



Bioactive Potential and Antioxidant Activity of Roasted and Kombucha-Like Beverage by *Musa acuminata* Peel

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Abstract

The purpose of this study was to investigate the production process of banana (*Musa acuminata*) peel tea, a waste material developed into fermented tea drinks. Various banana peel preparations were characterized for their physicochemical, antioxidant activity, bioactive compounds, and sensory qualities. The results indicated that banana peels steamed, then soaked in 2% citric acid, roasted for 10 min (BPR10), and dried, which had the highest antioxidant activity (mg TE/g) to scavenge 2,2-diphenyl-1-picrylhydrazyl (DPPH) ($3,058.3 \pm 43.8$), 2,2'-azino-bis(3-ethylbenzothiazoline)-6-sulfonic acid (ABTS+) free radicals ($2,460.0 \pm 17.8$), Ferric reducing antioxidant powder (FRAP) (990.3 ± 12.0), total phenolic content (TPC) 338.9 ± 1.1 mg GAE/g, total flavonoids content (TFC) 17.2 ± 0.6 mg QE/g, and total tannin content (TTC) 144.1 ± 7.5 mg CE/g ($p < 0.05$). Additionally, it was found that roasting banana peel infusion tea yielded the best sensory qualities. The kombucha-like BRP10 fermentation for 14 days significantly showed higher antioxidant activity (mg TE/g) quantified by DPPH (12.72 ± 0.23), ABTS (26.04 ± 0.29), FRAP (9.67 ± 0.04), TPC 3.15 ± 0.03 mg GAE/g, and TTC 0.48 ± 0.02 mg CE/g ($p < 0.05$) than infusion tea ($p < 0.05$) except TFC ($p \geq 0.05$). In summary, the kombucha-like roasted banana peel tea significantly influenced various aspects of antioxidant sources, highlighting its potential for applications in the beverage and industry sectors.

Keywords: Banana peel; By-product; Tea; Kombucha; Roasting; Bioactive compounds.

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1. Introduction

Banana peels, often considered waste from fruit consumption, are a source of highly bioactive phytochemicals. Banana peels have a diverse chemical composition, including phenolic compounds, flavonoids, tannins, alkaloids, and triterpene compounds, which exhibit pharmacological activities such as antibacterial, antifungal, antiviral, and anticancer effects. They are also high in dietary fiber, particularly pectin, which can be used in healthy food products.^[1-3] Recent studies examined the properties of banana peels from Southeast Asian native varieties, including Cavendish (*Musa* AAA), Kluai Nam Wa (*Musa* AAB), and Kluai Khai (*Musa* AA). They found that phenolic compounds such as rutin, chlorogenic acid, gentisic acid, chrysin, quercetin, catechin, cinnamic acid, and coumarin play a significant role in antioxidant and antibacterial activity.^[4] Banana peel extracts exhibit significant antioxidant activity, with Cavendish banana showing the most effective in ABTS and DPPH assays. These substances can

bind to metal ions and effectively inhibit the formation of free radicals.^[5] Banana peels contain 1.5–3 times more phenolic compounds than the banana pulp, with values ranging from 4.95–47 mg. GAE/gram of dry weight, which results in banana peels having better antioxidant capacity than other fruit peels,^[6] ranks as the second highest among avocados, pineapples, and watermelons.^[7] Studies have identified over 40 phenolic compounds in banana peels, which can be divided into four main groups: hydroxycinnamic acids, flavonols, flavan-3-ols, and catecholamines. Flavonols, such as rutin and quercetin glycosides, are the most abundant compounds found in banana peels. Several factors, including variety, fruit ripeness stage, growing environment, and sample preparation method before extraction, influence the composition and quantity of phenolic compounds in banana peels,^[7] which is important for developing agricultural waste into high-value raw materials for the food and health industries.^[4,8]

Approximately 114.08 million metric tons of banana peels were generated as waste. This waste consists of natural fibers, hemicellulose, and cellulose, which can be utilized to produce bioplastics, biofuels, activated carbon, and cost-effective wastewater treatment filters. Historically, banana peels served as a biofertilizer for crop cultivation. Due to population

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expansion, farmers transitioned to chemical fertilizers. It is currently regarded as an invaluable resource, its significance recognized, and numerous research initiatives are underway on it. Banana peels can be used to food and beverage products that possess significant nutritional value, providing antioxidants and boosting the immune system. Tea derived from banana peels facilitates weight reduction.^[9] Banana peel tea can be made by drying and grinding the peel, then brewing it into an herbal drink with a mild taste and unique aroma. Analysis of the nutritional composition found that tea made from banana peels has a satisfactory level of key nutrients and is moderately to well-tolerated by consumers.^[3] Therefore, the development of banana peel tea is another interesting approach to creating environmentally friendly and commercially viable healthy food products.^[3,9] However, the production conditions, specifically the effect of roasting time on antioxidant activity, have not been systematically studied.

