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Physicochemical and Antioxidant Properties of Oil- and Vinegar-Based Pickles Developed from Edible Mushrooms

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ABSTRACT

Edible mushrooms' fragility urges preservation such as drying, freezing, canning or pickling etc. to mitigate postharvest mushroom losses. A comparative study was carried out to evaluate the physicochemical, antioxidant and sensorial properties of oil- and vinegar-based pickles prepared from button and oyster mushrooms. A total of four pickle formulations were developed from edible mushrooms (EM) and pickling liquids (PL): BMxO (Button Mushroom with Oil), BMxV (Button Mushroom with Vinegar), OMxO (Oyster Mushroom with Oil), and OMxV (Oyster Mushroom with Vinegar). The physicochemical properties and antioxidant activities of the pickle samples were analyzed using standard analytical procedures. The results revealed significant differences ($P < 0.05$) among all formulations. OMxO exhibited significantly higher pH (5.12), protein (3.84%), fat (10.49%), crude fiber (2.89%) and overall acceptability score (8.4). In contrast, OMxV showed significantly higher titratable acidity (1.40%), water activity (0.90), salt concentration (2.00%), moisture content (76.92%), and antioxidant properties, including DPPH radical scavenging activity ($IC_{50} = 89.26 \mu\text{g/mL}$), ABTS radical scavenging activity ($IC_{50} = 75.38 \mu\text{g/mL}$), and total phenolic content (253.82 mgGAE/100 g). The findings from present study indicate that OMxV showed most favorable antioxidant profile, whereas OMxO demonstrated superior nutritional composition. Both button mushroom pickle formulations however exhibited intermediate performance for most attributes studied. Based on physicochemical, antioxidant, sensorial properties, it is concluded that oyster mushroom-based pickles showed promising outcomes since OMxO remained exceptional for its nutritional and sensory properties while OMxV featured distinct antioxidant activity.

KEYWORDS: Edible mushroom pickle, physicochemical properties, and antioxidant activity

INTRODUCTION

Edible mushrooms are gaining an exponential scientific attention (Li & Xu, 2022). They are rich in protein, crude fiber, polyunsaturated fats, vitamins, minerals and valuable bioactive compounds such as ergothioneine, ergosterols, beta glucans etc. with potent antioxidant activities (Sifat *et al.*, 2020). Among edible mushroom species, button mushroom (*Agaricus bisporus*) and oyster mushroom (*Pleurotus ostreatus*) are widely cultivated and consumed (Kumari *et al.*, 2025) edible mushrooms on global scale because of their affordability, nutritional value, palatability, and functionality. Recent research demonstrates that Button mushrooms are loaded with essential nutrients, phenolic compounds, and enzymatic antioxidants etc. contributing to oxidative stability and related health benefits. Oyster mushroom is rich in protein (15–30% by dry weight basis), possess low lipid, and higher levels of crude fibers like β -glucans, which significantly contribute to immunomodulatory and antioxidant activities (Ahmed *et al.*, 2016). Despite their nutritional richness, both oyster and button mushrooms are highly perishable. Moreover, their higher moisture levels (85 to 90%) make them susceptible to microbial spoilage and enzymatic browning etc. Due to these challenges, button and

oyster mushroom spoil faster even under controlled conditions. This constraint necessitates efficient mushroom preservation strategies to extend their shelf stability while retaining nutritional and functional quality intact (Khaskheli *et al.*, 2025). Among different mushroom preservation strategies, pickling is now emerging as a promising value addition technique for mushrooms. Vinegar acidification lowers pH value in pickles while in oil pickling, Lactic Acid Bacteria on surface of mushroom fruiting bodies serves the role of natural starter for fermentation. This attributes not merely increases mushroom's shelf life but improves the physicochemical and sensorial properties of the pickle matrix. Pickles prepared in oil can reduce oxidative degradation by narrowing oxygen exposure, whereas vinegar-based pickle exhibits lower pH, thereby limiting microbial contamination/ growth and inducing bioactive stability (Melese & Workneh, 2015). Nevertheless, mushroom pickling significantly influences overall physicochemical attributes. Moreover, process-mediated pickling changes induce degradation and retention of antioxidants, thereby facilitating functional quality of final mushroom pickles.

