

Article

The Usage of Fermented Milk By-Products in Cabbage Pickle Fermentation Through a Sustainable Food Production Approach

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Abstract

This study examined the physicochemical, microbiological, textural, organic acid, colour, and sensory aspects of cabbage pickles made with fermented dairy by-products as a brine medium. Yoghurt whey, whey, kefir whey, and buttermilk were used as brine media and compared with vinegar. Brine samples showed substantial changes in pH, Brix, colour, and rheology ($p < 0.05$). Yoghurt whey-based samples had the lowest brine pH (2.87) and Brix (10.04%), while buttermilk samples had the highest pH (3.26) and Brix (10.83%). Vinegar-based brine showed higher a^* and b^* values, whereas yoghurt whey-based brine had the highest L^* . Yoghurt whey-based samples had lower consistency and a lower viscosity index. Pickle samples made with different brine types showed significant differences in physicochemical, microbiological, textural, and organic acid properties ($p < 0.05$). Pickle samples made with vinegar had the lowest pH (2.99), while samples made with buttermilk had the highest (3.31). Vinegar-based pickles had the highest dry matter (5.27%) and drained weight (64.15%). Yoghurt whey-based samples had the highest counts of *Lactobacillus* spp. (6.38 log CFU/g) and *Lactococcus/Streptococcus* (6.81 log CFU/g), while vinegar-based samples had the highest counts of acetic acid bacteria and total aerobic mesophilic bacteria. However, kefir whey-based samples had the highest yeast count (5.72 log CFU/g). The textural analysis showed that yoghurt whey-based samples had the highest hardness (471.72 N) and springiness, whereas buttermilk-based samples had higher adhesiveness and cohesiveness. Whey-based samples had the highest gumminess and chewiness. Yoghurt whey-based samples had the highest levels of lactic acid (14,569.39 mg/L) and citric acid, whereas vinegar-based samples had the highest levels of acetic acid (63,795.64 mg/L) and propionic acid. Kefir whey-based samples had the highest butyric acid content. Yoghurt whey-based pickles were the most popular with panellists, followed by whey and vinegar-based pickles. Buttermilk-based samples scored lowest in sensory rating. Finally, fermented dairy by-products can be used as a functional brine medium for cabbage pickle. Yoghurt whey has shown promise in improving microbiological quality, textural characteristics, and sensory acceptability. Using dairy industry by-products in pickle making is an innovative way to produce sustainable food and add value to by-products.

Keywords: cabbage pickle; yoghurt whey; fermentation; postbiotic metabolite

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1. Introduction

Fermented vegetable products are among the traditional foods widely consumed worldwide due to their high nutritional value, long shelf life, characteristic aroma profiles and probiotic potential. In particular, cabbage pickle is recognised as an important fermented product, both for its sensory qualities and its health benefits, owing to its rich composition of organic acids, bioactive compounds, and functional microorganisms resulting from lactic acid fermentation. Fermented cabbage products, including sauerkraut and traditional cabbage pickles, are widely consumed in many regions of Europe and Asia. Their popularity has increased due to consumer demand for natural, functional, and probiotic-rich foods [1,2]. The fermentation process in pickle making is influenced by various factors, including the raw materials used, the brine composition, salt concentration, initial microbiota and fermentation conditions. These parameters directly determine the product's physicochemical, microbiological, textural and sensory properties. The quality of fermented cabbage pickles is commonly assessed through physicochemical parameters such as pH, colour, texture, salt content, and organic acid composition, as well as sensory attributes including flavour, aroma, crispness, appearance, and overall acceptability [1,2]. Traditionally, cabbage pickles are produced by fermenting shredded or chopped cabbage in salt-containing brine under anaerobic conditions, where naturally occurring lactic acid bacteria convert fermentable carbohydrates into organic acids and generate the characteristic flavour and texture of the final product [2].

In conventional pickle making, the brine is usually prepared with salt and vinegar, with the vinegar's acidity in particular playing a significant role in enhancing product safety and extending shelf life. However, in recent years, the shift among consumers towards natural, functional, and sustainable foods has led to increased research into alternative fermentation media. In this context, by-products of the dairy industry—such as yoghurt whey, whey, kefir whey, and buttermilk—are attracting attention as potential functional brine components due to their protein, peptide, mineral, organic acid, and live microorganism content [3–5].

Dairy by-products are considered functional ingredients in food formulations, particularly because they are rich in whey proteins, lactic acid bacteria and fermentation metabolites, all of which possess high biological value. Whilst yoghurt whey contains high levels of lactic acid and live starter cultures as a result of intensive lactic fermentation, kefir whey contains a more complex microbial structure due to the yeast–lactic acid bacteria symbiosis. Whilst whey is notable for its high concentration of whey proteins and minerals, buttermilk is an important source of milk fat globule membrane components and phospholipids [5,6]. The fermentation dynamics of these components may have significant effects on textural structure, organic acid profile and product stability. Therefore, these dairy by-products may serve not only as fermentation media but also as sources of nutrients, organic acids, and beneficial microorganisms that can improve the microbiological, physicochemical, and sensory quality of fermented vegetables [3–8].

On the other hand, the generation of large quantities of by-products from the dairy industry poses significant environmental and economic challenges. In particular, the direct discharge of these by-products—which contain a high organic load—into the environment can lead to serious waste management issues. For this reason, the utilisation of these by-products in value-added food products is of great importance for sustainable production and the circular economy [8,9]. The use of these by-products in the production of fermented vegetables offers an alternative approach to waste management. Also, it has the potential to enhance the products' functional properties. Furthermore, their incorporation into pickle production may increase the added value of dairy processing residues while simultaneously supporting the development of sustainable and functional food products [8].

Although numerous studies have examined the use of dairy-based by-products in beverages, bakery products, and fermented dairy products, research on their use as brine media in pickle production is quite limited. In particular, there appears to be a lack of comprehensive studies that compare the effects of different dairy by-products on the physicochemical, microbiological, textural, colour, organic acid, and sensory properties of cabbage pickle.

This study aimed to investigate the potential use of yoghurt whey, whey, kefir whey and buttermilk as alternative brine components in the making of cabbage pickle. Within this scope, the physicochemical, microbiological, rheological, colour, organic acid, and sensory properties of the pickle samples were evaluated, and the findings were compared with those of conventional vinegar-based pickle making. The aim is therefore to highlight the potential of dairy industry by-products for the production of sustainable, functional pickles.

2. Materials & Methods

2.1. Materials

The cabbage (*Brassica oleracea* L.), garlic (*Allium sativum* L.), vinegar (grape), salt and sugar used in this study were sourced from a local supermarket in Afyonkarahisar, Türkiye.

