

EXTRACTION AND CHARACTERIZATION OF FLUVIC ACIDS FROM AGRO-INDUSTRIAL WASTES: AN INNOVATIVE WASTE MANAGEMENT STRATEGY

Siraj Ahmed Baloch^{1,2}, Ghulam Murtaza Jamro^{1*}, Inayatullah Rajpar¹, Javaid Ahmed Shah³

¹ Department of Soil Science, Faculty of Crop Production, Sindh Agriculture University Tandojam, Pakistan.

² Agriculture Extension Department, Government of Balochistan, Pakistan.

³ Soil and Environmental Sciences Division, Nuclear Institute of Agriculture Tandojam, Pakistan.

Correspondence: gmjamro@sau.edu.pk

ABSTRACT

Extraction of fulvic acid (FA) from farmyard manure (FYM), banana waste compost (BWC), and sugarcane pressmud (SPM) can increase agro-industrial waste utilisation, minimize environmental issues, and assist sustainable crop growth. The current study was carried out to extract fluvic acids from organic sources, using a sequential alkaline and acidic method for the extraction and characterization of FA. In this context, the physicochemical properties of organic waste, fluvic acid recovery percentage, proximate analysis, elemental contents, and functional groups analysis of FA were determined. The results revealed that all three agro-industrial wastes showed significant physicochemical properties. Moreover, the highest FA recovery (%) was obtained from BWC (3.70%), followed by FYM (3.56%), and the lowest from SPM (2.45%). The highest moisture content, volatile matter, and Fixed carbon were observed in BWC waste, followed by FYM, and the lowest was observed in SPM. The elemental composition exhibited that the FA derived from BWC had the highest C content (46.1%), followed by FYM (44.7%) and SPM (44.3%). The highest hydrogen (H) in FA from BWC was (4.30%), compared to SPM (4.13%). The highest nitrogen (N) was recorded from BWC and SPM (3.50%), and the lowest was in FYM (3.40%) derived from FA. The highest oxygen (O) was observed in SPM (47.20%), followed by FYM (46.6), and the least in BWC-derived FA (45.2). In addition, the phosphorus (P) content was higher in FA extracted from SPM (0.08%) and lower in FYM (0.07%). The potassium content was highest in FA extracted from FYM (11.6%) and lowest in SPM (9.6%). The maximum sulphur (S), content was recorded in FA extracted from BWC, followed by FYM and SPM. Functional group analysis revealed that the highest total acidity, 11.33 meq g⁻¹, carboxyl groups 9.91 meq g⁻¹, and phenolic group (11.81 meq g⁻¹) were recorded in FA extracted from BWC. The lowest total acidity, 10.97 meq g⁻¹, the lowest carboxyl groups (9.32 meq g⁻¹), and the lowest phenolic group (1.66 meq g⁻¹) were recorded in BWC. The highest E4/E6 ratio (7.103 meq g⁻¹) was observed in FA from BWC, and the lowest E4/E6 ratio (6.9 meq g⁻¹) was recorded in FA isolated from SPM. It is concluded that the FA extracted from BWC exhibited superior structural maturity, aromaticity, and stability compared to the other two sources; hence, it may be more effective as a soil conditioner.

Keywords: Fulvic acids, Extraction, Organic waste, Nutrients, Organic carbon.

INTRODUCTION

An estimated 140 billion metric tons of agro-industrial waste are generated annually on a global scale, which presents a substantial opportunity for conversion into

valuable products (Gul et al., 2022; Wan et al., 2019). The annual generation of agricultural waste in Pakistan, which encompasses crop and animal residues, exceeds 650 million metric tons (Mekouar, 2023; Ahmed et al., 2024).

Nevertheless, these residues, which are primarily constituted of cellulose, hemicellulose, lignin, and nitrogen-rich compounds, can be converted into bio-fertilizers, biofuels, and soil amendments, such as humic and fulvic acids (Hou et al., 2017).

