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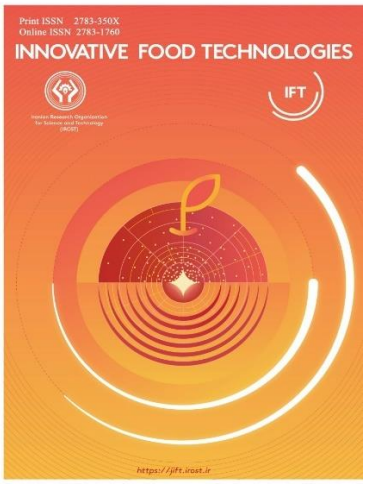

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Enhancement of phytochemical content and antioxidant activity of matoa (*Pometia pinnata*) mesocarp juice using ultrasound-assisted enzymatic extraction

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Abstract

Matoa (*Pometia pinnata*), also known as Brazilian longan, is an underutilised tropical fruit with a unique flavour resembling longan, rambutan, and lychee. Despite its nutritional and medicinal potential, its application as a functional food remains limited due to inefficient conventional extraction methods, which often result in low juice yield and degradation of heat-sensitive bioactive compounds. Ultrasound-assisted enzymatic extraction (UAEE) has emerged as a green and efficient technique that combines acoustic cavitation with enzymatic hydrolysis to improve extraction under mild conditions. This study investigated the effects of UAEE on the physicochemical properties and bioactive compounds of matoa mesocarp juice. Extraction was performed at fixed ultrasound conditions (52% amplitude, 6 min) while varying pectinase concentration (0.2–1.0%) and incubation time (20–140 min) at 50°C. Fresh juice and ultrasound-assisted extraction (UAE) without enzyme served as controls. The optimum extraction condition (0.6% pectinase, 100 min) achieved the highest juice yield (82.47 ± 1.63%), significantly higher than fresh juice (61.69 ± 2.93%) and UAE (65.36 ± 3.93%). UAEE also increased total soluble solids (6.80 °Brix), total phenolic content (6.25 ± 0.01 mg GAE/g), total flavonoid content (1.52 ± 0.03 mg CE/g), and DPPH radical-scavenging activity (82.87 ± 0.01%) compared with the controls, while maintaining an appreciable ascorbic acid content (10.98 ± 1.41 mg Ascorbic acid/L). Overall, UAEE effectively improved extraction efficiency and enhanced the recovery of bioactive compounds, demonstrating its potential as a sustainable extraction technique for producing high-quality functional matoa juice for food applications.

Keywords: **Matoa, ultrasound-assisted enzymatic extraction (UAEE), physicochemical, phytochemical content, Antioxidant activity**

1. Introduction

Natural plant-based foods rich in phytochemicals are increasingly recognised as functional ingredients for promoting human health and reducing the risk of chronic diseases, including diabetes and cardiovascular disorders (Chemat et al., 2017). Among tropical fruits, matoa *(Pometia pinnata)* has attracted scientific interest due to its high content of phenolic compounds, flavonoids, tannins, terpenoids, and vitamins A, C, and E, which contribute to high antioxidant activity (Li et al., 2017; Li et al., 2025; Suzuki et al., 2021). Ethnomedicinal reports from Indonesia and Papua indicate that matoa has traditionally been used for anti-inflammatory, antimicrobial, and general health-promoting purposes, implying a long-standing practical value of its bioactive constituents (Pagarra et al., 2025; Sarima et al., 2025; Sulastri et al., 2025).

However, most published studies on matoa have focused on crude solvent extracts from leaves, seeds, or peel, rather than optimised juice extraction from the fresh mesocarp (Patilaya & Sumantri, 2025; Shen et al., 2023; Suzuki et al., 2021). Conventional solvent-based extraction methods, such as maceration and Soxhlet extraction, are commonly used for the matoa plant. Still, they often require long processing times, high solvent volumes, and elevated temperatures that can degrade thermosensitive phytochemicals and increase environmental impact (Chemat et al., 2017; Mohd Amin et al., 2025). Recent work on matoa seed and fruit-peel extracts has shown that ultrasound-assisted extraction (UAE) can significantly enhance total phenolic and flavonoid content while improving antioxidant capacity, highlighting the potential of non-thermal, energy-efficient methods for valorising matoa by-products (Lestari et al., 2026; Patilaya & Sumantri, 2025).

Despite these advances, comprehensive studies on the extraction of matoa mesocarp juice using enzyme-assisted and ultrasound-assisted technologies are still scarce (Sarima et al., 2025). Furthermore, enzyme-assisted extraction (EAE) has emerged as a green strategy to enhance juice yield and bioactive recovery by selectively degrading structural polysaccharides such as pectin, cellulose, and hemicellulose in fruit cell walls (Chemat et al., 2017; Sujinda et al., 2025). Pectinase- and cellulase-based treatments have been shown to reduce juice viscosity, increase filterability, and enhance the release of phenolic acids and flavonoids from various tropical and temperate fruits (Li et al., 2025). Therefore, when combined with ultrasound treatment, EAE can further enhance mass transfer via micro-streaming and cavitation-induced cell-wall disruption, resulting in higher extraction yields in shorter times and at lower temperatures (Qian et al., 2023). For example, ultrasound-assisted enzymatic extraction of jackfruit juice has recently demonstrated significant improvements in juice yield, vitamin C, total carotenoids, total phenolics, and DPPH/FRAP antioxidant activity compared with conventional enzymatic treatment alone(Hu et al., 2026). Similarly, ultrasound-assisted enzymatic extraction of polysaccharides from sugarcane peel has increased yields and enhanced antioxidant activity compared with hot-water extraction, highlighting the combined effect of this method for bioactive recovery (Mao et al., 2025). Recent studies on grape pulp and berry-derived polyphenolics also indicate that combining ultrasound with enzymatic treatment markedly increases total phenolic and flavonoid content while preserving antioxidant functionality (Khurun Hizar et al., 2025; Yang et al., 2026). These findings suggest that the ultrasound-assisted enzymatic extraction (UAEE) approach may be highly promising for matoa mesocarp, where the primary goal is to maximise the recovery of hydrophilic antioxidants while maintaining physicochemical quality characteristics of the extracted juice.