2.2. Preparation of Cabbage Pickles

The cabbage pickle used in the study was prepared by modifying the formulation described by Di Cagno et al. [2] After being washed with sterile distilled water at 15 °C, the cabbages were chopped and transferred into sterile glass jars in portions of 200 g each. Six grams of garlic, 4% salt and 2% sugar (the weight of the cabbage in the jar) were added to each jar. To this formulation, 350 mL each of grape vinegar, yoghurt whey, whey, kefir whey and buttermilk were added separately. The lids of the jars were sealed tightly to prevent air ingress. The mixture was left to ferment in a dark environment at 18–22 °C for 15 days. The whey types from the fermented dairy products used in the study were obtained from freshly prepared products prepared under laboratory conditions.

2.3. Brine Analyses

Analyses were performed after the fermentation period. Before analysis, the cabbage and brine were separated using a strainer. The analyses were performed separately on brine and cabbage pickle. The pH values of the samples were measured using a calibrated pH meter (HANNA, HI 2215 pH/ORP meter) [10]. The % soluble dry matter content (Brix) values were determined using a benchtop refractometer (Atago Rx 5000, Tokyo, Japan) [11]. The lightness (L^*), redness (a^*) and yellowness (b^*) colour values of the brine samples were measured using a colourimeter (Minolta Chroma Meter CR-400, Osaka, Japan) [12].

The texture parameters of the brine samples (hardness, consistency, cohesion and viscosity index) were determined using the TA.XT Plus Texture Analyser (Stable Micro Systems, Godalming, Surrey, UK) in accordance with the method described by Akarca and Denizkara [13] using the back extrusion technique. To this end, a cylindrical acrylic back-extrusion probe with a diameter of 7.62 mm and a depth of 10 mm was immersed in brine samples at 25 °C, and a compression test was carried out at a crosshead speed of 1 mm s⁻¹. Force-time curves were plotted from the positive and negative areas obtained when the probe was immersed in and withdrawn from each sample, respectively. The Texture Exponent 32 (2007) software (Stable Micro Systems, Godalming, UK) was used to determine the textural properties of the samples. Of the parameters assessed, hardness (g) was defined as the maximum positive force, consistency (g.sec) as the area of the positive

region, cohesion as the maximum negative force, and the viscosity index (g.sec) as the area of the negative region.

2.4. Pickle Analyses

Samples were stored under refrigerator conditions (4 °C) until analysis and removed from the refrigerator just before analysis. The analysis of each sample took approximately 3 to 5 min.

2.4.1. pH, Dry Matter and Colour Measurements

The pH values of the cabbage pickle samples were determined using a pre-calibrated digital pH meter (HANNA, HI 2215 pH/ORP meter) [14]. The dry matter percentages of the pickled samples were determined by gravimetric analysis. The results are expressed as a percentage (*w/v*). The lightness (*L**), redness (*a**) and yellowness (*b**) colour values of the pickle samples were measured using a pre-calibrated colourimeter (Minolta Chroma Meter CR-400, Osaka, Japan) [12].

2.4.2. Drain Weight

The pickles in the jar were emptied onto a sieve with a 20 cm diameter and a 2.8 × 2.8 mm mesh size, after which they were left to drain for 10 min. They were then weighed together with the sieve, and the percentage of drained weight was calculated from the result [15].

2.4.3. Salt Ratio

Pickle samples weighing 5 g were placed in a porcelain mortar and crushed with warm distilled water; the resulting liquid was then transferred to a 500 mL graduated flask. This process was repeated 5–6 times to ensure that all the salt had dissolved into the water. After leaving the flask to cool for a while, it was filled to the mark with distilled water at room temperature and then filtered. 25 mL of the filtrate was taken, 1–2 drops of potassium chromate (K₂CrO₄) indicator were added, and it was titrated with 0.1 N silver nitrate until a brick-red colour appeared [16].

The salt results were calculated using the following formula:

$$\% \text{ Salt} = G \times 0.585/P \quad (1)$$

In this formula,

G = Volume of 0.1 N silver nitrate solution used in the titration (mL);

P = Weight of pickles used in the titration (g).

2.5. Microbiological Analyses

Microbiological analyses were initiated by preparing serial dilutions. Ten millilitres were taken from each sample, to which 90 mL of a sterile Ringer's solution prepared at ¼ strength using Ringer's tablets (Merck Millipore, 1,155,251, Darmstadt, Germany) was added, and the mixture was homogenised in a stock mixer (Bagmixer 400P, St Nom-la-Bretèche, France). Subsequently, further decimal dilutions were prepared using this resulting dilution. Microbiological analyses were carried out using the spread plate technique on these serial dilutions. The counts of microorganisms in the samples were determined as follows:

Analysis of lactic acid bacteria counts: Incubation for 24–48 h at 30 °C under anaerobic conditions using MRS (de Man, Rogosa and Sharpe) Agar (Merck 1.10661, Germany). Acetic acid bacterial count analysis: Incubation for 5–10 days at 30 °C under aerobic conditions on YCG (Yeast Extract Calcium Carbonate Glucose) Agar (Himedia M1182, Mumbai, India) [17]. Analysis of *Lactococcus*/*Streptococcus* bacterial counts: Incubation for 24–48

h under aerobic conditions at 30 °C on M-17 Agar (Merck, 1.15108, Germany) [18]. Total aerobic mesophilic bacterial (TAMB) count: According to the ISO [19,20] standard, using PCA (Plate Count Agar) (Merck, 1.05463) medium, incubation under aerobic conditions at 30 °C for 48–72 h

2.6. Texture Profile Analyses (TPA)

The textural characterisation of the cabbage pickle samples was carried out at 22 °C using a texture analyser (TA. XT, Stable Micro Systems, Godalming, UK). Before analysis, the samples were cut into 2.5 mm thick slices. A cylindrical probe with a 12.5 mm diameter and a 5 kg load cell was used in the experiments. The test settings were as follows: Approach speed 2 mm/s, test speed 3 mm/s, post-test speed 3 mm/s, dwell time 5 s, trigger force 10 g and strain rate 50% [21].

2.7. Organic Acid Analyses

The organic acid concentrations in the samples were determined using HPLC (Shimadzu Prominence, Shimadzu Corporation, Kyoto, Japan). For the analyses, 4 g of sample was first weighed, followed by the addition of 20 mL of 0.01 N H₂SO₄. The mixture was then vortexed and injected into the system using a 0.45 µm filter [22]. System specifications: CBM: 20ACBM; detector: DAD (SPD-M20A); column oven: CTO-10ASVp; pump: LC20 AT; autosampler: SIL 20AHT; software: LC Solution 5.65; column: ODS 4 (250 mm × 4.6 mm, 5 µm; Inertsil ODS-4, GP Sciences, Nakatsugawa, Japan); mobile phase: ultra-pure water adjusted to pH 3 with orthophosphoric acid. The mobile phase flow rate was 0.7 mL/min, and detection was performed at 210 nm [23].

