Valorization of banana inflorescence with integrated blanching and Taguchi-optimized ultrasound extraction

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Abstract

Banana inflorescence (BI) is discarded as agricultural waste as it competes for nutrients with banana fruits. Despite containing valuable nutrients, naturally occurring polyphenol oxidase deteriorates its bioactive compounds, challenging its utilization. This article proposed a new valorization platform, including in-farm blanching and an optimized novel extraction methodology, aiming to extract phytochemicals from bracts and male flowers of BI. In this sense, power ultrasound, an emerging nonthermal technology, is compared with conventional solvent extraction while optimizing the extraction conditions using the orthogonal $L_9(3^4)$ Taguchi method. Independent parameters were ultrasound power, solvent concentration, solid–liquid ratio, temperature, and time. Process optimization was followed by extract analysis, including total phenolic content (TPC), total flavonoid content (TFC), and antioxidant capacity (DPPH and ABTS radical scavenging activity). The highest TPC (8.76 ± 0.09 mg/g) for conventional extraction of banana bracts was obtained under 60% ethanol, 1:35 solid–liquid ratio, and 45 min of extraction at 50°C. At the same time, the highest TPC (50.64 ± 0.63 mg/g) of the male flowers was achieved with 40% ethanol, 1:35 solid–liquid ratio, and 45 min of extraction at 55°C. On the other hand, optimal ultrasound conditions were 150 W, 60% ethanol, and a solid–liquid ratio of 1:35 for 8 min, which yielded TPC of 9.43 ± 0.23 and 60.37 ± 0.54 mg/g for banana bracts and male flowers, respectively. Accordingly, ultrasound enhanced the extraction efficiency of bracts and male flowers by 7.6 and 19.2%, respectively, while saving substantial time (82.2%) compared to the conventional method. Besides, ultrasound-assisted extraction increased TFC by 1.29-fold. The findings highlighted the potential of BI as a rich resource for functional ingredients (e.g., for food and cosmetic industries) and the capability of the proposed integrated extraction approach to promote sustainability by utilizing and reducing agricultural waste to advance toward zero waste and more sustainable food production.

Keywords: antioxidant activity; *Musa paradisiaca*; resource efficiency; Taguchi optimization; ultrasound-assisted extraction; waste valorization

Introduction

Recycling and utilizing agricultural waste are crucial due to the significant volume of by-products generated during agricultural production, including roots, stems, leaves, flowers, peels, and seeds. Improper disposal of these waste materials can lead to environmental pollution and pest proliferation, while containing abundant

bioactive substances with antioxidant, anticancer, antimicrobial, cardiovascular disease-preventing, and antidiabetic properties (Patra *et al*., 2018). These substances can be extracted for developing food, nutritional supplements, pharmaceuticals, and cosmetics (Chamorro *et al*., 2022; Chaosuan *et al*., 2024).

In 2020, global banana production reached approximately 119.8 million tons, with a total cultivated area of about 5.2 million hectares (El Barnossi *et al*., 2021). Four metric tons of banana waste, including peels, pseudostems, leaves, and inflorescences, are generated per metric ton of bananas produced. Pseudostems account for the highest proportion of banana waste, approximately three metric tons (Sawarkar *et al*., 2022). Taking Taiwan as an example of a significant banana producer, about 220 metric tons of banana waste is estimated to be generated per hectare (Taiwan Banana Research Institute, 2022). Farmers may dispose of banana waste into rivers, leading to long-term emission of putrid odors in humid environments and river pollution (Ahmad and Danish, 2018). Therefore, it is necessary to develop effective approaches to utilize and reduce banana waste, such as banana inflorescence (BI).

Banana inflorescence, also known as banana blossom, banana flower, or banana heart, that grows at the end of the banana axis, is one of the agricultural waste materials generated during banana production, and contains bioactive substances. In India, Sri Lanka, Malaysia, and Thailand, banana inflorescence is used in cooking to promote human health as it is rich in nutritionally valuable compounds (Panyayong and Srikaeo, 2022). Researchers also explored the potential of this waste for nonfood applications such as bioethanol production (Bharathi and Jacob, 2024). Mathew and Negi (2017) mentioned that in Asian and African countries, banana inflorescence is used as a conventional medicinal plant for preventing diabetes, cancer, anemia, hypertension, respiratory diseases, and other ailments. Rodrigues *et al.* (2020) extracted banana bracts and male flowers using a solid–liquid ratio of 1:20 and water at temperatures of 95–100°C, resulting in total phenols of 106.24 and 181.25 mg/L and flavonoids of 9.55 and 20.68 mg/mL, respectively. Other studies have identified polyphenolic compounds in banana inflorescence, including gallic acid, p-hydroxybenzoic acid, catechol, chlorogenic acid, caffeic acid, sinapic acid, syringic acid, vanillin, p-coumaric acid, ferulic acid, ellagic acid, myricetin, cinnamic acid, quercetin, protocatechuic acid, catechin, epicatechin, kaempferol, and apigenin (Arun *et al*., 2017; Ramu *et al*., 2017).

