

Comparative Physicochemical Characterization of Green Waste Compost Tea from Different Feedstocks

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Rising concern over environmental impacts of excessive agrochemical fertilizer use has drove to surge in interest of converting waste into compost and compost tea, a sustainable alternative offering diverse physicochemical and biological interactions. This study characterizes the physicochemical properties of non-aerated green waste compost tea prepared from anaerobically composted green waste such as bamboo shoot (BS), banana peels (BP), green vegetables (GV) and leaves of java ginger (JG), *Curcuma xanthorrhiza*. Physicochemical parameters (pH, EC, TDS, ORP, salinity), nutrient concentrations (ammonium nitrogen, phosphorus), and antioxidant activity (DPPH assay) were determined alongside elemental (C, H, N, S) and FT-IR analyses. Results revealed a significant variation among feedstocks. BP consistently exhibited the most favourable composition, with significantly higher nutrient content (ammonium nitrogen 0.33 mg/L; phosphorus 11.07 mmol/L), ionic strength (EC 16.58 mS/cm; TDS 8204 mg/L), phenolic concentration, and antioxidant activity (77% inhibition). In contrast, GV and JG teas showed comparatively lower nutrient and bioactive profiles. Elemental and FT-IR analyses confirmed the presence of carbohydrates, proteins and phenolics, underscoring the chemical diversity contributed by different green wastes. Collectively, these findings demonstrate that feedstocks selection strongly influences nutrient dynamics and antioxidant potential of compost tea. This study highlights dual function of compost tea as both a nutrient source and bio-stimulant, supporting its application as an eco-friendly agriculture input.

Keywords: Elemental analyses, FT-IR, green waste compost tea, non-aerated, physicochemical properties.

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The global community is expected to reach 10 billion by 2050, which will subsequently lead to higher food demand and the reliance on synthetic fertilizers is expected to rise substantially [1]. Excessive fertilizer use has raised environmental concerns, spurring interest in sustainable alternatives such as compost and compost tea. Green waste offers an attractive feedstocks for composting because it is abundant, biodegradable, and typically free of hazardous contaminants [2]. Moreover, composting these residues directly at the site of generation offers clear economic benefits by reducing transportation and disposal costs [3]. From composting, agricultural practices has driven interest in organic amendments such as compost tea, a liquid extract produced by brewing compost in water at a defined ratio, yielding a solution rich in water-soluble constituents such as mineral nutrients, organic acids, and an array of active microorganisms, including bacteria, fungi, protozoa, and other microbial metabolites [4].

Compost tea is a water extract of compost containing soluble nutrients, organic acids, phenolics and microbial metabolites. Its performance depends strongly on physicochemical properties such as pH, electrical conductivity (EC), oxidation-reduction potential (ORP), salinity, and temperature which regulate nutrient solubility and microbial activity [5]. For instance, research on strawberries demonstrated that aerated compost tea improved yields while reducing the severity of grey mould (*Botrytis cinerea*), whereas non-aerated compost tea mainly contributed to disease suppression with little effect on yield [6]. Additionally, antioxidant activity and nutrient content, particularly phosphorus and ammonium nitrogen, are critical indicators of compost tea quality [7-9].

Regardless of how compost tea has been widely investigated, most previous studies focused primarily on agronomic performance or disease suppression, while comprehensive physicochemical characterization of compost teas produced from different green waste

feedstocks remains limited. Furthermore, comparative information integrating physicochemical properties, elemental composition, antioxidant activity and FTIR characterization is scarce. This study therefore comparatively characterizes GWCT prepared from bamboo shoot (BS), banana peel (BP), green vegetables (GV), and java ginger leaves (JG, *Curcuma xanthorrhiza*) chemical characterization, antioxidant assays, elemental analysis (C, H, N, S), and Fourier-transform infrared (FT-IR) spectroscopy. The results will uncover fresh perspectives and new understanding into the chemical basis of compost tea composition based on the availability of different types of green waste and its potential as an eco-friendly agricultural input.