Roasting is one of the key processes in tea production, especially in roasted teas such as yellow tea, oolong tea, and stem roasted tea, which play a role in modifying the chemical composition. Roasting significantly reduces the aroma, taste, and external characteristics of tea. Several studies have examined the effects of roasting in various aspects, including temperature, duration, and impact on important compounds in tea. Sasaki *et al.*^[10] found that a roasting temperature of 200 °C was the optimal level for stem tea, providing a distinct roasted aroma. In addition, research by Ye *et al.*^[11] states that roasting yellow tea at 130 °C for 22 minutes yields the best results, adding aromatic substances such as linalool and β -ionone, as well as sweet and umami substances. This results in high-quality products. Duan *et al.*^[12] found that medium roasting provides the most balanced aroma, adding floral and fruity aromas and reducing unpleasant burning odors. However, roasting influences the non-volatile substances in the tea. Roasting reduces the bitterness and astringency of green tea by reducing catechins and increasing organic acids and soluble sugars, which makes the flavor softer and more mellow.^[13]

Kombucha is a traditional fermented beverage that is gaining popularity worldwide, originating in China and spreading to Russia, Europe, and America. Kombucha fermentation is carried out by "SCOBY" (Symbiotic Culture of Bacteria and Yeast), which is a group of acetic acid bacteria, lactic acid bacteria, and various yeasts that work together to convert the sugar in tea into organic acids, vitamins, phenolic compounds, low levels of alcohol, and other bioactive compounds beneficial to health.^[14-16] Kombucha contains several biologically active compounds such as polyphenols, gluconic acid, and glucuronic acid, which have antioxidant.^[14-15] Kombucha can be produced from a variety of teas, such as black, green, white, red, and oolong teas, which provide different properties. Black tea is the most popular traditional ingredient.^[16] Both traditional and alternative methods, such as the use of herbs. It has been found to have a positive effect on the biological properties of the beverage, such as antioxidant, antimicrobial, anti-diabetic, anti-cancer, and promoting liver

function.^[15] Fermentation with kombucha reduced the phenolic content in black tea by about 50%, while in banana peels and secret leaves increased, which may be caused by protein degradation by lactic acid bacteria.^[17] In addition, kombucha drinks fermented with *Rhodiola rosea* residue were found to have significantly higher antioxidant capacity, with higher FRAP and TE values than fermentation without plant residues, and higher total phenolic content as well. Important substances that play an antioxidant role include gallic acid, salidroside, and tyrosol.^[18] Several publications have been reported regarding the use of different herbal teas mixed with banana peel as a medium for making kombucha; however, to the author's knowledge, no scientific report has been published on utilizing exclusively banana (*Musa acuminata*) peel infusions as substrate for kombucha fermentation. Numerous studies have indicated the antioxidant activity of banana peel.^[17,19]

To optimize banana peel tea preparation and to investigate the potential advantages of banana peel tea powder, banana peel tea infusion, and fermented banana peel tea on the antioxidant and bioactive compounds have been studied. This work represents the first attempt to identify the conditions under which banana peels are produced. To this end, various factors that could affect preparation efficiency were tested: the roasting time (5 or 10 min) on antioxidant activity has not been examined in banana peel tea. In addition, the bioactive compounds (phenolic compounds, flavonoids, and tannins) that may be responsible for antioxidant activity were characterised.

2. Materials and methods

2.1 Materials and sample preparation

The raw material used is Hom thong banana (*Musa acuminata*) peel from Pathum Thani, Thailand. The fresh, ripe, and disease-free banana peel was processed. The TPC, TFC, TTC, DPPH, ABTS, and FRAP analyses employed solvents and standards that were procured from Sigma-Aldrich, USA.

The raw material used is banana peel in maturity levels C2 to D1 (yellow with brown spots: very ripe), as follows Chuquimarca *et al.*^[20] Wash with tap water, place on a sieve to drain, and cut into pieces of about 1 inch. All 4 experiments (n=3) as follows: Banana peel was steamed for 10 min and soaked in 2% citric acid for 10 min then different roasted time on Teflon pan with heat at 150 ± 5 °C for 0 (BPR0), 5 (BPR5), and 10 (BPR10) min with control (banana peels without treatments: BP) and dried in a cabinet drier at 60 °C until the moisture content reached to 13% (wet basis). The dried peel was pulverized to a fine powder using a laboratory grinder, screened, packed in high-density polyethylene, and stored at -18 °C until further use. Then it is analyzed as follows: Color easurement Using Colorimeter in Hunter L* a* b*, % yield, and water activity. The research design for optimizing the preparation of banana peel tea to develop fermented banana peel tea was summarized in Fig. 1, based on the highest