At the same time, studies highlighted that the drying process could significantly affect the bioactive content of BI, as it contains polyphenol oxidase. This phenomenon can lead to browning reactions, phytochemical loss, and reduced bioactive content (Senevirathna *et al*., 2024). Therefore, polyphenol oxidase must be inactivated to preserve bioactive compounds (Xiao *et al*., 2017).

Ultrasound-assisted extraction is a novel processing technique that utilizes sound waves at high frequencies to induce physical and chemical effects in the medium, resulting in an effective extraction process (Gavahian *et al*., 2022a). By applying pressure to a liquid, vacuum bubbles are generated, and under high pressure, they undergo physical phenomena such as shockwaves, turbulence, and shear forces, leading to bubble collapse. This phenomenon is known as the cavitation effect, as explained in detail in the literature (Gavahian *et al*., 2022a; Tang *et al*., 2024). When cavitation occurs, the pressure from bubble collapse is transmitted to the cells, disrupting cell walls and releasing active ingredients into the solvent for extraction. However, there is a lack of research on the ultrasound-based valorization of Taiwanese banana inflorescence, especially if integrated with affordable thermal blanching. These highlight a need for a practical valorization platform for BI that could preserve the bioactive components of BI from oxidation in farms, combined with an effective extraction methodology in the industry.

Therefore, this study aimed to develop an integrated valorization approach for bracts and male flowers of BI based on thermal blanching and power ultrasound. It also aimed to utilize the Taguchi approach to identify the optimal conditions for conventional and ultrasound-assisted extraction of bioactive substances.

Materials and Methods

Sample preparation and the blanching process

The BI was harvested from a farm located in Xinpi Township, Pingtung County, Taiwan. The inflorescences were classified into bracts and male flowers, washed with clean water (Figure 1), and then cut into 3 cm pieces. Samples, with or without blanching pretreatment, were then dried using a hot air circulation oven (CTEH, Ji-Dian Industrial Co., Ltd., Taichung, Taiwan) at 55°C until reaching a constant weight. The blanching temperature was 95°C, and the blanching time was 10 and 4 min for bracts and male flowers, respectively. These temperatures and times were defined by preliminary experiments conducted in our laboratory. The blanched samples were put into an ice water bath for 5 min before removing the surface water with a paper towel. The oven-dried samples were ground with a grinder (Yu-Sheng-Guang Food Machinery, Taichung, Taiwan), sieved with a 40-mesh screen, placed in a zipper bag, and stored at 4°C (Jiuh Hsing, Kaohsiung, Taiwan).

Figure 1. Freshly harvested banana inflorescences were used in the present study.

Extraction process

Conventional extraction

Pulverized samples were put into conical flasks containing 50 mL ethanol at various concentrations (40, 50, and 60%) and shaken in an incubator (E600, Deng-Yng, Taipei, Taiwan) at 100 rpm. Process variables include solid–liquid ratios of 1:25, 1:30, and 1:35 (extract total weight of 50 g), extraction temperatures of 45, 50, and 55°C, and extraction times of 35, 40, and 45 min. The extract was then filtered with No. 1 filter paper and stored at 4°C.

Ultrasound-assisted extraction method

Pulverized samples were put into a beaker along with 50 mL of distilled water or different concentrations of ethanol (40, 50, and 60%) as the extraction solvent, extracted by a 20 kHz power ultrasound (SFX550, Branson Sonifier, Mexico) at different powers (150, 200,

and 250 W), solid–liquid ratios (1:25, 1:30, and 1:35), and extraction times (6, 7, and 8 min). The extraction temperature was kept constant (30°C) by circulating water around the beaker. Extracts were then filtered with No. 1 filter paper, collected, and stored at 4°C.

Taguchi method implementation

The optimal extraction conditions for extraction processes to achieve the highest concentration of total phenolic content (TPC) and an indicator of an efficient extraction process were defined using an orthogonal $L_9(3^4)$ of the Taguchi method (Chung *et al*., 2023). Independent variables and their levels are presented in Table 1. Each factor had three levels and was carried out with three replications. The signal-to-noise ratio (S/N) and response graph of the S/N ratio were calculated to analyze the effects of processing parameters (Equation 1).

$$S/N = -10 \times \log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (1)$$

Extracts analysis

Total phenol content

According to Siddiqui *et al*. (2017), 50% methanol was used to prepare 0, 50, 100, 150, and 200 g/mL gallic acid (Nacalai Tesque, Kyoto, Japan) solutions to obtain a standard curve. Then, 0.5 mL standard solution and extract were mixed with 5 mL of 0.2 M Folin-Ciocalteu phenol reagent (Merck, Darmstadt, Hamburg, Germany) and 4 mL of 1 M Na_2CO_3 (Nihon Shiyaku Reagent, Kyoto, Japan), and reacted in the dark for 15 min. The blank sample contained 0.5 mL of extract and 9 mL of distilled water. The absorbance was measured using a Double-Beam Ultraviolet-Visible Spectrometer (U-2001, Hitachi, Tokyo, Japan) at 765 nm, and TPC was expressed in mg/g, which referred to milligrams of gallic acid equivalence per gram of sample.

Total flavonoid content

Total flavonoid content (TFC) was determined according to Surana and Wagh (2017), using 80% ethanol to prepare 0, 20, 40, 80, 100, and 150 g/mL quercetin (Alfa Aesar, Lancashire, UK) to make a standard curve.