Mushroom pickle preservation media (oil, vinegar, brine or their combination) significantly influences

physicochemical attributes, antioxidant activity, and sensory attributes. For instance, pickles developed from shiitake mushroom reported to have measurable variations in total phenolic compounds (TPC), 2,2-diphenyl-1-picrylhydrazyl (DPPH), and 2,2'-Azino-bis-3-ethylbenzothiazoline-6-sulfonic acid (ABTS) free radical scavenging activities depending on oil incorporation, demonstrating that lipid-rich pickle media may modulate retention and release kinetics of antioxidant (Khaskheli *et al.*, 2017). Although limited comparative studies have been carried out on assessing physicochemical and antioxidant properties of oil- and vinegar-based pickles of button and oyster mushroom. Therefore, current study aimed to evaluate and compare the physicochemical properties and antioxidant potential (DPPH inhibitory concentration 50 value, ABTS inhibitory concentration 50 value) of oil- and vinegar-based edible mushroom pickles. This study will provide scientific insight into preservation media effect on quality retention and will further support in developing value-added edible mushroom-based functional foods with prolonged shelf stability and health-benefiting potential.

MATERIALS AND METHODS

Raw materials and study design: White button mushroom (*Agaricus bisporus*) at immature button

stage and white oyster mushrooms (*Pleurotus ostreatus*) at early maturity stage were procured from Sungold farm Bahawalpur, Pakistan. The identification of mushroom was done by the Department of Plant Pathology, Sindh Agriculture University Tandojam. The ingredients for pickle making were purchased from Dawood mart, Hyderabad. Reagents, chemicals and glassware used were of analytical grade. In this study, 2×2 factorial design was set for a simultaneous evaluation of main (independent) and interactive effects of Factor A (mushroom types) i.e. button mushroom (BM) and oyster mushroom (OM) and Factor B (pickling levels) i.e. oil (O) and vinegar (V) across four distinct pickle formulations.

Pickle processing: Mushroom pickles were developed as per method described by Singh *et al.* (2018) with slight modification. Mushrooms were washed, cut, and dried for 5 to 10 minutes in cabinet dehydrator at 40°C. All spices were manually cleaned, properly mixed and added into sterilized air-tight glass jars followed by adding mushroom. Finally, 10 ml of oil (mustard oil) and vinegar (5% acetic acid) were added into 80g of mushroom in respective jars (Table 1). The jars were placed at ambient temperature for 7 days and analyzed for physicochemical properties, antioxidant activity and sensory evaluation.

Table 1. List of ingredients used for the development of 100g of edible mushroom pickles

Ingredients	Button mushroom oil pickle (BMOP)	Button mushroom vinegar pickle (BMVP)	Oyster mushroom oil pickle (OMOP)	Oyster mushroom vinegar pickle (OMVP)
Mushroom (g)	80	80	80	80
Chilli powder (g)	2	2	2	2
Turmeric powder (g)	0.5	0.5	0.5	0.5
Mustard seed (g)	0.5	0.5	0.5	0.5
Cumin seeds (g)	1	1	1	1
Fenugreek seeds (g)	0.5	0.5	0.5	0.5
Carom seeds (g)	0.5	0.5	0.5	0.5
Salt (g)	1	1	1	1
Mustard oil (ml)	10	-	10	-
5% Vinegar (ml)	-	10	-	10
Fennel seeds (g)	1	1	1	1
Black seeds (g)	0.5	0.5	0.5	0.5
Asafetida (g)	0.5	0.5	0.5	0.5
Sugar (g)	2	2	2	2
Total weight (g)	100	100	100	100

Physicochemical properties : All pickle samples were determined for moisture, protein, fat, crude fiber, pH value and titratable acidity (TA) as per method described by AOAC (2019). Water activity (a_w) was measured as proposed by Chien *et al.* (2023). 3g of homogenized sample was placed in plastic vessel and reading was noted on water activity meter. Pickle salt concentration (SC) was determined by diluting homogenized pickle. Sample was cooled and filtered followed by gentle heating (10–15 minutes). Ten ml filtrate was mixed with potassium chromate indicator and titrated against 0.1 N AgNO_3 . Permanent brick red color was observed as endpoint and titer value was

noted. Following formula was used to calculate salt concentration:

$$\text{SC (\%)} = V \times N \times 58.44 \times 10 \times 100 / W \times 1000$$

[V = Volume of AgNO_3 used (mL), N = Normality of AgNO_3 , 58.44 = Molecular weight of NaCl, 10 = dilution factor, W = Weight of sample (g), 1000 = mg to g conversion factor]

Antioxidation activity

Preparation of mushroom pickle extracts: Pickle extract was prepared as per method described by Modi, *et al.* (2014) with slight modifications. Pickle was homogenized and extract was filtered. The pickle extract was vortexed and centrifuged while supernatant

(stock solution) from centrifuged extract was kept and used for preparing different pickle extract concentrations using 70% methanol for determining DPPH IC₅₀ /2,2-diphenyl-1-picrylhydrazyl inhibitory concentration₅₀) whereas for ABTS IC₅₀ /2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid), distilled water: 70% methanol (50:50) were used.

