basis (% inhibition).

2.8 *Volatile analysis*

Volatile analysis was done using Headspace Solid Phase Microextraction (HS-SPME) gas chromatography Mass Spectrometry (GC-MS) methods. Agilent 7890A-5975C GCMS equipped with an HP-5ms column (30 m x 250 µm x 0.25 µm) was used for analysis. The sample (5 g) of sliced raw or deep-fried shallot was put in a 20 ml SPME vial. Headspace extraction by SPME was carried out at 35°C for raw shallot and 80°C for deep-fried shallot for 30 mins. The SPME fiber was then injected into the GC injection port. The desorption was done at 250 °C for 20 mins in a splitless mode. The flow rate was 0.8 mL/min. The GC column oven was set as follows: initial temperature was 50 °C (3 mins), then ramped to 210 °C (5 °C/min). The MS was operated in electron impact mode at an ionization voltage of 70 eV and a source temperature of 230 °C. MS performed a scan at m/z 29-400. The volatile components were identified by comparing them with the NIST/EPA/NIH Mass Spectral Database library. An alkanes standard of C8-20 was used for the determination of linear retention index (LRI). The experimental LRI values were compared with the relevant literature. The semi-quantification of volatile compounds was done using relative peak areas (%).

2.9 *Sensory analysis (hedonic test and ranking test)*

The sensory evaluation was conducted using a hedonic test involving 40 panelists based on the method of Yofananda *et al.,* [2]. Although these individuals had prior experience in sensory methodologies for other food categories, they were untrained in the specific attributes of shallot products and participated as a consumer panel for this study. The sample (2 g of deep-fried shallot) was presented to each panelist. The five-point hedonic scale test (1 strongly dislike to 5 very like) and the ranking test were used to determine the consumer preferences for color, shape, crispness, aroma, taste, and overall acceptance. Ethical clearance was granted by the Ethical Committee Health Research STIKES Guna Bangsa Yogyakarta (Approval No. 019/KE PK/I/2026).

2.10 *Statistical analysis*

All analyses were done in triplicate (except for sensory analysis). One-way ANOVA, Duncan's multiple range test (DMRT), Kruskal Wallis, and principal component analysis (PCA) were done using XLSTAT 2014 (Lumivero, Addinsoft, Paris, France). Pearson correlation analysis was done using SPSS version 25 (IBM Corp., Armonk, NY, USA). Analyses were done at 5% significance level.

3 Results and Discussion

3.1 *Physicochemical properties*

The moisture content (MC) of raw PL, LP, and BB was 70.6, 65.12, and 72.8%, respectively (Figure 1A). This was lower than that reported by Sukasih *et al.,* [6], who found that the MC was in the range of 80 – 87%. In another study, the MC of LP could be as low as 63.9 to 66.6% [27]. The frying process significantly reduced the MC of shallots to 3.32, 2.56, and 3.84% for PL, LP, and BB, respectively. This was in agreement with the previous study of Alam *et al.,* [28], who found that the MC of fried shallots was in the range of 2.6 – 4.4%. These differences might be contributed to by various factors such as cultivar, ambient temperature, and humidity.

Shallots are a highly perishable food ingredient; thus, the MC of raw bulbs should be kept as low as possible. However, for the fried product, the MC should be kept in optimum condition (a maximum of 5%). Low MC increases the brittleness of fried shallots. This increases the risk of damage to the product during storage and transport. On the other hand, high MC (>5%) should be avoided due to its higher risk of textural changes (soggy) and rancidity of the product.

The texture of the raw shallot was slightly varied. Raw shallot of BB had a significantly softer texture (p-value <0.05) compared to that of PL and LP (p-value >0.05) (Figure 1B). This result showed that the origin of cultivation significantly affects the characteristics of shallots produced. This was in line with Hulzana *et al.,* [27]. Environmental factors such as altitude, climate and soil condition affect the texture of shallot by influencing the genetic expression of the shallot plant, modulating various characteristics of the shallot bulb obtained [29]. PL and LP originated from the same area, namely the Donggala Regency, Central Sulawesi Province. On the other hand, BB was obtained from Brebes Regency, Central Java Province.

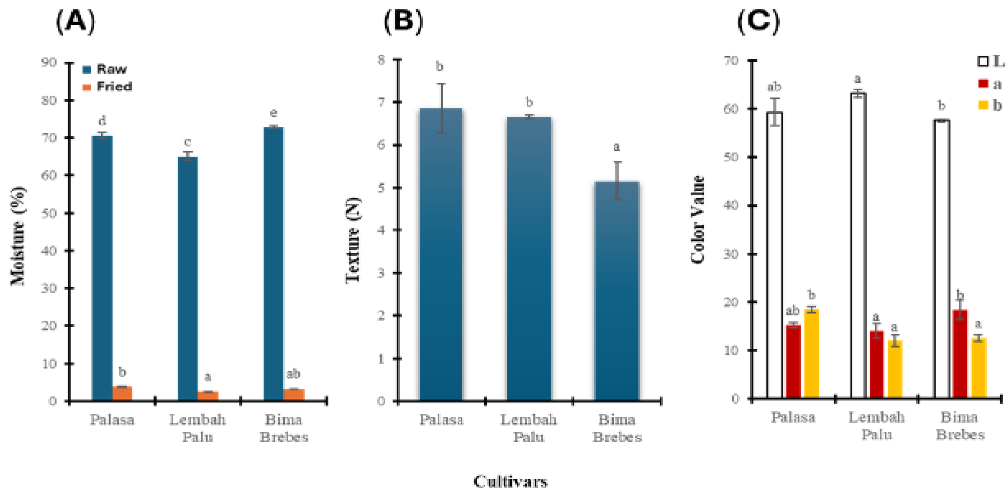

Figure 1: (A) Moisture content of raw and fried shallots obtained from different cultivars. (B) Texture, and (C) color value of raw shallots obtained from different cultivars. Different letters in the graph of each category show significant differences (p-value <0.05).

Shallots with denser texture are preferred over the softer ones [30]. This is related to the cell wall degradation during storage and processing [31]. PL and LP are more suitable for fried shallot production. This was in agreement with Yofananda *et al.,* [2].

Texture analysis of the fried shallots was not performed using instrumental methods due to their limitations in capturing the complex sensory perceptions experienced during consumption. Consequently, sensory analysis was employed to compare the textural properties of the samples, as discussed in detail in Section 3.5. This approach mirrors the color analysis in this study, which was also conducted via sensory evaluation to provide more consumer-oriented data and representative results.

