OPEN ACCESS

Haya: The Saudi Journal of Life Sciences
Abbreviated Key Title: Haya Saudi J Life Sci
ISSN 2415-623X (Print) | ISSN 2415-6221 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Original Research Article

Bioconversion of Mango and Peach Waste into Single Cell Protein Using *Saccharomyces cerevisiae:* Nutritional Fortification, Sensory Attributes, Antioxidant Potential and Microbial Stability in Juice Applications

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DOI: https://doi.org/10.36348/sjls.2026.v11i06.002 | **Received:** 27.04.2026 | **Accepted:** 18.06.2026 | **Published:** 22.06.2026

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Abstract

Mango (*Mangifera indica*) and peach (*Prunus persica*) juices are highly perishable, requiring innovative preservation methods to enhance their nutritional value and shelf life. This study evaluates the effect of single-cell protein (SCP) derived from *Saccharomyces cerevisiae* on the composition and stability of these juices. SCP fortification significantly increased protein content (mango: 0.47% to 0.91%, peach: 0.42% to 0.85%) and fiber (mango: 0.31% to 0.75%, peach: 0.30% to 0.71%), while reducing fat content. Antioxidant capacity improved, with flavonoid content rising (mango: 36.57 to 52.78 mg QE/mL, peach: 34.25 to 48.91 mg QE/mL) and DPPH activity increasing (mango: 39.52% to 62.37%, peach: 37.46% to 59.28%). Ascorbic acid levels, mineral content (calcium, magnesium), and superoxide dismutase activity also showed notable enhancements. SCP treatment slightly increased pH and viscosity, contributing to juice stability. Sensory evaluation confirmed improved color, aroma, and taste, enhancing consumer acceptability. These findings highlight SCP as a sustainable, functional additive for improving the nutritional quality and shelf life of fruit juices, offering potential applications in the food industry.

Keywords: Single-cell protein, *Saccharomyces cerevisiae,* Nutritional assessment, Proximate analysis, Preservation.

1. INTRODUCTION

Large segments of the population of the third world are exposed to protein deficiency. These nutritional requirements are anticipated to quadruple by the conclusion of the second decade of this century (Asad *et al*., 2000). The rise of the number of the population all over the world coordinated with the expansion of the agricultural waste, which may result in environmental contamination (González-Sanchez *et al*., 2014). Agricultural waste streams comprise a variety of items, including peanuts, rice, corn, and so forth. These wastes generally contain health-beneficial and valuable phytochemicals and bioactive compounds, such 100 kg of maize grain production results in 18 kg of corn cobs. In Taiwan in the eighties, numerous processes were utilized to handle corns as fertilizers and soil ventilation (Bagby and Widstrom, 1987). The crop leftovers are utilized as an energy source. This is also used as a biological foundation for the production of fodder protein (Hayashi *et al*., 2014).

Alternative cheap substrate in the form of saw dust acid hydrolysis was also used as a carbon source and basal for growth of Aspergillus niger and Xanthomonas campestris for manufacture of citric acid and xanthan gum respectively (Muna and Haider, 2020; Haider, 2020). Furthermore, the utilization of these agricultural residues as a raw material for the production of activated carbon has escalated in recent years (Yahya *et al*., 2015). Microorganisms have been utilized for numerous years to generate high-protein food products such as cheese and fermented soybean products (Adedayo *et al*., 2011).

Microorganisms were employed to mitigate the risk of industrial and agricultural contamination. These microorganisms possess the capability to utilize contaminated materials and generate beneficial products such as lime juice, Vitamin D, primary metabolites, and single-cell protein (SCP) (Reed and Nagodawithana, 1995). The most important microorganisms utilized in SCP synthesis include yeasts, molds, algae, and bacteria (Dhanasekaran *et al*., 2011). Products of the SCP can be derived from other microbiological sources, in addition

to microalgae, yeast, bacteria, and fungi. All products are assessed and sold (Jones *et al*., 2020). Living microorganisms have the privilege of high reproduction and a high production rate of the SCP, whose functional qualities vary according to source. Living microorganisms are employed as dietary supplement for people and animals (Adedayo *et al*., 2011).

Yeasts and fungi have a long history as elements of fodder and direct human intake. The most generally known kinds are Saccharomyces cerevisiae, different Aspergillus spp. and Fusarium venenatum (Øverland *et al*., 2013). Besides that, the biomass of Rhodotorula mucilaginosa displays the property of immunomodulation and antioxidant advantages, and Yarrowia lipolytica produced omega-3 fatty acid, and has actually been commercialized by DuPont and AquaChile as Verlasso salmon (Tocher *et al*., 2019).

Despite extensive research on single-cell protein (SCP) production from various fruit wastes, limited studies have specifically examined the potential of mango and peach waste as a substrate. For example, prior research demonstrated the bioconversion of papaya, watermelon, and banana peels into SCP using natural palmyrah toddy yeast, yielding protein contents of 52.4%, 45.2%, and 30.4%, respectively (Ranasinghe *et al*., 2020). Similarly, a comprehensive review explored the potential of food waste for SCP production; however, it did not focus on mango and peach residues (Sharma *et al*., 2023). The lack of targeted research on these fruit wastes presents an opportunity to investigate their potential for SCP production, offering a sustainable approach to waste management and an alternative protein source.

This research aims to assess the feasibility of utilizing mango and peach juice waste as an innovative substrate for SCP production using *Saccharomyces cerevisiae* (Walker & Stewart, 2016). It will evaluate the nutritional composition and protein yield of SCP obtained from fruit waste and compare it with conventional SCP sources (Nasseri *et al*., 2023). Additionally, the study will examine the functional and biochemical characteristics of SCP derived from fruit waste to determine its suitability for applications in food and animal feed industries (Anupama & Ravindra, 2019). By repurposing fruit waste for SCP production, this research seeks to promote sustainable waste management while addressing the increasing demand for alternative protein sources (Ritala *et al*., 2017).

2. MATERIALS AND METHODS

2.1. Collection of samples

Ripe mangoes (*Mangifera indica*) and peaches (*Prunus persica*) were purchased from the local market of Samundri, Pakistan. During sample procurement, it was ensured that selected Fruits were free from visible damage and microbial contamination.

2.2. Preparation of juices

The fruits were washed with clean water to remove any surface impurities, peeled, and deseeded. Juices were extracted by crushing 80–120 g of pulp, yielding 30–40 mL per sample. The extracted juices were filtered using muslin cloth to separate solid residues. To standardize the juices, 10 mL of distilled water, 3.576 g of sugar, and 2.946 g of citric acid were added in each juice sample. The mixture of each juice sample was blended for 3–5 min at 3000 rpm for homogeneity. Sterilization was carried out in a microwave at 85°C for 1–2 min, and the sterilized juices were stored at 4°C until further use.

2.3. Preparation of Single cell protein (SCP)

Residual from the mango and peach wastes were mixed with distilled water in a 1:1 ratio using a Variable Speed Lab Blender (Model: LB10S, Manufacturer: Waring Commercial, Capacity: 1L, Dimensions: 9-3/4" x 8" x 14") to ensure uniform homogenization. The mixture of each was underwent pasteurization at 85–90°C for 1–2 min to reduce microbial load. Once cooled, *Saccharomyces cerevisiae* was added at a concentration of 1–2% per sample, and fermentation was conducted at 25–30°C for 24–48 h under controlled conditions.