Humic substances (HS) are heterogeneous organic compounds that consist of humic acids (HA), and fulvic acids (FA) and are derived from the microbial and chemical decomposition of organic materials (de Melo et al., 2026). They are distinguished by their high resistance to biodegradation, complex structures,

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and the presence of functional groups, including carboxylic and phenolic constituents (Nardi et al., 2021; Zhrebtsov et al., 2020). These characteristics render them essential contributors to soil fertility, nutrient retention, microbial activity, and enhanced soil structure (Collado et al., 2018; Fuentes et al., 2018).

The commercially available traditional FA are mainly originated from Leonardite, lignite, and peat because of their high degree of humification and stable C content (Jarosz et al., 2025; Zhao et al., 2025). However, innovative sustainable agriculture and linear bio-economical approaches have shifted interest towards the use of renewable organic wastes like farmyard manure, sugarcane press mud, composted crop residues, and banana waste compost (Ansari, 2021). The degree of humification, nutritional composition, and functional group density of these organic materials are all different, and these differences affect the quantity and quality of FA (Campitelli & Ceppi, 2008; Amoah-Antwi et al., 2020).

The functionality and composition of FA is contingent upon its parent material. Organic wastes, including farmyard manure (FYM), banana waste compost (BWC), and sugarcane press mud (SPM), are rich in humic substances and can be used as effective raw materials for extraction (de Castro et al., 2021; García et al., 2021). These materials provide a sustainable and environmentally benign alternative to synthetic soil amendments, which is consistent with the principles of waste valorization and circular agriculture. Despite the acknowledged advantages of FA in enhancing soil health and fertility, there is a scarcity of research on their extraction and characterization from organic waste sources specific to a particular region in Pakistan (Ahmed et al., 2024; Raja & Devarajan, 2024). Understanding the agronomic potential, functional group composition, and chemical properties of FA from FYM, BWC, and SPM can make a substantial contribution to the implementation of sustainable waste management and organic agricultural practices (Nizami et al., 2017). Keeping in view the importance of agro-industrial waste, the study is planned to extract FA and its chemical characterization for substantial contribution to the implementation of sustainable waste management and organic agricultural practices.

MATERIAL METHODS

Selection of organic sources

The agro-industrial wastes such as farmyard manure (FYM), banana waste compost (BWC), and sugarcane press mud (SPM) were collected from the vicinity of Sindh Agriculture University, Tandojam. The samples were air-dried at 40°C, pulverized with a quartz mortar, and sieved through a 2 mm sieve. Prior to

extraction and analysis, the processed samples were stored in sealed polyethylene containers at 4°C to avoid oxidation and maintain their chemical integrity.

Physico-chemical characterization of organic wastes

The powdered samples of organic wastes were analyzed for physico-chemical properties such as bulk density, water holding capacity, organic matter (OM%), pH, and electrical conductivity in a 1:10 and 1:10 ratio of organic waste, and the Kjeldahl digestion and distillation technique was used for total nitrogen determination. Organic waste samples were separately digested using a diacid mixture to assess macro and secondary nutrients.

Extraction and quantification of fulvic acid

The extraction of fulvic acid (FA) from the selected organic sources was followed by the procedure described by Farid et al. (2018), with adaptations based on the International Humic Substances Society (IHSS) guidelines. One gram of air-dried and sieved (2 mm) sample from each organic source was placed into polypropylene centrifuge tubes. An alkaline extractant of 0.1 M potassium hydroxide (KOH) was added in a sample-to-extractant ratio of 1:10 (w/v). The tubes were gently shaken and then allowed to stand overnight at room temperature to facilitate the complete extraction of humic substances. The next day, the mixtures were centrifuged at 10,000 rpm for 15 minutes to separate the dark-coloured supernatant from the solid residue. The supernatants were carefully decanted into separate flasks, while the residues were washed three times with 10 mL of distilled water to recover any remaining extractable humic substances. Each wash was followed by centrifugation at 10,000 rpm for 15 minutes, and the supernatants were combined (Sanchez-Monedero et al., 2002). Ten ml (10) of the crude fulvic acid supernatant solution was diluted with 0.1 M NaOH and distilled water to 25 mL and pH values between 1 and 13. After overnight incubation, fulvic acid precipitates were centrifuged (6000 rpm, 15 min). Similar tests were done with 0.05 M phosphate and pyrophosphate to understand precipitate formation. A spectrophotometer (Hitachi U-2000) and a total organic carbon analyzer (TOC5000A, Shimadzu, Kyoto) were used to estimate the non-precipitated fraction of crude fulvic acid in the supernatant. Before measuring absorbance, 1 M NaOH was added to a 4 mL portion of the supernatant to get it to pH 13, and distilled water was added to make the final amount 6 mL. Percentages of precipitated crude fulvic acid fraction were used to compute recoveries (Hiradate 2006).