DPPH IC₅₀ value (µg/ml): DPPH IC₅₀ value of mushroom pickle extract was determined as per method proposed by Vamanu (2012) with slight modifications. A standardized stock solution, pickle to 70% methanol (1:10) was prepared and its different concentrations were mixed with DPPH solution. Absorbance was measured at 517 nm using spectrophotometer against control whereas % inhibition was computed using this formula:

$$\% \text{ Inhibition} = A_0 - A_1 / A_0 \times 100$$

[A₀ = Absorbance of control, A₁ = Absorbance of sample]

ABTS IC₅₀ value (µg/ml): The ABTS IC₅₀ value of edible mushroom pickle was measured by decolorization method as described by Mendes *et al.* (2011) with some modifications. 7 mM ABTS stock solution mixed with 2.45 mM potassium persulfate to develop ABTS radical-cation solution by keeping mixture in the dark for 16 hours at room temperature (26°C). Stock solution of pickle extract was prepared at pickle-to-solvent ratio (1:10 w/v) followed by serial dilution. Various concentrations of pickle extract and vitamin C (standard antioxidant) were added to ABTS solution and mixed gently. Mixture was set to react for 6 minutes at 26 °C.

The absorbance at 734 nm was measured. The given above for % Inhibition was used to calculate ABTS IC₅₀ value of edible mushroom pickle samples.

Total Phenolic Content (TPC): TPC were determined as follows the Folin-Ciocalteu method described by Cheung *et al.* (2003). Pickle stock solution was reacted with Folin-Ciocalteu reagent adding sodium carbonate. The content was incubated for color development, and absorbance was measured at 765 nm using spectrophotometer. Phenolic content was determined using following formula and expressed as mg of gallic acid equivalents (GAE) per 100 g of sample.

$$\text{TPC} = C \times V / W$$

[C = conc. obtained from GA standard curve (mg/mL), V = volume of extract used in reaction (mL), W = weight of sample used for extraction (g)]

Sensory evaluation: All pickle formulations were subjected to sensory assessment for appearance, color, taste, texture, aroma, and overall acceptability score using 9-point hedonic scale as per method described by Wichchukit and O'Mahony (2015).

Statistical analysis: Three replications of identically prepared pickle samples were subjected to perform each test using standard methods of analysis in similar

way on different days. The data was statistically evaluated through two-way ANOVA using IBM-SPSS 22. Tukey's post-hoc test was performed (at p < 0.05) to compare mean values as described by Hoshmand (2018).

RESULTS AND DISCUSSION

Table 2 shows the results regarding physicochemical and antioxidant properties of raw edible mushrooms and pickles formulations without mushroom. Oyster mushrooms had significantly higher (p<0.05) nutritional and antioxidant profile compared to button mushroom. In between the pickles without mushrooms, the vinegar proved to have significantly higher (p<0.05) nutritional and antioxidant properties. Results for physicochemical properties of oil and vinegar-based edible mushroom pickle are given in Table 3(a and b). It was reported that pH remained statistically different for mushroom types, pickling liquids and in their interaction. The pH in OM was statistically higher i.e. 4.30, indicating pH in pickle equilibrated below the critical safety threshold i.e. 4.6 and can facilitate inhibition of spoilage bacteria (LaFountain *et al.*, 2022). The SC was statistically different between pickling liquids and found significantly higher in V (1.97%) while SC for mushroom types and interaction effects was statistically non-significant. The V exhibited a significant impact in keeping SC higher to inhibit the growth of contaminated microbes and favors proliferation of halophilic lactic acid bacteria (Aljahani, 2020). Edible mushrooms and pickling liquids showed statistically different TA while their interactive effect remained statistically non-significant. Pickling liquid V had significantly higher TA (1.40%) which indicates that OM pickled in V may provide adequate natural defense. Higher TA in OM (1.20%) and V (1.30%) specifies suitability of their combination in pickle by facilitating lower acidity which may be effective in extending shelf life and mitigating survival of pathogenic bacteria. Radman *et al.* (2023) also reported higher TA in alcoholic pickle. Both mushroom types showed significant higher a_w. An increased a_w was also reported in vinegar-based vegetable pickle demonstrates availability of unbound water in pickle which may trigger microbial proliferation and pickle quality deterioration (Ahmada *et al.*, 2026). Moisture was reportedly higher in OM (71.69%) than BM (69.51%). In pickling liquids, V had higher moisture (75.63%) contrary to O (65.57%). The interactive effect, OMxV exhibited higher moisture (76.61%) in comparison to others. Higher moisture attributes more aqueous phase in pickle and promotes moisture diffusion in mushroom tissues by osmosis. In contrast, oil in pickles restricts availability of free water owing to hydrophobic barrier by oil (Devi *et al.*, 2021). Protein, fat and crude fiber were found significantly higher (p < 0.05) in OMxP i.e. 3.84%, 10.49%, 2.89%, respectively. Interestingly, protein, fat and crude fiber were found higher in OM (3.41, 6.28, and 2.28%, respectively) and in O (3.56, 10.36, 2.70%,

