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ORIGINAL RESEARCH ARTICLE

PRODUCTION OF BIO-FERTILIZER GRADE DERIVED FROM BIOCHAR AND AGRICULTURAL BY-PRODUCT

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ABSTRACT

Methods that are cost-effective for making organic fertilizers from agricultural waste which is locally available obstruct the development of environmentally sound farming practices. This study developed a complementary nitrogen, phosphorus, and potassium (NPK) biochar-based fertilizer using four materials that are locally available: chicken manure, bone meal, banana peel, and biochar made from black currant leaves. The materials were examined using proximate and ultimate analyses as well as BET, SEM-EDX, and ED-XRF techniques in order to evaluate their suitability as sources of nutrients and as soil conditioners. The carbonization of the black currant leaves yielded a mesoporous biochar having a BET surface area of 140.06 m^2/g, a micropore volume of 0.122 cm^3/g, and a pore diameter of 3.02 nm, thus confirming its effectiveness as a nutrient-retention agent. Once more, the ultimate analysis of chicken manure revealed it to have the highest nitrogen content (20.25%), while bone meal was found to have a high phosphorus content (26.0% P_2O_5 according to ED-XRF) and high calcium levels (73.92% Ca according to SEM-EDX). Furthermore, banana peels are rich in potassium, with 71.0% K_2O as determined by ED-XRF analysis. A mixture of 2000 g was prepared consisting of 1000 g of chicken manure, 500 g of bone meal, 200 g of banana peel, and 300 g of biochar, the amount of biochar being deliberately set at 15% of the total mass in order to act as a soil enhancer and as a medium for nutrient retention. The NPK composition of the resulting product was 2.4:5.1:2.1, an indication of the high nutrient density of the feedstocks chosen and showing that the fertilizer is appropriate for use with phosphorus-demanding crops such as legumes, tubers, and fruiting plants during their flowering phases. The study shows that it is feasible to turn agricultural waste into an environmentally friendly NPK bio-fertilizer and helps to improve crop productivity.

1.0 Introduction

Synthetic fertilizers are highly soluble, causing nutrients to be released quickly into the soil. Plants require different nutrients during growth, which may create a mismatch between the nutrients supplied by fertilizers and those required by plants, Abiola *et al.* (2023). At the moment the world's agricultural industry is going through a major change since the environmental effects of traditional synthetic fertilizers are becoming more and more obvious. Playing a important part in environmental care is the reuse of waste materials, as this offers a practical means of promoting sustainable production and protecting the environment (Kumari *et al.* 2023). It is essential to apply fertilizers in an optimized manner if agricultural output is to be improved and food security is to be ensured (Abiola *et al.* 2023). Overusing chemical fertilizers increases heavy metals and toxins in the soil, risking crop safety and quality, and also harms soil structure, resulting in reduced yields (Wang *et al.* 2022).

As global demand for sustainable agriculture increases, researchers have focused on using organic waste as fertilizer (Kumari *et al.* 2023). The handling of agricultural waste has become a major environmental issue as a result of the large amounts produced by intensive farming methods. Waste materials like crop straw and animal manure contain a lot of organic matter and important nutrients, which makes them suitable for improving the soil (Kumari *et al.* 2023).

One important advance in this field is using biochar (Wang *et al.* 2024). Hossain *et al.* (2020) indicated that biochar has the capacity to supply nutrients (NPK) and other trace elements inherently present in the original material from which it is derived. However, some of the nitrogen and sulfur are lost as gases during pyrolysis. Moreover, biochar can improve water retention and reduce surface runoff and leaching, helping decrease nutrient loss on agricultural land. (Hagemann *et al.* 2017a; Hagemann *et al.* 2017b).