Proximate analysis of fulvic acid

The components of the chemical analysis include moisture content (MC), and volatile matter (VM),

fixed carbon (FC), and ash content (AC). The analysis of moisture content of samples done by drying at a constant mass at 105 °C in an oven for overnight. The volatile matter determination was done by drying samples in muffle furnace at temperature of 950 °C then the difference was calculated in weight percent, and the weight loss during combustion using the standard (ASTM, D3175) technique. For ash content estimation the samples were burned for four hours at 750 °C in a muffle furnace (ASTM, D3174). The entire percentage of moisture, ash, and volatile matter content was added, and the result was deducted from the total percentage to get the fixed carbon content.

Elemental analysis of fulvic acid

The elemental composition of FA derived from organic wastes was determined using a CHNS Unicube model analyzer (Elementar Analysen Systeme GmbH, Germany). The carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) were obtained from the analysis, while the oxygen (O) content was determined using the formula $O\% = 100\% - (C\% + H\% + N\% + S\%)$, considering the ash yield of organic materials. The atomic ratios H/C, O/C, and N/C were computed based on elemental values. The mineral matter (MM) content was determined using the Parr formula:

$$MM = 1.08 \times \text{ash} + 0.55 \times \text{sulphur}$$

The internal oxidation degree (ω) was calculated based on the constituent composition as per Eq. (2) provided by Cieslewicz et al. (2008).

$$\omega = (2O + 3N - H) / C, (2)$$

While, O, N, H, and C represent the elemental composition in atomic percentages.

The aromaticities (fa) of the samples were estimated based on Eq. (3) provided by (Saikia et al., 2013).

$$fa = 0.035 (C/H + 0.057) + (0.175 + 0.022). (3)$$

Functional groups analysis of fulvic acid

Total acidity

Total acidity in FA was analyzed by the Barium hydroxide (Ba (OH)) method (Schnitzer & Gupta, 1964). The excess of Ba (OH)₂ was allowed to react, and the unreacted was retreated with the standard acid. In separate flasks, 50 mg of FA and 20 mL of 0.2 N Ba (OH)₂ was added, along with a blank Ba (OH)₂. After shaking the flask for 24 hours, the suspension was filtered through filter paper and washed with distilled water, making it free from CO₂. Further filtrate was titrated (0.5 N HCl) until achieving pH 8.4 (Gayathri et al., 219).

$$\text{Total acidity (meq g}^{-1}\text{)} = \frac{(\text{Blank V} - \text{Sample V}) \times 0.05 \times 1000}{\text{Sample Weight (mg)}}$$

Carboxylic groups analysis

The carboxyl group analysis was based on the release of acetic acid (CH₃COOH) upon the treatments of

filtered material/supernatant with calcium acetate, and titration with 0.1 N NaOH (Schnitzer & Khan, 1972). Further 50 mg of FA, added with 10 mL of 1 N (CH₃COO) 2Ca, and 40 mL of CO₂-free distilled water, along with a blank of 10 mL of 1 N (CH₃COO) 2Ca, were mixed in a stoppered flask. The flask was shaken for 24 hours at room temperature, and the residue were removed using CO₂-free distilled water. Further titration was performed using 0.1 N NaOH to achieve pH 9.8 (Gayathri et al., 219).

$$\text{Carboxylic groups (meq g}^{-1}\text{)} = \frac{(\text{Blank V} - \text{Sample V}) \times 0.1 \times 1000}{\text{Sample Weight (mg)}}$$