Table 1. The L_9 Taguchi design of conventional and ultrasound-assisted extraction conditions, indicating levels and variables of banana bract and male flower.

	Experiment	A Ethanol concentration (%)	B Solid-to-liquid ratio	C Temperature (°C)	D Time (minutes)
Conventional Extraction (CE)	CE1	40	1:25	45	35
	CE2	40	1:30	50	40
	CE3	40	1:35	55	45
	CE4	50	1:25	50	45
	CE5	50	1:30	55	35
	CE6	50	1:35	45	40
	CE7	60	1:25	55	40
	CE8	60	1:30	45	35
	CE9	**60**	**1:35**	**50**	**45**
	Experiment	**A Power (W)**	**B Ethanol concentration (%)**	**C Solid-to-liquid ratio**	**D Time (minutes)**
Ultrasound-assisted extraction (UE)	UE1	150	40	1:25	6
	UE2	150	50	1:30	7
	UE3	150	60	1:35	8
	UE4	200	40	1:30	8
	UE5	200	50	1:35	6
	UE6	200	60	1:25	7
	UE7	250	40	1:35	7
	UE8	250	50	1:25	8
	UE9	250	60	1:30	6

Briefly, 0.5 mL standard solution and extract were mixed with 1.5 mL 95% ethanol, 2.8 mL distilled water, 0.1 mL potassium acetate, and 0.1 mL 10% aluminum chloride and then reacted in the dark for 30 min. The blank sample contained 0.5 mL extract, 1.5 mL 95% ethanol, and 3 mL distilled water. Absorbance was measured at 415 nm using a spectrophotometer (U-2001, Hitachi, Tokyo, Japan), and TFC expressed in mg/g, which refers to milligrams of quercetin equivalents per gram of sample.

Determination of 1,1-diphenyl-2-picrylhydrazyl (DPPH) free radical scavenging ability

Based on the method described by Mansour *et al*. (2016), 0.1 mM DPPH with absolute methanol solution was prepared. The analytical method included dilute extract (stock solution, 2, 5-, 10-, 15-, and 20-times dilution), 50 µL for the extraction solution, and 150 µL DPPH in a 96-well microplate. After reacting in dark conditions for 30 min, the absorbance was measured at 517 nm (U-2001, Hitachi, Tokyo, Japan). Then, DPPH radical scavenging capacity was calculated according to Equation 2.

$$\text{DPPH free radical scavenging capacity} = \frac{\left(\text{A 517 nm control} - \text{A 517 nm sample}\right)}{\text{A 517 nm control}} \times 100\% \quad (2)$$

Determination of 2,2'-azina-bis (3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) free radical scavenging ability

A slightly modified method described by Liu *et al*. (2014) measured ABTS free radical scavenging ability. Briefly, 7 mM of ABTS (Sigma, St. Louis, MO, USA) solution was mixed with 2.45 mM potassium persulfate and kept at room temperature in the dark for 16 h. Then, ABTS solution was diluted with distilled water to an absorbance value of 0.7 ± 0.02 before use, and different diluents (stock solution, 2-, 5-, 10-, 15-, and 20-times dilution) were prepared. Then, 20 µL extracts and 180 µL ABTS were put in a 96-well microplate with three replications, while taking 20 µL distilled water as a blank test. The samples were reacted in the dark for 6 min before measuring the absorbance at 734 nm. Finally, the ABTS free radical scavenging capacity was calculated according to Equation 3.

$$\text{ABTS free radical scavenging capacity} = \frac{\left(\text{A 734 nm control} - \text{A 734 nm sample}\right)}{\text{A 734 nm control}} \times 100\% \quad (3)$$

Experimental design and statistical analysis

The experimental framework is visualized in Figure 2. SPSS Statistics 26.0 (IBM Statistical Package for the Social Sciences, USA) software was used for variance analysis (ANOVA), and Duncan's multiple range test was used to compare the differences between multiple groups of data at a significance level of $P < 0.05$.

Results and Discussion

Effects of blanching pretreatment and extraction conditions on total phenolic acid

The effects of blanching and extraction (conventional and ultrasound-assisted) processing variables on TPC were evaluated before designing the Taguchi approach as a preliminary study. The results elaborated on the effects of processing parameters, which were then utilized in designing the Taguchi approach, as explained in the next section.

Taguchi optimization

Taguchi optimization of conventional extraction

The Taguchi method, specifically the $L_9(3^4)$ orthogonal array, was employed to evaluate the optimal conditions for the conventional extraction method. Ethanol concentration, solid–liquid ratio, extraction temperature, and extraction time were selected as four process variables. Three levels were chosen for each factor based on single-factor experiments as follows: 40, 50, and 60% ethanol; solid–liquid ratios of 1:25, 1:30, and 1:35; temperatures of 45, 50, and 55°C; and extraction times of 35, 40, and 45 min (Table 1). Each group was subjected to triplicate experiments. The optimal conditions for extracting TPC from banana bracts (BCE) and male flowers (FCE) were analyzed, and the results are shown in Figure 3A. According to the results, BCE9 obtained the highest TPC (8.76 ± 0.09 mg/g) for banana bracts among the CE group. At the same time, significantly higher TPC was observed for banana male flowers than for bract samples (Table 2).