Besides bioactive compound recovery, physicochemical characteristics such as total soluble solids (TSS), ascorbic acid content, and colour attributes are important quality indicators

for evaluating the nutritional value, freshness, and consumer acceptability of fruit-based products. Ascorbic acid is a heat-sensitive antioxidant that may undergo degradation during processing, while colour changes can reflect the stability of pigments and phytochemical compounds affected by extraction conditions (Vivek et al., 2019). Therefore, evaluating these parameters is essential to determine the overall quality of matoa mesocarp juice produced through UAEE.

Current literature has emphasised the integration of non-thermal, energy-efficient extraction methods into functional-food platforms, particularly for underutilised tropical fruits that can be valorised as juice concentrates, functional beverages, or fortified ingredients (Chemat et al., 2017). Ultrasonic-assisted technologies highlight that combining ultrasound with enzymatic or other mild treatments not only improves extraction efficiency but also reduces energy, solvent, and time requirements (Furia et al., 2025; Luque-García & Luque De Castro, 2004; Patilaya & Sumantri, 2025). For matoa, such an approach could support the development of a value-added, antioxidant-rich mesocarp juice that utilises the whole fruit more efficiently, including fractions that are currently underexploited (Pagarra et al., 2025; Sarima et al., 2025).

The present study aimed to determine the effects of ultrasound-assisted enzymatic extraction (UAEE) of matoa mesocarp juice on its phytochemical and antioxidant properties. Specifically, the effects of varying enzyme concentrations and incubation times, under fixed ultrasound parameters, on juice yield, total phenolic content (TPC), total flavonoid content (TFC), and DPPH radical scavenging activity of matoa mesocarp juice were investigated. Furthermore, the efficiency of UAEE was compared with conventional enzymatic extraction and untreated mesocarp to elucidate the effects on the cell-wall disruption and recovery of bioactive compounds, while preserving thermo-labile antioxidants (Hu et al., 2026; Shen et al., 2023).

From an applied standpoint, this study contributes to the innovation of tropical-fruit valorisation by demonstrating a scalable, low-energy UAEE process of underutilised matoa mesocarp into a functional juice to enhance health-promoting properties (Sarima et al., 2025) and emphasises green extraction techniques (Chemat et al., 2017; Qian et al., 2023).

2. Material and methods

2.1 Materials

Matoa (*Pometia pinnata*) fruits were obtained from local markets in Kota Kinabalu, Sabah, Malaysia. A commercial enzymatic mixture, Pectinex® Ultra SP-L (Modenist Pantry, Eliot, USA), was utilised for enzymatic treatment. Figure 1 illustrates the overall ultrasound-assisted enzymatic extraction (UAEE) process used for the production of matoa mesocarp juice.

Figure 1
Schematic representation of ultrasound-assisted enzymatic extraction of juice from matoa *(Pometia pinnata)* mesocarps.

2.2 Preparation of fresh matoa mesocarps

Fresh matoa (*Pometia pinnata)* (approximately 3–5 kg) was manually peeled, and the mesocarp was separated for further processing. The obtained mesocarp was portioned into transparent polyethylene plastic bags (100 g per bag), vacuum-sealed, and stored at −20 °C in the freezer until further use. Before each experiment, the frozen samples were thawed at room temperature.

2.3 Ultrasound-assisted extraction (UAE) of matoa puree

A homogeneous mixture of matoa mesocarp and distilled water at a 1:2 ratio was placed in a 250 mL beaker before sonication (Shen et al., 2023). A probe-type ultrasonicator (Q700 Sonicator, Qsonica, USA) was used to deliver ultrasonic extraction at 52% amplitude. The sample was subjected to an ultrasound treatment time of 6 minutes, consisting of alternating pulse-on times of 10 seconds and pulse-off times of 10 seconds, a pulsing regime demonstrated to improve extraction efficiency while limiting thermal buildup. The ultrasonication probe was immersed to a depth of approximately 1.5 times the diameter of the beaker containing the sample to maximise energy distribution and cavitation effects (Luque-García & Luque De Castro, 2004). During ultrasound treatment, the temperature of the sample was maintained below 45 °C to minimise degradation of heat-sensitive compounds (Antony & Farid, 2022; Khurun Hizar et al., 2025).

2.4 Enzymatic extraction of matoa puree

The previous ultrasound-treated matoa mesocarp was used in the following enzymatic treatment according to Pui et al. (2022) method, where different concentrations of Pectinex® Ultra SP-L (0.2%-1.00% v/w (volume of enzyme preparation to weight of matoa mesocarp) were added to the ultrasound-pretreated samples. The pH of the samples was adjusted to 4.5-5.5 with citric acid, and the extraction temperature was set to 50°C in a thermostatic water bath (Memmert, Germany) for varying durations (20-140 minutes). After incubation, the samples were immediately placed at -20 °C to minimise further enzymatic activity before analysis. The enzyme-treated mesocarp was then pressed and filtered through two layers of cheesecloth to obtain the juice. The filtered juice yield was then calculated according to Eqn (1):

$$\text{Juice yield (\%)} = \frac{\text{Volume of juice after filtration}}{\text{Volume of puree before filtration}} \quad (1)$$

2.5 Total Soluble Solids

Method adapted from Agusri et al. (2024), where total soluble solids (TSS) of matoa juice is determined using the benchtop digital refractometer (RFM 700, Bellingham and Stanley, UK).