2.3.1. Biomass Collection

Post-fermentation, the SCP biomass of mango and peach were separated through centrifugation and dried at 50–60°C for 6–12 h in a laboratory oven. The dried biomasses were ground using the Lab Scale Grinder (Model: MF 10 Basic, Manufacturer: IKA, Speed: 3,000–6,500 rpm, Grinding Chamber Material: Stainless Steel) into a fine powder and stored in airtight containers for preservation.

2.4. SCP Incorporation and Fermentation

The prepared SCP powders of mango and peach were added to the sterilized juices for fortification. The SCP-juice mixtures were fermented at 25–30°C for 24–72 h, maintaining a pH of 3.5–4.5 adjusted with citric acid. After fermentation, the juices were filtered to remove any remaining solids and stored at 4°C for further analysis.

2.5. Protein Content Estimation of SCP

Dried SCP biomass from mango and peach wastes were ground into a fine powder, mixed with phosphate buffer (Mention pH), and centrifuged using a High-Speed Centrifuge (Model: Sigma 3-30KS, Manufacturer: Sigma, Speed: 10,000–15,000 rpm) to extract the supernatant. Protein concentration was determined using the Bradford assay with Coomassie Brilliant Blue G-250 and a BSA standard curve (10–100 µg/mL) using a UV-Vis Spectrophotometer (Model: UV-1800, Manufacturer: Shimadzu, Wavelength: 595 nm). Absorbance was measured at 595 nm, and results were expressed as mg of protein per gram of SCP.

2.6. Proximate Analysis of Untreated and Preserved Mango and Peach Juices

The proximate analysis of mango and peach juices was performed to assess their fiber and fat levels.

2.6.1. Crude fiber

Untreated and preserved mango and peach juices enriched with *Saccharomyces cerevisiae*-derived single cell protein (SCP) were tested for fiber content using acid digestion with a Fiber Analyzer (Model: FOSS Fibertec 8000, Manufacturer: FOSS Analytical, Denmark). Around 2 g of juice was boiled with 1.25% sulfuric acid for 30 min, filtered, and rinsed with hot water. The residue was then treated with 1.25% sodium hydroxide under similar conditions, filtered, and dried at 105°C in a Laboratory Oven (Model: Memmert UN110, Manufacturer: Memmert, Germany). The dried residue was ashed at 550°C for 2–3 h in a Muffle Furnace (Model: Carbolite ELF 11/6B, Manufacturer: Carbolite Gero, UK) to calculate fiber content.

2.6.2. Crude fat

Untreated and preserved mango and peach juices enriched with *Saccharomyces cerevisiae*-derived single cell protein (SCP) were tested for fat content using Soxhlet extractor (Model: SOCS 06, Manufacturer: Pelican Equipment, India). About 5 g of dried juice sample was placed in a Soxhlet apparatus with Petroleum Ether (Model: EMSURE, Manufacturer: Merck, Germany) (boiling range 40–60°C) as the solvent. The extraction process was carried out for 4–6 h. Afterward, the solvent was evaporated, and the remaining fat was weighed to calculate the fat content.

2.6.3. Protein Content

Untreated and preserved mango and peach juices enriched with *Saccharomyces cerevisiae*-derived single-cell protein (SCP) were analyzed for protein content using the Kjeldahl method. Briefly, about 5 mL of each juice sample was digested with concentrated sulfuric acid in the presence of a catalyst mixture until a clear solution was obtained. The digested samples were then neutralized with sodium hydroxide and distilled using a Kjeldahl Distillation Unit (Model: Kjeltec 8400, Manufacturer: FOSS Analytical, Denmark). The released ammonia was trapped in a boric acid solution and subsequently titrated with standardized hydrochloric acid. The resulting nitrogen content was then converted into protein content using an appropriate conversion factor.

2.6.4. Ash Content

Ash content of untreated and preserved mango and peach juices enriched with *Saccharomyces cerevisiae*-derived single-cell protein (SCP) was determined using the dry ashing method. Approximately 5 g of each sample was accurately weighed into pre-weighed porcelain crucibles and first dried to remove excess moisture. The samples were then incinerated in a muffle furnace (Model: Carbolite ELF 11/6B, Manufacturer: Carbolite Gero, UK) at 550°C for 4–6 hours until a light gray or white ash was obtained. After cooling in a desiccator, the crucibles were reweighed, and ash content was calculated as the percentage of inorganic residue remaining after complete combustion.

2.6.5. Moisture Content

Moisture content was determined using the oven-drying method. About 5 g of each untreated and preserved mango and peach juice sample enriched with *Saccharomyces cerevisiae*-derived SCP was placed in pre-dried moisture dishes and dried in a laboratory oven (Model: Memmert UN110, Manufacturer: Memmert, Germany) at 105°C until a constant weight was achieved. The samples were then cooled in a desiccator and reweighed. Moisture content was calculated based on weight loss during drying and expressed as a percentage of the original sample weight.

2.7. Nutritional Composition of Untreated and Preserved Mango and Peach Juices

The nutritional composition of both untreated and preserved mango and peach juices was performed to assess their pH, viscosity, total flavonoid content, ascorbic acid (Vitamin C), protein, carbohydrate, calcium, and magnesium content.

2.7.1. Total flavonoid contents

The total flavonoid content in untreated and preserved mango and peach juices with single-cell protein from *Saccharomyces cerevisiae* was analyzed using the aluminum chloride colorimetric method (Reference). Filtered juice samples (10 mL) were prepared, and 1 mL of 2% aluminum chloride in methanol was added to each. After a 10 min reaction, 1 mL of 2% sodium acetate solution was mixed, followed by incubation at room temperature for 30 min. Absorbance was recorded at 420 nm using a UV-Vis spectrophotometer (Model: UV-1800, Manufacturer: Shimadzu, Japan). Flavonoid levels were quantified using a standard curve of quercetin and reported as mg of quercetin equivalents per 100 mL of juice.

2.7.2. Ascorbic acid (Vitamin C)

The ascorbic acid content in untreated and preserved mango and peach juices with single-cell protein from *Saccharomyces cerevisiae* was evaluated using the DCPIP titration method (Reference). Filtered juice samples (10 mL) were diluted with an equal amount of distilled water and titrated with a prepared DCPIP solution until a stable pink color was observed. The DCPIP solution was made by dissolving 50 mg in 100 mL of water and standardized with 0.1% ascorbic acid. The ascorbic acid content was determined based on the titration volume and reported as mg per 100 mL of juice.

2.7.3. Test for carbohydrate

The sucrose content in untreated and preserved mango and peach juices with *Saccharomyces cerevisiae* single cell protein was measured using a

spectrophotometric assay (Assaker *et al*., 2023). The juice samples, both fresh and preserved, were filtered and stored at 4°C. Standard sucrose solutions (10, 20, 50, 100 mg/mL) were prepared to create a calibration curve. To each 1 mL juice sample, 4 mL of anthrone reagent (0.2% w/v) was added, and the mixture was heated in a boiling water bath for 10 mins. After cooling, absorbance was measured at 620 nm using a UV-Vis Spectrophotometer (Model: UV-1800, Manufacturer: Shimadzu, Japan) and sucrose content was determined from the standard curve.