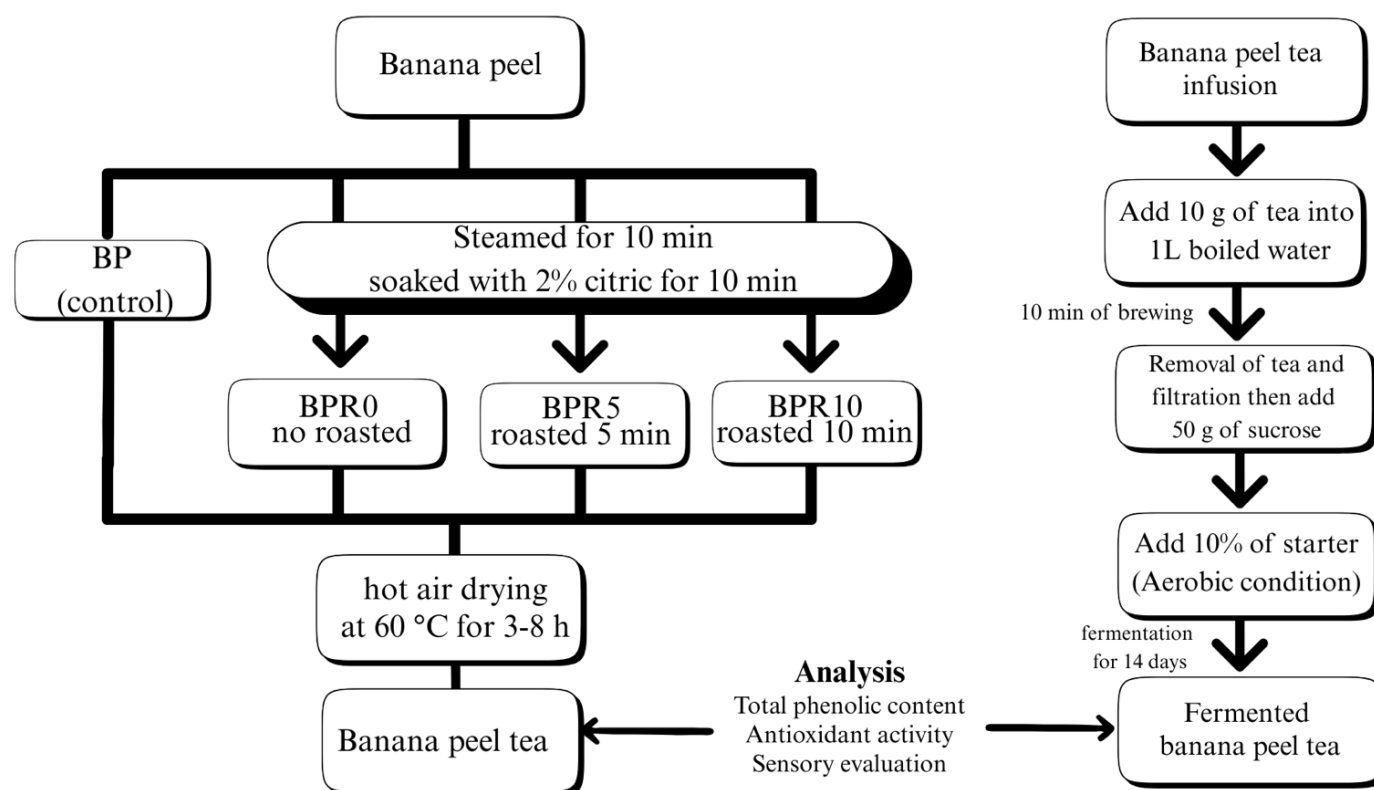


Fig. 1: Overview of the experiment methodology.

amounts of TPC, TFC, TTC, antioxidants (DPPH, ABTS, and FRAP), and sensory evaluation.

2.2 Kombucha production process

10 g/L banana peel tea was infused for 15 min into boiling water, and 150 g/L of sucrose was added, stirred to dissolve, and then filtered out. Pour the sweetened infusion into the sterilized glass jar and let it cool at 40 ± 5 °C. The sweetened infusion was inoculated with 10% of the previous fermented Kombucha tea, as inoculum, covered with sterilized muslin cloth, and incubated at 30 ± 5 °C in an incubator for 14 days or until pH reached between 2.7-3.2. The quality of kombucha was analyzed as follows: TPC, TFC, TTC, antioxidants (DPPH, ABTS, and FRAP).

2.3 DPPH radical scavenging activities

The DPPH radical scavenging ability was conducted as described by Hasan *et al.*^[21] 0.1 mM solution of DPPH was prepared and stored at 4°C. The 4 mg of BP was prepared in 10 mL of analytical grade methanol in order to prepare a concentration of 400 µg/mL, and then serial dilution with methanol in six different concentrations. 2 mL of BP solution from each concentration was taken in a test tube, and then 3 mL of DPPH solution was added. After 30 min incubation in the dark, the absorbance was measured at a maximum wavelength of 517 nm using a UV-Vis Spectrophotometer. The results were expressed in triplicate as µM Trolox equivalents/g dry matter (DM) or g fresh weight (FW), respectively, using Trolox as standard.