2.8. Sensory Analyses

Sensory evaluation of the pickle samples was conducted at the Faculty of Engineering, Afyon Kocatepe University. Fifteen volunteer panelists consisting of academic staff and postgraduate students with previous experience in sensory evaluation participated in the study. Panelists were selected according to the recommendations for sensory assessor recruitment and qualification described in ISO 8586 [24]. All participants were healthy adults, non-smokers, and regular consumers of fermented vegetable products.

Prior to evaluation, panelists were informed about the sensory attributes to be assessed and were familiarized with the evaluation procedure. The sensory characteristics evaluated included brine clarity, salinity, aroma, appearance and colour, chewiness, flavour, body, and overall acceptability. Samples were evaluated using an 8-point structured intensity/acceptability scale, where 1 represented the lowest intensity or acceptability and 8 represented the highest intensity or acceptability. The use of category scales for sensory assessment is widely accepted for measuring consumer perception and product quality attributes [25–27].

The pickle samples were served individually in a randomized order and identified only by three-digit coded labels to prevent bias. Drinking water was provided for palate cleansing between samples. To improve the reliability of the evaluations, the samples were presented to the panelists in two separate sessions, and different random codes were assigned during the second evaluation. Sensory data were analyzed using SPSS v.28 software, and results were expressed as mean values and standard deviations.

2.9. Statistical Analyses

Statistical analyses were performed using SPSS v.28 software. Data was subjected to one-way analysis of variance (ANOVA) to evaluate the effect of brine type on the measured parameters. When significant differences were detected ($p < 0.05$), Duncan's multiple

range test was used for mean comparisons among treatments. The study was conducted in duplicate. In each replicate, analyses were performed in triplicate.

3. Results and Discussion

There was a statistically significant difference between the pH and Brix values of the pickle brines ($p < 0.05$; Table 1). Whilst the lowest pH value of 2.87 was detected in samples made from yoghurt whey, the highest pH value of 3.26 was found in samples from buttermilk. The lower pH observed in yoghurt whey-based brines may be associated with the acidic nature of yoghurt whey, which is generally attributed to the intense lactic acid fermentation occurring during yoghurt production. During this process, *Streptococcus thermophilus* and *Lactobacillus delbrueckii* subsp. *bulgaricus* convert lactose into lactic acid, thereby increasing acidity and decreasing pH. In contrast, buttermilk obtained from fresh cream is generally less acidic because organic acid formation is more limited during butter production [3].

Among the samples, the lowest Brix value was 10.04% in the brine of pickles made with yoghurt whey, followed by 10.18% in the brine of pickles made with vinegar. The highest Brix value, at 10.83%, was found in the brine of pickles made with buttermilk (Table 1).

Table 1. Ph and Brix Values of Brine.

Brine pH	
Samples	Results
Vinegar	2.97 ± 0.01^d
Yogurt Whey	2.87 ± 0.02^e
Whey	3.11 ± 0.01^b
Buttermilk	3.26 ± 0.01^a
Kefir Whey	3.03 ± 0.02^c
Brine Brix	
Vinegar	10.18 ± 0.01^d
Yogurt Whey	10.04 ± 0.01^e
Whey	10.68 ± 0.02^b
Buttermilk	10.83 ± 0.01^a
Kefir Whey	10.52 ± 0.01^c

a–e: Values shown in the same column with the same lowercase letters differ significantly for each analysis ($p < 0.05$).

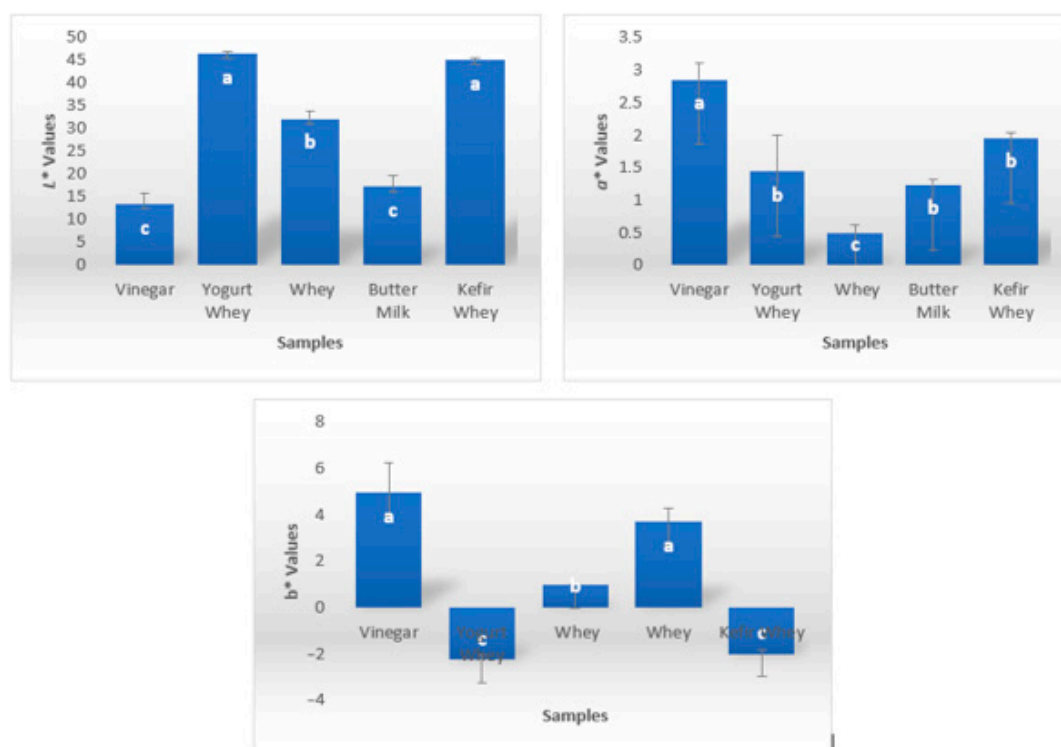
The lower Brix value observed in pickling brines using yoghurt whey may be associated with this by-product's low dissolved dry matter and residual sugar content, as a significant proportion of the lactose is converted into lactic acid during yoghurt fermentation. Furthermore, the retention of certain dry matter components in the curd phase during protein coagulation further reduces the total dissolved solids content of yoghurt whey. In contrast, whey and kefir whey are generally reported to contain higher levels of residual lactose, dissolved proteins, and minerals, which may contribute to higher Brix values in the corresponding brines [4]. In vinegar-based systems, dissolved organic compounds may also contribute to an increase in total dissolved solids.

Although the highest L^* value of 46.4 was found in the pickle brine samples made with yoghurt whey, the lowest L^* value of 13.42 was found in the samples made with vinegar ($p < 0.05$; Figure 1).