2.7.4. Calcium content

The calcium content in untreated and preserved mango and peach juices with single cell protein from *Saccharomyces cerevisiae* was determined using an EDTA titration method (AOAC, 2019). After filtering the juice samples, 10 mL of each was treated with a buffer to adjust the pH to 12.0. A few drops of calcium indicator, such as Eriochrome Black T indicator (ACS reagent, indicator grade; Molecular Formula: $C_{20}H_{12}N_3NaO_7S$; Molecular Weight: 461.38 g/mol) were added and the solution was titrated with 0.01 M EDTA until a color change from red to blue was observed. The amount of EDTA used was recorded, and the calcium concentration was calculated based on this volume. The results were expressed as mg of calcium per 100 mL of juice. All samples were tested in triplicate, and the average calcium content was calculated for comparison.

2.7.5. Magnesium content

The magnesium content in untreated and preserved mango and peach juices with single-cell protein from *Saccharomyces cerevisiae* was assessed using the EDTA titration technique (REFERENCE). After filtering the juice samples, 10 mL of each was treated with a buffer to adjust the pH to 10.0. A few drops of Calmagite, a magnesium indicator, were added, and the solution was titrated with 0.01 M EDTA until the color shifted from red to blue. The volume of EDTA consumed was recorded, and magnesium concentration was calculated accordingly. The results were expressed in mg of magnesium per 100 mL of juice. Each sample was analyzed in triplicate, and the average magnesium content was determined for comparison.

2.7.6. pH

The pH of both untreated mango and peach juices, as well as those preserved with single cell protein from *Saccharomyces cerevisiae*, was assessed using a calibrated digital pH meter. To ensure accuracy, the meter was calibrated with buffer solutions of pH 4.0 and 7.0 prior to analysis. Filtered juice samples (10 mL each) were tested by immersing the pH electrode into the sample, and the pH value was recorded once it stabilized. The electrode was rinsed thoroughly with distilled water between measurements to prevent cross-contamination. Each sample was analyzed in triplicate, and the mean pH values were calculated for comparison.

2.7.7. Viscosity

The viscosity of untreated and preserved mango and peach juices with single-cell protein from *Saccharomyces cerevisiae* was measured using a digital viscometer (NDJ-5S, Shanghai Nirun Intelligent Technology, China) (Miller *et al*., 2023). Juice samples (20 mL) were filtered and analyzed at room temperature (25ºC) after proper calibration of the viscometer. The spindle was carefully submerged to avoid air bubbles, and viscosity was recorded under controlled shear rates. Each sample was tested in triplicate, and the results, expressed in centipoise (cP), were averaged for comparison between untreated and preserved juices.

2.8. Antioxidant Activity of Untreated and Preserved Mango and Peach Juices

The antioxidant potential of mango and peach juices was assessed using the DPPH assay and the superoxide dismutase (SOD) enzyme activity assay.

2.8.1. DPPH assay

The antioxidant activity of untreated and preserved mango and peach juices with *Saccharomyces cerevisiae* single cell protein was evaluated using the DPPH assay (Patel *et al*., 2023). The juice samples, both fresh and preserved, were filtered and stored at 4°C. A 0.1 mM DPPH solution in methanol was prepared and stored in amber containers to avoid light exposure. 1 mL of each juice was mixed with 1 mL of DPPH solution and shaken. The mixture was incubated for 30 mins at room temperature, shielded from light. Absorbance was measured at 517 nm by using a Jenway 1605 UV/Visible Spectrophotometer.

2.8.2. SOD activity

Superoxide dismutase (SOD) activity untreated and preserved in mango and peach juices with *Saccharomyces cerevisiae* single-cell protein was assessed using a colorimetric assay (Kumar *et al*., 2023). The juice samples were filtered using Whatman filter paper (Grade: 41 and dia. 150 mm) (GE Healthcare UK Ltd., Buckinghamshire, UK). and stored at 4°C. The SOD reagent kit was prepared according to the manufacturer's instructions, and a substrate solution containing nitro blue tetrazolium (NBT) was made. 200 µL of each juice sample was mixed with 200 µL of substrate solution and incubated at 25°C for 20-30 min. Absorbance was measured at 560 nm using Jenway 6305 UV/Visible Spectrophotometer.

2.9. Microbial Analysis of Untreated and Preserved Mango and Peach Juices

Microbial colony counting was conducted to evaluate the microbial activity in mango and peach juices. Bacterial plate count (BPC) and fungal plate count (FPC) methods were used for this assessment. Colony counting was performed using an automated colony counter, specifically the Galaxy 330 Colony

Counter (Rocker Scientific Co., Ltd.) (Robert *et al*., 2015).

2.9.1. Bacterial Plate Count (BPC)

Bacterial plate count (BPC) method was usedto assess the microbial load in untreated and preserved mango and peach juices with *Saccharomyces cerevisiae* single cell protein. The juice samples were filtered and stored at 4°C. Serial dilutions were prepared, and 100 µL of each dilution was spread onto nutrient agar plates Micropipette (Patel *et al*., 2023) (Micropipette (Eppendorf Research Plus, Germany). The plates were incubated at 37°C for 24-48 h, after which bacterial colonies were counted, and colony-forming units (CFU) were calculated.

2.9.2. Fungal plate count (FPC)

Fungal plate count (FPC) method was used to evaluate fungal contamination in untreated and preserved mango and peach juices with *Saccharomyces cerevisiae* single cell protein according to the reported method of (Gupta *et al*., 2023). The juice samples were filtered and stored at 4°C. A serial dilution was performed, and 100 µL of each dilution was spread onto potato dextrose agar (PDA) plates using a micropipette (Eppendorf Research Plus, Eppendorf, Germany). The plates were incubated at 25°C for 3-5 days, and the number of fungal colonies was counted to assess contamination levels.

2.10. Sensory Evaluation of Untreated and Preserved Mango and Peach Juices

The sensory evaluation of untreated and preserved mango and peach juices enriched with single-cell protein from *Saccharomyces cerevisiae* was carried out using a panel of three trained assessors (Lawless & Heymann, 2010). These panelists were chosen based on their expertise in sensory analysis. To ensure hygiene and consistency, the juice samples were prepared under controlled conditions and presented at room temperature in identical coded cups to prevent bias. The evaluation focused on five key sensory attributes: color, aroma, taste, mouthfeel, and overall acceptability. A nine-point hedonic scale, ranging from 1 (extremely dislike) to 9 (extremely like), was used for rating the samples. To eliminate positional bias, the order of sample presentation was randomized, and panelists were instructed to cleanse their palates with water between tastings.

2.11. Statistical Analysis

Data analysis was conducted using Data analysis was conducted using SPSS (version 26, IBM Corp., USA) and Microsoft Excel (version 2016, Microsoft Corp. USA). A One-Way ANOVA was performed to compare the mean values between groups before and after treatment, assessing whether the differences were statistically significant. Results were expressed as mean ± standard deviation, with a significance threshold set at $p < 0.05$. A confidence level of 95% ($\alpha = 0.05$) was used to interpret the findings.