2.4 ABTS radical scavenging activity

The ABTS free radical scavenging activity was carried out based on the procedure described by Islam *et al.*^[22] Briefly, A 7 mM ABTS stock solution was prepared with 2.45 mM potassium persulfate and stored in a dark place overnight. The stock solution was diluted with phosphate buffer solution (pH 7.0) to an absorbance of 0.7 ± 0.1 at 734 nm. Afterward, 50 µL of extract was combined with 1.950 mL of ABTS solution and rested for 6 min. The absorbance was measured at 734 nm by a UV-vis spectrophotometer (UV-1800, Shimadzu Corporation, Japan). The ABTS scavenging activity of the extract was expressed as the percentage inhibition and calculated as follows: $\% \text{Inhibition} = [(A_c - A_s) / A_c] \times 100$ (1). Here, A_c = absorbance of the control (ABTS solution without sample), A_s = absorbance of the sample with ABTS solution.

2.5 Ferric reducing antioxidant powder (FRAP)

The FRAP assay was adapted from the protocol described by Hernández-Carranza.^[23] A fresh working solution of the FRAP reagent was prepared in a 10:1:1 ratio by mixing 25 mL of 0.3 M acetate buffer (pH 3.6), 2.5 mL of 10 mM TPTZ, and 2.5 mL of 20 mM Iron (III) chloride hexahydrate. The mixture was incubated in the dark at 37 °C before use. Subsequently, 20 µL aliquots of AEP were added to 180 µL of the FRAP reagent, and the reaction mixture was incubated at 37 °C for 10 min. Absorbance was quantified at 593 nm using a microplate reader (Nano Quant Infinite M 200, Tecan, Grodig, Austria) with a distilled water blank as reference. A Trolox calibration curve (200–600 µM Trolox/mL) with a coefficient of determination (R^2) of 0.9921 was employed to assess

antioxidant capacity. Results were presented as mM Trolox equivalents (mM TE)/g of sample weight.

2.6 Total phenolic content (TPC)

The total phenolic content was determined as described by Widodo *et al.*^[24] with modifications. Firstly, a gallic acid calibration curve was made. Folin-Ciocalteu reagent (1:10) and 7.5% Na₂CO₃ solution were prepared. 50 mg gallic acid was weighed and then dissolved in methanol to obtain a final volume of 50 mL. A series of dilutions was made. From each concentration, 1 mL of solution was pipetted into the vial, and 5 mL of Folin-Ciocalteu, 4 mL of Na₂CO₃ were added. The solution was incubated for 1 hour at room temperature in dark conditions. The absorbance was measured at 740 nm, and a calibration curve was made. Second, the total phenol content of the sample was determined. The 25 mg banana peel powder was weighed (3 replications), and 10 mL of methanol was added. 1 mL of solution was pipetted into the vial, and 5 mL of Folin-Ciocalteu reagent, 4 mL of Na₂CO₃ were added. The solution was incubated for 1 hour at room temperature in dark conditions. The absorbance was measured at 740 nm.

2.7 Total flavonoid content (TFC)

The total flavonoid content was determined based on Fatemeh *et al.*^[25] with some modifications. In brief, 1 mL of extract was mixed with 4 mL of distilled water and 0.3 mL of 5% NaNO₂ solution in a Falcon tube. After 5 min of rest, 0.3 mL of 10% AlCl₃ was added and allowed to stand for 1 min. Finally, 2 mL of 1 M NaOH and 2.4 mL of distilled water were added and mixed carefully. The mixture was centrifuged at 4000 × g for 10 min and left in a dark place for 15 min. Thereafter, the absorbance was read at 510 nm via a UV–vis spectrophotometer (UV-1800, Shimadzu Corporation, Kyoto, Japan) and the TFC (mg QE/g dry weight sample) was calculated from the quercetin (0–100 µM) calibration curve ($R^2 = 0.987$).

2.8 Total tannin content (TTC)

The total tannin of banana peel extracts was measured using the Folin-Ciocalteu reagent, as described in Aboul-Enein *et al.*^[5] Absorbance was measured against a prepared reagent blank at 775 nm using a spectrophotometer (Unicom UV 300). Total tannins in the sample were expressed as mg Catechin equivalent (CE)/g dry weight sample. All samples were analyzed in triplicate.

2.9 Sensory evaluation

The sensory quality of the tea was assessed by 50 untrained tasters from the Rajamangala University of Technology Thanyaburi, Faculty of Agricultural Technology, Thailand. Briefly, tea samples (1 g) were extracted with 100 mL of freshly steamed water for 5 min. BP tea infusions were individually presented in white porcelain bowls, and tea samples were blind-coded with random numbers using a 5-point hedonic scale.

2.10 Statistical data analysis

Statistical analysis was performed using SPSS ver. 26 for Windows. A Completely Randomized Design (CRD) for bioactive compounds and antioxidant activity was used to compare by Duncan's New Multiple Range Test at a significant level of 0.05, using one-way ANOVA. A Randomized Complete Block Design (RCBD) was used to compare the difference in mean values by Duncan's New Multiple Range Test method at a significant level of 0.05 for the sensory test.