2.6 Colour

The colour of juice is determined according to modified method from Puzovic & Mikulic-Petkovsek (2024). ColorFlex colorimeter (HunterLab, USA) is used to measure the colour of the juices, expressed as L* (lightness), a* (redness), and b* (yellowness) values. The total colour difference (ΔE*) of samples is calculated according to the following Eqn (2):

$$\Delta E* = \sqrt{(\Delta L*)2 + (\Delta a*)2 + (\Delta b*)} \quad (2)$$

where $\Delta L*$, $\Delta a*$, and $\Delta b*$ represent the differences between the juice samples produced using different treatments and the control samples. ΔE* represents the total colour difference between each treatment sample and the control group.

2.7 Ascorbic Acid

The ascorbic acid content was analysed according to Veer et al. (2026) with minor modifications, using the indicator dye 2,6-dichloroindophenol solution in the titration. Ascorbic acid reference standard, indophenol dye solution, blanks, and metaphosphoric acid–acetic acid solution are prepared according to the standard procedure. Standard, blank, and sample mixture are prepared in three separate conical flasks. Then all the mixtures are titrated against the indophenol dye

solution until a rose-pink colour persists. The amount of ascorbic acid (mg/L) present in the enzyme-treated matoa juice is calculated as Eqn (3):

$$mg\ Ascorbic\ acid/L = [(A - B) \times (D/C) \times (E/F)] \times 1000 \quad (3)$$

Where A is the average titer value of enzyme-treated Matoa juice (ml); B is the average titer value of blanks (ml); C is the titer of dye (mg ascorbic acid equivalent to 1 ml indophenol standard solution); D is the sample taken (2 ml); E is the volume of initial assay solution (7 ml); and F is the volume of sample aliquot titrated (7 ml).

2.8 Total phenolic content (TPC).

Total phenolic content (TPC) was determined using the Folin–Ciocalteu method as described by Khurun Hizar et al. (2025) and Mohd Amin et al. (2025). Briefly, 100 µL of sample extract was mixed with 750 µL of Folin–Ciocalteu reagent and incubated at room temperature for 5 min. Subsequently, 750 µL of sodium bicarbonate solution was added, and the mixture was incubated for 90 min. Absorbance was measured at 725 nm using a spectrophotometer. Gallic acid was used as the standard, and results were expressed as mg gallic acid equivalents per gram of sample (mg GAE/g) (Majitol et al., 2024). TPC was calculated using Eqn (4):

$$TPC\ (mg\ GAE/g) = (C \times V \times DF)/m)] \quad (4)$$

where C is the concentration obtained from the calibration curve (mg/mL), V is the total extract volume (mL), DF is the dilution factor, and m is the sample mass (g).

2.9 Total flavonoid content (TFC)

Total flavonoid content (TFC) was determined using the aluminium chloride colourimetric method described by Khurun Hizar et al. (2025) and Li et al. (2025). Approximately 1 mL of extract was mixed with 4 mL of distilled water and 0.3 mL of 5% sodium nitrite. After 6 min, about 0.6 mL of 10% aluminium chloride was added, and the mixture was allowed to stand for 5 min. Subsequently, 2 mL of 1 M sodium hydroxide and 2.1 mL of distilled water were added, and the mixture was vortexed. Absorbance was measured at 510 nm. Catechin was used as the standard, and results were expressed as mg catechin equivalents per gram of sample (mg CE/g). TFC was calculated using Eqn (5):

$$TFC\ (mg\ CE/g) = (C \times V \times DF)/m)] \quad (5)$$

where C is the catechin equivalent concentration (mg/mL), V is the extract volume (mL), DF is the dilution factor, and m is the sample mass (g).

2.10 DPPH Free Radical Scavenging Activity

Antioxidant activity was evaluated using the DPPH radical scavenging assay, following the modified method of Majitol et al.(2024). Approximately 1 mg of extract was dissolved in 1 mL of methanol. A 20 µL sample solution was mixed with 80 µL of 0.1 mM DPPH solution. Methanol (100 µL) was used as the blank, while ascorbic acid served as the positive control. The absorbance was measured at 517 nm after 30 min using a UV–Vis spectrophotometer (Tecan Nanoquant Infinite M200, Switzerland). The percentage inhibition of DPPH radicals was calculated using Eqn (6):

$$DPPH\ Scavenging\ Activity\ (\%) = [(A_{blank} - A_{sample})/A_{blank})] \times 100 \quad (6)$$

where A_{blank} is the absorbance of the control (methanol + DPPH), and A_{sample} is the absorbance of the sample or standard.

2.11 Experimental design and statistical analysis.

Data were analysed using one-way analysis of variance (ANOVA) followed by Tukey's post hoc test using GraphPad Prism software (GraphPad Software, USA). Differences were considered statistically significant at $p < 0.05$.

3. Results and discussion

In this study, sonication parameters were maintained constant throughout the extraction process. The ultrasound parameters were selected based on preliminary optimisation and previous studies reporting effective extraction while minimising degradation of thermolabile compounds. Therefore, the differences observed among treatments were mainly attributed to variations in enzyme concentration and incubation time.

Juice yield is a key indicator of extraction efficiency, reflecting the extent of cell wall disruption and release of intracellular components from the fruit mesocarp. The effects of ultrasound-assisted enzymatic extraction (UAEE) conditions on juice yield, Total Soluble Solids (TSS), colour characterisation, ascorbic acid (vitamin C), total phenolic content (TPC), total flavonoid content (TFC), and DPPH radical scavenging activity of matoa mesocarp juice are summarised in Table 1 and Table 2. Overall, the UAEE-treated samples exhibited significantly improved extraction performance and phytochemical properties compared with the control samples (untreated mesocarp and ultrasound-treated only).

Table 1

Effect of ultrasound-assisted enzymatic extraction (UAEE) with different pectinase concentrations and incubation times on juice yield and physicochemical properties (total soluble solids and colour characteristics) of *Pometia pinnata* mesocarp juice.