Phenolic groups analysis

The phenolic group was determined by calculating the difference between the acidity of the carboxylic groups and the overall acidity.

$$\text{Phenolic -OH groups (meq g}^{-1}\text{)} = \text{Total acidity (meq g}^{-1}\text{)} - \text{Carboxylic groups (meq g}^{-1}\text{)}$$

E4/E6 ratio analysis

The extracted FA, was subjected to analysis E4/E6 ratio through Ultraviolet-Visible Spectroscopy (Hitachi U-2000). The degree of humification and aromaticity of fulvic acid was measured using the E4/E6 ratio. A known quantity of the sample was taken and dissolved in 10 ml of 0.05 mol (NaHCO₃) L⁻¹ solution. The absorbance and ratio were recorded at wavelengths 465 and 665 nm (Lamar et al., 2014; Rani et al., 2024).

Statistical analysis

Statistical analyses were performed using Statistics version 8.1 (Analytical Software®, 2018). One-way analysis of variance (ANOVA) for significant ($p \leq 0.05$) differences between determined spectral, physicochemical parameters for the fulvic acid and analyzed fractions. Means were compared by LSD Least Significance Differences at α 5%.

RESULTS AND DISCUSSION

Physico-chemical properties organic wastes

The data on the physical and chemical characteristics of farmyard manure (FYM), banana waste compost (BWC), and sugarcane press mud (SPM) significantly influence their suitability for humic substance extraction and soil amendment are presented in Table 1. The bulk density of organic wastes varied from 0.55 to 0.52 g/cm⁻³, in the BWC and FYM. Similar results were reported by (Aylaj et al., 2023; Dudło et al., 2024). Water-holding capacity was highest in BWC (45.20%), and lowest in SPM (41.56%). Higher water retention is beneficial for microbial processes and nutrient cycling (Debicka, 2024). BWC was slightly more alkaline (pH 7.68), while FYM was closer to neutral (pH 7.15). FYM had the highest EC (1.29 dS m⁻¹), indicating a greater concentration of soluble

salts, which may affect nutrient availability. The high salt content and alkaline nature of organic waste might be because it has basic cations in it. The results are in line with the work (El Nahhas & Mohamed, 2021). The organic carbon content was highest in SPM (37.15%), and lowest (18.23) in FYM. Similarly, SPM had more phosphorus (1.20%), potassium (1.16%), calcium (3.33%), and magnesium (1.02%), making it a nutrient-dense amendment. BWC had the highest nitrogen (1.57%) and sulfur (0.32%). FYM was

generally lower in major and secondary nutrients. Similar findings were reported by (Asariha & Zarabi, 2023; Ditta & Khalid, 2016). The variation in physical and chemical properties among these organic wastes reflects their origin and decomposition state. BWC with high water-holding capacity and N content, and SPM with high organic carbon and mineral nutrients, suggest both are promising for humic substance extraction (Akimbekov et al., 2021; Arrobas et al., 2022).

Table 1: Physical-chemical characteristics, primary and secondary nutritional composition of various organic wastes utilized to extract fulvic acid.

Organic Wastes	BD g/cm ⁻³	WHC %	pH	EC dSm ⁻¹	OC %	N %	P %	K %	Ca %	Mg %	S %
BWC	0.54a	45.20a	7.68a	1.12b	26.10b	1.56a	0.41b	1.12a	2.89b	0.98a	0.32a
FYM	0.52a	42.87a	7.14a	1.29a	18.23c	0.34c	0.23b	0.46b	1.23c	0.76b	0.20b
SPM	0.543a	41.56a	7.20a	1.09b	37.15a	0.98b	0.83a	1.16a	3.33a	1.02a	0.29a

Recovery percentage of fulvic acid

Figure 1 shows the recovery percentage of fulvic acid from various types of organic wastes. The highest of fulvic acid recovery (3.70%) was recorded in BWC, and the lowest recovery (2.45%) was from SPM. The higher recovery from BWC is likely due to its higher

organic matter content, optimal C:N ratio, and advanced decomposition, which favor humification. The findings are in line with the work of (Abbas et al., 2020; Gayathri et al., 2020). SPM with lower recovery may be due to its denser, more recalcitrant organic structure as reported by (Anielak et al., 2023).