Biochar utilisation has gained more attention, mainly because of its low cost and environmentally sound characteristics, for example, its ability to enhance carbon sequestration and clean up contaminated soil (Hossain *et al.* 2020). It has an effect on soil nutrients and on the microbial communities present and acts as a nutrient sink, which in turn influences the mobility and bioavailability of nutrients (Hossain *et al.* 2020). Research carried out by Abiola *et al.* (2023) and Piccirillo (2023) shows that combining precision techniques with biochar-based fertilizers can greatly reduce nutrient runoff and thus help to preserve water quality while at the same time improving crop productivity. Bio-fertilizers that release nutrients slowly or in a controlled way, based on what crops need, offer many benefits. These innovations are not only environmentally advantageous but also cost-effective since they lead to lower fertilizer costs in the long term.

Regulatory and policy changes are now encouraging the use of environmentally sustainable fertilizers. For example, in China the government is actively promoting among farmers the use of bio-fertilizers which have a slow release and minimal environmental impact in order to improve the sustainability of land resources and social welfare (Dang *et al.* 2022). A recent study examined different materials for making biochar. Blackcurrant leaves stood out as a good option because they have a high carbon content (Satomi *et al.* 2025). To examine these materials, techniques involving elemental analysis have been employed, particularly ED-XRF and SEM-EDX (Utama *et al.* 2022).

The circular economy is essential for achieving sustainable fertilizer production since recycling nutrients from organic waste and returning them to the soil finishes the nutrient cycle (Schmidt *et al.* 2024). For sustainable food production, bio-fertilizers can be produced by using agricultural by-products such as banana peels, rice husks, and chicken manure.

The study is focused on the development of an environmentally sustainable NPK bio-fertilizer made from biochar and waste materials, such as the by-products of agriculture including banana peels, bone meal, and chicken manure. Biochar made from blackcurrant leaves will be combined with these nutrient-rich waste materials to produce a balanced NPK bio-fertilizer. The research also includes the analysis of the raw materials in order to determine their NPK content and the formulation of the bio-fertilizer in order to optimise the availability of nutrients for sustainable agricultural practices.

2. Materials and Method

2.1 Samples Collection and Preparation

The banana peels, bone meal, and chicken manure were obtained from the Gamboru market in Maiduguri, Borno State, Nigeria, while the fallen black currant leaves were collected from a tree on the campus of the University of Maiduguri in Borno State, Nigeria.

2.1.1 Black currant leaves

Black currant leaves were collected without any soil, pesticides, or debris. The leaves were sun-dried in a closed area to lower their moisture content, which is important for efficient carbonization (Edwards and Birmingham, 2023). Once dried, the leaves were put into a carbonizer that works with limited oxygen to avoid combustion.

2.1.2 Banana peel

Two kilograms of banana peels were gathered, the leftover fruit material and any contaminants were removed and the peels were then washed and cut into segments measuring 10 to 15 mm in order to speed up the drying process (Abubakar *et al.* 2024). They were sun-dried for three to five days to reduce their moisture content. After drying, the peels were manually broken down into smaller pieces and then ground to increase their surface area.

2.1.3 Bone meal

A bone specimen that weighed 2 kg was thoroughly washed and was then boiled for about four hours in order to get rid of the adipose tissue, muscular matter and soft tissues. The bones were rinsed once more and left to dry in the sunlight (Khalil *et al.* 2017). When they had dried completely, the samples were manually broken into pieces and the pieces were ground into a fine, uniform powder (<2 mm) with the use of a grinder.

2.1.4 Chicken manure

Fresh chicken was sun-dried to sterilize it and remove any germs or insects that might affect the later growth of the crop (Dikinya and Mufwanzala, 2010). The dry sample was ground into a fine powder with particles smaller than 2 mm.

2.2 Characterisation of Feedstocks

2.2.1 Proximate analysis

2.2.1.1 Moisture content determination

The moisture content was measured using the ASTM-E871 oven-drying method. A sample weighing between 2 and 5 grams was placed in a crucible and dried in an oven set to 105 ± 5°C until its weight stayed the same, which usually took 2 to 3 hours. After cooling, the sample was weighed again (Ahn *et al.* 2014). The moisture loss was then calculated using equation 1.

$$\text{Moisture content (\%)} = \frac{\text{Initial weight} - \text{Dry weight}}{\text{Initial weight}} \times 100 \qquad 1$$