As shown in Table 1, juice yield increased significantly ($p<0.05$) in all UAEE treatment samples compared to control samples. The highest juice yield was observed in S19 (83.79 ± 2.60%) after treatment with 0.8% enzyme concentration for 140 minutes. These values were higher than those of the untreated control (matoa puree) (61.69 ± 2.93%) and ultrasound-only treatment (UAE) (65.36 ± 3.93%), demonstrating the synergistic effect of ultrasound and enzymatic hydrolysis (Mao et al., 2025; Mohd Amin et al., 2025; Vo et al., 2023). Similar findings were reported by Vivek et al. (2019), who found that UAEE extraction increased the juice yield by 20% in sohiong fruit. Meanwhile, Dang et al. (2012) enhanced the juice yield and nutritional quality of acerola mash using a pectinase-assisted ultrasonication method.

The improvement in juice yield was due to the combined action of acoustic cavitation from the ultrasound treatment and enzymatic degradation of structural polysaccharides (Luque-García & Luque De Castro, 2004; Veer et al., 2026; Yang et al., 2026). Ultrasound generates microbubbles that collapse violently, producing shear forces and microjets that disrupt cell walls and enhance solvent penetration (Chemat et al., 2017; Qian et al., 2023). This mechanical effect facilitates greater accessibility of pectinase to the plant matrix, allowing more efficient hydrolysis of pectic substances in the middle lamella (Pui et al., 2022). Consequently, cell

adhesion is weakened, and intracellular fluids are more readily released into the juice(Khurun Hizar et al., 2025; Sujinda et al., 2025).

In addition, enzymatic treatment plays a crucial role in reducing juice viscosity (Qian et al., 2023) and improving mass transfer by breaking down pectin-rich structures (Khurun Hizar et al., 2025; Mohd Amin et al., 2025) that otherwise retain water within the fruit matrix (Fidelis et al., 2019). Similar enhancements in juice yield have been reported in other fruits subjected to ultrasound-assisted enzymatic extraction, confirming the effectiveness of this combined approach in improving extraction efficiency (Li et al., 2025; Qian et al., 2023; Sujinda et al., 2025; Vo et al., 2023).

However, the increase in juice yield was not strictly proportional to extraction time or enzyme concentration (Hu et al., 2026; Sujinda et al., 2025). Although the highest yield was observed in samples treated at the highest incubation time and enzyme concentration, such as in S19, samples which incubated at 100 min with 0.6% (S13), 0.8% (S14), and 1.0% (S15) enzyme concentration produced comparable results, suggesting that the extraction process approached equilibrium at shorter incubation times (Hou et al., 2024; Li et al., 2023). Beyond this point, further treatment may not significantly enhance juice yield due to substrate depletion or enzyme saturation (Córdova et al., 2022; Kabawa et al., 2023). This indicates that prolonged enzymatic treatment may not be economically or technically advantageous, highlighting the importance of process optimisation (Díaz-de-Cerio & Trigueros, 2025; Sujinda et al., 2025).

3.1 Effect of UAEE on Total Soluble Solids (TSS)

The total soluble solids (TSS) of UAEE matoa juice are presented in Table 1. Compared with the untreated puree (5.20 °Brix) and UAE control (5.40 °Brix), enzymatic treatments significantly increased the TSS, with values ranging from 6.20 to 7.30 °Brix. The highest TSS was obtained in Sample S5 (7.30 ± 0.71), while most enzyme-treated samples recorded values above 6.0 °Brix. The increase in TSS can be attributed to the hydrolysis of pectic substances by pectinase, which disrupted the fruit cell wall and promoted the release of soluble sugars, organic acids and other water-soluble compounds into the juice (Costa et al., 2025; Veer et al., 2026; Vivek et al., 2019). Ultrasound further enhanced mass transfer by increasing cell permeability, thereby improving the extraction of soluble solids. Similar increases in TSS following ultrasound-assisted enzymatic extraction have been reported for tropical fruit juices due to the synergistic effects of enzymatic degradation and acoustic cavitation (Kabawa et al., 2023). However, extending the extraction time beyond 20 min did not consistently increase TSS, suggesting that most soluble compounds had already been released during the early stage of extraction (Pui et al., 2022). This finding indicates that prolonged extraction may provide limited additional benefits for soluble solid recovery (Souza et al., 2026).

3.2 Colour Characterisation

The colour characteristics of UAEE matoa juice were significantly influenced by enzymatic treatment (Table 1). Compared with the untreated puree and UAE controls, all enzyme-treated samples exhibited significantly lower L* values, indicating a darker juice colour. The reduction in lightness is attributed to pectin hydrolysis, which disrupted the cell wall structure and enhanced the release of intracellular pigments, phenolic compounds and soluble solids into the juice matrix (Pui et al., 2022; Veer et al., 2026). Similar observations have been reported in enzyme-assisted extraction of fruit juices, where increased extraction efficiency resulted in lower L* values due to greater pigment release (Rosa Zorzenon et al., 2020; Yang et al., 2026).

The a* values remained negative throughout all treatments, indicating that the juice retained its natural greenish appearance (Mohd Amin et al., 2025), although values shifted closer to zero following enzymatic extraction. This suggests a slight reduction in green intensity, possibly due to the increased extraction of carotenoids and other coloured compounds (Amin et al., 2025; Pui et al., 2022). Likewise, the b* values remained negative, with only minor variations among treatments, indicating that enzyme concentration and extraction time had limited influence on the yellow-blue colour component (Priyanka et al., 2026).