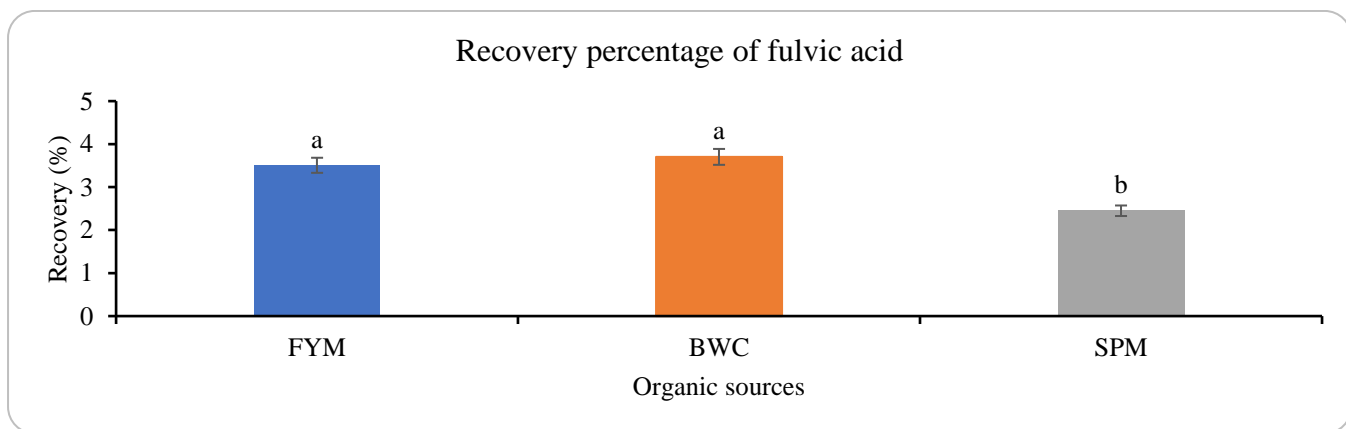


Figure 1: Recovery of fulvic acids from farmyard manure, banana waste compost and sugarcane press mud.

Proximate analysis of fulvic acid

The proximate analyses of fulvic acid revealed significant variations in moisture, volatile matter, ash, and fixed carbon contents, are presented in Table 2. The highest moisture content was 6.77% in FA from BWC, suggesting relatively higher hydrophilic functional groups in FA (Rani et al., 2024). The maximum volatile matter was 38.50% in FA from BWC, indicating its reactive groups and aliphatic composition (Aylaj et al., 2023). Ash content was highest in FA derived from FYM (21.78%) and least in FA from BWC (15.30%). Higher ash content shows availability of cation (Ca, Mg), whereas low ash content revealed pure FA and minimal

mineral contamination (Rani et al., 2024). Fixed carbon was varied from 41.20% (FA from BWC) to 39.85% (FA from SPM) higher C content suggests enhanced structural stability and condense C structure. These findings are in line with the work of (Rani et al., 2024; Lamar et al., 2014). BWC derived FA has shown the most stability and agronomic potential, with FYM being less effective and SPM being moderate (Omar et al., 2018; Pedroso-Rodriguez et al., 2022). Future research should examine mixed organic sources and optimal extraction (Rani et al., 2024; Lamar et al., 2014).

Table 2: Proximate analysis of the fulvic acid samples extracted from different organic wastes.