EXPERIMENTAL

Preparation of Compost Tea

Four types of green waste, BS, BP, GV and JG were prepared by mixing mature compost that was composted for approximately 9 months at a compost-to-water ratio of 1:3 (w/v) (non-chlorinated) in 50 L drum, supplemented with 0.5% (v/v) molasses, sealed, and brewed under non-aerated conditions at ambient temperature of 25–30°C. Each GWCT sample was collected and filtered through cheesecloth. Freshly prepared GWCT samples were immediately measured for the determination of physicochemical parameters, including pH, oxidation–reduction potential (ORP), electrical conductivity (EC), total dissolved solids (TDS), and salinity. The remaining filtrate was aliquoted into sterile polypropylene tubes and stored at -80°C for subsequent analyses to preserve its nutrient concentrations and to prevent microbes' degradation.

Physicochemical Properties

The physicochemical properties including pH, oxidation reduction potential (ORP), electrical conductivity (EC), total dissolved salts (TDS) and salinity were measured in triplicate and recorded using multi-meter digital water quality tester (Model No.: JQ006), which was calibrated with standard solutions prior to analysis; samples were gently homogenized before measurement, all analyses were conducted using undiluted GWCT.

Total Ammonium Nitrogen Content

Ammonium nitrogen was measured using the salicylate method (Hach Method 8155). A calibration curve (0.10–0.50 mg/L, $R^2 = 0.999$) was prepared from a 1 mg/mL stock solution. For analysis, 10 mL of each GWCT sample (or deionized water as blank) was treated sequentially with Ammonia Salicylate and Ammonia Cyanurate reagents, allowed to react for 15 min, and read at 655 nm. Results were expressed in mg/L.

Total Phenolic Content

Total phenolics were quantified using the Folin–Ciocalteu colorimetric method [8]. A gallic acid calibration curve (10–100 µg/mL, $R^2 = 0.98$) was prepared, and 20 µL of each sample was reacted with diluted Folin–Ciocalteu reagent and 7% Na₂CO₃. Absorbance was measured at 760 nm after 90 min incubation at 25 °C (Multiskan GO, Thermo Fisher Scientific). Results were presented as mg gallic acid equivalents (GAE) per mL.

Total Inorganic Phosphorus

Phosphorus content was quantified using the Elabscience® Phosphorus (Pi) Colorimetric Assay Kit (Phospho Molybdate Method, Catalog No. E-BC-K245-S) following the manufacturer's protocol. Standards and chromogenic agents were freshly prepared. For protein precipitation, 0.1 mL of GWCT was mixed with 0.4 mL of protein precipitator, vortexed, and centrifuged at 1,100 × g for 10 min; 200 µL of the supernatant was used for analysis. 200 µL of sample was mixed with 2 mL of chromogenic agent, incubated at 37 °C for 30 min and measured at 660 nm. Phosphorus concentration was calculated by the equation below:

$$\text{Phosphorus (mmol/L)} = \frac{OD_{\text{Sample}} - OD_{\text{blank}}}{OD_{\text{Standard}} - OD_{\text{blank}}} \times c \times 5 \times f$$

Where;

c is the concentration of the standard (0.5 mmol/L), f is the dilution factor of sample and 5 is the dilution factor of sample in preparation of supernatant.

Antioxidant Activity

Antioxidant capacity was assessed using DPPH (2,2-diphenyl-1-picrylhydrazyl) free-radical scavenging assay [8]. The assay was initiated by adding 50 µL of each GWCT (1 mg mL⁻¹) to 150 µL of a 0.3 mM DPPH solution in ethanol. Meanwhile, 50 µL of distilled water was added to the DPPH ethanol solution to create a blank. The solution was vortexed for 2 minutes, and incubated in the dark for an hour at room temperature. The absorbance was measured at wavelength of 517 nm using a MultiSkán GO spectrophotometer (Thermo Fisher Scientific). The results were expressed as percentage of inhibition using the following equation:

$$\% \text{ RSA} = \{[(A_0 - A_i) / A_0] \times 100\}$$

Where;

A₀ is the absorbance of the control solution and A_i is the GWCT absorbance.