In terms of color, BB had the darkest color compared to PL and LP. The BB raw shallot had the highest redness (+a), lowest yellowness (+b) and the lowest brightness/lightness value (L) (Figure 1C). This represents a range of bulb colour of light red to dark red [32] (Figure 2). On the other hand, the color of PL and LP was lighter and more yellowish. The red colour in shallots is caused by anthocyanins consisting of cyanidin or peonidin glucosides [33]. The appearance of fried shallots, as presented in this study, is also presented (Figure 2). Adiyoga and Nurmalinda [34] reported that the skin color of shallot was the most important parameter perceived by consumers, followed by price, size and aroma. Dark violet to red color is the most preferred color by consumers.

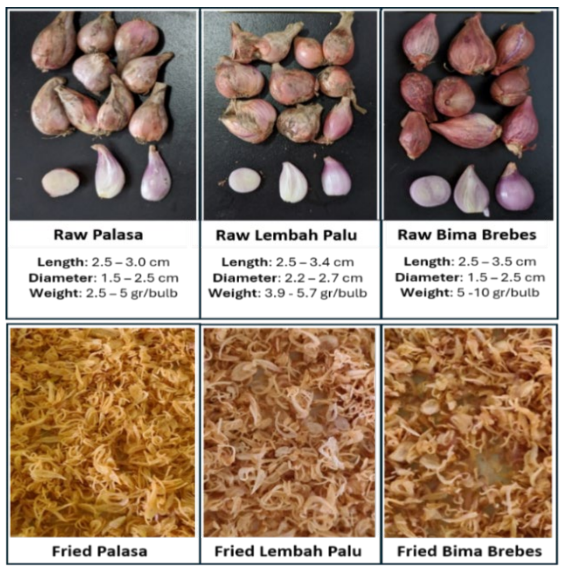

Figure 2: Appearance of raw and fried shallots obtained from different cultivars.

3.2 *Changes in the total phenolic content and antioxidant activity*

Deep frying of the shallots promoted the increase of TPC. Raw and fried shallots had TPC ranging from 6.39 to 12.1 mg GAE/100 g DB, equivalent to 2.22 to 11.7 mg GAE/100 g WB. TPCs evaluated in this study were higher than those reported by Ratseewo *et al.,* [35]. The BB cultivar was found to have the highest TPC, followed by PL and LP.

Raw shallots generally had lower TPC than that of fried ones (Figure 3). Shallots contain various phenolic acids such as vanillic, caffeic, syringic, p-coumaric, protocatechuic, ferulic, p-hydroxybenzoic, and sinapic acid. In addition, they also contain rutin, quercetin, apigenin, myricetin, and kaempferol from the flavonoid group. The increase in TPC after heat treatment might be due to several factors. The degradation of cell-wall components during high heat treatment [36] could promote the release of phenolics for improved extractability [37]. This is usually observed in low to moderate heat treatment, such as drying. However, frying is an extreme heat treatment. This process induces a high rate of Maillard non-enzymatic browning reaction, resulting in the production of Maillard Reaction Products (MRPs). The occurrence of MRPs could interfere with TPC analysis due to their reactivity with Folin reagent, resulting in an increase of TPC in the samples [35]. Hence, the increase in TPC should be noted as due to the occurrence of Folin-reactive compounds such as MRPs, and not from the release of phenolic compounds from cell walls. This was later confirmed by the result of AA analysis.

DPPH analysis was used to measure the AA. This was in line with the study of Locatelli *et al.*, [38] who reported that the AA of major antioxidant compounds, such as phenolic-based bioactive and some organosulfur, could be well-represented by the DPPH assay. The frying process significantly reduced the bioactivity of shallot samples. In this study, frying treatment significantly reduced (p-value <0.05) the antioxidant activity of shallot.

Raw shallots had an AA of 28.66 to 43.73% inhibition and were greatly reduced to only 3.98 – 7.89 % inhibition in fried shallots. Considering that phenolics are the major contributor of AA in shallot, this result shows that the degradation of phenolics occurred in shallot during frying. Flavonoids are susceptible to heat. Heat treatment could lead to the formation of various degradation products; for example, rutin can be polymerized during heating [39]. Phenolic acids, on the other hand, can bond with high MW compounds such as MRPs, rendering their bioactivity [40]. Furthermore, the less antioxidant activity of deep-fried shallots could be due to the losses (leached out) during frying. The discrepancies between TPC and AA analysis, specifically in wet and dry basis, emphasized that the differences in AA responses might be more contributed by the types of phenolic compounds, and the occurrence of MRPs. Raw BB, for example, had the lowest AA despite its high TPC, indicating the occurrence of low-AA phenolic.

Phenolics in shallot extracts were in the form of free phenolic acids and their glycosylated forms [41]. Thus, it is suspected that BB contains more glycosylated phenolic, which has less AA than their free counterparts, than that of PL and LP. However, detailed compositional analysis, such as employing chromatography, is needed to confirm this hypothesis.

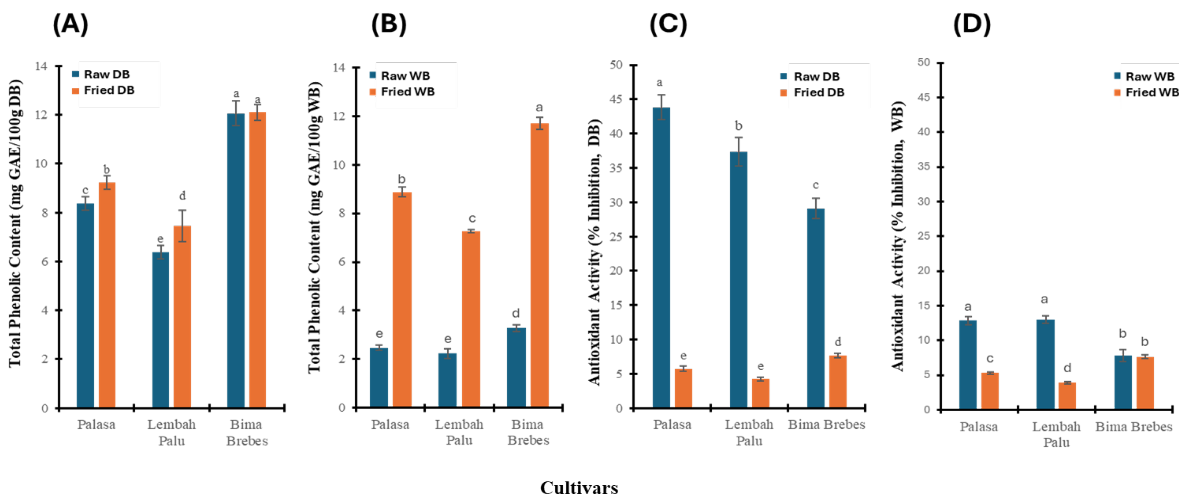

Figure 3: Total phenolic content of raw and fried shallot in dry basis (A) and wet basis (B) and antioxidant activity of raw and fried shallot in dry basis (C) and wet basis (D) obtained from different cultivars. Different letters in the graph of each category show significant differences (p-value <0.05).