The total colour difference (ΔE*) increased markedly after enzymatic extraction, with all treated samples showing values above 26 compared with the UAE control (ΔE* = 1.85). Since ΔE* values greater than 3 are visually distinguishable, the results indicate that UAEE produced substantial colour changes (Pui et al., 2022; Veer et al., 2026). Overall, the darker colour and larger ΔE* values corresponded with the increased juice yield and total soluble solids (Table 1), suggesting that improved cell wall degradation enhanced the release of pigments and soluble constituents (Aktı & Yildiz, 2025; Lalremmawii et al., 2025). These findings indicate that colour modification was primarily associated with increased extraction efficiency rather than deterioration of juice quality (Błaszak et al., 2025).

Sensory evaluation was not conducted in the present study. Therefore, direct assessment of consumer perception, including taste, aroma, mouthfeel, and overall acceptability, could not be determined. However, physicochemical parameters such as colour, total soluble solids, and ascorbic acid content provide preliminary indicators related to product quality and potential consumer acceptance. Future studies should incorporate sensory evaluation to validate further the suitability of UAEE-treated matoa mesocarp juice for functional food applications.

Table 2
Effects of ultrasound-assisted enzymatic extraction conditions on ascorbic acid (Vitamin C), total flavonoid content (TFC), total phenolic content (TPC), and antioxidant activity (DPPH) of matoa mesocarp juice.

3.3 Effect of UAEE on Ascorbic Acid

The ascorbic acid content of UAEE matoa juice was significantly affected by extraction conditions (Table 2). The untreated puree contained the highest ascorbic acid concentration (16.96 mg/L), while ultrasound treatment alone reduced the value to 12.94 mg/L, indicating partial degradation of vitamin C during processing (Mousavi Kalajahi & Ghandiha, 2022; Priyanka et al., 2026; Souza et al., 2026). Following enzymatic treatment, ascorbic acid ranged from 6.98 to 12.97 mg/L, with the highest retention observed in Sample S10 (60 min, 1.0% pectinase). The reduction in vitamin C can be attributed to its sensitivity towards oxidation during ultrasound processing and prolonged exposure to oxygen, despite improved release from disrupted plant tissues (Hou et al., 2024; Priyanka et al., 2026).

Interestingly, the treatment with the highest juice yield (Table 1) did not correspond to the highest ascorbic acid content (Table 2), indicating that greater extraction efficiency did not necessarily improve vitamin C retention (Thanasegaran & Mahror, 2025). This suggests that ascorbic acid stability depends on the balance between enhanced cellular release and oxidative degradation during extraction (Priyanka et al., 2026). Furthermore, although samples with higher ΔE* values (Table 1) generally exhibited greater pigment extraction, no direct relationship was observed between colour changes and ascorbic acid retention (Table 2), as the two quality attributes are governed by different mechanisms.

3.4 Effect of UAEE on Phytochemical Profile (TPC and TFC)

The effects of UAEE conditions on total phenolic content (TPC) and total flavonoid content (TFC) of matoa mesocarp juice are presented in Table 2. Overall, UAEE-treated samples exhibited significantly ($p<0.05$) higher phytochemical content compared to control treatments, confirming the effective combination of ultrasound and enzymatic processes in enhancing bioactive compound extraction (Pui et al., 2022; Vo et al., 2023).

The results showed that the highest TPC and TFC were observed in different ranges of UAEE conditions. For example, the highest TPC was observed in S4 (6.09 ± 0.05 mg GAE/g), and have no significant different ($p>0.05$) in TPC content with S10 (6.22 ± 0.04 mg GAE/g), S13 (6.25 ± 0.01 mg GAE/g), S14 (6.06 ± 0.05 mg GAE/g), S15 (6.10 ± 0.03 mg GAE/g) and S18 (5.43 ± 0.03 mg GAE/g). Similarly, for TFC, S3 (20 min, 0.6% enzyme, 1.49 ± 0.01 mg CE/g) showed no significant difference ($p>0.05$) with S20 (140 min, 1.0% enzyme, 1.49 ± 0.02 mg CE/g).

These findings indicate that high phytochemical recovery is achieved at moderate-to-high enzyme concentrations combined with sufficient incubation time (Qian et al., 2023; Sujinda et al., 2025; Wu et al., 2021). The enhancement in TPC and TFC in UAEE treatment can be explained by the disruption of cell wall matrices and the release of bound phenolic compounds (Pui et al., 2022), as well as the release of polysaccharides and cell wall proteins (Alves et al., 2020). Ultrasound-induced cavitation increases solvent penetration (Córdova et al., 2022; Khurun Hizar et al., 2025) and facilitates the desorption of phenolics from plant tissues (Li et al., 2025), while enzymatic hydrolysis breaks down polysaccharide networks that entrap these compounds (Furia et al., 2025). The synergistic interaction between physical and biochemical mechanisms enhances mass transfer and extraction efficiency (Khurun Hizar et al., 2025; R. Li et al., 2025; Majitol et al., 2024).

Notably, the highest phytochemical content did not coincide with the highest juice yield (Challana et al., 2025; Smirani et al., 2025). For instance, although S19 produced the highest juice yield, its TPC (4.12 ± 0.04 mg GAE/g) and TFC (1.43 ± 0.02 mg CE/g) values were significantly lower. Therefore, these findings suggest that excessive processing intensity may lead to the degradation or transformation of phenolic compounds (Antony & Farid, 2022; Khurun Hizar et al., 2025; Priyanka et al., 2026). Additionally, prolonged ultrasound exposure can generate reactive oxygen and localised heat, which may negatively affect the stability of sensitive bioactive compounds (Spréa et al., 2025; Sun et al., 2025), such as phenolics and flavonoids.

Furthermore, increasing enzyme concentration beyond an optimal level did not result in proportional increases in TPC or TFC content (Priyanka et al., 2026; Zafeiria et al., 2026). This may be due to substrate limitation or potential interactions between phenolics and other macromolecules, which can reduce their concentration (Hu et al., 2026; Sujinda et al., 2025). These findings highlight that optimal extraction conditions require a balance between sufficient matrix disruption and preservation of compound stability (Díaz-de-Cerio & Trigueros, 2025; Stanek-Wandzel et al., 2025).