To further enhance the extraction of TPC, the S/N ratio was calculated using the obtained values for banana bracts and male flowers. The highest S/N ratios for banana bracts were achieved with levels A3, B3, C3, and D3 (Figure 3A). The optimal conditions were 60% ethanol, a solid–liquid ratio of 1:35, a temperature of 55°C, and an extraction time of 45 min. For banana male flowers, the highest S/N ratios were obtained with levels A1, B3, C3, and D3 (Figure 3B), which indicated that 40% ethanol, a solid–liquid ratio of 1:35, a temperature of 55°C, and an extraction time of 45 min were the optimal conditions for extraction from banana male flowers.

The above results indicated the capability of the Taguchi approach in identifying the optimal extraction conditions for maximizing TPC from both banana bracts and male

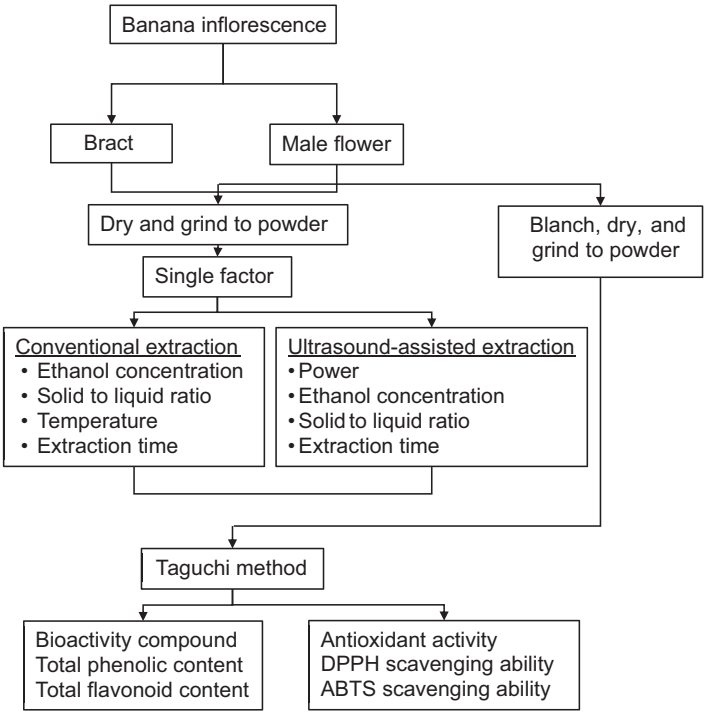

Figure 2. Experimental design in the present study. ABTS: 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) assay; DPPH: 2,2-diphenyl-1-picrylhydrazyl) test.

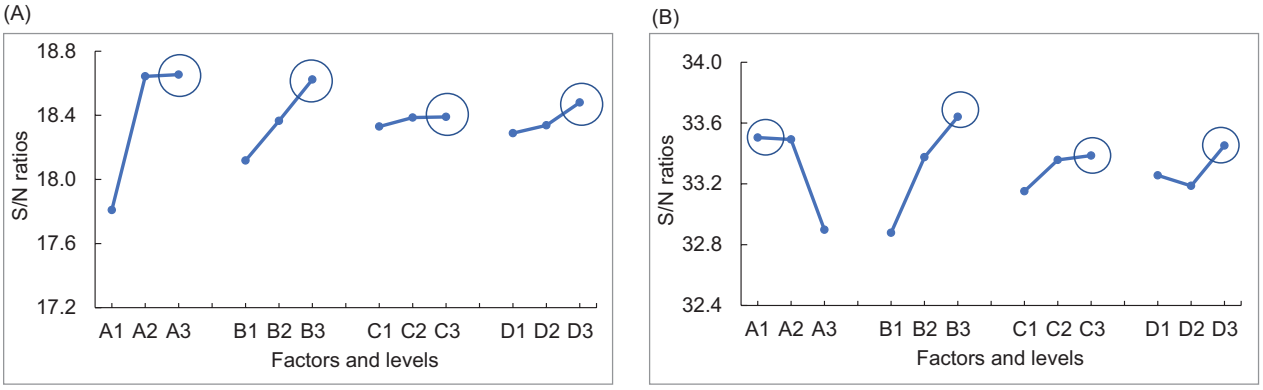

Figure 3. Response graph of various conventional extraction conditions for total phenolic compound content in banana bract (A) and male flower (B). In this Figure, the higher the signal-to-noise ratio, the better it is. A: ethanol concentration (40, 50, 60%), B: solid-to-liquid ratio (1:25, 1:30, 1:35), C: temperature (45, 50, 55°C), D: time (35, 40, 45 min). S/N refers to signal-to-noise ratio. Factors and levels are explained in Table 1.

flowers. Accordingly, these findings and future studies could eventually underscore the Taguchi method's precision in optimizing ultrasound-based extraction processes and enhancing the recovery of valuable bioactive compounds from banana waste.

Taguchi optimization of ultrasound-assisted extraction

According to the Taguchi method, each group was subjected to triplicate experiments to screen for the optimal factors for extracting TPC from banana bract (BUE) and male flowers (FUE). As shown in Table 2, the highest TPC of banana bracts (9.43 mg/g) was obtained at BUE3 conditions. For banana male flowers, the FUE3 condition yielded the highest TPC (60.37 mg/g).