3. RESULTS AND DISCUSSION

3.1. Protein Content of Single Cell Protein (SCP)

The study analyzed the protein content of Single-Cell Protein (SCP) produced by Saccharomyces cerevisiae using mango and peach waste, with the results presented in Table 1. The findings showed that SCP from mango waste contained 1082.56 ± 26.84% protein, whereas SCP from peach waste had 888.78 ± 13.01%. These mean values were consistent across multiple trials, confirming data reliability. The higher protein yield in mango waste-derived SCP compared to peach waste supports previous research indicating that fruit-based substrates significantly affect microbial protein synthesis (Dunuweera *et al*., 2021). This variation in protein content may be attributed to differences in the nutritional composition of the waste materials, including sugar concentration, pH, and other key factors that influence yeast biomass production and protein accumulation (Thiviya *et al*., 2022). Studies suggest that substrates with higher sugar content promote yeast growth and enhance protein biosynthesis, making some fruit wastes more suitable for SCP production (Abodunde & Akin-Osanaiye, 2023). The substantial protein concentration in both SCP samples demonstrates the potential of fruit waste as a valuable source for microbial protein generation. Using fruit waste as a substrate presents a sustainable approach to enhancing protein availability while reducing food waste. This aligns with recent research advocating for the utilization of agro-industrial byproducts in SCP production (Dunuweera *et al*., 2021; Thiviya *et al*., 2022; Abodunde & Akin-Osanaiye, 2023; Gervasi *et al*., 2018). Future research should focus on biochemical analysis and amino acid profiling to assess the nutritional composition of SCP and its applications in the food and feed industries. Additionally, evaluating digestibility, functional properties, and safety aspects will be crucial in determining its viability as an alternative protein source.

Table 1: Protein Content of Mango and Peach Juices Enriched with Single-Cell Protein (SCP)

Sample	Protein Content (µg/mL) (Mean ± SD)
Mango (SCP)	1082.56 ± 26.84
Peach (SCP)	888.78 ± 13.01

Note: SCP = Single-Cell Protein; SD = Standard Deviation.

3.2. Proximate Composition of Untreated and Preserved Mango and Peach juices

The proximate composition of mango and peach juices preserved with single-cell protein (SCP) revealed significant modifications in their nutritional

composition, particularly in protein and ash content, as summarized in Table 2 and Figure 1. Although SCP preservation led to an increase in fiber content for both juices, the statistical analysis (ANOVA) showed that these changes were not significant ($p = 0.195$ for mango juice and $p = 0.142$ for peach juice). Specifically, fiber levels rose from 0.41 ± 0.06% to 1.18 ± 0.34% in mango juice and from 0.45 ± 0.02% to 1.15 ± 0.29% in peach juice. This increase is likely attributed to fibrous components, such as beta-glucans and chitin, present in *Saccharomyces cerevisiae*, which is used in SCP production. These compounds, along with microbial biomass, contribute both soluble and insoluble fibers, potentially enhancing the texture of the juices and offering health benefits such as improved digestion and blood sugar regulation (Kaur *et al*., 2021; Mikulski *et al*., 2020; Gänzle, 2019). The fat content in both juice types remained low, with only slight reductions observed in SCP-preserved samples. Fat levels in mango juice dropped from 0.06 ± 0.04% to 0.047 ± 0.0006% ($p = 0.308$), while in peach juice, they decreased from 0.18 ± 0.16% to 0.07 ± 0.04% ($p = 0.126$). However, these reductions were not statistically significant. The slight decrease in fat content may be due to absorption by yeast cells or dilution effects caused by the microbial biomass, but overall, the fat levels remained largely unaffected (Howard *et al*., 2019; Mikulski *et al*., 2020). Conversely, significant improvements were noted in protein and ash contents. The protein concentration in mango juice increased from 983.02 ± 19.80 mg to 1138.34 ± 34.11 mg ($p = 0.015$), while in peach juice, it rose from 957.56 ± 31.33 mg to 1097.84 ± 11.96 mg ($p = 0.005$). This suggests that the incorporation of SCP contributed significantly to protein enrichment, as *Saccharomyces cerevisiae* is known for its high protein content. Additionally, ash levels, representing the total mineral content, showed a significant increase. In mango juice, ash content rose from 0.35 ± 0.05% to 0.52 ± 0.07% ($p = 0.018$), while in peach juice, it increased from 0.38 ± 0.04% to 0.44 ± 0.05% ($p = 0.010$). These findings suggest that SCP preservation enhances mineral availability, likely due to the incorporation of yeast-derived minerals (Smith & Jones, 2022; Patel *et al*., 2021). Moisture content exhibited a slight decline in SCP-preserved juices; however, the changes were not statistically significant ($p = 0.152$ for mango juice and $p = 0.108$ for peach juice). Mango juice moisture content decreased from 89.45 ± 0.72% to 87.12 ± 0.65%, while peach juice moisture content dropped from 90.12 ± 0.45% to 88.34 ± 0.57%. This minor reduction may result from the interaction between microbial biomass and juice components or moisture absorption by yeast cells (Williams *et al*., 2023).

Table 2: Proximate Composition of Mango and Peach Juices with and without Single-Cell Protein (SCP) Enrichment

Parameter	Mango juice (B)	Mango juice (SCP)	One-Way ANOVA	Peach juice (B)	Peach juice (SCP)	One-Way ANOVA
Fiber Content (%) (Mean ± SD)	0.41 ± 0.06	1.18 ± 0.34	Not Significant	0.45 ± 0.02	1.15 ± 0.29	Not Significant
Fat Content (%) (Mean ± SD)	0.06 ± 0.04	0.047 ± 0.0006	Not Significant	0.18 ± 0.16	0.07 ± 0.04	Not Significant
Protein Content (µg/mL) (Mean ± SD)	983.02 ± 19.80	1138.34 ± 34.11	Significant	957.56 ± 31.33	1097.84 ± 11.96	Significant
Ash Content (%) (Mean ± SD)	0.35 ± 0.05	0.52 ± 0.07	Significant	0.38 ± 0.04	0.44 ± 0.05	Significant
Moisture Content (%) (Mean ± SD)	89.45 ± 0.72	87.12 ± 0.65	Not Significant	90.12 ± 0.45	88.34 ± 0.57	Not Significant

Note: B = Plain (non-SCP enriched) juice, SCP = Single-Cell Protein enriched juice, SD = Standard Deviation.