2.2.1.2 Volatile matter determination

Each sample was positioned within a crucible and weighed accordingly. Thereafter, heated to 600°C. Following the heating process, the crucible was allowed to cool within a desiccator and reweighed. The quantity of volatile matter present is determined by the weight loss observed after heating the sample to 600°C, as documented by Nwaokobia *et al.* (2018) in accordance with equation 2.

$$\text{Volatile matter content (\%)} = \frac{\text{Dry weight} - \text{Weight after heating}}{\text{Dry weight}} \times 100 \qquad 2$$

2.2.1.3 Ash content determination

Ash content in the respective sample was determined by heating the residue of the volatile matter at 750 °C for 2 hours without the lid. The ash was weighed and calculated using the equation reported by Quirino *et al.*, (2023) based on equation 3.

$$\text{Ash content (\%)} = \frac{\text{R} - \text{T}}{\text{W} - \text{DM}} \times 100 \qquad 3$$

Where R is the weight of crucible + residue on ignition, T is the weight of the crucible, W is the weight of test portion, DM is the dry matter content of the sample.

2.2.1.4 Fixed carbon determination

To calculate the fixed carbon content, the sum of the moisture and volatile matter contents was subtracted from 100 (Satomi *et al*., 2025) based on equation 4.

$$\text{Fixed carbon } (\%) = 100 - (\text{Moisture content} + \text{Volatile Matter} + \text{Ash content}) \qquad 4$$

2.2.2 BET (Brunauer–Emmett–Teller) Analysis

The samples were carefully weighed into the sample cell, after which the cell was placed in the heating mantle. The clamp was then used both to fasten the mantle and to make sure that the sample cell stayed in position. The stem of the sample cell was placed into the sample preparation station described by Brame and Griggs (2016). The knurled ring was then tightened clockwise to hold it in place. The temperature was set to 300℃ and the system was switched on in order to begin the degassing process. The heater was then turned on. After a period of three hours the heating mantle was switched off so that both the mantle and the sample cell could cool down. When they had cooled, the outgas station was unloaded and the samples were carefully removed. The sample cell was then reweighed in order to find its weight after outgassing (Karg *et al.* 2008).

2.2.3 ED-XRF analysis

The samples were ground into a uniform powder with a particle size ranging from 100 to 200 mesh; approximately 5 g of each sample was weighed and placed into 32 mm sample cups which had been lined with polypropylene X-ray film 4 µm thick, after which they were pressed hydraulicly (Cro *et al.* 2020) using a NEX DE EDXRF spectrometer (Rigaku Holdings Corporation, United States) operated at 60 kV and 10 µA with a 10 mm beam spot.

2.2.4 SEM-EDX analysis

The X-rays are generated and then accelerated towards the target material when a voltage of 10 kV is applied. The samples are placed on the sample holder and then inserted into the instrument. The monitor displays images which are similar to those acquired using a standard compound microscope, and the brightness and contrast are carefully adjusted so as to obtain very detailed images. The images are subsequently converted into SEM images, photographs being taken at various magnifications.

2.2.5 Formulation of NPK bio-fertilizer

To correct the specific deficiencies in nitrogen, phosphorus, and potassium, the feedstocks were mixed in complementary ratios with the aim of producing a well-balanced, organic-mineral NPK fertilizer. The formulation took into account the individual contributions of each nutrient and the physicochemical properties of the feedstocks, these properties having been determined by means of proximate, ultimate, BET, SEM-EDX, and ED-XRF analyses. A total mass of 2000 grams was used in the formulation since this amount provided a manageable and representative sample for the practical calculations involved in blending the nutrients and also enabled all the feedstocks to be included in sufficient quantity without affecting the homogeneity of the mixture. Moreover, biochar was added at a constant rate of 300 grams (that is, 15% of the total formulation).

- Chicken manure (1000 g) – selected as the major nitrogen source.
- Bone meal (500 g) – selected for its high phosphorus (P_2O_5) contribution.
- Banana peel (200 g) – selected as the major potassium (K_2O) contributor.

The methodology flow chart adopted in this study is presented in Figure 1.