The higher L^* values observed in pickle brines made with yoghurt whey have been attributed to increased light scattering resulting from the low-fat content and the homogeneous colloidal structure. Fine protein particles and dissolved milk components have

increased optical clarity by causing greater light reflection within the system. In contrast, in the vinegar, kefir whey, whey, and buttermilk systems, greater heterogeneity, pigment formation, and the presence of a fat phase increased light absorption, resulting in a decrease in the L^* value [28].

The brine samples made with vinegar had the highest a^* and b^* values, at 2.85 and 4.96, respectively. The lowest a^* value among the samples was 0.5, observed in the sample made with whey, whilst the lowest b^* value was -2.26 , observed in the sample made with yoghurt whey ($p < 0.05$; Figure 1).



Error bars represent the standard deviation

Figure 1. Color Values of Brine Samples.

The higher values of a^* and b^* found in pickle brines made with vinegar are linked to the fact that high acetic acid concentrations cause structural changes in plant pigments, thereby increasing the visibility of carotenoids, and to the emergence of olive-green and brown tones resulting from chlorophyll degradation. Conversely, in milk-based systems, colour intensity—and consequently the a^* and b^* values—was lower due to the protein and lipid phases masking the pigments by increasing light scattering, and because lactic fermentation created a more reducing environment [29,30].

Although statistically significant differences were observed in the consistency and viscosity index values of the pickle brines ($p < 0.05$), no differences were found in the firmness and cohesiveness values ($p > 0.05$). Among the samples, the lowest firmness and consistency values—11.71 g and 142.83 g.sec, respectively—were observed in those made with yoghurt whey. In contrast, the highest values—11.77 g and 145.95 g.sec—were found in the samples made with vinegar (Table 2).

The textural interaction between plant tissue and brine depends primarily on cell wall integrity and the stability of the pectin network. Under acidic conditions, pectin depolymerisation and the weakening of calcium-pectin bridges reduce intercellular adhesion and disrupt the tissue matrix. This process is particularly pronounced in

environments with high lactic acid content, such as yoghurt whey; fermentative acidification caused by *S. thermophilus* and *L. delbrueckii* subsp. *bulgaricus* accelerates turgor loss by reducing cell wall stability. These microstructural changes are directly reflected in the brine system, leading to reduced viscosity, firmness, and consistency. In contrast, in whey and kefir whey systems with higher mineral and total dissolved solids content, calcium-mediated pectin stabilisation is partially maintained, resulting in greater textural stability [7,31].

Similarly, the lowest values for cohesiveness (−4.56 g) and viscosity index (−0.61 g.sec) among the brine samples were observed in those made with yoghurt whey. In contrast, the highest cohesiveness (−4.98 g) and viscosity index (−0.46 g.sec) were observed in samples made with buttermilk (Table 2).

Table 2. Textural Values of Brine.

Firmness (g)	
Samples	Results
Vinegar	11.77 ± 0.03 ^a
Yogurt Whey	11.71 ± 0.06 ^a
Whey	11.77 ± 0.03 ^a
Buttermilk	11.74 ± 0.04 ^a
Kefir Whey	11.76 ± 0.01 ^a
Consistency (g.sec)	
Vinegar	145.95 ± 0.18 ^a
Yogurt Whey	142.83 ± 1.29 ^b
Whey	142.99 ± 0.86 ^b
Buttermilk	145.24 ± 0.19 ^a
Kefir Whey	145.87 ± 0.34 ^a
Cohesiveness (g)	
Vinegar	−4.91 ± 0.38 ^a
Yogurt Whey	−4.56 ± 0.28 ^a
Whey	−4.80 ± 0.11 ^a
Buttermilk	−4.98 ± 0.05 ^a
Kefir Whey	−4.91 ± 0.01 ^a
Index of Viscosity (g.sec)	
Vinegar	−0.53 ± 0.01 ^a
Yogurt Whey	−0.61 ± 0.03 ^b
Whey	−0.51 ± 0.01 ^a
Buttermilk	−0.46 ± 0.03 ^a
Kefir Whey	−0.53 ± 0.04 ^a

a–b: Values shown in the same column with the same lowercase letters differ significantly for each analysis ($p < 0.05$).

The low cohesiveness and viscosity index values in pickling brines containing yoghurt whey are attributed to the system's low macromolecular content, weak colloidal structure and texture degradation resulting from acid fermentation. During yoghurt fermentation, the conversion of lactose into lactic acid by *S. thermophilus* and *L. delbrueckii* subsp. *bulgaricus* reduces the amount of dissolved dry matter in the serum phase and limits the residual carbohydrate/protein content, which could increase viscosity. Furthermore, the low protein dispersion of the yoghurt whey obtained after casein coagulation prevents the formation of a continuous rheological network, thereby reducing the cohesiveness value.

In contrast, whey is generally reported to form a stronger colloidal structure due to the presence of whey proteins such as β -lactoglobulin and α -lactalbumin, whilst kefir whey may exhibit enhanced viscoelastic properties because of exopolysaccharides produced during kefir fermentation. In vinegar-based systems, dissolved acetic acid and extractive compounds may increase the viscosity index by increasing ionic strength and total dissolved solids. Therefore, the lower rheological stability observed in yoghurt whey-based brines may be associated with the compositional characteristics commonly reported for yoghurt whey compared with other brine media [3,4,6].

Among the samples, the lowest pH value of 2.99 was recorded for those made with vinegar, followed by those made with yoghurt whey, which had a pH of 3.00. In contrast, the highest pH value of 3.31 was recorded in samples made with buttermilk (Table 3).

The lower pH of yoghurt whey is attributed to its high lactic acid content and low buffering capacity. In contrast, the higher mineral- and protein-based buffering capacity of whey and kefir whey limits the drop in pH [7].

It was determined that the interaction between sample type and % drained weight was statistically significant ($p < 0.05$). The lowest dry matter and drained weight values (3.80% and 58.81%, respectively) were observed in pickles made with yoghurt whey. Conversely, the highest values (5.27% and 64.15%) were found in pickle samples made with vinegar (Table 3).

The lower dry matter content observed in pickles produced with yoghurt whey may be related to the lower accumulation of soluble solids within the pickle tissue during fermentation. The relatively low total solids content of yoghurt whey, together with enhanced diffusion of water and soluble components between the cabbage tissue and the surrounding brine, may have reduced solid retention in the pickle matrix. In contrast, whey, kefir whey, buttermilk, and vinegar-based brines provided greater amounts of dissolved solids and fermentation metabolites, which may have contributed to higher dry matter values in the final pickle samples. Similar trends have been associated with differences in mass transfer and solute retention during vegetable fermentation [32].