Increased level of AA observed from fried BB compared to that of PL and LP was mostly affected by the formation of MRPs, resulting in high AA response (Figure 3C & D). MRPs were also found to exhibit high AA [42].

3.3 *Volatile compounds*

The volatile composition of raw and fried shallots was diverse. GCMS analysis identified 33 volatiles in fresh shallots and 23 in deep-fried shallots (Table 1). Based on their functional groups, volatiles in both fresh and deep-fried shallots can be classified into nine groups, namely disulfides (13), trisulfides (6), tetrasulfides (2), thiophenes (7), thianes (2), furan and pyran (2), pyrazines (3), Strecker degradation and other aldehydes (3), and miscellaneous (5). This was different from that of [24], who detected 11 volatile compounds in fresh onion and shallot. Among identified volatiles, two volatiles were unique in raw Palasa (dimethyl disulfide and dimethyl tetrasulfide) and 5 volatiles were unique in raw Bima Brebes (methyl propyl disulfide, 1-methylethyl 2-propenyldisulfide, allyl propyl trisulfide, dipropyl tetrasulfide and 3, 4-dimethylthiophene) (Figure 4A). These unique compounds contributed to a distinct sulfury, cabbage, onion flavor in raw Palasa and sulfurous, savory, roasted and onion flavor in raw Bima Brebes.

Recent studies confirm that shallot aroma is dominated by sulfur-containing volatiles, often accounting for more than 50% of total volatile compounds [43], and that these compounds are highly sensitive to biochemical and environmental modulation. A previous study showed that frying temperature significantly affects the composition and intensity of key aroma compounds in fried shallot oil [20]. In addition to processing effects, cultivation methods, environmental factors such as temperature, altitude, soil characteristics, and geographical origin may influence volatile composition and sensory characteristics [29],[44], [45]. Raw Bima Brebes had a significantly different aroma profile compared to that of Palasa and Lembah Palu. This might be attributed by its distinct cultivation area (Brebes) than that of PL and LP (Donggala). Thus, considering that the cultivars were cultivated in different regions, differences in volatile profiles among cultivars in this study could be attributed to both genetic diversity and growth conditions, suggesting a strong genotype × environment interaction [46].

The composition of volatiles based on their functional groups was different between raw and fried samples (Figure 4). Fried shallots generally have similar volatiles, indicating a similar flavor profile. Disulfides, trisulfides and thiopenes were the major groups in raw shallots. Disulfides and trisulfides are commonly identified in shallot [14], [19], [33], [47], and fried shallot oil [20]. Thiophenes are commonly found in fresh, fried shallots [19], [47], and fried shallot oil [20]. A smaller group of thianes was found in fresh shallots and onion oil [5], [48]. Disulfides, trisulfides, tetrasulfides, and thianes belong to sulfur-containing compounds. They are important flavor components in raw shallots. dimethyl tetrasulfide was identified in Persian shallot essential oils [49] but not found in fresh shallot [19], [31], [33] or fried shallot oil [20]. Fried shallots had disulfide, trisulfides, Strecker degradation product and aldehydes, pyrazine, furan and pyran as the major volatiles group. This represents the changes in the aroma profile from sulfury, earthy and cabbage found in raw shallots towards pungent, savory, roasted and nutty for fried shallots.

Several volatiles were found to be the determining factor differentiating the flavor of raw shallots from that of fried ones. Eighteen VCs (2-methyl-2-pentenal, 3,4-dimethylthiophene, methyl isopropyl disulfide, methyl propyl disulfide, 1-allyl-2-isopropyldisulfane, trans-propenyl propyl disulfide, 2-mercapto-3,4-dimethyl-2,3-dihydrothiophene, dimet-hyl 2-(2-methylprop-2-enyl)propanedioate, 3,4-dimet hylthiophene-2-thiol, 1-allyl-3-propyltrisulfane, 5-methyl-1,2,3,4-tetrathiane, 1-(1-(methylthio)propyl) -2-propyldisulfane, methyl 1-(1-propenylthio) propyl disulfide, hexathiane, 3,4-dimethyl-2-(methyl disulfanyl) thiophene, 1-(1-propenylthio) propyl propyl disulfide, 3,4-dimethyl-2-(propyldisulfanyl) thiophene, (E)-3,4-dimethyl-2-(prop-1-en-1-yldi sulfanyl) thiophene) were only identified in the fresh shallots. On the other hand, ten VCs (2-methyl-2-butenal, 2,6-dimethylpyrazine, methyl cis-propenyl disulfide, 2-ethyl-5-methylpyrazine, phenylacet aldehyde, 3-ethyl-2,5-dimethylpyrazine, 2,3-dihydro-3,5-dihydroxy-6-methyl-4H-pyran-4-one, unknown 1 (MW 180), 1,2,3,4-tetrahydro-1,1,6-trimethyl naphthalene, and butylated hydroxytoluene) were only identified in the deep-fried shallots.

Table 1: Volatiles compounds of raw and fried shallot obtained from different varieties.