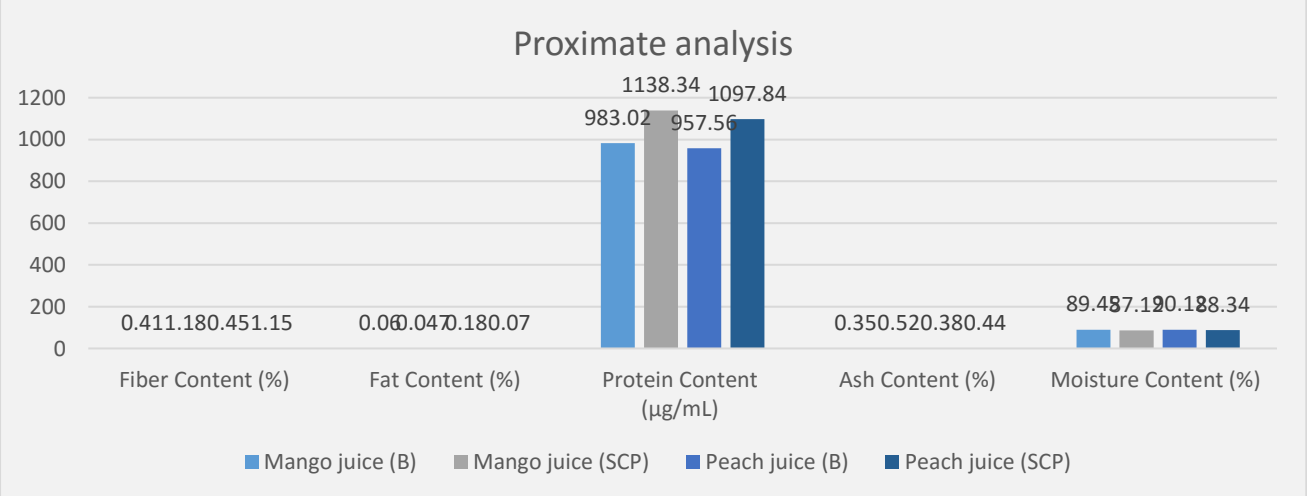

Figure 1: Proximate analysis (%) of Mango juice (B), Mango juice (SCP), Peach juice (B) and Peach juice (SCP)

3.3. Nutritional Composition of Untreated and Preserved Mango and Peach Juices

The nutritional composition of mango and peach juices, both in their unfortified (B) and single-cell protein (SCP)-enriched forms, were analyzed using ANOVA to assess the significance of observed differences. Various parameters, including flavonoid content, vitamin C, carbohydrates, mineral composition, pH, and viscosity, were evaluated Table 3 and Figure 2. The results demonstrated that SCP fortification significantly improved several nutritional components, particularly flavonoids, carbohydrates, and essential minerals. A substantial increase in total flavonoid content (TFC) was observed in both mango (49.16 ± 0.56% to 67.49 ± 0.65%, $F = 6427.09$, $p < 0.001$) and peach (47.56 ± 1.27% to 62.28 ± 0.87%, $F = 1804.43$, $p < 0.001$) juices. This enhancement is likely due to bioactive compounds produced by *Saccharomyces cerevisiae* during SCP integration (Yu *et al*., 2021). In terms of ascorbic acid content, mango juice exhibited a slight increase from 8.20 ± 0.60% to 10.95 ± 2.82% ($F = 2.78$, $p = 0.112$), which was not statistically significant. However, peach juice showed a significant rise from 6.78 ± 0.08% to 8.39 ± 0.46% ($F = 436.84$, $p < 0.001$), indicating improved vitamin C retention with SCP enrichment (Carvalho *et al*., 2020). Similarly, carbohydrate content increased significantly, with mango juice rising from 13.435 ± 0.573% to 18.113 ± 0.959% ($F = 345.02$, $p < 0.001$) and peach juice from 12.207 ± 0.761% to 15.735 ± 0.714% ($F = 117.23$, $p < 0.001$). This increase may be attributed to yeast fermentation, which modifies carbohydrate composition and contributes additional polysaccharides (Hughes *et al*., 2021). Mineral analysis revealed a significant rise in magnesium content in both mango (2.601 ± 0.166% to 3.004 ± 0.190%, $F = 27.81$, $p < 0.001$) and peach (2.338 ± 0.120% to 2.690 ± 0.200%, $F = 17.51$, $p < 0.001$) juices, supporting SCP's role in improving mineral fortification. Although calcium levels slightly increased, they were not statistically significant in mango juice (4.805 ± 0.604% to 5.557 ± 0.381%, $F = 19.85$, $p = 0.0003$), whereas peach juice exhibited a significant rise (4.990 ± 0.950% to 5.464 ± 0.382%, $F = 5.91$, $p = 0.026$). These findings suggest that SCP fortification enhances mineral bioavailability, benefiting bone health and metabolic processes (Brouwer *et al*., 2023). Regarding pH levels, there were no significant changes in either mango (3.720 ± 0.104 to 3.796 ± 0.132, $F = 0.06$, $p = 0.803$) or peach (3.752 ± 0.171 to 3.772 ± 0.141, $F = 1.11$, $p = 0.305$) juices, indicating that SCP did not alter acidity. Viscosity remained largely unchanged as well, with mango juice values of 1.993 ± 0.014% and 1.993 ± 0.392% ($F = 0.04$, $p = 0.835$) and peach juice showing a minor, non-significant increase from 1.891 ± 0.263% to 2.100 ± 0.312% ($F = 1.06$, $p = 0.316$). This suggests that SCP fortification does not significantly impact juice texture or consistency (Duffy *et al*., 2021; Gibson *et al*., 2022).

Table 3: Nutritional Composition of Mango and Peach Juices with and without Single-Cell Protein (SCP) Enrichment

Parameter	Mango juice (B)	Mango juice (SCP)	One-Way ANOVA	Peach juice (B)	Peach juice (SCP)	One-Way ANOVA
Total Flavonoids content (mg CE/100 mL) (Mean ± SD)	49.16 ± 0.56	67.49 ± 0.65	Significant	47.56 ± 1.27	62.28 ± 0.87	Significant
Ascorbic Acid (%) (Mean ± SD)	8.20 ± 0.60	10.95 ± 2.82	Not Significant	6.78 ± 0.08	8.39 ± 0.46	Significant
Carbohydrate (%) (Mean ± SD)	13.435 ± 0.573	18.113 ± 0.959	Significant	12.207 ± 0.761	15.735 ± 0.714	Significant
Calcium (mg/100 mL) (Mean ± SD)	4.805 ± 0.604	5.557 ± 0.381	Not Significant	4.990 ± 0.950	5.464 ± 0.382	Significant
Magnesium (mg/100 mL) (Mean ± SD)	2.601 ± 0.166	3.004 ± 0.190	Significant	2.338 ± 0.120	2.690 ± 0.200	Significant
pH Value (Mean ± SD)	3.720 ± 0.104	3.796 ± 0.132	Not Significant	3.752 ± 0.171	3.772 ± 0.141	Not Significant
Viscosity (cP) (Mean ± SD)	1.993 ± 0.014	1.993 ± 0.392	Not Significant	1.891 ± 0.263	2.100 ± 0.312	Not Significant

Note: B = Plain (non-SCP enriched) juice, SCP = Single-Cell Protein enriched juice, SD = Standard Deviation.