The results of the S/N ratios for banana bracts and male flowers are shown in Figure 4. Levels A1, B3, C3, and D3 exhibited the highest S/N ratios for both bracts (15.70, 15.96, 17.53, and 16.51) and male flowers (33.78, 34.61, 34.32, and 33.59). Therefore, the optimal factors were

determined to be a power of 150 W, ethanol concentration of 60%, solid–liquid ratio of 1:35, and extraction time of 8 min. These conditions matched the conditions of UE3, as shown in Table 2. Increasing the ultrasound power may provide an expectation for enhanced extraction due to higher energy input. However, the results provide insights into the importance of identifying optimal conditions (UE3, Table 2) instead of a higher energy input. Specifically, when other parameters (e.g., extraction time and solid-to-liquid ratios) were optimized, a power of 150 W yielded higher TPC than those of higher powers (e.g., 200 and 250 W) (Table 2). This could be related to parameters such as excessive cavitation, localized thermal effects, or degradation of phenolic compounds at higher power levels and effects of other processing variables used in this study, such as extraction time, solvent, and sample-to-solvent ratio. These findings highlighted that increasing ultrasound power would not necessarily lead to a higher yield of bioactive compounds in some examples of processing conditions, highlighting the importance of process optimization.

Table 2. Conventional and ultrasound extraction obtained the total phenolic contents of banana bracts and male flowers under various conditions.

	Experiment	Bract (mg/g)	Male flower (mg/g)
Conventional extraction (CE)	CE1	7.45 ± 0.16^{d}	44.13 ± 0.20^{d}
	CE2	7.77 ± 0.26^{d}	47.54 ± 1.83^{b}
	CE3	8.13 ± 0.12^{c}	50.64 ± 0.63^{a}
	CE4	8.44 ± 0.14^{abc}	46.18 ± 0.95^{bc}
	CE5	8.50 ± 0.19^{ab}	47.97 ± 1.02^{b}
	CE6	8.75 ± 0.22^{a}	47.75 ± 1.02^{b}
	CE7	8.32 ± 0.31^{bc}	42.01 ± 1.54^{e}
	CE8	8.64 ± 0.08^{ab}	44.59 ± 0.87^{d}
	CE9	8.76 ± 0.09^{a}	46.02 ± 0.57^{bcd}
Ultrasound-assisted extraction (UE)	UE1	5.34 ± 0.13^{e}	34.86 ± 2.01^{f}
	UE2	3.76 ± 0.51^{f}	54.35 ± 0.95^{b}
	UE3	9.43 ± 0.23^{a}	60.37 ± 0.54^{a}
	UE4	3.75 ± 0.35^{f}	39.42 ± 0.56^{e}
	UE5	7.41 ± 0.19^{c}	60.05 ± 1.91^{a}
	UE6	8.23 ± 0.09^{b}	49.29 ± 0.42^{cd}
	UE7	6.17 ± 0.59^{d}	39.01 ± 2.65^{e}
	UE8	8.55 ± 0.21^{b}	46.13 ± 2.18^{d}
	UE9	3.28 ± 0.56^{f}	52.69 ± 4.22^{bc}

*The values are shown as mean ± SD (n = 3). The column's data with different superscript letters differ significantly (P < 0.05). Please refer to Table 1 for details of the experimental codes of CE1-9 and UE1-9.

Impact of conventional and ultrasound-assisted extraction on BI extracts

Total phenolic content

Table 3 compares the TPC of banana bracts and male flowers obtained through conventional and ultrasound-assisted extraction under optimal conditions. The TPC obtained through conventional extraction was 8.76 and 50.64 mg/g for banana bracts and male flowers, respectively.

Ultrasound-assisted extraction significantly improved the TPC values of banana bracts and male flowers, with values of 9.43 and 60.37 mg/g for bracts and male flowers, respectively. Simultaneously, it achieved the desired effect and completed the process in a shorter time.

While there are reports on the effects of drying on the TPC content of banana inflorescence (Vieira Nogueira *et al.*, 2024), there is limited documented data on the impact of ultrasound on the TPC of this agricultural