Compounds	Code	LRI exp	LRI lit	Raw (Relative peak area, %)			Fried (Relative peak area, %)			Aroma description
				Palasa	*Lembah Palu*	*Bima Brebes*	*Palasa*	*Lembah Palu*	*Bima Brebes*	
Disulfides										
Dimethyl disulfide	ds1		770	0.74 ±0.159a	nd	nd	nd	nd	nd	onion, cabbage, putrid [A]
Methyl isopropyl disulfide	ds2	934		3.94 ±0.647a	1.32 ±0.411b	nd	nd	nd	nd	
Methyl cis-propenyl disulfide	ds3	936	932	nd	nd	nd	3.64 ±0.065a	2.91 ±0.363b	3.53 ±0.048a	
Methyl trans-propenyl disulfide	ds4	942	940	7.66 ±1.075a	1.45 ±0.549b	nd	19.1 ±0.832a	11.4 ±1.354c	13.9 ±0.266b	
Methyl propyl disulfide	ds5	944	946	nd	nd	3.89 ±0.980	nd	nd	nd	sulfury, onion [B]
1-Methylethyl 2-propenyl disulfide	ds6	1109	1100	nd	nd	0.60 ±0.039a	nd	nd	nd	
Dipropyl disulfide	ds7	1110	1107	nd	21.2 ±7.918b	59.2 ±3.389a	9.37 ±0.470c	16.1 ±0.176a	12.8±0.646b	sulfury, earthy [B]
cis-Propenyl propyl disulfide	ds8	1121	1110	20.2 ±3.820a	26.8 ±4.372a	tr	5.71 ±0.128b	12.2 ±0.138a	8.95 ±0.258c	
trans-Propenyl propyl disulfide	ds9	1131	1118	34.8 ±1.314a	33.5 ±3.117a	22.38 ±3.836b	nd	nd	nd	
1-(Methylthio)propyl propyl disulfide	ds10	1424	1431	0.02 ±0.005a	0.01 ±0.003b	nd	nd	nd	nd	
Methyl 1-(1-propenylthio)propyl disulfide	ds11	1432	1437	0.09 ±0.007a	0.01 ±0.000b	nd	nd	nd	nd	
1-(1-Propenylthio)propyl propyl disulfide	ds12	1600	1592	0.17 ±0.029a	0.10 ±0.007b	0.13 ±0.006ab	nd	nd	nd	
Trisulfides										
Dimethyl trisulfide	ts1	971	964	0.66 ±0.094	tr	nd	15.8 ±0.333a	8.12 ±1.160b	8.77 ±1.155b	sulfur, fish, cabbage [A]
Methyl propyl trisulfide	ts2	1157	1154	2.22 ±0.506a	0.25 ±0.058b	0.65 ±0.239b	3.53 ±0.112b	4.48 ±0.326a	2.79 ±0.114c	sulfurous, onion [B]
Methyl (1E)-1-propen-1-yl trisulfide	ts3	1170	1169	0.60 ±0.052a	0.05 ±0.019b	0.09 ±0.022b	13.9 ±0.457a	9.77 ±0.742b	7.57 ±0.237c	NF2
Allyl propyl trisulfide	ts4	1321	1321	nd	nd	0.04 ±0.005a	nd	nd	nd	sulfurous, alliaceous [B]
Dipropyl trisulfide	ts5	1330	1337	1.02 ±0.212b	0.82 ±0.039b	4.34 ±1.304a	tr	5.91 ±0.698	nd	sulfurous, green [B]
Di(1-propenyl) trisulfide	ts6	1352	1348	0.49 ±0.376	0.25 ±0.199	nd	1.27 ±0.122a	1.11 ±0.109a	0.76 ±0.032b	
Tetrasulfides										
Dimethyl tetrasulfide	te1	1218	1209	0.12 ±0.021	nd	nd	2.95 ±0.181a	2.31 ±0.298b	tr	cabbage, sulfur [A]
Dipropyl tetrasulfide	te2	1584	1570	nd	nd	0.35 ±0.035a	nd	nd	nd	
Thiophenes										
2,4-Dimethylthiophene	to1	913	903	5.36 ±0.159a	2.72 ±0.620b	nd	2.77 ±0.085	2.84 ±0.546	2.95 ±0.159	
3,4-Dimethylthiophene	to2	922	908	nd	nd	4.53 ±1.157	nd	nd	nd	savory, roasted, onion [B]
2-Mercapto-3,4-dimethyl-2,3-dihydrothiophene	to3	1141		7.45 ±0.736a	3.88 ±1.091b	nd	nd	nd	nd	
3,4-Dimethylthiophene-2-thiol	to4	1190	1194	0.38 ±0.112a	0.17 ±0.075b	0.17 ±0.084b	nd	nd	nd	
3,4-Dimethyl-2-(methyldisulfanyl)thiophene	to5	1498	1500	0.20 ±0.034a	0.02 ±0.012b	0.02*b	nd	nd	nd	
3,4-Dimethyl-2-(propyldisulfanyl)thiophene	to6	1662	1664	0.30 ±0.032ab	0.14 ±0.090b	0.38 ±0.137a	nd	nd	nd	
(E)-3,4-Dimethyl-2-(prop-1-en-1-yldisulfanyl)thiophene	to7	1668	1671	0.06 ±0.012	0.05 ±0.045	0.05 ±0.023	nd	nd	nd	
Thianes										
5-Methyl-1,2,3,4-tetrathiane	ta1	1365	1369	0.02 ±0.006a	0.01 ±0.003b	0.02 ±0.006a	nd	nd	nd	

Table 1: Volatiles compounds of raw and fried shallot obtained from different varieties. (Continued)

Compounds	Code	LRI exp	LRI lit	Raw (Relative peak area, %)			Fried (Relative peak area, %)			Aroma description
				Palasa	*Lembah Palu*	*Bima Brebes*	*Palasa*	*Lembah Palu*	*Bima Brebes*	
Hexathiane	ta2	1493	1499	0.02 ±0.006	0.01 ±0.003	0.01**	nd	nd	nd	
Strecker degradation & other aldehydes										
2-Methyl-2-butenal	sd1		676	nd	nd	nd	8.36 ±0.838b	6.93 ±0.457b	11.0 ±1.249a	pungent, green [B]
2-Methyl-2-pentenal	sd2	835	830	1.57 ±0.457ab	1.12 ±0.457b	2.11 ±0.190a	nd	nd	nd	pungent, fruity [B]
Phenylacetaldehyde	sd3	1045	1047	nd	nd	nd	1.72 ±0.085b	1.08 ±0.122c	4.82 ±0.326a	green, floral [B]
Pyrazines										
2,6-Dimethylpyrazine	py1	917	906	nd	nd	nd	tr	tr	tr	ethereal, cocoa, nutty [B]
2-Ethyl-5-methylpyrazine	py2	1001	1002	nd	nd	nd	tr	tr	tr	coffee, beany, nutty [B]
3-Ethyl-2,5-dimethylpyrazine	py3	1081	1083	nd	nd	nd	5.12 ±0.342a	3.34 ±0.164b	5.24 ±0.447a	potato, cocoa, roasted, nutty[B]
Pyran and furan										
2,3-Dihydro-3,5-dihydroxy-6-methyl-4H-pyran-4-one	pf1	1142	1130	nd	nd	nd	1.20 ±0.192b	0.67 ±0.163b	7.09 ±0.922a	
2-Hexyl-5-methyl-3(2H)-furanone	pf2	1442	1446	0.10 ±0.134	0.24 ±0.168	0.17 ±0.070	0.25 ±0.092b	0.96 ±0.208a	0.28 ±0.136b	
Miscellaneous										
Dimethyl 2-(2-methylprop-2-enyl) propanedioate	mc1	1183		11.8 ±1.372a	5.83 ±1.852b	nd	nd	nd	nd	
Naphthalene	mc2	1188	1182	0.05 ±0.034	0.03 ±0.005	0.05 ±0.013	2.42 ±0.300b	2.44 ±0.218b	3.98 ±0.359a	tar [A]
Unknown 1 (MW 180)	mc3	1344		nd	nd	nd	2.05 ±0.356c	5.97 ±0.714a	4.09 ±0.092b	
1,2,3,4-Tetrahydro-1,1,6-trimethylnaphthalene	mc4	1359	1284	nd	nd	nd	0.45 ±0.050c	0.60 ±0.092b	1.03 ±0.061a	
Butylated hydroxy toluene	mc5	1516	1510	nd	nd	nd	0.24 ±0.039c	0.32 ±0.048b	0.54 ±0.034a	phenolic [B]
Unknown 2	mc6	1587		0.04 ±0.003b	0.06 ±0.020b	0.80 ±0.514a	0.23 ±0.067b	0.48 ±0.119a	nd	