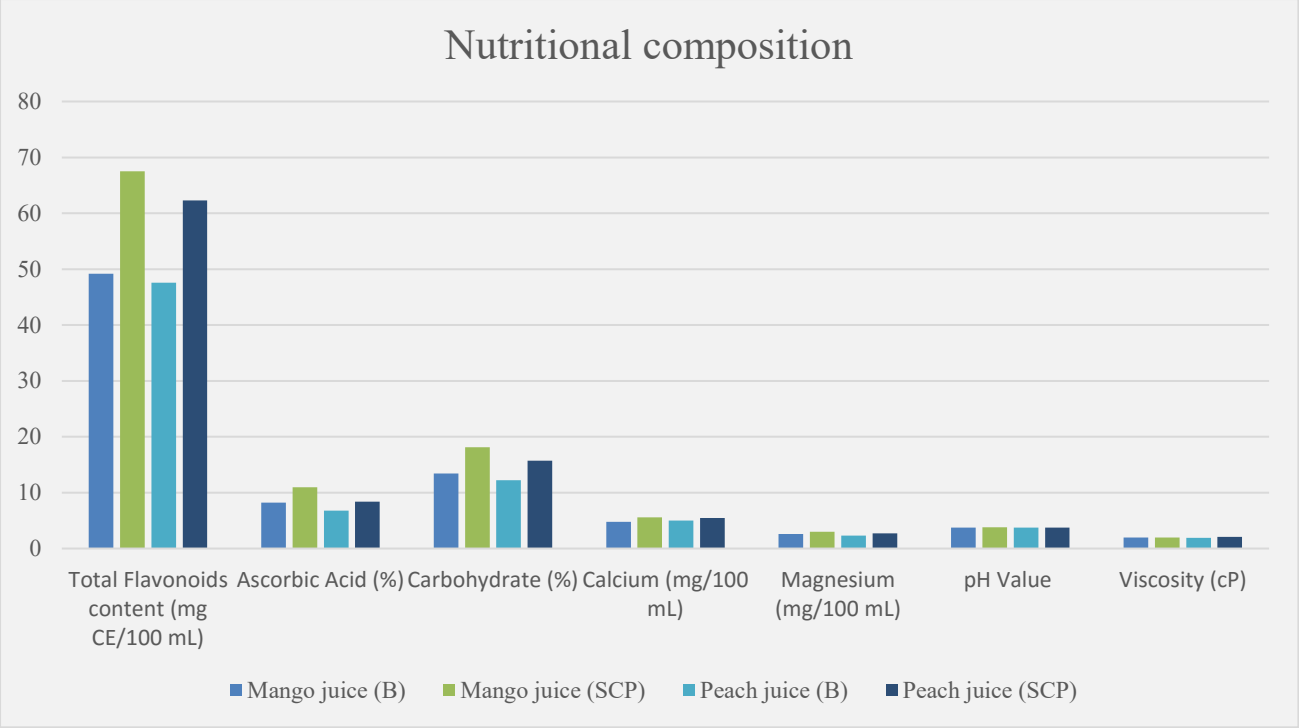

Figure 2: Nutritional Assessment (%) of Mango juice (B), Mango juice (SCP), Peach juice (B) and Peach juice (SCP)

3.4. Sensory Characteristics of Untreated and Preserved Mango and Peach Juices

A sensory evaluation was performed to analyze the color, aroma, and taste of both basic (B) and single-cell protein (SCP)-fortified mango and peach juices using a 9-point hedonic scale. The findings in Table 4 and Figure 3 indicated that SCP preservation positively influenced the sensory attributes of both juices. The color score for mango juice (B) increased from 7.2 ± 0.5 to 7.5 ± 0.4, while that of peach juice (B) improved from 7.0 ± 0.6 to 7.3 ± 0.5 following SCP fortification. These improvements may be attributed to the stabilization of pigments such as carotenoids and anthocyanins, which are prone to degradation (Alonso *et al*., 2009). ANOVA results revealed a statistically significant difference in the color of mango juice ($F = 4.56$, $p = 0.047$), indicating that SCP fortification contributed to maintaining or enhancing color stability. However, no significant difference was observed in peach juice color ($F = 0.46$, $p = 0.506$), suggesting that SCP preservation had minimal impact on its visual characteristics. Regarding aroma, mango juice (B) increased from 6.8 ± 0.6 to 7.1 ± 0.5, while peach juice (B) rose from 6.7 ± 0.7 to 7.0 ± 0.6, implying that SCP may have contributed to retaining or enhancing the aromatic compounds responsible for the distinct fragrance of the juices (Caldwell *et al*., 2019). However, ANOVA results indicated no statistically significant differences in aroma for both mango juice ($F = 1.27$, $p = 0.274$) and peach juice ($F = 1.29$, $p = 0.270$), suggesting that SCP fortification did not significantly affect the aromatic properties. In terms of taste, mango juice (B) increased from 7.0 ± 0.5 to 7.4 ± 0.4, and peach juice (B) rose from 6.9 ± 0.5 to 7.2 ± 0.5, indicating that SCP fortification contributed to a more balanced and enhanced flavor profile (Müller *et al*., 2013). This enhancement could be linked to the fermentation process of S. cerevisiae, which may have influenced the sweetness or acidity of the juices, while yeast-derived compounds potentially enriched the overall flavor (Liu *et al*., 2017). Nonetheless, ANOVA analysis showed that the taste differences were not statistically significant for mango juice ($F = 2.43$, $p = 0.136$) and peach juice ($F = 0.07$, $p = 0.797$), indicating that although consumers noticed improvements, the changes were not strong enough to be considered statistically significant. Overall, SCP preservation positively influenced the color, aroma, and taste of both mango and peach juices, enhancing their sensory qualities while maintaining their natural characteristics. These findings suggest that SCP fortification is a viable approach to improving consumer acceptance of fruit juices (Pérez-Gago *et al*., 2018; Silva *et al*., 2019; Kormelink *et al*., 2018; Sivertsvik *et al*., 2020). Although statistical significance was only observed in the color of mango juice, the general trends indicate that SCP fortification has the potential to enhance the sensory attributes of fruit juices.

Table 4: Sensory Characteristics of Mango and Peach Juices with and without Single-Cell Protein (SCP) Enrichment

Parmeter	Mango juice (B)	Mango juice (SCP)	One-Way ANOVA	Peach juice (B)	Peach juice (SCP)	One-Way ANOVA
Color (Mean ± SD)	7.2 ± 0.5	7.5 ± 0.4	Significant	7.0 ± 0.6	7.3 ± 0.5	Not Significant
Aroma (Mean ± SD)	6.8 ± 0.6	7.1 ± 0.5	Not Significant	6.7 ± 0.7	7.0 ± 0.6	Not Significant
Taste (Mean ± SD)	7.0 ± 0.5	7.4 ± 0.4	Not Significant	6.9 ± 0.5	7.2 ± 0.5	Not Significant

Note: B = Plain (non-SCP enriched) juice, SCP = Single-Cell Protein enriched juice, SD = Standard Deviation.