Samples	Proximate Analysis of Fulvic Acid			
	Moisture (%)	Volatile mater (%)	Ash content (%)	Fixed carbon (%)
BWC	6.77a	38.50a	15.30c	41.20a
FYM	4.77b	30.93c	21.78a	40.42b
SPM	2.30c	36.10b	19.95b	39.85c

Elemental composition of fulvic acid

The general variations were shown in the carbon, hydrogen, nitrogen, sulfur, oxygen, and their molar ratios in FA extracted from selected organic wastes are presented in Table. 3. The highest C was recorded in FA derived from SPM (45.3%), and the minimum was observed in FA from FYM (44.8%). The identified difference in elemental carbon composition highlights the distinct decomposition mechanisms and indicates the inherent compositional properties of the source materials, thus forming the major determinants of fulvic acid stability and biological activity (de Melo et al., 2016; Nardi et al., 2021). The constant high content of carbon in all samples is in line with the stoichiometry of humic substances that are expected to be formed in the process of degradation of organic matter (Zherebtsov et al., 2020). The highest F was recorded in FA derived from FYM (5.35%), and the lowest was recorded in FA from BWC (3.66%), respectively. This heterogeneity of hydrogen content reflects the relative concentrations of aromatic and aliphatic structural motifs of the FA macromolecules (de Melo et al., 2016). The increased proportion of hydrogen in the fulvic acid produced by FYM indicates more aliphatic side chains and functional groups, which can increase the activity

of FYM as a plant growth promoter by enhancing its bioavailability and reactivity with soil components (Nardi et al., 2021). The N content in FA from both BWC and SPM was 3.5%, and the lowest N content was in FA from FYM, 3.4%, respectively. The nitrogen in FA is of special significance since it is part of the structural elements of amino acid residues and nitrogenous functional groups that determine the chemical reactivity and nutrient-providing ability of these compounds (Hou et al., 2017).

The maximum O in content in FA from BWC, was 46.2%, and the minimum was from FYM (46.0%) respectively. The high oxygen level in FA of BWC could indicate a higher level of oxygen containing functional groups (e.g., carboxyl and phenolic groups), enhancing polarity and chemical reactivity and lead to a higher nutrient-binding capacity and control of bioavailability in soils (de Melo et al., 2016). The S contained in FA from BWC was 0.91%, and the least was from SPM 0.81%. Sulphur functional groups, in particular thiols and thiophenes, increase the redox potential and reactivity of FA in soil systems, thereby affecting the complexation of heavy metals and microbial activity (Zherebtsov et al., 2020). Based on molecular ratios, the highest H/C ratio was recorded for

FA from FYM (0.097), compared with FA from BWC (0.096), and the lowest was 0.095. The FA from SPM, FYM, and BEC had similar H/C ratios (0.097, 0.096, and 0.095). These ratios show that the structures are mainly aromatic with minimal aliphatic substituents, which is in line with the mature and polymerized nature of fulvic acid fractions formed in the process of advanced decomposition. The comparatively small spread of H/C ratios among sources indicates that, although the sources differ in precursor materials, the decomposition and oxidation process produces chemically similar end products of similar aromatic nature (Nardi et al., 2021). The N/C ratio of FA from BWC was the highest (0.060), followed by FA from FYM (0.045), and the lowest was 0.041 in FA from SPM. Such changes provide information on the original nitrogen provisioning in the substrate and the extent of sequestration in condensed aromatic structures during decomposition and maturation. The increased N/C ratio in BWC-derived fulvic acid can be used as a sign of greater nitrogen supply potential under soil conditions, especially when BWC-derived FA integration increases nutrient retention (Hou et al., 2017). As for O/C ratios, the highest was recorded in FA extracted from SPM was 1.06, followed by 1.04, and the lowest was 0.98. This ratio plays a vital role in gaining insight into fulvic acid reactivity, since oxygen-containing functional groups (carboxyl, hydroxyl, phenolic, and ester groups) mediate the complexation of metal cations, nutrient binding, and pH-dependent charge development (de Melo et al., 2016). High O/C ratios give increased nutrient complexation and possible alteration of soil