Elemental Analyses and Fourier Transform Infrared Spectroscopy (FT-IR)

Freeze-dried GWCT powders (≈ 0.05 g) were analyzed using a Bruker INVENIO R FT-IR spectrometer with ATR accessory. Spectra were recorded in the 4000–400 cm^{-1} range at 4 cm^{-1} resolution, averaging 32 scans per sample. Baseline correction and vector normalization were applied prior to interpretation. Functional group assignments were made based on established FT-IR libraries and published compost/biopolymer spectra [8, 10, 11].

Statistical Analyses

Data normality was assessed using Shapiro–Wilk. One-way ANOVA with Tukey’s HSD was applied to normally distributed data (e.g., DPPH), while non-parametric data (e.g., EC, pH, TDS, nutrients) were analysed using the Kruskal–Wallis test with Bonferroni correction. The threshold for statistical significance was defined as $p < 0.05$ (IBM SPSS v27).

RESULTS AND DISCUSSION

Physicochemical Properties

GWCT derived from different green waste feedstocks exhibited significant variation in their physicochemical parameters, including pH, oxidation–reduction potential (ORP), electrical conductivity (EC), total dissolved

solids (TDS), salinity, ammonium nitrogen, phosphorus, phenolics, and antioxidant activity. The summarized data are presented in Table 1.

The physicochemical characteristics of GWCT were significantly influenced by feedstocks type, demonstrating that substrate composition governs nutrient release and the chemical properties of compost tea during non-aerated brewing. Significant differences ($p < 0.05$) were observed for pH, oxidation–reduction potential (ORP), electrical conductivity (EC), total dissolved solids (TDS), salinity, ammonium nitrogen, phosphorus, phenolic content, and antioxidant activity. Among the four treatments, BP consistently exhibited the highest EC (16.58 mS cm^{-1}), TDS (8204.33 mg L^{-1}), salinity (0.91%), ammonium nitrogen (0.33 mg L^{-1}), phosphorus (11.07 mmol L^{-1}), and DPPH radical scavenging activity (77%), indicating superior nutrient availability and bioactive potential. In contrast, GV compost tea contained the lowest ammonium nitrogen and phosphorus concentrations, whereas JG exhibited the lowest EC, TDS, salinity, and a negative ORP. BS generally displayed intermediate physicochemical characteristics and antioxidant activity comparable to BP, suggesting its potential as a balanced compost tea.

Table 1. Physicochemical properties of GWCT

Properties	BS	BP	GV	JG
pH	$6.62 \pm 0.02^{\text{ab}}$	$6.06 \pm 0.07^{\text{a}}$	$7.76 \pm 0.05^{\text{ab}}$	$8.30 \pm 0.02^{\text{b}}$
ORP (mv)	$41.33 \pm 1.53^{\text{ab}}$	$65.33 \pm 0.60^{\text{a}}$	$10.67 \pm 0.58^{\text{ab}}$	$-46.67 \pm 0.58^{\text{b}}$
EC (mS/cm)	$12.03 \pm 0.14^{\text{ab}}$	$16.58 \pm 0.02^{\text{a}}$	$12.17 \pm 0.03^{\text{ab}}$	$10.28 \pm 0.08^{\text{b}}$
TDS (mg/L)	$5963.67 \pm 32.35^{\text{ab}}$	$8204.33 \pm 40.80^{\text{a}}$	$6009.67 \pm 35.22^{\text{ab}}$	$5151.33 \pm 32.75^{\text{b}}$
Salinity (%)	$0.67 \pm 0.01^{\text{ab}}$	$0.91 \pm 0.01^{\text{a}}$	$0.67 \pm 0.01^{\text{ab}}$	$0.57 \pm 0.01^{\text{b}}$
Ammonia Nitrogen (mg/L)	$0.17 \pm 0.00^{\text{ab}}$	$0.33 \pm 0.00^{\text{a}}$	$0.08 \pm 0.00^{\text{b}}$	$0.18 \pm 0.00^{\text{ab}}$
Phosphorus (mmol/L)	$9.29 \pm 0.14^{\text{ab}}$	$11.07 \pm 0.95^{\text{a}}$	$4.95 \pm 0.17^{\text{b}}$	$7.02 \pm 0.11^{\text{ab}}$
Phenolic (GAE)	$0.16 \pm 0.00^{\text{a}}$	$0.16 \pm 0.00^{\text{a}}$	$0.16 \pm 0.00^{\text{b}}$	$0.16 \pm 0.00^{\text{ab}}$
DPPH (% inhibition)	$70.0 \pm 5.0^{\text{a}}$	$77.0 \pm 6.1^{\text{a}}$	$33.3 \pm 3.5^{\text{b}}$	$33.6 \pm 2.4^{\text{b}}$