Presentation of data on the relative amount of compounds from the calculation of the average relative area of 3 replications ± standard deviation (SD); nd = no detection; nf = not found; tr= trace; * = components obtained only at 1 replication; ** = components obtained only at 2 replications.
LRIexp = linear retention index from this study; LRIlit= linear retention index from literature. Linear Retention Indexes (LRIes) literature (LRI lit) was obtained from references utilizing HP-5MS column [50]-[52],[53]-[55],[56]-[58].
Different letters within the same row in the same category (raw of fried) for fresh or fried shallots denote significant differences. A, Aroma description obtained from a database on the web at http://flavornet.org/flavornet.html. B, Aroma description obtained from a database on the web at http://www.thegoodscentscompany.com/search3.php

However, Chyau *et al.,* [15] reported dimethyl disulfide and 2-methyl-2-pentenal in the deep-fried shallot. Hence, this great difference in the volatile type shows that the frying process significantly alters the chemical composition of the shallots.

The deep-frying process is a complex reaction that includes lipid oxidation, Maillard reaction, hydrolysis, and amino acid degradation [31]. Pyrazines and Strecker degradation are some volatile products of the Maillard reaction. The Maillard reaction is a chemical reaction between amino acids and reducing sugars at elevated temperatures. This reaction produces a complex set of volatiles, namely sugar dehydration products (furans, pyrones, cyclopentenes, carbonyl compounds), amino acid (Strecker) degradation products (aldehydes, sulfur compounds, nitrogen compounds), and volatile compounds (pyrroles, pyridines, pyrazines, imidazoles, oxazoles, thiazoles, thiophenes, dithiolanes, trithiolanes, dithianes, trithianes, furanthiols) [59].

In this study, Maillard-derived volatiles, i.e., 2,6-dimethylpyrazine, 2-Ethyl-5-methylpyrazine, 3-Ethyl-2,5-dimethylpyrazine, 2-methyl-2-butenal, and phenylacetaldehyde were unique volatiles identified only in the fried shallot samples.

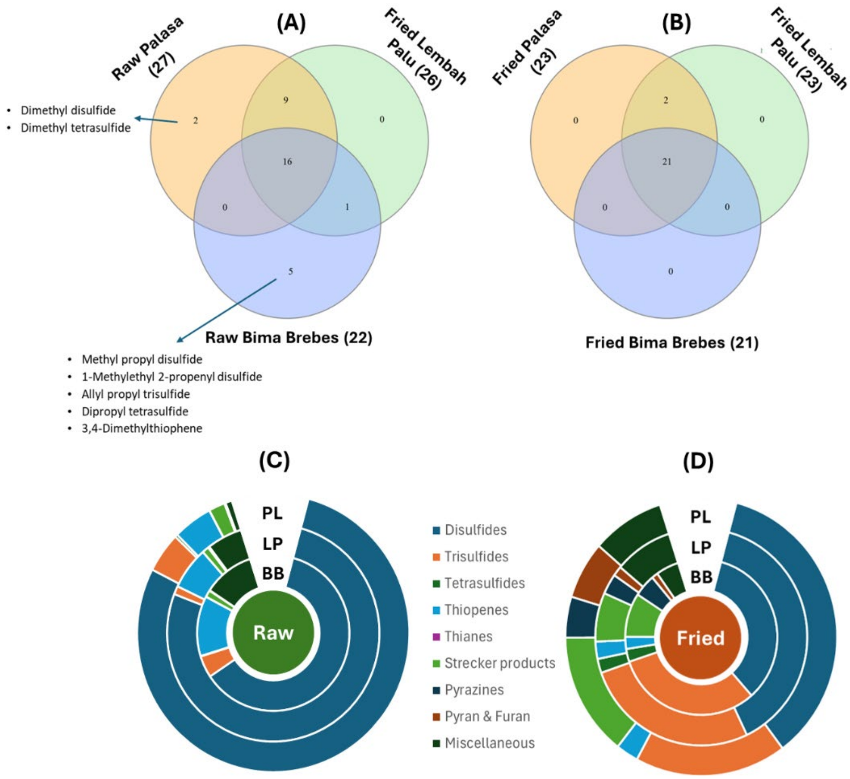

Figure 4: (A) Venn diagram of volatiles compounds of raw shallots from different cultivars; (B) Venn diagram of volatiles compounds of fried shallots from different cultivars; (C) Circular stacked bar chart of volatiles based on the functional group of raw shallots from different cultivars; (D) Circular stacked bar chart of volatiles based on the functional group of fried shallots from different cultivars. PL, Palasa; LP, Lembah Palu; BB, Bima Brebes.