physicochemical characteristics and thus affect nutrient availability and uptake by plants. Phosphorus levels were low in all samples of FA from SPM, followed BWC, and FYM ranged from 0.08% to 0.06%. This low absolute phosphorus value corresponds to the predicted distribution of phosphorus in humic materials, in which phosphorus is mainly present as phosphate groups attached to organic frameworks as opposed to being present as free inorganic phosphate (Debicka, 2024). Although at low concentrations, phosphate in fulvic acid can be an agent of phosphorus mobilisation in calcareous soils, where fixation of calcium and magnesium carbonates usually limits bioavailability (Delgado et al., 2002). The organic phosphorus pool contained in fulvic acid can be made labile through mineralization by microbes. The potassium levels of FA derived from SPM recorded the highest K (0.90%), followed by BWC-derived FA (0.86%), and the lowest in FA from FYM (0.34%). Potassium is a key macronutrient that affects osmotic balance, activation of enzymatic systems, and photosynthetic efficiency (Gul et al., 2022). The strong levels of potassium observed in SPM and BWC fulvic acids suggest that these waste products contain large amounts of both easily exchangeable and complexed potassium, which are likely to bind to the fulvic acid matrix during isolation. The high discrepancy of more than two times between SPM/BWC and FYM-derived fulvic acid highlights the high variability in the bioavailability and the capacity to supply this essential nutrient, depending on the selected feedstock source used to extract and use fulvic acid.

Table 3: Elemental composition of fulvic acid extracted from different organic wastes.

Organic sources		BWC	FYM	SPM
Elemental (%)	C	44.9b	44.8c	45.3c
	H	4.30b	4.30b	4.13b
	N	3.50c	3.40c	3.50c
	O	46.2c	46.0b	46.1b
	S	0.91a	0.88b	0.80c
	P	0.07c	0.06c	0.08bc
	K	0.86c	0.34e	0.90c
Molar Ratio	H/C	0.09b	0.09b	0.091b
	N/C	0.07c	0.07c	0.07c
	O/C	1.03ab	1.04ab	1.02ab
MM (%)		17.0d	24.0a	21.9b
Internal oxidation degree (ω)		2.20e	2.22c	2.18b

Aromaticities (f_a)

0.56b

0.56b

0.58b

Functional groups of fulvic acid

Figure 2 presents the data that the highest total acidity, 7.51 meq g^{-1} , was recorded in FA isolated from BWC, followed by 6.12 meq g^{-1} in FA isolated from SPM, and the lowest, 5.5 meq g^{-1} , in FA isolated from FYM. The BWC and SPM showed the highest total acidity content for FA as compared to FYM. The gradient measured shows that the concentration of acidic functional groups in BWC is significantly higher, which can be explained by the fact that the microbial oxidative processes take a long time to complete during decomposition (de Melo et al., 2016). As a result, the increased acidity of BWC and SPM-derived FA increases their cation-exchange capacity, which enables the mobilization of nutrients in calcareous soils, and buffering of pH gains a special role in this case (Nardi et al., 2021). However, the highest carboxyl groups (5.71 and 4.71 meq g^{-1}) and the lowest (3.9 meq g^{-1}) were recorded in FA isolated from BWC, SPM, and FYM, respectively. The maximum phenolic hydroxyl group (1.91 and 1.62 meq g^{-1}), and minimum (1.41 meq g^{-1}) was recorded in FA produced from BWC, FYM, and SPM, respectively. The identified difference implies that BWC has a higher percentage of aromatic phenolic compounds formed

during the lignin breakdown, whereas SPM and FYM have been more phenolically oxidised (Sanchez-Monedero et al., 2002). These phenolic groups provide the molecules with ionic properties that are dependent on pH with a pKa of 8.10 that is especially beneficial in alkaline substrates and increases the adsorption of heavy metals and redox reactions (Roulia, 2024).

E4/E6 ratio of fulvic acid

The information about the FA E4/E6 ratios is shown in Figure 2. The results revealed that the highest E4/E6 ratio (5.43 meq g^{-1}) was observed in FA from BWC. However, it was followed by FA isolated from SPM with a mean ratio (4.89 meq g^{-1}). Whereas the lowest E4/E6 ratio (4.13 meq g^{-1}) was recorded in FA isolated from FYM, respectively. Fulvic acid from BWC and SPM ratios were higher overall confirming lower molecular weight and aliphatic content typical of FA (Mahgoub & Abdelhameed, 2023). Whereas, lower E4/E6 ratios (FYM) denote higher molecular weight and aromaticity, while higher ratios (FYM, SPM) indicate lower molecular weight and more aliphatic character (Farid et al., 2018; Abbas et al 2020).