respectively). This suggests adequate nutritional content of oyster mushroom pickled in oil. Jaziri & Awang (2025) also reported higher fat content in oil-based sardine pickles. Oil acts as a matrix that reduces leaching of intracellular substances and enzymatic breakdown by restricting availability of oxygen for microbial activity (Bori *et al.*, 2026). Moreover, oyster mushrooms are known to have relatively higher tendency to hold lipophilic components. Acidic

medium in pickle enhances solubilization of proteins and soluble fiber into the pickle system. Moreover, button mushrooms generally contain lower native structural complexity when compared to oyster mushrooms, which further contributes to reduced retention of macronutrients (Kumari *et al.*, 2025). It is also factual that different species of mushroom differ from each other in their nutrient profile.

Table 2. Physicochemical and antioxidant properties of raw mushrooms and mushroom blank pickles (Mean±SD)

Properties	Raw edible mushrooms (Control)		Pickles without mushroom (-ve control)	
	Button mushroom (BM)	Oyster mushroom (OM)	Pickle in oil	Pickle in vinegar
pH	6.15±0.03b	6.43±0.05a	5.15±0.19a	3.87±0.12b
SC (%)	0.01±0.01b	0.05±0.01a	2.00±0.02a	2.00±0.01a
TA (%)	0.03±0.01a	0.08±0.01b	0.13±0.01b	3.03±0.7a
<i>a_w</i>	0.9±0.02a	0.98±0.01b	0.58±0.03b	0.81±0.09a
Moisture (%)	90.03±0.09b	91.26±0.06a	2.14±0.17b	82.11±0.32a
Protein (%)	2.64±0.11b	2.97±0.09a	0.29±0.01b	0.34±0.02a
Fat (%)	0.22±0.02b	0.33±0.01a	8.3±0.11a	0.3±0.03b
Crude fiber (%)	2.33±0.11b	2.68±0.09a	0.49±0.05b	0.55±0.02a
DPPH IC ₅₀ (µg/mL)	403.44±0.55a	384.55±0.48b	359.86±0.35a	316.72±0.31b
ABTS IC ₅₀ (µg/mL)	333.61±0.48a	312.46±0.39b	278.52±0.42a	203.18±0.42b
TPC (mgGAE/100g)	359.74±0.54a	347.81±0.67b	316.22±0.37a	289.03±0.29b

Table 3(a). Physicochemical properties of oil and vinegar-based edible mushroom pickles

Physicochemical properties	Edible mushrooms (EM)		Pickling liquids (PL)		Edible mushrooms x Pickling liquids			
	BM	OM	O	V	BM x O	BM x V	OM x O	OM x V
pH	4.20 B	4.50 A	5.03 A	3.67 B	4.95 b	3.46 d	5.12 a	3.88 c
SC (%)	1.88 A	1.96 A	1.87 B	1.97 A	1.82 a	1.95 a	1.92 a	2.0 a
TA (%)	0.95 B	1.20 A	0.85 B	1.30 A	0.70 c	1.20 ab	1.00 b	1.40 a
<i>a_w</i>	0.81 A	0.84 A	0.78 B	0.87 A	0.77 b	0.85 ab	0.79 b	0.90 a
Moisture (%)	69.51 B	71.69 A	65.57 B	75.63 A	64.37 d	74.65 b	66.78 c	76.61 a
Protein (%)	2.93 B	3.41 A	3.56 A	2.78 B	3.28 b	2.59 c	3.84 a	2.98 b
Fat (%)	5.8600 B	6.28 A	10.36 A	1.78 B	10.24 a	1.48 b	10.49 a	2.08 b
Crude fiber (%)	2.01 B	2.28 A	2.70 A	1.59 B	2.52 b	1.51 d	2.89 a	1.67 c