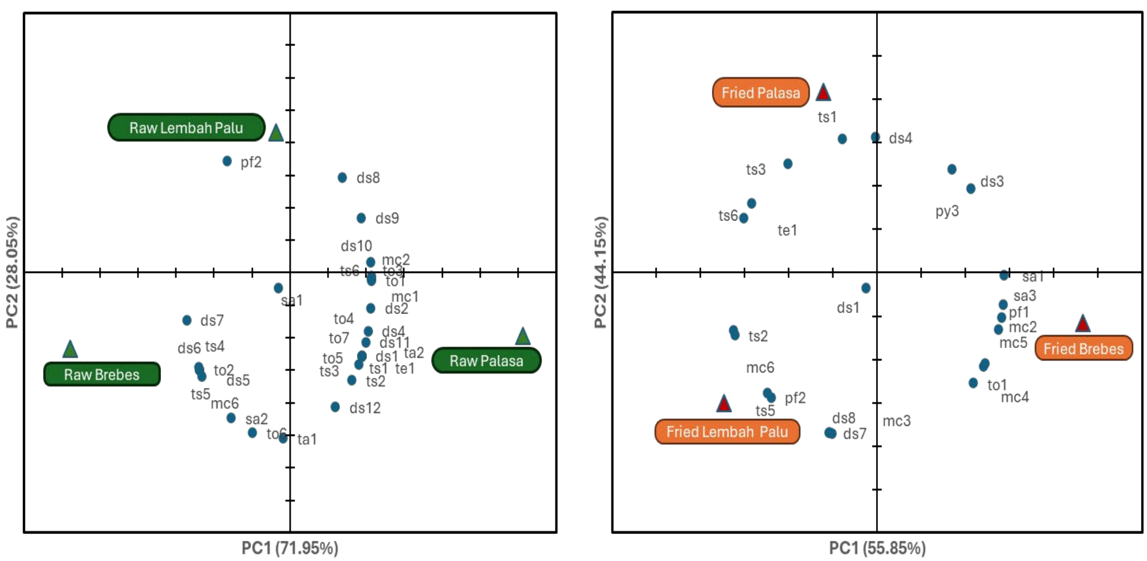

Figure 5: Principal component analysis result on the volatiles composition of raw (*left*) and fried shallots (*right*) obtained from different cultivars. Quadrant, (x, y): I, (+, +); II, (-, +); III, (-, -); IV, (+, -). Abbreviations in the compounds should refer to Table 1.

3.4 *Principal component analysis*

Principal component analysis (PCA) was done on the volatiles to explain their variations among raw and fried shallot samples (Figure 5). Due to a limited number of samples analyzed, a total of 100% of the variances could be explained by PC1 (71.95%) and PC2 (28.05%) for raw samples and PC1 (55.85%) and PC2 (44.15%) for fried samples. Clear separation of raw and fried samples was obtained. Raw PL and were placed in quadrant IV, characterized by a high concentration of volatiles such as disulfides and thiophene, while Raw LP was positioned in quadrant II. In contrast, raw BB was placed in quadrant III, characterized by a high concentration of dipropyl disulfide. Different groupings, as shown between raw PL, LP and BB showed great differences in the volatiles profile between raw BB, PL and LP. Horizontally, raw LP was in the middle part, resembling a combination of BB and PL. This separation highlighted their cultivar differences. However, as mentioned in the previous section (physicochemical properties), raw PL, LP and BB were cultivated in different areas. Thus, it is possible that the differences in volatiles on raw shallots were more affected by the environmental factor of the cultivation origin. However, analysis of the shallot obtained from multi-location trials should be done to further confirm this finding.

Fried shallot samples had a similar volatile composition. They were all placed in the intersection between quadrants II and III. They were characterized by the occurrence of Maillard reaction products, pyran & furans, and miscellaneous compounds. Fried shallots were dominated by the roasted, pungent, savory, and nutty flavor rather than the sulfury, onion, and cabbage flavor found in the raw shallots.

This shows that frying of the shallots could eliminate/reduce a great concentration of volatiles occurring in raw shallots. This produced a similar volatile composition of fried shallots.

In terms of volatiles, the frying treatment could reduce the effect of environmental conditions. This was shown by the similarity of volatiles composition of fried samples despite the occurrence of unique volatiles in raw shallots.

This finding is important for industrial purposes. A product with uniform flavor characteristics can be obtained by frying treatment despite their different origin and cultivars. However, despite that they have similar volatile profiles, the sensory quality of the fried shallots was still determined by other sensory attributes, such as taste, color, crispness, and form/shape.

3.5 *Sensory quality*

Fried shallots of PL, LP and BB have different sensory profiles, significantly affecting customer preferences (Figure 6). Yofananda *et al.,* [3] reported that the definition of good quality fried shallot is attributed to golden brown color, fragrant sulfury aroma, sweet aroma, no/low rancid aroma, savory taste, sweet taste, salty and low bitterness. In the textural context, it is preferred that fried shallots are intact in form/shape and crispy. In this context, fried PL and LP were known to have superior form and crispness, incomparable to fried shallot from different origin [60].

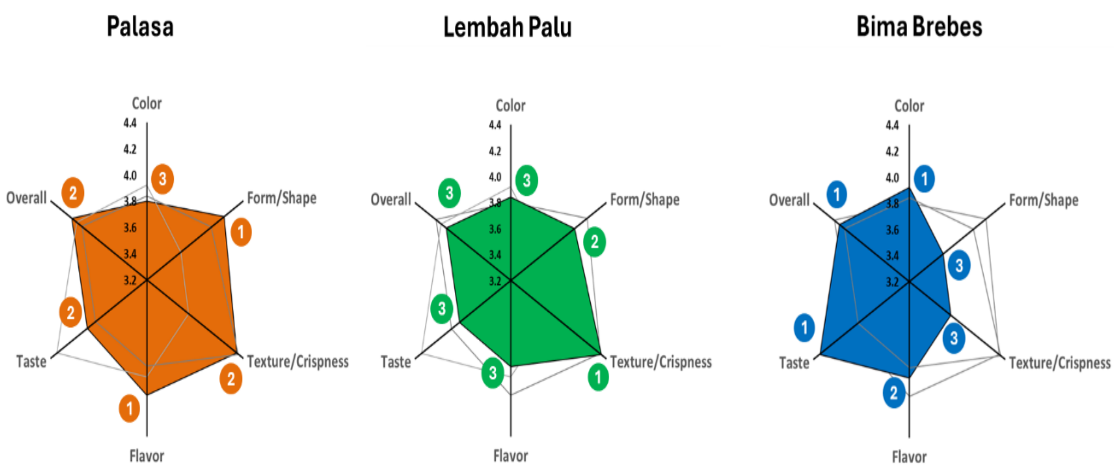

Figure 6: Hedonic and ranking test results on the fried shallots obtained from different cultivars. The radar plot showed the hedonic test result. The numbers on the outside part of the radar chart showed the ranking of customer preferences.

Crispness relied heavily on the perception of "sound" by the consumer, which may not be fully captured or variably perceived with the use of a texture analyzer [61]. This was a similar case to the soup product, in which the soup viscosity significantly affects customer acceptance [62]. Hence, sensory analysis was the best method for representing the acceptance of texture by the consumer.

Fried PL and LP showed somewhat similar sensory perception, while BB showed otherwise. Fried PL showed high preferences in form/shape, texture/crispness and flavor. Fried PL is characterized by its intact form after frying, boosting its ability to retain its sliced form during frying. This feature is preferred by customers rather than having fried shallots with broken form/shape [3].

This character was one of the best features of fried PL, significantly higher than that of LP and BB. Furthermore, it was supported by good texture/crispness and strong flavor. This result was in line with the physicochemical changes previously discussed. Texture, flavor, and aroma were indirectly related to one another. More porous texture facilitates an increased release of aroma compounds during consumption by expanding the surface area for volatilization. This results in high perceivability of flavor by panelists. However, intact texture may inhibit the release of volatiles. On the other hand, high concentrations of specific volatiles often indicate an intensive Maillard reaction that comprises the cell wall matrix; it serves as a chemical marker for the structural breakdown, altering the textural integrity.