3. Results and discussion

3.1 The optimal conditions for the banana peel tea production

The free pesticide banana peel pieces were processed to reduce bitterness in banana peels by steaming, soaking in citric acid, and then roasting in different times (0, 5, and 10 min: BPR0, BPR5, and BPR10, respectively) to enhance the aroma of banana peels, then drying the banana peels in a hot air oven with a_w value of less than 0.6 as shown in Table 1.

From Table 1, it was found that the percentage of yield and water activity obtained did not show a statistically significant difference, with values ranging from 15.45 to 15.57. Additionally, it was discovered that BPR10 dried the fastest, at approximately 3 hours, compared to 6 hours for BPR5, BPR0, and BP took 8 hours to reach water activity lower than 0.5. The color quality results of banana peel processed with different conditions and roasted times are listed in Table 1. BPR0, BPR5, and BPR10 that were steamed and soaked in citric acid had significantly greater lightness compared with BP ($p < 0.05$). Results indicated that the boiling treatment had a positive effect on the color quality during the drying process. Moreover, the anti-browning activity of citric acid showed significant anti-browning effects on banana peel treatment, as previously reported that citric acid effect on preventing the color changes of green tea extract during processing and storage.^[26] The different roasted times also caused a distinct impact on the lightness and the hue of tea (a^* and b^*).^[11] The color of dried BPR10 became redder than others with the extension of roasting time, while there were no differences in lightness (L^*) between BPR0 and BPR5.

Table 1 displays the results of how roasting time affects drying time. It has been found that the longer the roasting period, the rapid the drying occurs. Meanwhile, the brightness value (L^*) is between the range of 37.76–38.32 as the roasting time increases. However, the BP showed the lowest brightness value (35.90 ± 0.12) ($p < 0.05$). As known to all, the optimal roasting time is an important process that affects the quality of tea, both in terms of smell, taste, and physical characteristics. However, roasting at high temperatures also results in a significant reduction in important substances in tea, such as catechins and amino acids.^[10–12] Note that the best time to reduce the bitter and astringent compounds of tea and enhance its flavor is during intermediate roasting, which occurs at 130–150 °C.^[13] In addition, the results of the analysis of antioxidant

Table 1: Physicochemical properties of banana peel tea powder prepared by different treatments.

Banana peel powder	% yield	L*	a*	b*	a _w
BP	15.53 ^a ±0.23	35.90 ^b ±0.12	5.22 ^b ±0.27	17.91 ^b ±0.27	0.39 ^a ±0.11
BPR0	15.49 ^a ±0.17	38.11 ^a ±0.31	5.44 ^b ±0.27	18.34 ^b ±0.27	0.40 ^a ±0.07
BPR5	15.57 ^a ±0.15	38.32 ^a ±0.28	5.74 ^b ±0.27	20.14 ^a ±0.27	0.42 ^a ±0.01
BPR10	15.45 ^a ±0.09	37.76 ^a ±0.19	6.76 ^a ±0.27	20.50 ^a ±0.27	0.44 ^a ±0.02

Note: Values are the mean ± standard deviation ($n = 3$). Within a column (a–c), different letters denote significant differences ($p < 0.05$).

Table 2: Antioxidant activity, total phenolic content, total flavonoid content, the total tannin content of banana peel tea powder prepared by various roasted times.

Antioxidant activity (mg TE/g)	Banana peel tea powder			
	BP	BPR0	BPR5	BPR10
DPPH	2,311.0 ^c ±65.9	2,469.6 ^c ±77.8	2,907.8 ^b ±53.5	3,058.3 ^a ±43.8
ABTS	1,491.0 ^c ±34.3	1,492.2 ^c ±22.6	2,329.5 ^b ±18.0	2,460.0 ^a ±17.8
FRAP	552.2 ^c ±7.3	542.6 ^c ±9.7	975.2 ^b ±9.7	990.3 ^a ±12.0
Bioactive compounds				
TPC (mg GAE/g)	219.3 ^b ±2.4	205.2 ^b ±8.6	328.6 ^a ±1.6	338.9 ^a ±1.1
TFC (mg QE/g)	13.5 ^a ±1.0	10.5 ^c ±0.7	13.8 ^b ±0.4	17.2 ^a ±0.6
TTC (mg CE/g)	92.1 ^c ±3.0	116.0 ^b ±6.8	115.6 ^b ±6.0	144.1 ^a ±7.5

Note: TE = Trolox equivalent, GAE = Gallic acid equivalent, QE = Quercetin equivalent, CE = Catechin equivalent. Values are the mean ± standard deviation ($n = 3$). Within a column (a–c), different letters denote significant differences ($p < 0.05$).

activity, TPC, TFC, and TTC of banana peel tea powder prepared by various methods are shown in Table 2.