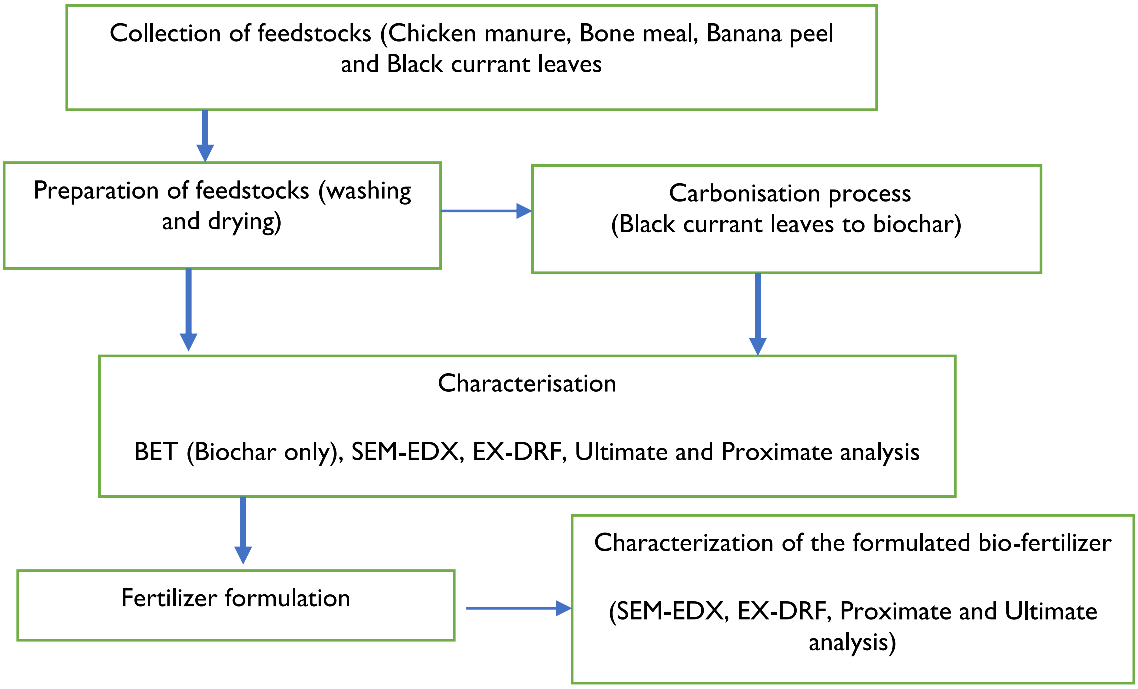


Figure 1: Methodology Flow Chart

3. Results and Discussion

3.1 Proximate Analysis

The proximate analysis of feedstocks is presented in Table 1.

Table 1: Proximate Analysis of Feedstocks

Parameter (g/100g)	Chicken Manure	Biochar	Banana Peel	Bone meal
Moisture (%)	2.39	3.98	5.99	3.12
Ash (%)	67.31	20.00	15.27	61.03
Volatile Matter (%)	13.85	15.50	11.82	14.23
Fixed Carbon (%)	16.45	60.52	66.92	21.62

3.1.1 Moisture content

Moisture contents varied between 2.39% and 5.99% (Table 1), the smallest amount being recorded in the case of chicken manure and the highest in the banana peel sample. A low moisture content suggests greater structural stability and increased resistance to microbial degradation, which is advantageous for the long-term storage and handling of organic fertilizer feedstocks. On the other hand, a high moisture content promotes microbial activity, causing quicker decomposition of organic matter and possibly faster nutrient release, effects that are beneficial in composting or when fertilizers are applied (Islam *et al.* 2023).