3.5 DPPH Free Radical Scavenging Activity

The antioxidant activity of matoa mesocarp juice under different UAEE conditions is summarised in Table 2. The UAEE treatments significantly ($p<0.05$) improved antioxidant capacity compared to the control samples. The highest antioxidant activity was observed with S8

(84.04%), followed by S6 (83.55%), S12 (82.90%), and S13 (82.87%) when treated at moderate incubation times (60 min and 100 min) and enzyme concentrations. This indicated that moderate extraction conditions were most effective in preserving antioxidant functionality (Ng et al., 2025; Pattarapisitporn & Noma, 2025). This also suggests that antioxidant activity is influenced not only by the total concentration of phenolic compounds but also by their structural characteristics and synergistic interactions (Herbani & Tilaqza, 2026; Khurun Hizar et al., 2025). Certain phenolic compounds exhibit stronger radical-scavenging activity due to conjugated systems, which enhance their electron-donating capacity (Wu et al., 2021).

As shown in Table 2, the longer incubation time (140 min) showed lower antioxidant activity, which may be attributed to the degradation of bioactive compounds (Challana et al., 2025; Chemat et al., 2017). Prolonged ultrasound exposure can promote the formation of reactive species, leading to oxidation of phenolics and a reduction in their antioxidant effectiveness (Chemat et al., 2017; Cira-Chávez et al., 2025; Spréa et al., 2025). This finding indicates that shorter incubation times are more favourable for preserving antioxidant properties (Streimikyte et al., 2022; Zhao et al., 2021).

Based on the overall results in Table 2, sample S13, which had the highest TPC and TFC values and a high juice yield, is potentially suitable for functional food applications. The results demonstrate that UAEE is an effective and sustainable extraction technique (Lestari et al., 2026; Mao et al., 2025) to enhance the recovery of bioactive compounds (Furia et al., 2025; Stanek-Wandzel et al., 2025) from matoa mesocarp. The synergistic interaction between ultrasound and enzymatic treatment significantly improves extraction performance, supporting its potential application in the development of value-added functional food products (Mohd Amin et al., 2025; Pui et al., 2022).

4. Conclusions

This study demonstrated that ultrasound-assisted enzymatic extraction (UAEE) effectively improved the juice yield, phytochemical content, antioxidant activity, and physicochemical properties of matoa mesocarp juice. The optimal extraction condition was achieved at a pectinase concentration of 0.6% and an incubation time of 100 min, resulting in the highest juice yield (82.47 ± 1.63%), total phenolic content (6.25 ± 0.01 mg GAE/g), and total flavonoid content (1.52 ± 0.03 mg CE/g). UAEE represents an efficient and sustainable approach for enhancing the recovery of bioactive compounds from matoa mesocarp while maintaining desirable juice quality characteristics. Although the present study demonstrated the effectiveness of UAEE, future investigations should include sensory evaluation, pH, titratable acidity, mineral composition, and storage stability to provide a more comprehensive assessment of product quality and its potential application as a functional food ingredient.

Conflict of interest

No conflict of interest has been declared by the authors.

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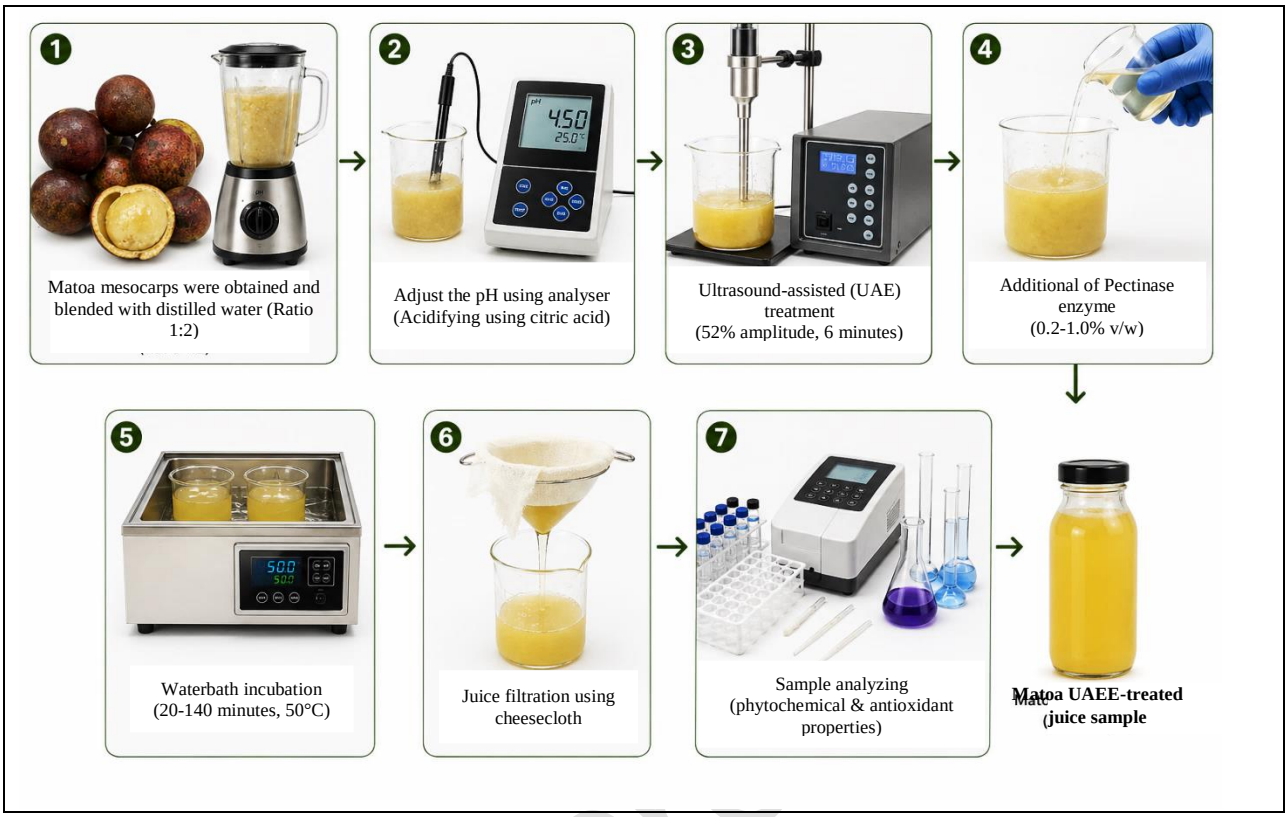