Table 2 presents banana peel tea powder prepared by different roasting times. As a result, antioxidant activity, TPC, TFC, and TTC were determined. In our study, the TPC in BP, BPR0, BPR5, and BPR10 powder was 219.3, 205.2, 328.6, and 338.9 mg GAE/g, respectively. Extending the roasting duration increased the TPC, TFC, and TTC. BPR10 showed that TPC, TFC, and TTC were 338.9, 17.2, and 144.1 mg/g DW, respectively. There were significant differences in the roasting time ($p < 0.05$) on TPC, TFC, and TTC. The TPC and TTC in banana peel were higher than those previously reported by Aboul-Enein *et al.*,^[5] who found 17.89 and 24.21 mg/g DW in methanol-extracted samples. In our investigation, the TFC in BPR10 was determined (17.2 mg QE/g), which, although lower than the findings of Akhter *et al.*^[27] at 19.89 mg QE/g. The variation in bioactive compounds might be due to factors such as fruit maturity, variety, and analytical methods.

The highest DPPH radical scavenging activity was found in the banana peel tea infusion of BPR10 (3,058.3±43.8 mg TE/g), followed by BPR5 sample (2,907.8±53.5 mg TE/g), BPR0 (2,469.6±77.8 mg TE/g), and BP sample dried at 120 °C (2,311.0±65.9 mg TE/g). A similar trend was also found for ABTS free radical scavenging activity and FRAP. This study revealed that steam and roasting treatment significantly elevated the antioxidant activity. Moreover, roasting also produces new substances through the Maillard reaction, which may exhibit higher antioxidant activity.^[28–29] Dehydrated products at temperatures of 60 and 80 °C exhibit greater

antioxidant capacity compared to the unripe banana peel sample. This result suggests that temperature can enhance the extraction of compounds, indicating that processed vegetables do not always offer lower nutritional quality.^[30] Corresponds to Hew *et al.*^[31] determined that the combination of steam and drying is the optimal method to produce jute leaf tea, which increases antioxidant activity and improves sensory quality to be acceptable to consumers because steam reduces the bitterness of tea leaves. It inhibits the enzyme polyphenol oxidase, responsible for oxidation in fresh leaves. Then, the sensory quality (Table 3), antioxidant activity, TPC, TFC, and TTC (Table 4) of the banana peel tea infusion were evaluated.

The sensory evaluation of banana peel tea was conducted using a hedonic scaling test among 50 untrained sensory panelists. According to the results in Table 3, BPR5 and BPR10 had the highest score in all terms of the banana peel tea infusion. There was no significant difference in the mean score between both BPR5 and BPR10 ($p \geq 0.05$). The tea infusion of roasted banana peel tea is better than the unroasted tea. The sensory analysis of the banana peel tea infusion samples indicates a significant influence of roasting time enrichment on consumer perceptions. As mentioned previously, roasting is a crucial process in tea manufacturing that modifies the chemical composition. Numerous studies have investigated the effects of roasting concerning temperature, time, and important compounds in tea. Sasaki *et al.*^[10] determined that a roasting temperature of 200 °C was an ideal level for stem tea, providing a roasted aroma. Our study examined a roasting temperature of 150 ± 5 °C for durations of 5 and 10 min. Moreover, Ye *et al.*^[11] state that roasting yellow

Table 3: Sensory evaluation scores of banana peel tea infusion using a 5-point hedonic scale.

Banana peel tea infusion	Color	Odor	Flavor	Appearance	Overall acceptance
BP	2.40 ^b ±0.67	2.43 ^b ±0.86	2.17 ^b ±0.65	2.37 ^b ±0.56	2.30 ^b ±0.53
BPR0	2.30 ^b ±0.53	2.17 ^b ±0.53	2.33 ^b ±0.71	2.33 ^b ±0.48	2.20 ^b ±0.41
BPR5	3.57 ^a ±0.50	3.30 ^a ±0.65	2.90 ^a ±0.76	2.87 ^a ±0.35	3.23 ^a ±0.43
BPR10	3.97 ^a ±0.41	3.53 ^a ±0.57	2.83 ^a ±0.65	3.07 ^a ±0.37	3.40 ^a ±0.50

Note: Values are the mean ± standard deviation ($n = 50$). Within a column (a–b), different letters denote significant differences ($p < 0.05$).

Table 4: Antioxidant activity and bioactive compounds comparison of banana peel tea infusion and kombucha-like banana peel tea.