The moisture content of the biochar that was observed—3.98%—is within the acceptable range for biomass that has been thermally treated, which aligns with the findings of Satomi *et al.* (2025), who found that biochar made from different agricultural residues and having a moisture content between 3.5 and 5.0% shows improved stability and adsorption capacity, especially when used as a soil amendment. Moreover, the moisture content recorded for banana peel is in line with the figures given by Islam *et al.* (2023) and Ndarubu *et al.* (2021), namely 5.61% and 9.83 ± 0.03%, respectively. These values indicate that the banana waste in question is fresh and has only undergone slight drying, meaning it is highly susceptible to microbial action and therefore suitable for composting or for being mixed with other feedstocks that have low moisture content. As for chicken manure, its low moisture content of 2.39% also supports its use as a stable organic nitrogen source.

3.1.2 Ash content

The ash content, which stands for the total mineral content in a waste sample, is higher when minerals such as Ca, K, Mn, Mg, P, and Na are present (Singh *et al.* 2011). The ash content values obtained for bone meal, banana peel, and biochar in this study are comparable to those found in the literature. Islam *et al.* (2023) found a crude ash content of 37.86% in cow bone, a figure which is very close to the one obtained in the present study. With regard to banana peel, Kabenge *et al.* (2018), Ndarubu *et al.* (2021), and Pyar-Hassan (2018) recorded ash contents of 8.8 ± 0.54%, 9.56 ± 0.06%, and 9.28 ± 0.22%, respectively.

3.1.3 Volatile matter (VM)

The VM present in the soil may temporarily reduce the effectiveness of fertilizers by causing nitrogen to be immobilised. For instance, banana peel had a volatile matter content of 88.02 ± 1.33% (Kabenge *et al.* 2018), and chicken manure contained 67.5% VM (Tańczuk *et al.* 2019).

3.1.4 Fixed carbon

Banana peel has a fixed carbon content of 2.70 ± 0.78% (Kabenge *et al.* 2018), while chicken manure contained 16.9% (Tańczuk *et al.* 2019). Pandey *et al.* (2019) and Satomi *et al.* (2025) both reported a fixed carbon value for chicken manure and biochar, as shown in Table 1.

3.2 Ultimate Analysis

Table 2 presents the ultimate analyses of the feedstocks.

Table 2: Ultimate Analysis of Feedstocks

Parameter (g/100g)	Chicken Manure	Biochar	Banana Peel	Bone meal
Carbon (%)	19.60	71.87	38.90	19.22
Hydrogen (%)	4.80	2.14	5.30	2.91
Nitrogen (%)	20.25	1.06	6.95	18.71
Sulfur (%)	0.54	0.12	0.08	0.02
Oxygen (%)	43.00	5.41	39.97	36.33

3.2.1 Carbon content

Carbon is important for improving soil structure, the ability of soil to retain water, and microbial activity. As shown in Table 2, biochar has the highest carbon content (71.87%), consistent with Pan *et al.* (2021), who reported carbon contents in biochar ranging from 70% to 80%. This is due to the carbonization process, during which volatile compounds are removed, and carbon is thus concentrated. Because of its high carbon content, biochar is an excellent soil amendment material. Banana peel has a carbon content of 38.90%, a figure similar to that reported by Islam *et al.* (2023) and the 35.65% reported by Kabenge *et al.* (2018). Chicken manure and bone meal have lower carbon contents, 19.60% and 19.22%, respectively. Even though their carbon content is low, these materials are rich in other essential nutrients and therefore make valuable contributions to balanced fertilizer formulations.

3.2.2 Hydrogen content

The amount of hydrogen points to the presence of organic compounds and has an effect on the energy value of the material. As shown in Table 2, banana peel has the highest hydrogen content at 5.30%, a figure that aligns with the findings of Islam *et al.* (2023) and Kabenge *et al.* (2018). This high hydrogen content thus promotes microbial activity in the composting process. Chicken manure and bone meal have hydrogen contents of 4.80% and 2.91%, respectively, matching the results of Tańczuk *et al.* (2019), who found 4.72% for chicken manure, and Olafadehan *et al.* (2019), who found 1.72% for bone meal. These figures indicate moderate to low levels of biodegradable organic matter, which in turn affect their decomposition rates and nutrient release patterns.