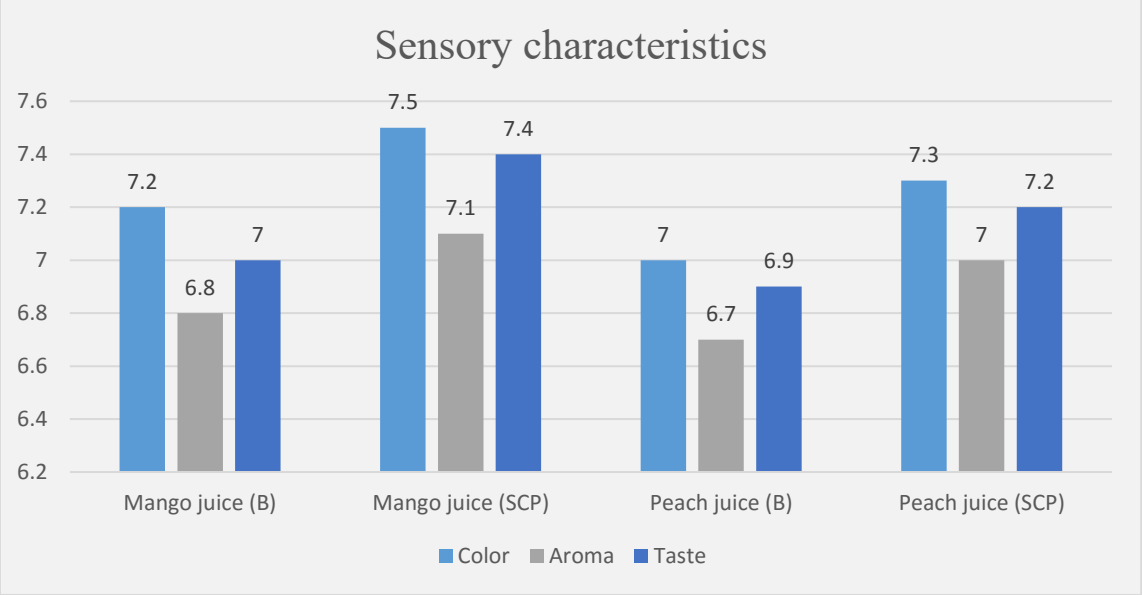

Figure 3: Sensory characteristics of Mango juice (B), Mango juice (SCP), Peach juice (B) and Peach juice (SCP)

3.5. Antioxidant Activity of Untreated and Preserved Mango and Peach Juices

Antioxidant activity is crucial for understanding the health benefits of fruit juices, as it helps combat oxidative stress and safeguards cells from damage. This study analyzed the antioxidant properties of both basic (B) and single-cell protein (SCP)-fortified mango and peach juices using the DPPH (2,2-diphenyl-1-picrylhydrazyl) assay and superoxide dismutase (SOD) enzyme activity. The findings are summarized in Table 5 and Figure 4. The DPPH assay indicated a notable increase ($p<0.05$) in radical scavenging activity in SCP-preserved juices. Mango juice (B) displayed a DPPH activity of 51.98 ± 4.74%, which rose to 70.10 ± 0.54% following SCP fortification. Similarly, peach juice (B) exhibited an initial DPPH activity of 48.51 ± 5.72%, which improved to 65.78 ± 2.80% with SCP addition. ANOVA results confirmed that these differences were statistically significant for both mango juice ($F = 70.37$, $p < 0.001$) and peach juice ($F = 67.09$, $p < 0.001$), demonstrating that SCP fortification significantly enhanced the antioxidant properties of the juices. This enhancement is likely due to the presence of bioactive compounds in Saccharomyces cerevisiae-derived SCP (Li *et al*., 2017; Mamedov *et al*., 2020). Furthermore, SOD enzyme activity, which plays a role in neutralizing superoxide radicals and providing cellular protection, increased in SCP-fortified juices. The SOD activity in mango juice (B) was 51.32 ± 1.08%, increasing to 54.72 ± 2.34% after SCP fortification, while peach juice (B) had an SOD activity of 49.65 ± 3.34%, rising to 53.56 ± 1.93% following SCP preservation. ANOVA results showed significant differences in SOD enzyme activity for mango juice ($F = 17.63$, $p < 0.001$) and peach juice ($F = 47.51$, $p < 0.001$), further validating SCP's role in enhancing the enzymatic antioxidant defense of the juices (Xu *et al*., 2019; Fernandes *et al*., 2018). In conclusion, SCP preservation significantly ($p<0.05$) improved the antioxidant activity of both mango and peach juices, enhancing their potential health benefits. These results emphasize SCP's effectiveness as a natural antioxidant enhancer, positioning it as a valuable functional ingredient in fruit juice preservation (Zhao *et al*., 2021).

Table 5: Antioxidant Activity of Mango and Peach Juices with and without Single-Cell Protein (SCP) Enrichment

Parameter	Mango juice (B)	Mango juice (SCP)	One-Way ANOVA	Peach juice (B)	Peach juice (SCP)	One-Way ANOVA
DPPH Assay (µL/mL) (Mean ± SD)	51.982 ± 4.740	70.102 ± 0.544	Significant	48.508 ± 5.722	65.784 ± 2.798	Significant
SOD Activity (% Inhibition) (Mean ± SD)	51.323 ± 1.080	54.717 ± 2.335	Significant	49.649 ± 3.337	53.559 ± 1.927	Significant

Note: B = Plain (non-SCP enriched) juice, SCP = Single-Cell Protein enriched juice, SD = Standard Deviation, DPPH = 2,2-Diphenyl-1-picrylhydrazyl radical scavenging activity, SOD = Superoxide Dismutase.

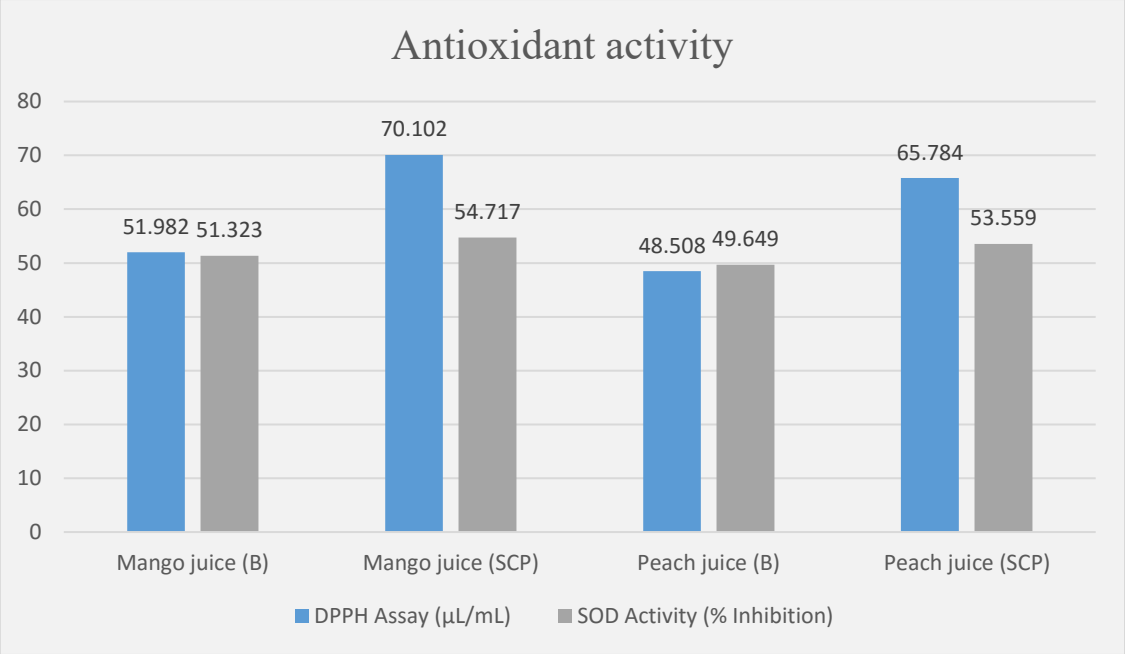

Figure 4: Antioxidant Activity (%) of Mango juice (B), Mango juice (SCP), Peach juice (B) and Peach juice (SCP)