In terms of flavor, customers prefer sulfury and sweet flavor but dislike the occurrence of rancid flavor [2], [18]. In this term, PL had no rancid flavor as a limiting factor for the fried shallot's flavor. However, the color was the weakness of fried PL. It had the lowest customer preferences. This might be due to its undercooked color (brownish white) or overcooked color (dark brown).

Customers prefer the golden-brown color rather than lighter or darker brown color [2].Fried LP showed a similar character to that of fried PL. However, in most of the aspects, they were inferior. Texture/crispness was the strong point of LP. It was similar to that of PL but was preferred by consumers. It was less intact than that of PL but was still acceptable. However, in terms of flavor, taste, color and overall quality, fried LP showed the lowest preference. This might be due to unwanted attributes such as rancid flavor, bitter taste, and undercooked/overcooked color. Consumers desired a savoury taste but disliked the bitter taste in fried shallots [2]. Furthermore, the bitter taste is a sensory limiting factor in the acceptance of fried shallots. Yofananda *et al.,* [18] studied the correlation between amino acid profiles and fried shallot sensory properties. They concluded that L-phenylalanine, L-arginine, and glycine were critical amino acids for the sweet taste of deep-fried shallots. Hence, it could be hypothesized that LP had low concentrations of those amino acids, resulting in a low sweetness-high bitterness taste. However, further comprehensive analysis of the amino acid composition should be carried out. BB showed different sensory profiles compared to those of PL and LP. BB showed high preferences on taste, color and overall acceptance. Taste-wise, BB was more appetizing than PL and LP. However, it had the worst acceptance on the attributes of form/shape and crispness. Fried BB tends to break apart after frying and is unable to preserve its intact structure. It was also less crispy than PL and LP. Thus, it was concluded that fried shallot samples used in this study excelled in two different aspects: textural (PL and LP) and taste (BB). Their combination of characteristics would be fried shallots with optimum preferences. However, on its own, these fried shallots might be suitable for usage for different purposes.

3.6 *Industrial relevance*

This study showed that there was a great difference between observed raw and fried shallot samples in terms of physicochemical, volatiles, and sensory quality. However, the interpretation of the results showed that the samples belong to three distinct groups of shallots. One group consisted of PL and LP. They had similar characteristics in almost every attribute analyzed (texture, color, appearance, TPC, AA, and volatile composition). Furthermore, they belonged to a fried shallot with high textural attributes in terms of sensory quality. They were significantly different from that of BB, which was taste-focused in quality.

Considering that the samples came from different origins, it is suspected that geographical conditions may affect the quality of shallots more than genetics. Furthermore, soil characteristics and cultivation practices, including fertilization and irrigation, significantly affect the physicochemical properties of bulbs [63]. Further study, such as a multi-location trial, related to environmental factors and inputs, is needed to confirm this hypothesis.

In terms of bioactivity, AA of fried shallots was significantly low despite its increased TPC. This contradiction needs to be confirmed further. Shallots are known as an ingredient with health benefits. Hence, a study utilizing different methods of antioxidant analysis, such as ABTS, FRAP, CUPRAC, and *in vivo* based biological activity, should also be carried out as complementary to that of the DPPH method. The bioactive compounds in shallot may act differently as antioxidants compared to known bioactive compounds such as flavan-3-ols and anthocyanins. A study on the bioavailability of these bioactives in digestion system should also be evaluated. The complex of phenolic acid-Maillard reaction product has been reported to have high bioavailability in the colon rather than in other digestion track.

Some interesting relationship between physicochemical, volatiles and sensory quality was found in this study (Figure 7). For example, AA of raw shallots was positively correlated (p-value <0.05) with the occurrence of thianes and negatively correlated with that of pyran and furan (p-value <0.05). On the other hand, in term of sensory quality, color was found to be correlated with Strecker degradation product (–, p-value <0.05), crispness with Strecker degradation product (+, p-value <0.05), flavor with miscellaneous (–, *p-value* <0.05), taste with pyrazines, Strecker, pyran and furan, and misc (–, p-value <0.05), flavor, taste, and overall with trisulfides and tetrasulfides (+, p-value >0.05) and overall quality with that of pyran and furan (–, p-value <0.05). Interestingly, an intensive Maillard reaction during frying was not desirable.

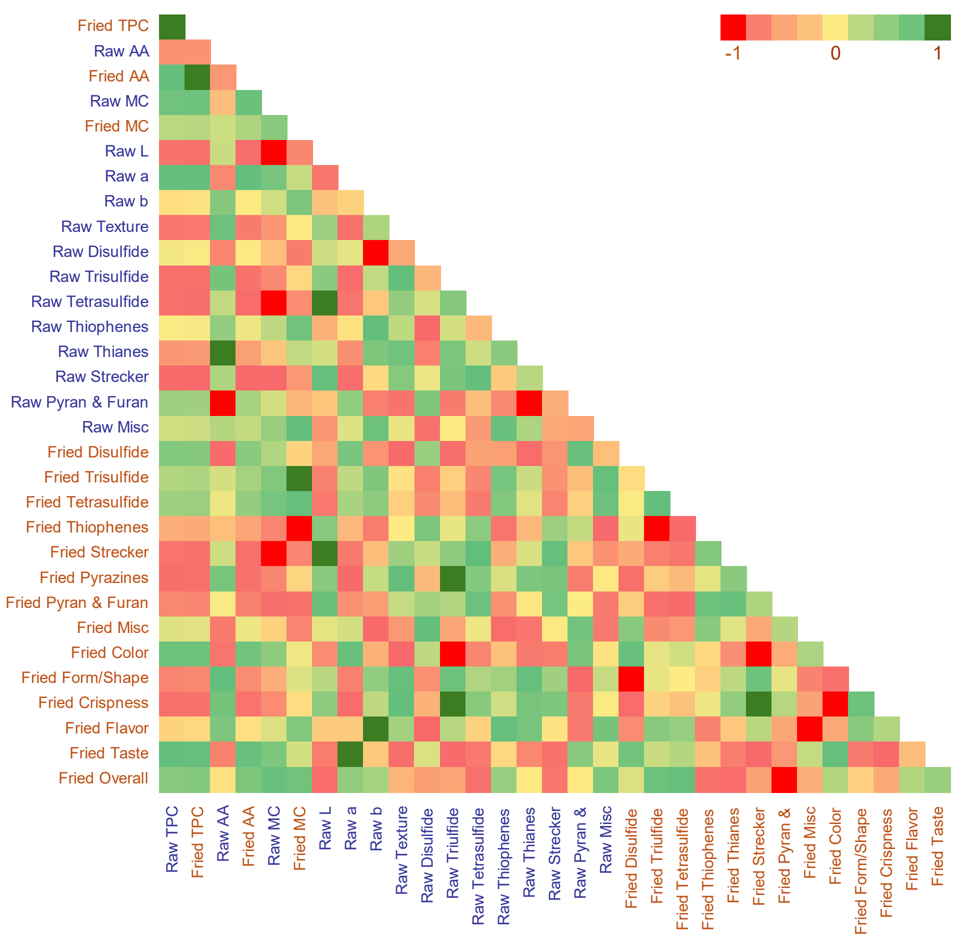

Figure 7: Correlation between physicochemical, volatiles and sensory quality of raw and fried shallot based on Pearson correlation analysis.