3.2.3 Nitrogen content

Nitrogen affects vegetative growth as well as chlorophyll synthesis. As shown in Table 2, chicken manure has the highest nitrogen content at 20.25%, this being considerably higher than the 5.49% stated by Tańczuk *et al.* (2019) and the 3.93% mentioned by Pandey *et al.* (2019). The fact that it contains such a high level of nitrogen shows that it is a powerful organic fertilizer. Bone meal also has a high nitrogen content of 18.71%, which confirms its role not only as a source of phosphorus but also as a contributor of nitrogen. Banana peel contains 6.95% nitrogen, which is more than the 1.94% reported by Kabenge *et al.* (2018), and this suggests that it could be used as an additional nitrogen source in composting. Biochar has the lowest nitrogen content at 1.06%, this indicating the loss of nitrogen that occurs during pyrolysis. Yet biochar is still useful in retaining nitrogen in the soil because it adsorbs ammonium and nitrate ions and thus reduces leaching losses.

3.2.4 Sulfur content

Sulfur is essential for protein synthesis and for enzymatic activity in plants. As shown in Table 2, chicken manure has the highest sulfur content at 0.54%, a figure that agrees with that recorded by Tańczuk *et al.* (2019). Biochar and banana peel have lower sulfur levels of 0.12% and 0.08% respectively, while bone meal has the lowest at 0.02%, a value that is in line with the 0.10% cited by Olafadehan *et al.* (2019). Nevertheless, it is still a major source of sulfur in organic fertilizers.

3.2.5 Oxygen content

Table 2 shows that banana peel and chicken manure have oxygen contents of 39.97% and 43.00%, respectively, figures which are comparable to the 45.94% cited by Kabenge *et al.* (2018) for banana peel and the 34.12% given by Tańczuk *et al.* (2019) for chicken manure. The high level of oxygen means that there is a large amount of organic matter, which is advantageous for microbial activity. Bone meal has an oxygen content of 36.33%, a value similar to the 48.30% reported by Olafadehan *et al.* (2019), whereas biochar has the lowest at 5.41%, a figure showing that there has been a loss of oxygenated compounds during carbonization.

3.3 BET Analysis

An analysis of the biochar made from black currant leaves by means of BET showed that it had a high surface area of 140.06 m^2/g, a pore volume of 0.069 cc/g and a modal pore diameter of 3.02 nm. Generally, the surface area and the total pore volume of biochar vary between 8 and 132 m^2/g and 0.016 and 0.083 cm^3/g, respectively. If an appropriate precursor is chosen and the pyrolysis conditions are optimised, these values can be greatly increased, the surface area reaching as high as 490.8 m^2/g and the pore volume as high as 0.25 cm^3/g (Leng *et al.* 2021). The fact that it has these physical properties shows that the biochar is mainly mesoporous, with the presence of microporosity also being demonstrated by micropore volumes of 0.122 cc/g (DA method) and 0.046 cc/g (DR method).