Figure 1. Schematic diagram of ultrasound-assisted enzymatic extraction (UAEE) of matoa (*Pometia pinnata*) mesocarp juice. The process includes homogenisation with distilled water (1:2, w/v), pH adjustment, ultrasound treatment (6 min, 52% amplitude), enzymatic hydrolysis using pectinase (0.2–1.0%, v/w), incubation (20–140 min, 40–50°C), filtration using cheesecloth, and subsequent phytochemical and antioxidant analyses.

Table 1. Effect of ultrasound-assisted enzymatic extraction (UAEE) with different pectinase concentrations and incubation times on juice yield and physicochemical properties (total soluble solids and colour characteristics) of *Pometia pinnata* mesocarp juice.

Sample	Time (Min)	Enzyme (%)	Juice yield (%)	Brix °	Colour Characteristic			
					L*	a*	b*	ΔE*
Control (Puree)	0	0	61.69 ± 2.93^{d}	5.20 ± 0.28^{b}	38.48 ± 0.60^{b}	-1.48 ± 0.09	-2.52 ± 0.16^{a}	–
Control (UAE)		0	65.36 ± 3.93^{cd}	5.40 ± 0.30^{bc}	41.98 ± 0.51^{a}	-1.32 ± 0.04	-2.54 ± 0.15^{a}	1.85
S1	20	0.2	74.88 ± 5.05^{abc}	6.20 ± 0.30^{abc}	11.43 ± 0.08^{c}	-0.65 ± 0.06^{cde}	-3.43 ± 0.08^{cdef}	26.88
S2		0.4	71.86 ± 5.15^{bd}	6.40 ± 0.28^{abc}	10.33 ± 0.76^{c}	-0.57 ± 0.04^{ab}	-3.04 ± 0.10^{b}	27.99
S3		0.6	77.22 ± 4.29^{ab}	6.70 ± 0.42^{abc}	11.39 ± 0.13^{c}	-0.59 ± 0.06^{bc}	-3.63 ± 0.09^{efg}	26.92
S4		0.8	76.9 ± 0.28^{ab}	7.20 ± 0.57^{a}	10.35 ± 0.03^{c}	-0.93 ± 0.05^{c}	-3.41 ± 0.06^{bcdef}	27.96
S5		1.0	79.58 ± 1.43^{ab}	7.30 ± 0.71^{a}	10.94 ± 0.88^{c}	-0.93 ± 0.03^{c}	-3.40 ± 0.06^{bcdef}	27.37

S6		0.2	78.25 ± 0.11^{ab}	6.70 ± 0.14^{abc}	9.61 ± 0.02^{c}	-0.87 ± 0.05^{de}	-3.31 ± 0.13^{bcde}	28.71
S7		0.4	81.33 ± 6.36^{ab}	6.60 ± 0.28^{abc}	11.54 ± 0.88^{c}	-0.74 ± 0.08^{abcde}	-3.28 ± 0.16^{bcde}	26.77
S8	60	0.6	77.85 ± 1.79^{ab}	6.70 ± 0.42^{abc}	9.55 ± 0.78^{c}	-0.78 ± 0.03^{bcde}	-3.41 ± 0.19^{bcdef}	28.76
S9		0.8	79.89 ± 3.65^{ab}	6.90 ± 0.14^{ab}	9.78 ± 1.16^{c}	-0.85 ± 0.08^{cdef}	-3.25 ± 0.14^{bcde}	28.53
S10		1.0	77.02 ± 7.42^{ab}	6.30 ± 0.14^{abc}	8.90 ± 1.41^{c}	-0.91 ± 0.08^{def}	-3.63 ± 0.14^{efg}	29.42
S11		0.2	79.33 ± 1.98^{ab}	6.60 ± 0.01^{abc}	8.91 ± 0.70^{c}	-0.79 ± 0.08^{bcdef}	-3.29 ± 0.10^{bcde}	29.42
S12		0.4	79.16 ± 2.52^{ab}	6.40 ± 0.28^{abc}	10.16 ± 1.21^{c}	-0.81 ± 0.04^{bcdef}	-3.21 ± 0.04^{bcde}	28.16
S13	100	0.6	82.47 ± 1.63^{ab}	6.80 ± 0.57^{ab}	10.22 ± 0.36^{c}	-0.91 ± 0.12^{de}	-3.61 ± 0.07^{efg}	28.09
S14		0.8	81.12 ± 3.23^{ab}	6.20 ± 0.01^{abc}	9.17 ± 0.45^{c}	-0.48 ± 0.06^{a}	-3.08 ± 0.06^{b}	29.16
S15		1.0	82.25 ± 4.13^{ab}	7.20 ± 0.85^{a}	10.92 ± 0.31^{c}	-1.01 ± 0.06^{f}	-3.40 ± 0.02^{bcdef}	27.38
S16		0.2	79.74 ± 4.11^{ab}	6.80 ± 0.57^{ab}	9.16 ± 0.26^{c}	-1.03 ± 0.11^{f}	-3.51 ± 0.16^{cdefg}	29.16
S17		0.4	77.61 ± 1.90^{ab}	6.60 ± 0.28^{abc}	10.24 ± 0.07^{c}	-0.93 ± 0.01^{e}	-3.78 ± 0.10^{g}	28.06
S18	140	0.6	80.82 ± 1.58^{ab}	6.40 ± 0.01^{abc}	10.18 ± 0.52^{c}	-0.97 ± 0.01^{ef}	-3.90 ± 0.06^{g}	28.12
S19		0.8	83.79 ± 2.60^{a}	6.50 ± 0.14^{abc}	10.21 ± 0.33^{c}	-1.04 ± 0.09^{f}	-3.16 ± 0.03^{bcd}	28.10
S20		1.0	79.37 ± 1.78^{ab}	6.70 ± 0.52^{abc}	9.76 ± 0.05^{c}	-0.98 ± 0.04^{ef}	-3.64 ± 0.19^{efg}	28.55