Table 3(b). Main and interaction effects of means for physicochemical properties of oil and vinegar-based edible mushroom pickles

Physicochemical properties	p-value			LSD (0.05)			SE±		
	EM	PL	EM x PL	EM	PL	EM x PL	EM	PL	EM x PL
pH	0.0000	0.0000	0.0000	0.02	0.02	0.01	0.01	0.01	0.04
SC (%)	0.09	0.03	0.53	0.09	0.09	0.18	0.03	0.03	0.05
TA (%)	0.04	0.0002	0.4	0.13	0.13	0.27	0.05	0.05	0.07
<i>a_w</i>	0.1738	0.0042	0.5598	0.0529	0.0529	0.1058	0.0216	0.0216	0.0306
Moisture (%)	0.0012	0.0000	0.5763	0.9253	0.9253	1.8518	0.3781	0.3781	0.5347
Protein (%)	0.0007	0.0000	0.3031	0.1847	0.1847	0.3697	0.0755	0.0755	0.1067
Fat (%)	0.0282	0.0000	0.2813	0.3618	0.3618	0.7240	0.1478	0.1478	0.2091
Crude fiber (%)	0.0002	0.0000	0.0156	0.0770	0.0770	0.0445	0.0314	0.0314	0.1540

Antioxidant activity of all pickle formulations was determined through DPPH IC₅₀, ABTS IC₅₀ values, and TPC Table 4a and 4b. OMxV showed lower DPPH and ABTS IC₅₀ values (89.26, and 75.38 µg/ml, respectively) among all pickle formulations signifying higher antioxidant activity against both free radicals (DPPH and ABTS). Significantly higher TPC in OMxV (253.82mgGAE/100g) again supports antioxidative strength of this formulation. Higher DPPH and ABTS IC₅₀ values (234.44 and 141.21 µg/mL, respectively) together with lower TPC (68.92mgGAE/100g) in BMxO indicate reduced antioxidant activity. It can be noted that pickle

formulations in vinegar exhibited higher antioxidant activity (Aljahani, 2020; Bristy *et al.*, 2022). This improvement in antioxidant activity against free radicals could be due to acidic environment of vinegar-based pickles. Vinegar acidity enhances the leaching of bound phenolic components from mushrooms through rupturing cell walls or acid hydrolysis. Aqueous medium in the pickle further supports extraction followed by diffusion of polar antioxidants, leading to enhanced concentration of TPC. Acidic conditions also help in inhibiting the activity of polyphenol oxidase, reducing oxidative degradation of phenolic compounds and protecting antioxidant potential during pickling

and storage (Dai & Mumper, 2010). Contrary, oil phenolics which results in lower antioxidant activity matrix in pickle restricts extraction of hydrophilic and TPC.

Table 4(a). Antioxidant activity of oil and vinegar-based edible mushroom pickles

Antioxidant activity		Edible mushrooms (EM)		Pickling liquids (PL)		Edible mushrooms x Pickling liquids			
		BM	OM	O	V	BM x O	BM x V	OM x O	OM x V
DPPH (µg/mL)	IC ₅₀	183.45 A	133.81 B	206.41 A	110.86 B	234.44 a	132.45 c	178.37 b	89.26 d
ABTS (µg/mL)	IC ₅₀	132.43 A	86.31 B	119.22 A	99.51 B	141.21 a	123.64 b	97.23 c	75.38 d
TPC (mgGAE/100g)		143.13 B	173.64 A	81.19 B	235.57 A	68.92 d	217.33 b	93.45 c	253.82 a

Table 4(b). Main and interaction effects of means for antioxidant activity of oil and vinegar-based edible mushroom pickles