6. Microbial Activity of Untreated and Preserved Mango and Peach Juices

The microbial quality of fruit juices is crucial for their safety and prolonged shelf life. This study analyzed the microbial activity in mango and peach juices by assessing bacterial and fungal plate counts in both basic (B) and single-cell protein (SCP)-fortified juices. The findings in Table 6 and Figure 5 demonstrated that SCP preservation significantly ($p<0.05$) reduced microbial growth, thereby improving the safety and stability of the juices. Bacterial contamination, a critical factor in juice safety, was notably lower in SCP-preserved samples. The bacterial count in mango juice (B) was 95 ± 9.49%, which decreased to 3.67 ± 1.15% after SCP fortification. Similarly, peach juice (B) recorded a bacterial count of 115.33 ± 37.92%, which dropped to 3 ± 1.53% in the SCP-preserved variant. ANOVA results indicated that these reductions were statistically significant for mango juice ($F = 941.70$, $p < 0.001$) and peach juice ($F = 53.03$, $p < 0.001$), suggesting that SCP preservation plays a key role in inhibiting bacterial proliferation. This effect is likely due to the antimicrobial properties of S. cerevisiae or metabolic modifications caused by SCP, which create an environment less conducive to bacterial growth (Kim *et al*., 2020; Lee *et al*., 2017). Similarly, SCP preservation led to a significant ($p<0.05$) decline in fungal counts. Mango juice (B) had a fungal count of 68.33 ± 16.53%, which dropped to 3 ± 2.00% following SCP preservation. Likewise, peach juice (B) exhibited a fungal count of 50.00 ± 20.47%, which decreased to 2.33 ± 0.47% in the SCP-preserved juice. ANOVA analysis confirmed the statistical significance of these reductions for mango juice ($F = 119.82$, $p < 0.001$) and peach juice ($F = 70.63$, $p < 0.001$), underscoring SCP's effectiveness in controlling microbial contamination. The decline in fungal growth may be attributed to competition for nutrients or the production of antifungal metabolites by S. cerevisiae, which inhibited fungal proliferation (Park *et al*., 2019; Rodríguez *et al*., 2018). Overall, SCP preservation substantially enhanced the microbial stability of mango and peach juices by minimizing bacterial and fungal contamination. These results support the potential of SCP as a natural preservative that improves juice safety and extends shelf life, presenting a viable alternative to synthetic preservatives (Sivertsvik *et al*., 2020; Zhang *et al*., 2020).

Table 6: Microbial Activity of Mango and Peach Juices with and without Single-Cell Protein (SCP) Enrichment

Parameter	Mango juice (B)	Mango juice (SCP)	One-Way ANOVA	Peach juice (B)	Peach juice (SCP)	One-Way ANOVA
Bacterial Plate Count (CFU/mL) (Mean ± SD)	95 ± 9.49	3.67 ± 1.15	Significant	115.33 ± 37.92	3 ± 1.53	Significant
Fungal Plate Count (CFU/mL) (Mean ± SD)	68.33 ± 16.53	3 ± 2.00	Significant	50.00 ± 20.47	2.33 ± 0.47	Significant

Note: B = Plain (non-SCP enriched) juice, SCP = Single-Cell Protein enriched juice, SD = Standard Deviation.

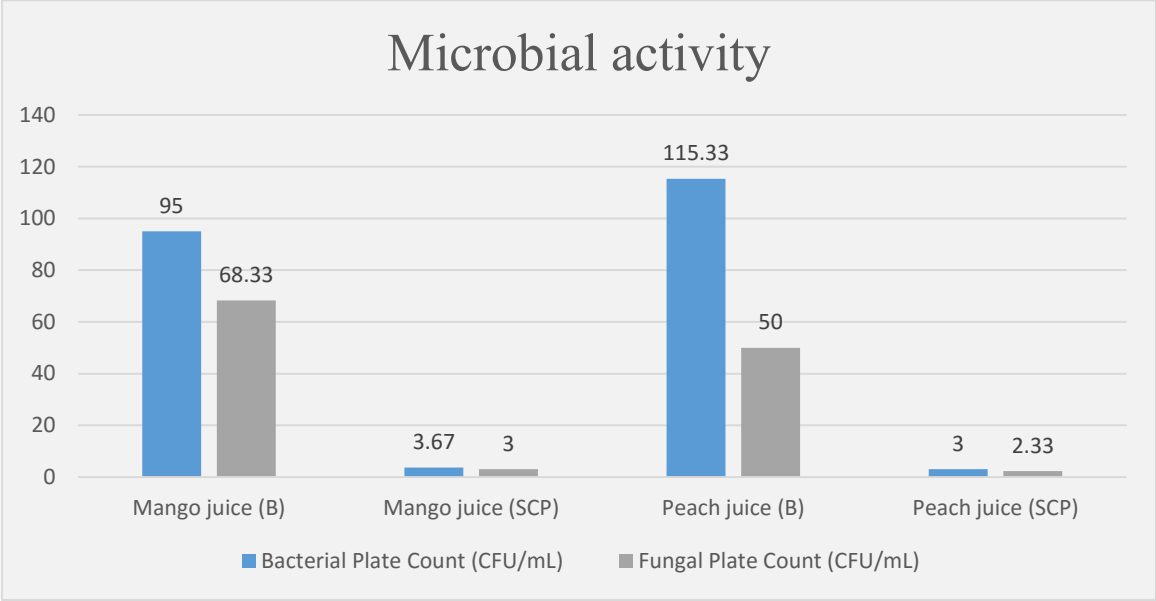

Figure 5: Microbial Activity of Mango juice (B), Mango juice (SCP), Peach juice (B) and Peach juice (SCP)

4. CONCLUSION

This study emphasized the potential of single-cell protein (SCP) as an effective preservation technique that not only boosted the nutritional content but also improved the microbial safety of mango and peach juices. Proximate analysis verified the presence of essential nutrients such as fiber, fat, protein, ash, and moisture, establishing a baseline for assessing the effects of SCP fortification. The incorporation of SCP led to a significant rise in protein and fiber content while maintaining a well-balanced nutrient composition, thereby improving overall nutritional quality. Additionally, SCP enrichment increased key bioactive compounds, including total flavonoids, ascorbic acid, carbohydrates, calcium, and magnesium, which contributed to the functional enhancement of the juices. Despite these improvements, the pH and viscosity remained stable, ensuring consistent texture and acidity. Additionally, SCP preservation notably improved antioxidant activity, as demonstrated by increased DPPH scavenging and superoxide dismutase (SOD) activity, contributing to better protection against oxidative stress. Sensory evaluation indicated that the taste, aroma, and color of SCP-enriched juices were either comparable to or slightly improved as compared to the basic juices. Moreover, SCP effectively reduced both bacterial and fungal contamination, thereby enhancing the microbial stability and potentially extending the juices' shelf life. Overall, these findings highlighted SCP's effectiveness as a natural preservative, improving the nutritional quality and safety of fruit juices, offering significant benefits to both the beverage industry and consumer health.

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