Notes: Values are presented as mean $\pm$ standard deviation ($n = 3$) to sensible precision; pH to two decimal places; EC to 0.01 mS/cm; TDS to the nearest 10 mg/L; nutrient concentrations (e.g., ammonium nitrogen, phosphorus, phenolics) to two decimal places; ORP to the nearest whole number; salinity to two decimal places; and antioxidant activity (DPPH % inhibition) to one decimal place. Superscript letters within the same row indicate significant differences among treatments. All physicochemical parameters were analysed using the Kruskal–Walli’s test followed by Bonferroni-adjusted pairwise comparisons, except DPPH antioxidant activity was analysed using one-way ANOVA followed by Tukey’s HSD ($p < 0.05$). Treatments sharing the same letter are not significantly different.

The elevated EC and TDS observed in BP indicate greater concentrations of dissolved ions and soluble nutrients, reflecting more efficient mineralisation of organic matter during composting [12, 13]. These findings are supported by the simultaneously higher ammonium nitrogen and phosphorus concentrations, suggesting enhanced nutrient solubilisation from banana peel, which is rich in readily degradable carbohydrates, pectin, and soluble minerals. In contrast, the lower EC, TDS, and nutrient concentrations recorded in GV and JG indicate comparatively reduced nutrient release during brewing. Differences in pH and ORP further reflect variations in microbial metabolism and redox conditions among feedstocks. The slightly acidic pH of BP may have promoted phosphorus solubility, whereas the alkaline conditions observed in JG may reduce the availability of certain nutrients through precipitation reactions [14, 15]. Similarly, the negative ORP recorded in JG indicates a more reducing environment associated with anaerobic microbial activity, while the positive ORP values of BP and BS suggest relatively oxidising conditions that favour different microbial processes [5, 16].

Although total phenolic content varied only slightly among treatments, antioxidant activity differed significantly, with BP and BS exhibiting approximately two-fold greater DPPH radical scavenging activity than GV and JG. This observation indicates that antioxidant capacity depends not only on the concentration of phenolic compounds but also on their chemical composition and radical scavenging efficiency. Banana peel is known to contain abundant flavanols, hydroxycinnamic acids, catecholamines, and other phenolic compounds with strong antioxidant properties [17, 18], which likely contributed to the superior antioxidant activity observed in BP. Likewise, lignocellulosic degradation products

released from bamboo shoot may account for its relatively high antioxidant capacity. Overall, these findings demonstrate that feedstocks selection is the primary determinant of the nutrient composition and bioactive properties of non-aerated GWCT, with BP producing the most nutrient-rich and biologically active compost tea, while BS represents a promising alternative with a balanced physicochemical profile.

Elemental Analyses

Elemental composition analysis revealed clear differences in the carbon, hydrogen, nitrogen, and sulfur content of the GWCT, reflecting the chemical diversity of the feedstocks. Table 2 summarizes the elemental values and corresponding C/N and H/C ratios.

Elemental analysis revealed clear differences in the carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) contents of the four GWCT feedstocks (Table 2), indicating that feedstocks composition strongly influences nutrient dynamics during composting. BS and BP exhibited the highest carbon contents, whereas GV and JG contained considerably lower carbon concentrations. The C/N ratio also varied substantially, ranging from 5.31 in GV to 33.74 in BP. Low C/N ratios observed in BS and GV suggest rapid microbial decomposition and efficient nutrient mineralisation because sufficient nitrogen is available to support microbial activity [19]. In contrast, the higher C/N ratios of BP and JG indicate slower decomposition and prolonged nutrient release, as microorganisms require additional nitrogen to degrade carbon-rich substrates [20]. However, compost maturity and nutrient availability depend not only on the C/N ratio but also on the biochemical composition of the feedstocks.