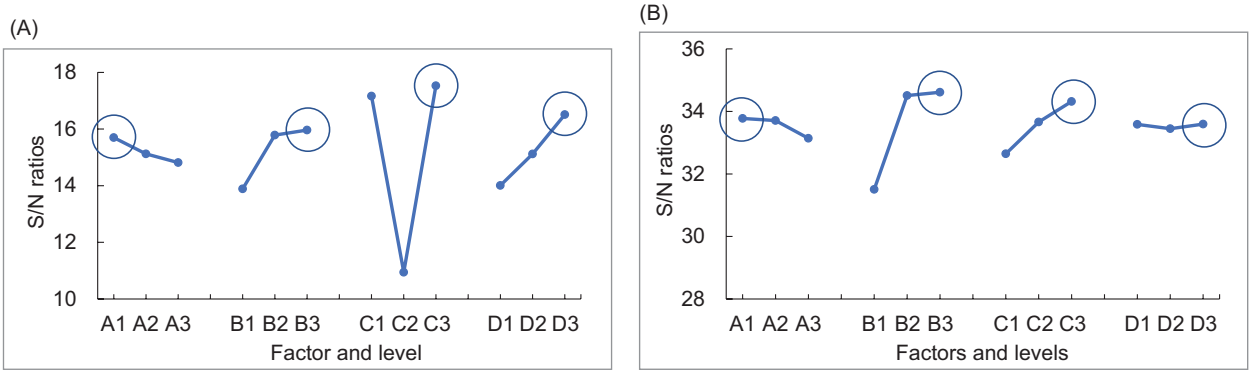

Figure 4. Response graph of the high-the-better signal-to-noise ratio of different ultrasound-assisted extraction conditions for total phenolic compound content in banana bract (A) and male flower (B). A: power (150, 200, 250 W), B: ethanol concentration (40, 50, 60%), C: solid to liquid ratio (1:25, 1:30, 1:35), D: time (6, 7, 8 minutes). S/N refers to signal-to-noise ratio. Factors and levels are explained in Table 1.

Table 3. The total phenolic and flavonoid content and IC*50* in DPPH and ABTS assays of banana bract and male flower by conventional and ultrasound-assisted extraction at optimal conditions.

Sample	TPC (mg/g)	TFC (mg/g)	DPPH (IC_{50})	ABTS (IC_{50})
BCE	8.76 ± 0.09^{A}	0.59 ± 0.05^{A}	3.13 ± 0.08^{A}	3.86 ± 0.15^{A}
BUE	9.43 ± 0.23^{A}	0.65 ± 0.03^{A}	1.50 ± 0.04^{B}	3.77 ± 0.14^{A}
FCE	50.64 ± 0.63^{b}	0.76 ± 0.09^{a}	0.47 ± 0.02^{a}	0.87 ± 0.01^{a}
FUE	60.37 ± 0.54^{a}	0.83 ± 0.01^{a}	0.23 ± 0.01^{b}	0.66 ± 0.02^{b}

*The values are shown as mean ± SD (n = 3). For each measurement, data marked by different capital and small letters indicate significant differences for bract and male flowers, respectively.
BCE: conventionally extracted bracts; BUE: ultrasound-extracted bracts; FCE: conventionally extracted male flowers; FUE: ultrasound-extracted male flowers.

waste. In a study by Nipornram *et al.* (2018), 80% acetone was used as the extraction solvent to investigate the effects of ultrasound time and power on the TPC of citrus peels. The results showed that as the extraction time increased, the TPC decreased. This was attributed to the prolonged extraction, which led to the degradation and breakdown of bioactive components. Additionally, the TPC of citrus peels obtained through ultrasound-assisted extraction was significantly higher than that obtained through conventional soaking methods, similar to the results of this experiment with banana male flowers. This can be explained by the mechanisms involved, such as ultrasound cavitation, which accelerates the disruption of the plant cell surface and releases the compounds into the solution.

Total flavonoid content

Table 3 compares the differences in total flavonoid content between conventional and ultrasound-assisted extraction methods at optimal conditions for banana bracts and male flowers. According to the results, BCE and BUE had the TFC of 0.59 and 0.65 mg/g, respectively, for banana bracts. For banana male flowers, the TFC under the FCE and FUE conditions were 0.76 and 0.83 mg/g, respectively. It was noted that ultrasound-assisted extraction achieved a similar effect to conventional extraction in a shorter duration, reducing the processing time and contributing to sustainable production.

DPPH free radical scavenging ability

The half maximum inhibitory concentrations (IC_{50}) of DPPH radical scavenging of extracts obtained by conventional and ultrasound-assisted extraction methods on banana bracts and male flowers were investigated. The results are shown in Table 4. Among the conventional extraction conditions, BCE3, BCE6, and BCE9 exhibited the lowest IC_{50} for DPPH radical scavenging in banana bracts. For banana male flowers, the lowest IC_{50} were obtained under the FCE5, FCE3, and FCE2 extraction conditions. Among the ultrasound-assisted extraction conditions, the lowest IC_{50} for DPPH radical scavenging in male flowers was obtained under the FUE3 condition (Table 4).

By comparing the optimal extraction conditions for IC_{50} of DPPH radical scavenging activity, it was observed that the IC_{50} of BUE was significantly lower than BCE in banana bracts, with concentrations of 1.50

Table 4. The IC_{50} in DPPH assay of banana bract and male flower by conventional and ultrasound-assisted extraction conditions.