Antioxidant activity		p-value		LSD (0.05)			SE±		
		EM	PL	EM x PL	EM	PL	EM x PL	EM	PL
DPPH (µg/mL)	IC ₅₀	0.0000	0.0000	0.0005	2.3169	2.3169	4.6368	0.9468	0.9468
ABTS (µg/mL)	IC ₅₀	0.0000	0.0000	0.0001	0.6013	0.6013	1.2033	0.2457	0.2457
TPC (mgGAE/100g)		0.0000	0.0000	0.0000	1.0169	1.0169	2.0351	0.4155	0.4155

Table 5 (a and b) present the results for sensorial attributes. Significantly higher score for appearance and texture was perceived by BMxO (8.5 and 9.0, respectively) and BMxV (8.5 and 8.5, respectively). Taste score among all pickles remained statistically non-significant. OMxV perceived significantly higher color score (8.5) while aroma score in OMxO (8.5). Significantly higher overall acceptability was attained by oil-based pickles of both button and oyster mushrooms.

According to studies conducted on sensorial

profile of pickle oil-based pickles generally preferred over vinegar-based might be due to efficient accumulation of lipophilic compounds from mushrooms or spices in oil phase. Physical barrier of oil layer in pickle slows loss of moisture and tissue breakdown which preserves crisp and plump texture of mushrooms. In an analogous study by Devi *et al.* (2021), combining effect of oil and vinegar gave best sensorial score rather than selecting oil pickle over vinegar-based pickle.

Table 5(a). Sensory attributes of oil and vinegar-based edible mushroom pickles

Sensory attributes	Edible mushrooms (EM)		Pickling liquids (PL)		Edible mushrooms x Pickling liquids			
	BM	OM	O	V	BM x O	BM x V	OM x O	OM x V
Appearance	8.25 A	7.75 A	8.5 A	7.5 B	8.5 a	8.5 a	8.0 ab	7.0 b
Color	7.5 A	7.75 A	8.25 A	7.0 B	8.0 ab	7.0 b	7.0 b	8.5 a
Taste	7.25 A	7.25 A	7.75 A	6.75 B	7.5 a	7.0 a	8.0 a	6.5 a
Texture	8.5 A	7.75 B	8.75 A	7.5 B	9.0 a	8.5 a	8.0 ab	7.0 b
Aroma	7.5 B	8.0 A	8.25 A	7.25 B	8.0 ab	7.0 c	8.5 a	7.5 bc
Overall acceptability	7.8 A	7.7 A	8.3 A	7.2 B	8.2 a	7.4 b	8.4 a	7.0 c

Table 5(b) Main and interaction effects of means for sensory attributes of oil and vinegar-based edible mushroom pickles

Sensory attributes	p-value		LSD (0.05)			SE±		
	EM	PL	EM x PL	EM	PL	EM x PL	EM	PL
Appearance	0.1144	0.0102	0.1144	0.6627	0.6627	1.3262	0.2708	0.2708
Color	0.3731	0.0030	0.3731	0.6358	0.6358	1.2724	0.2598	0.2598
Taste	1.0000	0.0448	0.2530	0.9677	0.9677	1.9367	0.3955	0.3955
Texture	0.0170	0.0016	0.3171	0.5607	0.5607	1.1221	0.2291	0.2291
Aroma	0.0427	0.0022	1.0000	0.4774	0.4774	0.9554	0.1951	0.1951
Overall acceptability	0.0690	0.0000	0.0006	0.1106	0.1106	0.2214	0.0452	0.0452

CONCLUSION

The present study demonstrates that the type of pickling medium significantly influences the nutritional, physicochemical, sensory, and antioxidant properties of button and oyster mushroom pickles. Among the formulations, oyster mushroom pickles OMxO and OMxV showed greater commercial

potential. OMxO exhibited superior nutritional and sensory attributes, making it suitable for gourmet and health-oriented food markets, whereas OMxV demonstrated notable antioxidant activity, indicating potential for functional food applications. The button mushroom formulations BMxO and BMxV showed comparatively moderate physicochemical, antioxidant,

and sensory characteristics. Overall, the findings provide a useful framework for food processors to diversify mushroom-based products and select appropriate formulations according to consumer preferences, nutritional value, and targeted market applications.

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AUTHOR CONTRIBUTIONS

A.H.S.: Conceptualization, methodology, supervision, and writing review and editing. A.M.: Investigation, methodology, and data collection. A.A.K.: Laboratory analysis, validation, and data interpretation. N.S.: Experimental work, data collection, and literature review. A.Mg.: Laboratory assistance, data organization, and manuscript preparation. All authors reviewed and approved the final version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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