3.1.1 Surface area and nutrient retention

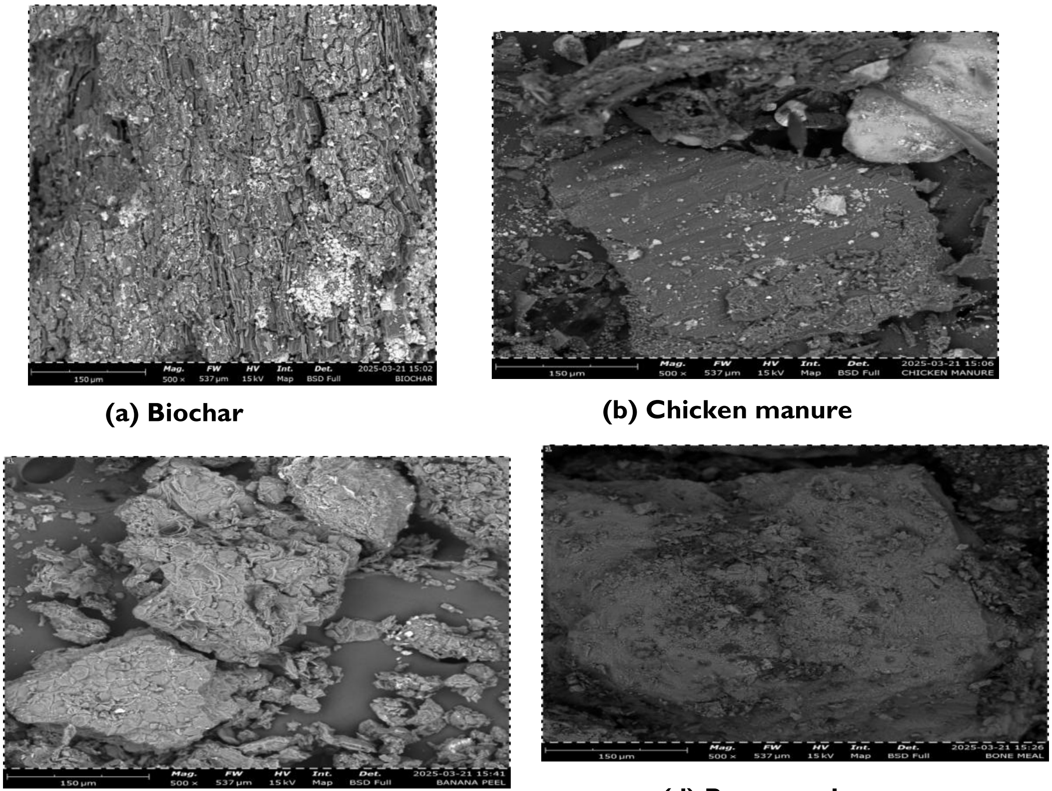
The high BET surface area increases the biochar's ability to adsorb and hold nutrients in the soil. Since a larger surface area provides more active sites, this in turn gives more opportunities for microbial growth and for the fixation of nutrients (Leng *et al.* 2021). It also has a direct effect on the CEC and on the adsorption of the essential macronutrients (NH_4^+), (K^+), and (Ca^{2+}) (Zeng et al., 2013). Because its surface area is 140.06 m^2/g, the biochar is suitable for use in controlled nutrient-release products or in more efficient fertilizers.

3.1.2 Pore volume and water/nutrient holding

A pore volume of 0.069 cc/g shows a moderate ability to retain water and nutrients. Together with its mesoporous features, this volume allows for the slow release of nutrients and improves the availability of moisture to plant roots (Sun and Lu, 2014). Even though this figure is less than that of some activated biochars, it is still sufficient for ordinary use as a soil modification, particularly in sandy or soils with low retention capacity. Since its modal pore diameter is 3.02 nm, the biochar falls within the mesoporous range (2–50 nm), a feature that is favourable for holding onto and enabling the slow diffusion of nutrient molecules. Mesopores are especially good at adsorbing organic molecules and small ions, thus balancing the accessibility of nutrients with microbial activity (Gryta *et al.* 2024). The extra microporosity detected using DA and DR techniques shows that there are finer pores capable of trapping smaller molecules such as ammonium or phosphate ions, a feature that helps to reduce nutrient losses from fertilizers (Baiamonte *et al.* 2015).

3.4 SEM-EDX Analysis

Plate 1 presents the SEM results for biochar, chicken manure, banana peel, and bone meal.



(a) Biochar **(b) Chicken manure**

(c) Banana Peel **(d) Bone meal**

Plate 1: The SEM results for (a) biochar, (b) chicken manure, (c) banana peel, and (d) bone meal.

3.4.1 Biochar composition

Table 3 presents the EDX analysis of the feedstocks. Biochar is mainly made up of carbon, which makes up 50 to 90% by weight. The fact that its carbon content is so high shows that the carbonisation process has been effective and suggests that the biochar has the potential to act as a carbon sink (Li and Tasnady, 2023). There is a correlation between a high carbon content and greater stability, as well as a higher capacity for adsorbing nutrients, which means that this type of biochar is appropriate for use as a soil amendment over the long term (Shyam *et al.* 2025). The EDX analysis of the biochar, as shown in Table 3a, showed that the main elements were C (67.57%), Ca (11.66%), Mg (8.02%), and N (6.85%). Moreover, mineral components such as Si (1.64%), K (1.40%), Al (1.05%), Cl (0.82%), Fe (0.33%), P (0.25%), Ti (0.23%), and S (0.19%) were also detected.