	Experiment	Bract (mg/mL)	Male flower (mg/mL)
Conventional extraction (CE)	CE1	12.66 ± 0.15^{a}	0.76 ± 0.23^{a}
	CE2	10.08 ± 0.64^{b}	0.49 ± 0.01^{bc}
	CE3	3.13 ± 0.08^{e}	0.47 ± 0.02^{c}
	CE4	10.79 ± 0.22^{b}	0.59 ± 0.03^{b}
	CE5	4.08 ± 0.51^{d}	0.44 ± 0.02^{c}
	CE6	3.10 ± 0.10^{e}	0.54 ± 0.00^{b}
	CE7	7.66 ± 0.85^{c}	0.54 ± 0.02^{b}
	CE8	12.15 ± 0.85^{a}	0.55 ± 0.04^{b}
	CE9	3.52 ± 0.03^{de}	0.53 ± 0.03^{b}
Ultrasound-assisted extraction (UE)	UE1	1.65 ± 0.03^{b}	0.28 ± 0.00^{d}
	UE2	1.60 ± 0.16^{cde}	0.27 ± 0.00^{d}
	UE3	1.50 ± 0.04^{cd}	0.23 ± 0.01^{e}
	UE4	1.96 ± 0.08^{ab}	0.39 ± 0.01^{b}
	UE5	1.90 ± 0.05^{bc}	0.34 ± 0.04^{c}
	UE6	1.81 ± 0.10^{c}	0.29 ± 0.03^{d}
	UE7	2.02 ± 0.01^{a}	0.42 ± 0.00^{a}
	UE8	1.98 ± 0.08^{a}	0.35 ± 0.01^{c}
	UE9	1.86 ± 0.08^{b}	0.28 ± 0.01^{d}

*The values are shown as mean ± SD (n = 3). For each measurement in each extraction method, the data with different superscript letters in the column were significantly different ($P < 0.05$). Please refer to Table 1 for details of the experimental codes of CE1-9 and UE1-9.

and 3.13 mg/mL, respectively (Table 3). Similarly, for banana male flowers, the IC_{50} of FUE was lower than FCE, with concentrations of 0.23 and 0.47 mg/mL, respectively. These results indicate that optimal ultrasound-assisted extraction can achieve lower IC_{50} than conventional extraction methods, suggesting that ultrasound-assisted extraction can effectively enhance the antioxidant capacity of banana bracts and male flowers within 8 minutes. In contrast, conventional extraction could not yield extracts with comparable antioxidant activity, even at extended extraction times.

Dahmoune *et al*. (2015) investigated the DPPH free radical scavenging ability of mastic tree (*P. lentiscus*) leaves using ultrasound-assisted and conventional extraction methods. The results showed that the IC_{50} obtained under the optimal ultrasound-assisted extraction condition was 18.74 ± 0.284 g/mL, while the IC_{50} under conventional extraction was 19.74 ± 0.06 g/mL. These results are similar to the findings of this experiment, indicating that ultrasound-assisted extraction can reduce the IC_{50} of free radical scavenging in plants, effectively releasing bioactive substances and enhancing antioxidant capacity.

ABTS free radical scavenging ability

According to Table 3, the IC_{50} of ABTS free radical scavenging ability in banana bracts and male flowers using the conventional extraction method were different. While FUE exhibited an IC_{50} value of 0.66 mg/mL, BCE and BUE demonstrated considerably lower ABTS free radical scavenging ability with IC_{50} values of 3.86 and 3.77 mg/mL, respectively.

Among the conventional extraction conditions, BCE9 and BCE8 exhibited the lowest IC_{50} in banana bracts, significantly lower than other groups, with values of 3.15 and 3.20 mg/mL, respectively (Table 5). Among the ultrasound-assisted extraction conditions, the highest IC_{50} was obtained under UE1 for both bracts and flowers. The optimal conditions for the ABTS assay are summarized in Table 3. According to the results, ultrasound-assisted extraction can enhance the antioxidant capacity of banana bracts and male flowers at a relatively low power of 150 W.

These findings indicated that the ultrasound-assisted extraction significantly enhances the antioxidant capacity of banana bracts and male flowers, achieving lower IC_{50} values than conventional methods. Notably, the optimal conditions yielded substantial improvements, particularly in male flowers, highlighting the potential of ultrasound for efficient recovery of bioactive compounds, which can eventually benefit the food and agricultural industry through waste reduction and valorization and also underscores the value of BI as a sustainable resource.

Table 5. The IC_{50} in ABTS assay of banana bract and male flower by conventional and ultrasound-assisted extraction conditions.

	Experiment	IC_{50} (mg/mL)	
		Bract	Male flower
Conventional extraction (CE)	CE1	5.04 ± 0.15^{a}	0.90 ± 0.05^{ab}
	CE2	4.70 ± 0.14^{abc}	0.94 ± 0.01^{a}
	CE3	3.86 ± 0.15^{d}	0.87 ± 0.01^{bc}
	CE4	4.93 ± 0.26^{ab}	0.91 ± 0.01^{ab}
	CE5	4.55 ± 0.12^{bc}	0.88 ± 0.00^{bc}
	CE6	4.32 ± 0.15^{c}	0.91 ± 0.00^{ab}
	CE7	4.52 ± 0.19^{bc}	0.83 ± 0.03^{c}
	CE8	3.20 ± 0.55^{de}	0.83 ± 0.05^{c}
	CE9	3.15 ± 0.13^{e}	0.88 ± 0.02^{bc}
Ultrasound-assisted extraction (UE)	UE1	10.57 ± 0.93^{a}	1.07 ± 0.21^{a}
	UE2	8.77 ± 0.11^{c}	0.74 ± 0.02^{cd}
	UE3	3.77 ± 0.14^{fg}	0.66 ± 0.02^{e}
	UE4	9.94 ± 0.67^{ab}	0.89 ± 0.03^{b}
	UE5	4.17 ± 0.14^{ef}	0.68 ± 0.01^{de}
	UE6	4.73 ± 0.04^{e}	0.83 ± 0.00^{bc}
	UE7	6.36 ± 0.42^{d}	0.79 ± 0.04^{bcd}
	UE8	9.31 ± 0.48^{bc}	0.82 ± 0.02^{bcd}
	UE9	3.03 ± 0.08^{g}	0.77 ± 0.05^{bcd}

*The values are shown as mean ± SD (n = 3). For each measurement and each extraction method, the data with different superscript letters in the column were significantly different ($P < 0.05$). Please refer to Table 1 for details of the experimental codes of CE1-9 and UE1-9.