Sample		Antioxidant activity (mg TE/g)			Bioactive compounds		
		DPPH	ABTS	FRAP	TPC (mg GAE/g)	TFC (mg QE/g)	TTC (mg CE/g)
Banana peel tea infusion	BP	2.49 ^f ±0.38	5.50 ^f ±0.15	2.08 ^d ±0.24	0.87 ^d ±0.10	0.11 ^a ±0.01	0.11 ^d ±0.14
	BPR0	2.23 ^f ±0.17	5.01 ^f ±0.40	1.87 ^d ±0.25	0.83 ^d ±0.04	0.09 ^a ±0.02	0.15 ^d ±0.07
	BPR5	4.61 ^e ±0.26	12.94 ^e ±0.66	4.95 ^c ±0.14	1.18 ^c ±0.05	0.12 ^a ±0.01	0.20 ^{cd} ±0.18
	BPR10	5.42 ^d ±0.90	16.37 ^d ±1.83	5.38 ^c ±0.08	1.22 ^c ±0.09	0.11 ^a ±0.03	0.23 ^c ±0.07
kombucha-like banana peel tea	BP	11.89 ^b ±0.56	24.54 ^b ±0.29	9.63 ^a ±0.06	3.06 ^a ±0.06	0.12 ^a ±0.06	0.51 ^a ±0.02
	BPR0	10.35 ^c ±0.51	20.03 ^c ±0.18	7.34 ^b ±0.06	2.26 ^b ±0.10	0.12 ^a ±0.00	0.38 ^b ±0.01
	BPR5	12.94 ^a ±0.45	26.52 ^a ±0.25	9.83 ^a ±0.05	3.37 ^a ±0.03	0.14 ^a ±0.00	0.50 ^a ±0.03
	BPR10	12.72 ^a ±0.23	26.04 ^a ±0.29	9.67 ^a ±0.04	3.15 ^a ±0.03	0.14 ^a ±0.01	0.48 ^a ±0.02

Note: TE = Trolox equivalent, GAE = Gallic acid equivalent, QE = Quercetin equivalent, CE = Catechin equivalent, Values are the mean ± standard deviation ($n = 3$). Within a column (a–f), different letters denote significant differences ($p < 0.05$).

tea at 130 °C for 22 min yields optimal results, enhancing sweet and umami substances. Duan *et al.*^[12] discovered that medium roasting provides the most balanced aroma and reduces undesirable burning odors. According to Mao *et al.*^[13] indicates that roasting diminishes the bitterness and astringency of green tea and enhances organic acids and soluble sugars, resulting in a softer and more mellow flavor. As discussed earlier regarding all aspects of sensory evaluation, BPR10 received the greatest score compared to the others. This finding highlights the advantageous nutritional qualities of roasted banana peel tea infusion over the non-roasted tea. This suggests the necessity for a balanced strategy in roasted tea, considering both nutritional benefits and consumer preferences.

The comparison of banana peel tea infusion and kombucha-like banana peel tea was analyzed for antioxidant activity, TPC, TFC, and TTC (Table 4). Antioxidant properties of the kombucha-like banana peel tea, as indicated by DPPH radical scavenging activity assay, ABTS, and FRAP assay, are shown in Table 4. The DPPH radical scavenging activity assay of kombucha-like BPR5 and BPR10 was the highest value (12.94 and 12.72 mg TE/g, respectively), and ABTS also showed the highest value (26.52 and 26.04 mg TE/g, respectively). The results of the present study indicated that both tea infusion and the kombucha-like tea of BP, BPR5, and BPR10 demonstrated significantly higher TPC than BPR0. Similarly, as found in TPC, it was also observed for TTC, while no significant on TFC ($p \geq 0.05$). However, the present results determined that the antioxidant properties and bioactive substances are present in the fermented banana peel

tea in higher amounts than in tea infusion (unfermented tea), as previously reported.^[32] The effect of varying fermentation periods on the phenolic composition was found to be that in the early stages of fermentation (e.g., 3–7 days), the amount of TPC is relatively low. When fermented for longer (e.g., 10–14 days), TPC increases significantly.^[33–34] The kombucha fermented in the middle to late (10–14 days) has the highest antioxidant capacity. In addition, kombucha was found to have significantly higher antioxidant activity than unfermented red tea, as measured by the FRAP method, with a value of 1318.56 mg TE/L compared to 345.59 mg TE/L in regular red tea, and the TPC in kombucha was 412.25 mg GAE/L, which is higher than that of regular red tea (180.17 mg GAE/L).^[35]

The dramatic increase in antioxidant activity after roasting and fermentation can be explained by a series of synergistic mechanisms (Fig. 2). Initially, roasting acts by (1) thermally degrading the cell wall matrix, (2) generating novel antioxidants like melanoidins via the Maillard reaction, and (3) inactivating endogenous polyphenol oxidase, thus preserving native phenolics. These processes result in a measurable increase in antioxidant activity. Liu *et al.*^[36] revealed that light to medium roasting enhanced glucomoringin levels in moringa seed kernels, whereas dark roasting led to its thermal degradation, resulting in different breakdown products such as nitriles and thiourea. In addition, although roasting caused a significant reduction of some phenolic compounds (e.g., gallic, chlorogenic, *p*-coumaric acids, and trigonelline), other phenolic acids (e.g., caffeic and ferulic acids) and alkaloids (e.g., caffeine, theobromine, and theophylline) exhibited significant increases post-roasting that

Pre-treatment



Roasting

- Thermal degradation
- Maillard reaction
- Enzymatic inactivation



BPR10

Fermentation

- Biotransformation
- Biosynthesis

Fig. 2: Diagram illustrating the mechanism for the enhancement of antioxidant activity in roasted and fermented banana peel tea.