All values are expressed as mean ± standard deviation (n = 3). Different superscript letters (a–g) within the same column indicate significant differences ($p < 0.05$) as determined by one-way ANOVA followed by Tukey's post hoc test. Control (Puree) refers to untreated mesocarp, while Control (UAE) represents ultrasound-treated samples without enzyme addition.

Table 2. Effects of ultrasound-assisted enzymatic extraction conditions on ascorbic acid (Vitamin C), total flavonoid content (TFC), total phenolic content (TPC), and antioxidant activity (DPPH) of matoa mesocarp juice.

Sample	Time (Min)	Enzyme (%)	Ascorbic Acid (mg/L)	TFC (mg CE/g)	TPC (mg GAE/g)	DPPH (%)
Control (Puree)	0	0	16.96 ± 1.41^{b}	1.29 ± 0.09^{bc}	3.94 ± 0.06^{c}	50.09 ± 0.16^{c}
Control (UAE)		0	12.94 ± 1.41^{a}	1.23 ± 0.02^{c}	4.47 ± 0.03^{bc}	46.20 ± 0.08^{c}
S1	20	0.2	6.99 ± 1.41^{d}	1.43 ± 0.12^{a}	5.41 ± 0.06^{ac}	72.62 ± 0.04^{ab}
S2		0.4	8.98 ± 1.41^{cd}	1.39 ± 0.06^{ac}	5.51 ± 0.05^{ac}	77.01 ± 0.02^{ab}
S3		0.6	8.98 ± 1.41^{cd}	1.49 ± 0.01^{a}	5.93 ± 0.04^{ab}	73.85 ± 0.05^{ab}
S4		0.8	8.98 ± 1.41^{cd}	1.45 ± 0.05^{ab}	6.09 ± 0.05^{a}	66.05 ± 0.05^{b}
S5		1.0	10.98 ± 1.41^{cd}	1.41 ± 0.04^{ab}	5.91 ± 0.05^{ab}	75.91 ± 0.03^{ab}
S6	60	0.2	6.99 ± 1.41^{d}	1.40 ± 0.02^{ac}	5.01 ± 0.05^{ac}	83.55 ± 0.01^{a}
S7		0.4	8.98 ± 1.41^{cd}	1.47 ± 0.03^{a}	5.89 ± 0.07^{ab}	74.37 ± 0.09^{ab}
S8		0.6	7.99 ± 0.01^{cd}	1.47 ± 0.02^{a}	5.80 ± 0.04^{ab}	84.04 ± 0.01^{a}
S9		0.8	10.97 ± 1.41^{cd}	1.51 ± 0.05^{a}	5.84 ± 0.03^{ab}	79.04 ± 0.01^{ab}
S10		1.0	12.97 ± 1.41^{bc}	1.44 ± 0.04^{ab}	6.22 ± 0.04^{a}	79.5 ± 0.03^{ab}
S11	100	0.2	6.99 ± 1.41^{d}	1.41 ± 0.02^{ab}	4.98 ± 0.03^{ac}	78.11 ± 0.05^{ab}
S12		0.4	6.98 ± 1.41^{d}	1.45 ± 0.06^{ab}	5.51 ± 0.03^{ac}	82.9 ± 0.01^{a}
S13		0.6	10.98 ± 1.41^{cd}	1.52 ± 0.03^{a}	6.25 ± 0.01^{a}	82.87 ± 0.01^{a}
S14		0.8	8.98 ± 1.41^{cd}	1.51 ± 0.07^{a}	6.06 ± 0.05^{a}	79.06 ± 0.05^{ab}
S15		1.0	10.97 ± 1.41^{cd}	1.49 ± 0.05^{a}	6.10 ± 0.03^{a}	80.14 ± 0.05^{ab}
S16	140	0.2	12.96 ± 1.40^{bc}	1.38 ± 0.08^{ac}	5.39 ± 0.03^{ac}	80.66 ± 0.03^{ab}
S17		0.4	7.99 ± 0.01^{cd}	1.36 ± 0.09^{ac}	5.82 ± 0.07^{ab}	79.93 ± 0.02^{ab}
S18		0.6	8.98 ± 1.41^{cd}	1.41 ± 0.03^{ab}	5.43 ± 0.03^{a}	74.74 ± 0.06^{ab}
S19		0.8	10.97 ± 1.41^{cd}	1.43 ± 0.02^{ab}	4.12 ± 0.04^{c}	75.57 ± 0.05^{ab}
S20		1.0	8.98 ± 1.41^{cd}	1.49 ± 0.02^{a}	4.84 ± 0.05^{ac}	79.99 ± 0.01^{ab}

All values are expressed as mean ± standard deviation (n = 3). Different superscript letters (a–d) within the same column indicate significant differences ($p < 0.05$) as determined by one-way ANOVA followed by Tukey's post hoc test. Control (Puree) refers to untreated mesocarp, while Control (UAE) represents ultrasound-treated samples without enzyme addition.