Table 2. Elemental analyses (C, H, N, S) and C/N and H/C ratios of GWCT.

GWCT	Total C	Total H	Total N	Total S	C/N	H/C
BS	29.36 ± 0.12	5.57 ± 0.07	4.17 ± 0.26	0.35 ± 0.17	7.04	0.19
BP	27.67 ± 0.03	4.46 ± 0.13	0.82 ± 0.10	0.03 ± 0.01	33.74	0.16
GV	10.72 ± 0.32	1.84 ± 0.06	2.02 ± 0.08	0.24 ± 0.04	5.31	0.17
JG	12.56 ± 0.34	2.00 ± 0.21	0.52 ± 0.16	0.46 ± 0.03	24.15	0.16

Notes: The elemental analysis of the four GWCT sources revealed substantial variation in their organic composition (Table 2). BS and BP exhibited the highest carbon concentrations (29.36 ± 0.12% and 27.67 ± 0.03%, respectively), whereas GV (10.72 ± 0.32%) and JG (12.56 ± 0.34%) contained considerably lower carbon levels. Nitrogen content also varied, with BS (4.17 ± 0.26%) and GV (2.02 ± 0.08%) providing higher nitrogen levels compared to BP (0.82 ± 0.10%) and JG (0.52 ± 0.16%). Sulphur content was highest in JG (0.46 ± 0.03%). The calculated C/N ratios ranged from 5.31 (GV) to 33.74 (BP). Specifically, BS and GV exhibited low C/N ratios (7.04 and 5.31), while BP and JG displayed elevated values (33.74 and 24.15). All GWCT demonstrated low H/C ratios from 0.16 to 0.19.

Interestingly, despite its relatively high C/N ratio, BP produced the highest concentrations of soluble ammonium nitrogen and phosphorus (Table 1). This finding suggests that the abundance of readily degradable carbohydrates, pectin, and soluble minerals in banana peel promotes nutrient solubilisation during brewing, resulting in greater nutrient availability in the final compost tea. In comparison, BS contained the highest nitrogen content, which likely contributed to its balanced physicochemical properties and relatively high antioxidant activity. JG, on the other hand, exhibited the highest sulphur concentration. Sulphur is an essential secondary macronutrient involved in the synthesis of sulphur-containing amino acids and defence-related metabolites such as glucosinolates, which enhance plant resistance to pests and diseases [21, 22]. Therefore, sulphur-rich compost tea may provide additional benefits beyond nutrient supply by supporting plant defence responses.

All treatments exhibited relatively low H/C ratios (0.16–0.19), indicating the presence of chemically stable organic compounds, including aromatic and humic-like substances formed during composting [8, 23]. These stable organic compounds

may contribute to the persistence of dissolved organic matter and enhance the bio-stimulant properties of compost tea. Overall, the elemental analysis complements the physicochemical results by demonstrating that feedstocks chemistry governs both nutrient release and the composition of organic matter in GWCT. Among the evaluated feedstocks, BP produced the most nutrient-rich compost tea despite its higher C/N ratio, while BS exhibited a balanced elemental profile and JG showed potential as a sulphur-rich amendment for improving plant resilience.

FTIR

FT-IR spectroscopy (Figure 1) was employed to characterise the functional groups present in GWCT and to determine how feedstocks composition influenced the chemical constituents extracted during non-aerated brewing. Although the four compost teas shared several common absorption bands associated with carbohydrates, proteins, and lignocellulosic materials, each feedstock exhibited distinct spectral features, reflecting differences in biochemical composition that were consistent with their physicochemical properties.