The decrease in drained weight, however, is associated with low dissolved solids content, a weak colloidal structure and limited water-binding capacity. Yoghurt whey leads to poor gel formation in the pickle matrix due to low protein dispersion and low polysaccharide content, thereby reducing water-holding capacity and decreasing the weight obtained after draining. Conversely, whey and kefir whey, due to their higher whey protein content, mineral content and the presence of exopolysaccharides, form a stronger structure, thereby increasing dry matter and drained weight [7].

The main reason why pickles made using vinegar have higher dry matter and drained weight is that vinegar introduces a large amount of dissolved acetic acid and extractive organic compounds into the system from outside, whilst also facilitating the extraction of more intracellular material from the plant tissue. This increases the total dissolved solids whilst accelerating the transfer of water and soluble components, thereby raising both the brine concentration and the drained weight [1,32,33].

Although the salt content of the pickle samples varied, the differences were not statistically significant ($p > 0.05$). The highest salt content was 3.62% in samples made with vinegar and buttermilk, whilst the lowest was 3.59% in samples made with yoghurt whey and whey (Table 3).

Table 3. Physicochemical Properties of Cabbage Pickle Tissue Samples.

Pickle pH	
Samples	Results
Vinegar	2.99 ± 0.01 ^d
Yogurt Whey	3.00 ± 0.01 ^d
Whey	3.24 ± 0.01 ^b
Buttermilk	3.31 ± 0.01 ^a
Kefir Whey	3.10 ± 0.01 ^c
Pickle Dry Matter (%)	
Vinegar	5.27 ± 0.09 ^a
Yogurt Whey	3.80 ± 0.17 ^d
Whey	4.13 ± 0.06 ^c
Buttermilk	4.80 ± 0.11 ^b
Kefir Whey	3.86 ± 0.13 ^{cd}
Draining Weight (%)	
Vinegar	64.15 ± 0.85 ^a
Yogurt Whey	58.81 ± 0.64 ^c
Whey	59.85 ± 0.58 ^c
Buttermilk	61.94 ± 0.14 ^b
Kefir Whey	60.03 ± 0.81 ^c
Salt Content (%)	
Vinegar	3.62 ± 0.02 ^a
Yogurt Whey	3.59 ± 0.02 ^a
Whey	3.59 ± 0.01 ^a
Buttermilk	3.62 ± 0.01 ^a
Kefir Whey	3.60 ± 0.01 ^a

a–d: Values shown in the same column with the same lowercase letters differ significantly for each analysis ($p < 0.05$).

Among the samples, the highest counts of *Lactobacillus* spp. (6.38 log CFU/g) and *Lactococcus/Streptococcus* spp. (6.81 log CFU/g) were found in the sample made with yoghurt whey; the highest counts of acetic acid bacteria (6.74 log CFU/g) and total aerobic mesophilic bacterial count (6.70 log CFU/g) were found in samples made with vinegar, whilst the highest total yeast count (5.72 log CFU/g) was found in samples made with kefir whey ($p < 0.05$; Table 4).

Table 4. Microbiological Values of Pickle Samples (log cfu/g).

<i>Lactobacillus</i> spp. Count	
Samples	Results
Vinegar	2.03 ± 0.06 ^d
Yogurt Whey	6.38 ± 0.24 ^a
Whey	5.26 ± 0.26 ^b
Buttermilk	3.89 ± 0.05 ^c
Kefir Whey	4.99 ± 0.06 ^b
<i>Lactococcus/Streptococcus</i> spp. Count	
Vinegar	3.80 ± 0.03 ^e
Yogurt Whey	6.81 ± 0.02 ^a
Whey	5.73 ± 0.04 ^d
Buttermilk	5.82 ± 0.01 ^b
Kefir Whey	5.79 ± 0.03 ^{cd}
Acetic Acid Bacteria Count	

Vinegar	6.74 ± 0.06 ^a
Yogurt Whey	1.53 ± 0.18 ^c
Whey	1.69 ± 0.03 ^c
Buttermilk	1.51 ± 0.03 ^c
Kefir Whey	4.70 ± 0.05 ^b
Total Aerobic Mesophilic Bacteria Count	
Vinegar	6.70 ± 0.01 ^a
Yogurt Whey	6.15 ± 0.01 ^c
Whey	6.15 ± 0.02 ^c
Buttermilk	6.24 ± 0.02 ^b
Kefir Whey	6.19 ± 0.04 ^{bc}
Total Yeast Count	
Vinegar	4.21 ± 0.06 ^b
Yogurt Whey	3.21 ± 0.04 ^d
Whey	2.57 ± 0.05 ^e
Buttermilk	3.79 ± 0.02 ^c
Kefir Whey	5.72 ± 0.07 ^a

a–e: Values shown in the same column with the same lowercase letters differ significantly for each analysis ($p < 0.05$).

The higher counts of *Lactobacillus* spp. and *Streptococcus/Lactococcus* spp. found in cabbage pickles made with yoghurt whey may be associated with the microbiological and compositional characteristics generally reported for yoghurt whey, including the high populations of lactic acid bacteria, acidic character, and the presence of fermentation-derived nutrients such as peptides, amino acids, residual lactose, and other metabolites reported in the literature for yoghurt whey. These characteristics may contribute to the suppression of competing microbiota while supporting the growth and persistence of lactic acid bacteria. In contrast, the lower counts observed in whey- and buttermilk-based samples may be related to differences in microbial composition and nutrient availability. Similarly, yeast–bacteria interactions commonly reported in kefir whey may have influenced the microbial dynamics observed during fermentation [34,35].