Overview of the results and considerations

It should be noted that other innovative approaches have also been proposed to valorize banana waste. For example, lysozyme-assisted extraction has been developed to extract bioactive compounds from banana peels that yielded an extract with TPC, TFC, DPPH, and ABTS of 25 mg/g, 14 mg/g, 82%, and 88%, respectively, at optimal conditions (Islam *et al*., 2023). In another recent study, researchers developed a new ultrasound-based system to extract phytochemicals from the banana flower and achieved an extract with a considerable DPPH antioxidant capacity after 15 min of extraction (Susilo *et al*., 2024). Ultrasound has also been applied to valorize other fruit by-products, such as lemon peel (Gavahian *et al*., 2022b). As researchers are working hard to develop new sustainable approaches for valorizing agricultural waste, such as banana by-products, it should be considered that each method has its benefits and drawbacks that should be verified through parallel comparison and upscaling studies. Overall, compared with conventional thermal extraction, the proposed valorization platform based on affordable in-farm blanching and innovative nonthermal ultrasound extraction yielded extracts with higher concentrations of

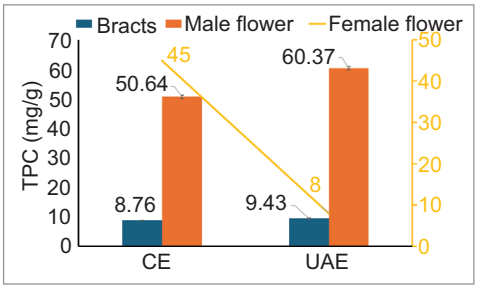

Figure 5. A comparison between maximum total phenolic content (TPC) obtained by ultrasound-assisted extraction (UAE) and conventional extraction (CE) from male flowers and bracts of banana, along with the time required to accomplish the extraction (processing time).

bioactive compounds (e.g., TPC by 7.6–19.2%) while saving substantial (82.2%) of time (Figure 5), contributing to achieving sustainable development goals (SDGs) (United Nations, 2024) if implemented into the industry.

According to the results (Tables 4 and 5), bioactive compounds recovered from the male flowers and bracts of bananas have enormous potential for various uses in food, nutritional supplements, and cosmetics. These extracts are rich in phenolic and flavonoid compounds with significant antioxidant activities; they can be used to develop functional foods with enhanced nutritional content or made into dietary supplements that address oxidative stress and general health. The cosmetics industry could also use their bioactive and antioxidant characteristics to create skincare products that could delay aging and support healthier skin. Such achievements require further follow-up research focusing explicitly on this topic and integrating the findings with in vivo tests. Furthermore, the ultrasound-assisted extraction technique showed exceptional efficiency, significantly cutting down on extraction time and energy usage while simultaneously increasing yield. The valorization of BI is positioned as a sustainable innovation that supports environmentally friendly production methods while converting agricultural waste into valuable ingredients. At the same time, it should be noted that challenges are involved in the practical implementation of large-scale ultrasound-assisted extraction for BI. For example, equipment cost and technology availability should be considered for successful implementation to ensure operational and economic feasibility.

Conclusion

This study demonstrated that ultrasound-assisted extraction can accelerate the process and yield an extract with a greater concentration of phenolic compounds and antioxidant capacity. Combined with affordable in-farm hot water blanching, these could develop a practical valorization platform to help farmers benefit further from planting bananas and reduce environmental concerns associated with untreated waste disposal. At the same time, the high antioxidant activity and phytochemical concentrations of banana male flowers, compared with banana bracts, make it a potential ingredient for developing functional food. According to the data obtained, it can also be concluded that implementing the Taguchi method could be considered a promising approach to optimize the extraction process and fully benefit from novel extraction technologies. Also, the proposed ultrasound-assisted extraction method maximizes the recovery of bioactive compounds from banana inflorescence. It demonstrates a significant leap towards sustainable agricultural waste valorization, offering a scalable solution for producing functional ingredients with enhanced efficiency and environmental responsibility. Future consecutive research may explore the application of ultrasound to extract bioactive compounds from other agricultural by-products and its integration with other green technologies to enhance compound recovery and sustainability. Also, quantitative chemical studies on extract composition and biological effects could promote the application of these valorized products in the food and cosmetic industries.

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Authors Contributions

S-C.S: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Review & Editing, Supervision, Project administration, Funding acquisition; Y-Y.S.: Software, Investigation, Writing - Original Draft; M.G.: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition.

Conflicts of Interest

The authors have no conflict of interest to declare.

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