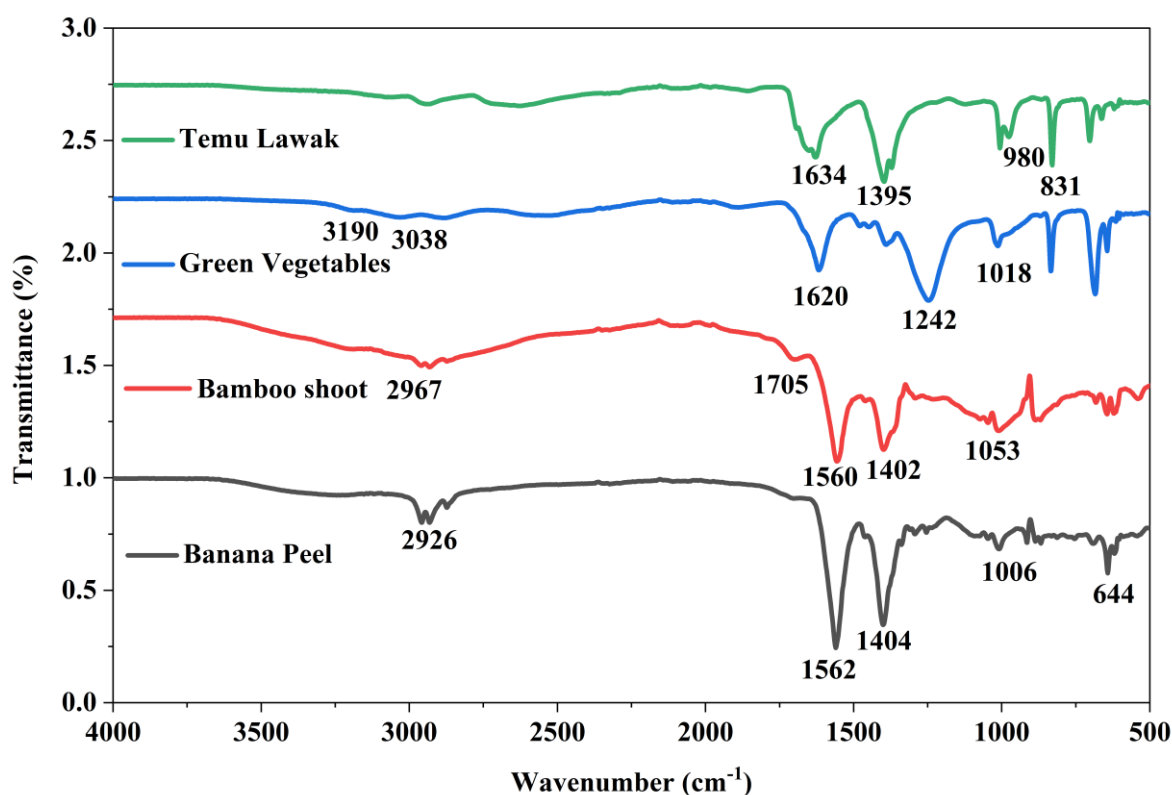


Figure 1. Fourier transform infrared (FTIR) spectra of GWCT prepared from Temu lawak (*Curcuma xanthorrhiza*), green vegetables, bamboo shoot and banana peel. Major absorption bands (cm^{-1}) corresponding to the predominant functional groups are indicated on each spectrum.

BS exhibited characteristic absorption bands at 2967 cm^{-1} , 1705 cm^{-1} , 1560 cm^{-1} , 1402 cm^{-1} , and 1053 cm^{-1} , corresponding to C–H stretching of cellulose and hemicellulose, carbonyl (C=O) groups from pectin and acetylated polysaccharides, amide II vibrations, hydroxyl bending, and C–O–C stretching of polysaccharides, respectively (Carballo et al., 2008; Li et al., 2022). These functional groups indicate that BS contains abundant structural carbohydrates and lignocellulosic polymers, which provide a continuous carbon source for microbial metabolism during composting. The presence of both carbohydrate- and protein-associated functional groups is consistent with the balanced nutrient profile and relatively high antioxidant activity observed in BS (Table 1), suggesting that bamboo shoot biomass supports both nutrient mineralisation and the release of bioactive organic compounds.