Table 5: Correlation matrix between antioxidant activity and bioactive compounds of banana peel tea infusion and kombucha-like banana peel tea.

Variable	1	2	3	4	5
DPPH	1				
ABTS	0.992**	1			
FRAP	0.976**	0.986**	1		
TPC	0.983**	0.986**	0.987**	1	
TFC	0.656 ^{ns}	0.643 ^{ns}	0.619 ^{ns}	0.634 ^{ns}	1
TTC	0.958**	0.961**	0.957**	0.956**	0.579 ^{ns}

Note: Pearson's correlation analysis was conducted using averaged values of each variable (n=8). **, *, ^{ns} indicate that significant at p=0.01, 0.05, and non-significant, respectively.

contribute to the enhanced total phenolic content (up to 2.9-fold) and antioxidant capacity (up to 5.8-fold) of the roasted moringa seed kernels. Additionally, the radical scavenging activity of the non-phenolic fraction increased with the degree of roasting to brown-hued Maillard reaction products.^[37] Furthermore, the Maillard reaction often occurs during food processes, attracting many researchers to investigate the influence of melanoidins on the nutritional quality and antioxidant properties.^[38]

Subsequently, the kombucha-like fermentation further amplifies this effect through microbial biotransformation, where enzymes produced by the symbiotic culture hydrolyze complex polymers into simpler, more bioavailable antioxidants and potentially synthesize new active compounds. This second stage led to the highest antioxidant values observed (e.g., DPPH up to ~12.9 mg TE/g). This proposed mechanism is strongly supported by our correlation analysis, which showed a highly durable positive relationship ($p < 0.01$) between antioxidant assays and total phenolic content. Malbasa *et al.* reported quercetin as the dominant phenolic compound in black tea kombucha.^[39] Also, the IC₅₀ value for fermented beverages is 4.96 times larger than infusions.^[17] Acidified samples have a larger IC₅₀ value than fresh infusion, but are still shorter (2.8 times) than the fermented sample; also, neutralizing the fermented beverage increases IC₅₀. So, it indicates that acetic acid is effective in antioxidant activity of fresh and fermented black tea infusions. Belgheisi^[40] suggested that decomposition of phenolics may be due to microbial enzymes and acids produced during fermentation. It can be concluded that a substantial portion of the antioxidant activity in banana peel kombucha is

attributable to other acids and phenolics. Acetic acid is the predominant acid in kombucha.^[17,41] Jayabalan *et al.* also reported the presence of gluconic acid, glucuronic acid, vitamins, and amino acids in kombucha.^[42]

The analysis revealed that the three antioxidant capacity assays—DPPH, ABTS, and FRAP—were all extremely strongly and positively correlated with each other ($r > 0.97$, $p < 0.01$ for all pairs) (Table 5). This indicates that despite their different chemical principles, these methods consistently measured the same underlying antioxidant potential in our samples. First of all, the DPPH assay correlated with ABTS, FRAP, TPC, and TTC but not TFC. Furthermore, the antioxidant capacities showed very strong positive correlations ($r > 0.95$, $p < 0.01$) with TPC and TTC, suggesting that phenolics and tannins are the primary contributors to the antioxidant activity. The TFC showed a moderate and non-significant correlation with other measures. This statistical analysis effectively synthesizes complex data, demonstrating that the different antioxidant indicators are not conflicting but, in fact, highly consistent and mutually reinforcing. The strong relationships between TPC and antioxidant activity were expected, given the closeness of the redox reactions involved in these assays.^[43] Therefore, further research is necessary to separate and identify specific phenolic compounds in these banana peels to determine the bioactive components responsible for the observed antioxidant activity. Other unidentified chemicals in the banana peel may have contributed to the antioxidant activity.

4. Conclusion

The results concluded that banana peel could be considered as

an effective source of antioxidants and bioactive compounds, which encourage its potential as a substitute in kombucha production. Results of steamed and roasted banana peel for 10 min also showed the highest antioxidant activity and bioactive ingredients were chosen as the best processing method in developing kombucha-like banana peel tea. From the sensory point of view, the roasted banana peel tea was present with the highest score in all terms. The kombucha-like banana peel tea fermentation showed TPC, TTC, and antioxidant activity, higher than infusion tea. The results of our study reveal that banana peel can be used to produce herbal tea that is acceptable to consumers. Further studies are required to extract other active ingredients and assess their cytotoxicity effects. These discoveries led to the suggestion that the kombucha-like drinks from banana peel may serve as a powerful source of food and beverage ingredients.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

CRedit Statement

Palida Tanganurat: Conceptualization, Investigation, Writing - Original draft preparation. **Unchalin Singkhum:** Conceptualization, Investigation, Visualization, Review and Editing. All authors have read and agreed to the published version of the manuscript. All authors read and approved the final manuscript.

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