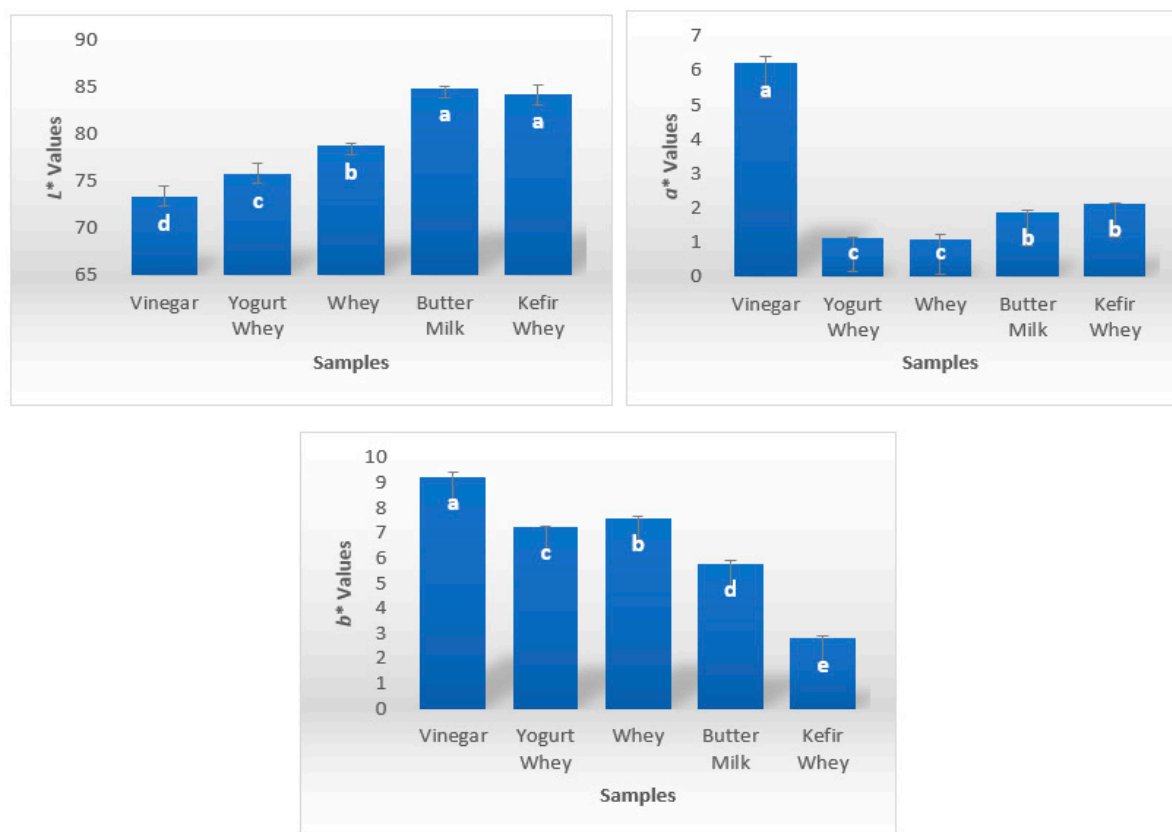
In pickles made with vinegar, the high initial acetic acid concentration and the dominance of acetic acid fermentation favoured the growth of acid-tolerant aerobic microorganisms, thereby increasing the total number of aerobic bacteria. Conversely, in samples containing dairy-based by-products, the dominance of lactic acid bacteria in the microbiota and the production of antimicrobial metabolites have limited the growth of total aerobic bacteria [2].

The higher total yeast counts observed in pickles made with kefir whey may be associated with the yeast-rich microbial composition and the presence of lactose, amino acids, and fermentation-derived metabolites commonly reported for kefir whey. Furthermore, the yeast–lactic acid bacterium symbiosis characteristic of kefir may have contributed to maintaining yeast viability during fermentation [36].

The highest L^* value among the pickle samples was 84.92 for those made with buttermilk, followed by 84.23 for those made with kefir whey. The lowest L^* value among the samples was 73.39, found in those made with vinegar ($p < 0.05$; Figure 2).

The higher L^* values observed in pickle samples prepared with kefir whey and buttermilk have been attributed to the strong light scattering caused by the fat globules, phospholipid membranes and gas bubbles present in these systems. This heterogeneous colloidal structure increases the system's optical clarity by enhancing Mie-type light scattering. On the other hand, due to the low particle content in vinegar-based systems and protein aggregation in yoghurt/whey systems, light scattering decreases, resulting in lower L^* values [37,38].

Among the samples, the highest a^* and b^* values were observed in cabbage pickles made with vinegar, at 6.22 and 9.24, respectively. In contrast, the lowest a^* and b^* values were found in the samples made with whey (1.075) and kefir whey (2.81), respectively ($p < 0.05$; Figure 2).



Error bars represent the standard deviation

Figure 2. Color Values (L^* , a^* and b^*) of Cabbage Pickle Tissue (Not Brine) Samples.

The higher a^* and b^* values observed in pickles made with vinegar are linked to the strong acidic environment created by acetic acid, which increases the release of plant pigments from within the cells and accelerates the conversion of chlorophyll into pheophytin, thereby reducing green tones and making yellow and red/brown pigments more visible. In contrast, in dairy-based systems, colour intensity is perceived as lower due to the light-scattering and pigment-masking effects of the protein and fat phases [39,40].

Among the samples, the highest hardness (471.72 N) and springiness (0.982 mm) values were observed in those made with yoghurt whey, whilst the highest adhesiveness (−0.097 N·s) and cohesiveness (0.693) values were found in those made with buttermilk. Similarly, the highest gumminess (289.90 N) and chewiness (278.64 N) values were found in samples made with whey. In contrast, the highest resilience value (0.521) was observed in cabbage pickles made with vinegar ($p < 0.05$; Table 5). It should be noted that absolute hardness values obtained by TPA may vary considerably among studies due to differences in sample thickness, probe type, compression conditions, and instrumental configurations; therefore, direct comparison of numerical values should be interpreted cautiously.

Table 5. Texture Profile Analysis (TPA) Parameters of Cabbage Pickle Tissue Samples.

Hardness (N)

Samples	Results
Vinegar	413.40 ± 15.78 ^b
Yogurt Whey	471.72 ± 2.56 ^a
Whey	457.57 ± 2.33 ^a
Buttermilk	205.01 ± 15.05 ^c
Kefir Whey	209.23 ± 18.22 ^c
Adhesiveness (N.s)	
Vinegar	−0.636 ± 0.02 ^d
Yogurt Whey	−0.265 ± 0.04 ^b
Whey	−0.518 ± 0.01 ^c
Buttermilk	−0.097 ± 0.01 ^a
Kefir Whey	−0.136 ± 0.01 ^a
Springiness (mm)	
Vinegar	0.878 ± 0.02 ^b
Yogurt Whey	0.982 ± 0.02 ^a
Whey	0.962 ± 0.04 ^a
Buttermilk	0.978 ± 0.01 ^a
Kefir Whey	0.945 ± 0.01 ^a
Cohesiveness	
Vinegar	0.572 ± 0.02 ^b
Yogurt Whey	0.597 ± 0.02 ^{ab}
Whey	0.633 ± 0.02 ^b
Buttermilk	0.693 ± 0.02 ^a
Kefir Whey	0.626 ± 0.01 ^b
Gumminess (N)	
Vinegar	236.81 ± 16.34 ^b
Yogurt Whey	281.64 ± 10.87 ^a
Whey	289.90 ± 12.80 ^a
Buttermilk	141.94 ± 6.95 ^c
Kefir Whey	131.06 ± 13.18 ^c
Chewiness (N)	
Vinegar	207.73 ± 8.99 ^b
Yogurt Whey	276.81 ± 15.66 ^a
Whey	278.64 ± 1.24 ^a
Buttermilk	138.86 ± 5.90 ^c
Kefir Whey	123.94 ± 14.31 ^c
Resilience	
Vinegar	0.521 ± 0.01 ^a
Yogurt Whey	0.501 ± 0.01 ^b
Whey	0.512 ± 0.01 ^{ab}
Buttermilk	0.458 ± 0.01 ^c
Kefir Whey	0.360 ± 0.01 ^d

a–d: Values shown in the same column with the same lowercase letters differ significantly for each analysis ($p < 0.05$).