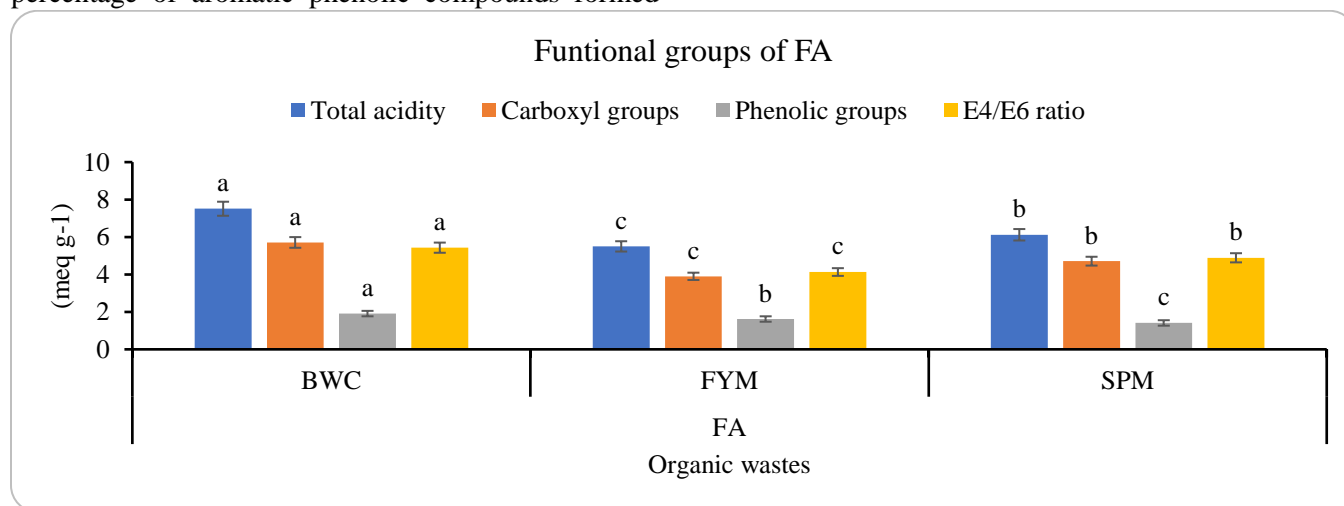


Figure 2: Functional groups of fulvic acid extracted from the different organic wastes.

CONCLUSION

The current study comprehensively explored the suitability of BWC, FYM, and SPM as potential source for the extraction of fulvic acid (FA). Among the other sources, BWC was the most promising for extracting FA, which can be explained by its high water-holding capacity, nitrogen content, and the highest FA recovery, favoring microbial activity and humification, whereas SPM was rich in organic carbon and mineral nutrients and exhibited a smaller FA recovery. Moreover, high carbon and hydrogen content fraction was observed in BWC derived FA. Followed by SPM and FYM. In addition, the extremely narrow range of hydrogen to carbon ratios indicates that decomposition produces aromatic end products regardless source. Importantly, potassium concentrations differed substantially SPM followed by BWC and FYM. The concentration of phosphorus was relatively low in all treatments however maximum in SPM followed by BWC and FYM. Functional group analysis showed that fulvic acids formed by BWC had the highest total acidity and carboxyl groups. These properties give it a better cation-exchange capacity and pH buffering capacity, especially in alkaline soils. Therefore, BWC exhibited the most promising organic source for producing chemically reactive, agronomically effective fulvic acid with superior structural maturity, aromaticity, and stability, followed by SPM and FYM. These findings highlight the innovative agro-industrial waste management strategy to improve the nutrient availability under calcareous soil conditions.

AUTHOR CONTRIBUTIONS

All authors contributed equally.

COMPETING OF INTEREST

The authors declare no competing interests.

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