The FT-IR spectrum of BP was characterised by prominent aliphatic C–H stretching (2926 cm^{-1}), amide II and aromatic C=C vibrations (1562 cm^{-1}), C–H bending (1404 cm^{-1}), carbohydrate-associated C–O stretching (1003 cm^{-1}), and a low-frequency band at 644 cm^{-1} attributed to aromatic ring deformation or mineral–organic interactions [8]. These spectral features confirm the abundance of cellulose, hemicellulose, pectin, proteins, and other readily degradable organic compounds in banana peel [24, 25]. The high proportion of easily degradable carbohydrates likely promoted rapid microbial metabolism and enhanced nutrient solubilisation during brewing, explaining the significantly higher EC, TDS, ammonium nitrogen, and phosphorus concentrations measured in BP compost tea. Furthermore, the abundance of aromatic and phenolic structures is consistent with its superior antioxidant activity, supporting the hypothesis that feedstocks chemistry plays a major role in determining both nutrient availability and bioactive potential.

Unlike the other treatments, GV exhibited a broad O–H stretching band at 3190 cm^{-1} , indicating abundant hydroxyl groups associated with carbohydrates, phenolics, and bound water. Additional absorption bands at 3038 cm^{-1} , 1620 cm^{-1} , 1242 cm^{-1} , and 1018 cm^{-1} corresponded to aromatic C–H stretching, carbonyl groups of amides and carboxylic acids, and C–O stretching of esters, ethers, and polysaccharides [10]. These functional groups are characteristic of fresh leafy biomass containing soluble carbohydrates and organic acids that can readily serve as microbial substrates. Nevertheless, despite the presence of these compounds, GV produced comparatively lower nutrient concentrations and antioxidant activity than BP and BS. This finding suggests that the abundance of hydroxyl-containing compounds alone is insufficient to enhance nutrient extraction, and that the overall biochemical composition of the feedstocks, particularly its mineral content and degradability, exerts a greater influence on compost tea quality.

The FT-IR spectrum of JG displayed strong aliphatic C–H stretching (2930 cm^{-1}), carbonyl absorption at 1634 cm^{-1} , C–H bending (1395 cm^{-1}), C–O stretching (980 cm^{-1}), and aromatic C–H bending (831 cm^{-1}), indicating the presence of lipids, proteins, conjugated ketones, and aromatic compounds that are characteristic of *Curcuma xanthorrhiza* [26]. In addition, these compounds are likely associated with curcuminoids, terpenoids, and other secondary metabolites known for their antimicrobial and antioxidant activities. The predominance of these relatively complex bioactive compounds may partially explain the lower EC, TDS, and nutrient concentrations observed in JG, as antimicrobial phytochemicals can influence microbial activity and reduce the rate of organic matter decomposition during brewing. Although JG exhibited lower nutrient availability than BP, its unique phytochemical composition suggests potential value as a bio-stimulant.

Overall, the FT-IR analysis corroborated the physicochemical and elemental findings by demonstrating that feedstocks composition directly determines the chemical constituents extracted into compost tea. BP and BS were characterised by functional groups associated with readily degradable carbohydrates, structural polysaccharides, and proteins, which supported efficient nutrient mineralisation and enhanced antioxidant activity. In contrast, GV contained abundant hydroxyl-rich carbohydrates but generated comparatively lower nutrient availability, whereas JG was enriched with lipid- and aromatic-associated compounds that may contribute more to biological activity than nutrient supply. These findings demonstrate that the molecular composition of green waste feedstocks governs not only nutrient release during compost tea production but also the functional properties of the resulting extracts, reinforcing the importance of feedstocks selection when developing compost teas for sustainable agricultural application.

CONCLUSION

This study demonstrated that green waste compost teas prepared from bamboo shoot, banana peel, green vegetables, and *Curcuma xanthorrhiza* leaves exhibited distinct physicochemical properties, elemental composition, antioxidant activity, and FTIR functional groups. Banana peel compost tea showed the highest antioxidant activity and phosphorus content, whereas bamboo shoot compost tea contained the highest nitrogen concentration. These findings indicate that the different feedstocks strongly influence GWCT composition, offering a practical lever to tune nutrient strength and antioxidant capacity. Because outcomes were chemical rather than agronomic, we frame these findings as hypothesis-generating for field use; standardized bioassays should validate crop- and dose-specific responses. Further investigations on plant growth performance and field application are highly recommended to validate their agricultural potential.

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