The soluble proteins, calcium, and dominant lactic acid bacteria microbiota present in yoghurt whey have contributed to increased hardness and springiness values in the pickled samples by supporting the stabilisation of cell wall pectins. In particular, calcium-induced pectin cross-linking and controlled fermentation have been effective in preserving tissue integrity [2,41].

The free fat globules, phospholipids and milk fat globule membrane components contained in buttermilk form a hydrophobic film on the surface of vegetables, thereby

increasing their adhesiveness. Furthermore, lipid–pectin and protein–lipid interactions support cell wall integrity, thereby strengthening internal structural cohesion. Lower acid stress and controlled fermentation conditions also help limit tissue breakdown, resulting in higher cohesiveness values than in systems based on vinegar, kefir whey, yoghurt whey, and whey [6,42].

The high levels of gumminess and chewiness observed in pickles made with whey have been attributed to whey proteins, which denature in an acidic environment, forming a strong three-dimensional gel network. This structure is stabilised by protein–protein and protein–pectin interactions, thereby increasing the viscoelastic resistance of the product matrix. Furthermore, the mineral content of whey has contributed to a more compact structure by strengthening cross-linking mechanisms, particularly through calcium ions. Due to the low lipid content and limited tissue-softening effect, the gumminess and chewiness values in these systems were higher than those in systems based on vinegar, kefir whey, yoghurt whey, and buttermilk [43,44].

The finding that pickles made with vinegar have higher resilience values than those made with other dairy by-products is linked to the high acetic acid concentration, which causes rapid, reversible structural rearrangements in cell wall pectins. The absence of protein-based gel networks in the acidic environment has reduced energy loss during deformation, thereby providing a higher capacity for elastic recovery. Conversely, the viscoelastic energy dissipation behaviour exhibited by the protein–polysaccharide matrices formed in dairy by-product-based fermentation systems has increased permanent deformation, thereby reducing resilience values [2,45,46].

Among the cabbage pickle samples, the highest levels of lactic (14,569.39 mg/L), citric (14,223.80 mg/L) and butyric (54.68 mg/L) acids were found in the samples made with yoghurt whey, whilst the highest levels of acetic (63,795.64 mg/L) and propionic (140.06 mg/L) acid values were found in the samples made with vinegar ($p < 0.05$; Table 6).

Table 6. Organic Acid Contents of Cabbage Pickle Tissue Samples (mg/L).

Lactic Acid	
Samples	Results
Vinegar	1798.90 ± 75.71 ^d
Yogurt Whey	14,569.39 ± 472.72 ^a
Whey	7292.78 ± 54.67 ^c
Buttermilk	1682.88 ± 40.06 ^d
Kefir Whey	9861.01 ± 102.73 ^b
Citric Acid	
Vinegar	419.50 ± 23.64 ^b
Yogurt Whey	1422.38 ± 93.24 ^a
Whey	1270.65 ± 84.28 ^a
Buttermilk	1395.37 ± 49.26 ^a
Kefir Whey	1269.60 ± 29.78 ^a
Acetic Acid	
Vinegar	63,795.64 ± 1750.11 ^a
Yogurt Whey	262.01 ± 37.27 ^b
Whey	140.49 ± 9.49 ^b
Buttermilk	50.19 ± 2.79 ^b
Kefir Whey	1496.21 ± 52.92 ^b
Propionic Acid	
Vinegar	140.06 ± 4.51 ^a
Yogurt Whey	85.25 ± 4.39 ^b
Whey	10.63 ± 1.08 ^d

Buttermilk	7.34 ± 1.69 ^d
Kefir Whey	59.87 ± 3.47 ^c
Butyric Acid	
Vinegar	38.76 ± 7.51 ^c
Yogurt Whey	54.68 ± 3.28 ^b
Whey	13.86 ± 1.64 ^d
Buttermilk	10.30 ± 1.45 ^d
Kefir Whey	129.06 ± 6.24 ^a

a–d: Values shown in the same column with the same lowercase letters differ significantly for each analysis ($p < 0.05$).

The higher levels of lactic acid, butyric acid, and citric acid found in pickles made with yoghurt whey may be associated with the fermentation characteristics commonly reported for yoghurt whey, including the presence of lactic acid bacteria, lactic acid, and other fermentation-derived organic acids typically associated with yoghurt whey. Furthermore, the secondary fermentation of lactate by butyric acid bacteria in anaerobic micro-niches may have contributed to the accumulation of these organic acids. In contrast, the formation of these acids may have been more limited in the vinegar, kefir whey, whey, and buttermilk systems due to differences in substrate composition and microbial interactions [7,47,48].

High levels of acetic and propionic acids in vinegar-based pickles are linked to the vinegar's high initial acetic acid content and the continuous oxidation of ethanol to acetic acid by acetic acid bacteria under aerobic conditions. In contrast, in dairy-based by-products, the dominant metabolism of lactic acid bacteria causes a rapid drop in pH, thereby limiting the growth of microorganisms that produce acetic and propionic acids and reducing their accumulation [49,50].

The higher sensory acceptance of yoghurt whey-based pickles may be associated with their higher firmness and springiness values, elevated lactic acid concentration, and greater abundance of lactic acid bacteria. These characteristics may have contributed to a balanced acidic taste, desirable texture, and overall consumer acceptance. In contrast, the lower sensory scores of buttermilk-based samples may be related to their higher adhesiveness and distinct compositional characteristics, which could have negatively influenced sensory perception. Similarly, the high acetic acid content of vinegar-based samples may have resulted in a sharper acidic taste, limiting overall acceptability despite their favourable physicochemical properties.

The panelists awarded the highest scores across all criteria (excluding brine salinity) to the pickle samples made with yoghurt whey. These samples received the highest overall rating of 7.5; they were followed by pickles made with whey (7.11) and vinegar (6.98). The samples made using buttermilk received the lowest overall rating of 5.74 ($p < 0.05$; Figure 3).

The sensory evaluation should be interpreted with caution, as it was conducted using a relatively small group of untrained panelists ($n = 15$). Therefore, these findings should be considered exploratory and may not fully represent broader consumer preferences. Future studies involving larger consumer populations and trained sensory panels are recommended to improve the robustness and generalizability of the results.