The occurrence of Maillard reaction products such as pyrazines, Strecker degradation products, aldehyde, pyran and furan reduces the quality of color and taste despite improving the flavor and texture. Thus, taste-wise, it was concluded that the consumer desires a fried shallot product that retains its unique raw shallot flavor (such as disulfides, trisulfides and tetrasulfides).

In industrial practices, cooking oil is often used repeatedly to reduce costs, leading to the accumulation of oil oxidation products. These volatiles, often perceived as rancid, can compromise the sensory quality of fried shallot products. In this study, fresh oil was utilized to minimize the formation of such compounds.

However, further research mimicking current industrial practices is necessary to optimize the process, specifically focusing on producing high-quality fried shallots while maintaining cost efficiency. Alternative frying methods, such as vacuum frying, should be evaluated for their possibilities to replace the currently practiced deep-fried process. Low-temperature vacuum frying on these cultivars, especially PL and LP, is expected to produce fried shallots with improved taste properties. Furthermore, it will also help to preserve the bioactive compounds and their activity on the products.

In the context of the possible substitution of region-specific PL and LP, BB is prospective due to its lower price. PL and LP were priced at around IDR 55,000 (eq. USD 3.13, 1 USD ~ IDR 17,578) per kg, significantly higher than BB (IDR 40,000 ~ USD 2,28). Furthermore, the region-specific nature of PL and LP cultivation inherently results in a limited and localized supply. In contrast, the adoption of non-region-specific varieties like BB could potentially increase supply stability for larger-scale production. However, our findings suggest otherwise; our results indicate that BB possesses a significantly different chemical and sensorial profile that does not align with those of PL and LP. Consequently, BB cannot be considered a suitable substitute if the objective is to maintain the authentic aromatic and sensory characteristics of the Central Sulawesi-origin shallots. While BB offers a distinct economic advantage, its chemical divergence suggests that the premium market value of PL and LP is fundamentally tied to their unique volatile compositions, which are not replicated by the more widely available BB variety.

Similar to the result of Kitsawad and Tuntusripreecha [64] on the evaluation of instant spices (powder-, paste- and liquid-based) and Ting Chen *et al.,* [62] on soup-based products, physicochemical and sensory attributes strongly influence consumer perception and product utilization. Therefore, current fried BB products may be utilized for different purposes based on their strong sensory attributes. Fried BB, which had good taste-related attributes but low in texture, may be used for powdered spice, purposefully for enhancing the sensory quality of food.

4 Conclusions

Deep frying induced substantial physicochemical and chemical transformations in the three shallot cultivars–Palasa (PL), Lembah Palu (LP), and Bima Brebes (BB). The significant reduction in moisture content confirmed the intensity of thermal treatment across all cultivars. Although total phenolic content increased after frying, antioxidant activity decreased in PL, LP, and BB, which may be associated with thermal–induced alteration of phenolic structures and potential interactions with thermally generated Maillard reaction products that could influence radical-scavenging capacity. Volatile profiling demonstrated a clear transition from sulfur–dominated compositions in raw samples–characterized primarily by disulfides, trisulfides, and thiophenes–toward thermally generated compounds in fried samples, including pyrazines, Strecker-derived aldehydes, furans, and pyrans. Raw PL and LP exhibited similar sulfur profiles, whereas raw BB was characterized by a higher abundance of dipropyl disulfide, indicating cultivar-dependent differences in intrinsic sulfur composition. After frying, all cultivars showed reorganization of the volatile matrix, although variations in the relative distribution of thermally formed compounds were observed. Principal component analysis further confirmed distinct separation between raw and fried samples and highlighted differential clustering among cultivars. Overall, these findings demonstrate that intrinsic biochemical composition governs the thermal transformation pathways of each cultivar. This study provides mechanistic insight into sulfur compound transformation and flavor generation during deep frying and highlights cultivar-specific chemical responses in thermally processed *Allium*-based products, especially *Allium cepa* L. var. *aggregatum* products.

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Author Contributions

S.D.I.: Conceptualization, Methodology, Data Curation, Validation, Writing - Original Draft, and Writing - Review & Editing; H.P.: Conceptualization, Methodology, Data Curation, Validation, Writing - Original Draft, and Writing - Review & Editing; D.D.H. : Methodology, Data Curation, Validation, Writing - Original Draft, and Writing - Review & Editing; E.A.: Conceptualization, Methodology, Data Curation, Validation, Writing - Original Draft and Writing - Review & Editing; Saidah: Conceptualization, Methodology, Data Curation, Validation, Writing - Original Draft and Writing - Review & Editing; I.A.: Conceptualization, Methodology, Data Curation, Validation, Writing - Original Draft, and Writing - Review & Editing; M.F. : Methodology, Data Curation, Validation, Writing - Original Draft, Writing - Review & Editing; Yulianti : Methodology, Data Curation, Validation, Writing - Original Draft and Writing - Review & Editing ; Y.A. : Conceptualization, Methodology, Data Curation, Validation, Writing - Original Draft, and Writing - Review & Editing; D.K. : Methodology, Data Curation, Validation, Writing - Original Draft and Writing - Review & Editing; J.J.: Methodology, Data Curation, Validation, Writing - Original Draft; Sudarmaji: Conceptualization, Methodology, Data Curation, Validation, Writing - Original, and Writing - Review & Editing.

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Ethical approval

Ethical approval for the sensory evaluation was granted by the Ethical Committee Health Research STIKES Guna Bangsa Yogyakarta (Approval No. 019/KEPK/I/2026).

Informed Consent

Informed consent was obtained from all panellists involved in the sensory evaluation

Data Availability

The data supporting the findings of this study are presented within the article. Raw dataset generated during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors utilized the ChatGPT tool to enhance the language and readability of the manuscript.

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