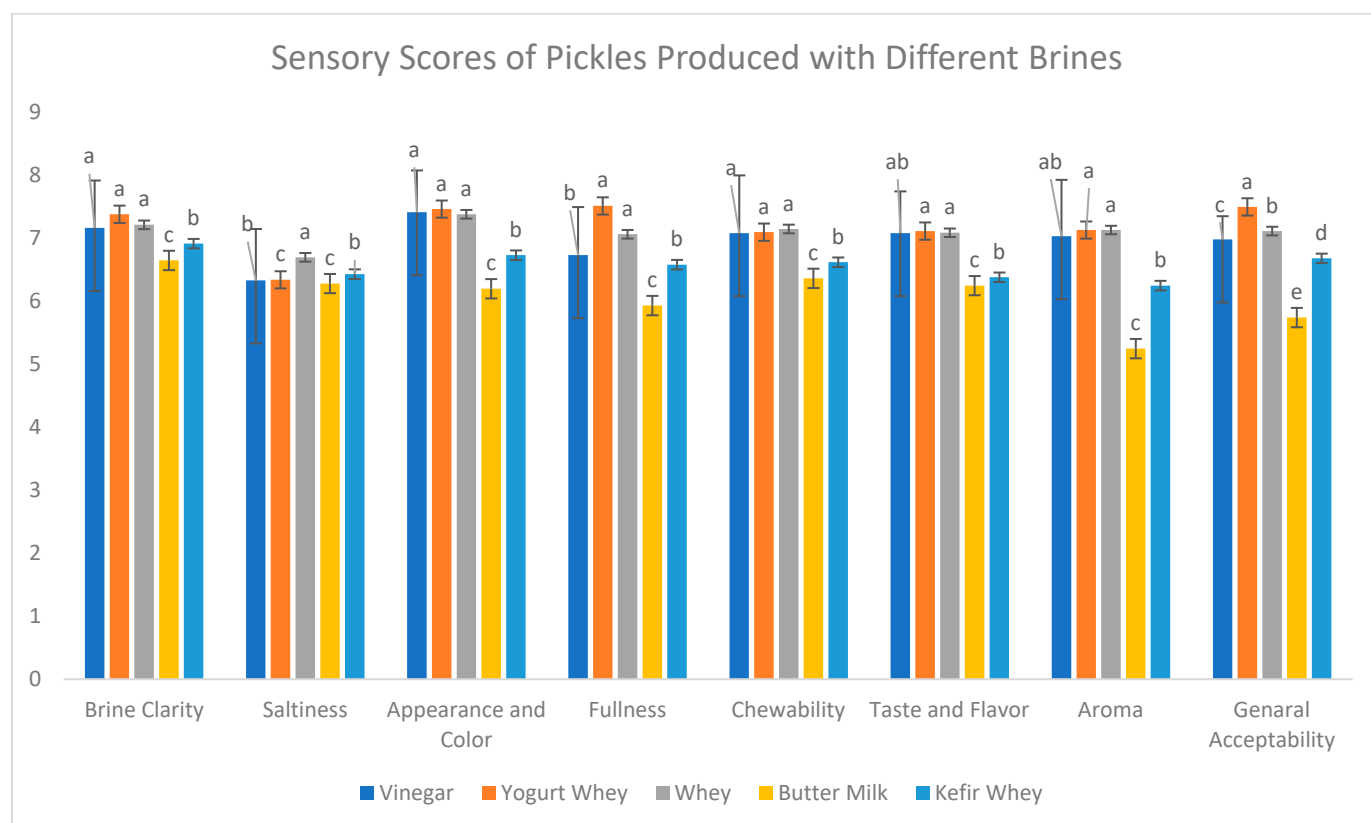


Figure 3. Sensory scores of pickle samples prepared with different brines. Values are presented as mean $\pm$ standard deviation ($n = 15$). Different letters indicate significant differences among treatments within the same sensory attribute ($p < 0.05$).

4. Conclusions

In this study, the effects of using various by-products of fermented dairy products (yoghurt whey, whey, kefir whey and buttermilk) and vinegar in the making of cabbage pickle on physicochemical, microbiological, textural, colour, organic acid and sensory characteristics were comprehensively evaluated. The findings revealed that the brine medium used is a decisive factor in pickle quality.

The results of this study demonstrated that different fermented dairy by-products and vinegar used as brine media significantly influenced the quality characteristics of cabbage pickles. Changes in the brine composition resulted in significant differences in the physicochemical properties, microbial composition, textural characteristics, organic acid profile, and sensory attributes of the products. These findings indicate that the type of brine medium is one of the key factors governing the fermentation process and the final quality of pickled products. Pickles produced with yogurt whey exhibited a pronounced lactic acid fermentation profile, characterized by low pH values, high lactic acid concentrations, and elevated counts of *Lactobacillus* spp. and *Streptococcus/Lactococcus* spp. Although these samples showed lower dry matter content, drained weight, and some rheological parameters, they achieved the highest sensory scores and were the most preferred by the panelists. These results suggest that yogurt whey positively contributes to both the microbiological quality and flavor profile of cabbage pickles.

Vinegar-based pickles were distinguished by their high acetic and propionic acid contents, more intense color characteristics, and superior performance in certain textural parameters. While the high acidity promoted color development and resilience, excessive acidity appeared to limit some sensory attributes. Samples produced with cheese whey exhibited higher gumminess and chewiness values, likely due to their protein and mineral

content, whereas kefir whey promoted yeast growth and enhanced viscoelastic properties. Buttermilk improved brightness (L^*) as well as adhesiveness and cohesiveness; however, it showed lower overall consumer acceptance compared with the other treatments.

Overall, the findings indicate that fermented dairy by-products can be successfully utilized as alternative and functional brine ingredients in cabbage pickle production. Among the tested treatments, yogurt whey emerged as the most promising option due to its ability to enhance sensory acceptance while supporting the growth of beneficial lactic acid bacteria. Furthermore, the valorization of dairy industry by-products in pickle production offers an environmentally sustainable approach for converting processing residues into value-added food products, thereby contributing to circular economy practices. Future studies should investigate different vegetable varieties, starter culture combinations, and storage conditions to further explore the industrial application potential of these by-products in fermented vegetable production.

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Institutional Review Board Statement: There is no requirement that sensory evaluation must undergo ethical approval at Afyon Kocatepe University. There are no formal documentation procedures available for sensory evaluation at Afyon Kocatepe University. The experimental protocol involving sensory evaluation was in accordance with the relevant operational specifications in ISO guidelines (ISO 8589 [51], ISO 11132 [52]).

Informed Consent Statement: Written informed consent was obtained from all participants prior to their involvement in the study, in accordance with the General Data Protection Regulation (GDPR) 2016/679. Participation in the sensory evaluation was entirely voluntary, and all data were collected anonymously. The study was conducted in accordance with the ethical principles outlined in the Declaration of Helsinki.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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