Nutrients including K, P, Ca, and Mg, together with biochar's ability to retain nutrients, can increase the fertility of acidic soils. As a result of pyrolysis, the amounts of P, K, Ca, and Mg in the biochar rise since carbon and nitrogen are lost, leading to concentrations that are higher than those in the original feedstock (Shi *et al.* 2019). Biochar, especially when made from feedstocks that are high in magnesium, has the potential to boost the CEC, and hold on to important nutrients such as magnesium and other positively charged ions. This helps to reduce nutrient loss by leaching (Alkharabsheh *et al.* 2021).

Silicon-rich materials enhance plant growth, increase grain yield, and improve photosynthetic efficiency. These materials also reduce heavy metal concentrations in plants Li *et al.* (2022). This effect is likely due to the ability of silica-rich materials to mitigate the impact of heavy metals in soil and facilitate the repair of oxidative damage. Additionally, nitrogen-rich biochar may function as a slow-release nitrogen fertilizer and enhance soil fertility. Thus, nitrogen use efficiency can be increased, and less nutrient is lost compared with conventional fertilizers (Liao *et al.* 2020).

3.4.2 Chicken manure composition

The EDX analysis of chicken manure (as shown in Table 3b) reveals a varied elemental composition, which shows that it has the potential to be a fertile, organic fertilizer. The main elements are carbon at 66.25%, nitrogen at 11.15%, and silicon at 8.65%. Other elements of note are K at 3.96%, Ca at 2.36%, Al at 2.02%, Fe at 1.73%, P at 1.25%, Cl at 0.85%, Mg at 0.76%, S at 0.68%, Ti at 0.19%, and Na at 0.16%. Chicken manure acts as an effective bio-fertilizer and is rich in vital nutrients (NPK). These nutrients are necessary for vigorous plant growth (Verner, 2023).

Table 3: EDX Analyses of Feedstocks

(a) Biochar					(b) Chicken Manure				
Element No	**Element Symbol**	**Element Name**	**Atomic Conc.**	**Weight Conc.**	**Element No**	**Element Symbol**	**Element Name**	**Atomic Conc.**	**Weight Conc.**
6	C	Carbon	81.34	67.57	6	C	Carbon	78.65	66.25
20	Ca	Calcium	4.20	11.66	7	N	Nitrogen	11.35	11.15
12	Mg	Magnesium	4.77	8.02	14	Si	Silicon	4.39	8.65
7	N	Nitrogen	7.07	6.85	19	K	Potassium	1.44	3.96
14	Si	Silicon	0.84	1.64	20	Ca	Calcium	0.84	2.36
19	K	Potassium	0.52	1.40	13	Al	Aluminium	1.07	2.02
13	Al	Aluminium	0.56	1.05	26	Fe	Iron	0.44	1.73
17	Cl	Chlorine	0.34	0.82	15	P	Phosphorus	0.58	1.25
26	Fe	Iron	0.09	0.33	17	Cl	Chlorine	0.34	0.85
15	P	Phosphorus	0.12	0.25	12	Mg	Magnesium	0.45	0.76
22	Ti	Titanium	0.07	0.23	16	S	Sulfur	0.30	0.68
16	S	Sulfur	0.08	0.19	22	Ti	Titanium	0.06	0.19
11	Na	Sodium	0.00	0.00	11	Na	Sodium	0.10	0.16
25	Mn	Manganese	0.00	0.00	25	Mn	Manganese	0.00	0.00

(c) Banana Peel					(d) Bone Meal				
Element No	**Element Symbol**	**Element Name**	**Atomic Conc.**	**Weight Conc.**	**Element No**	**Element Symbol**	**Element Name**	**Atomic Conc.**	**Weight Conc.**
6	C	Carbon	77.50	63.52	20	Ca	Calcium	68.10	73.92
19	K	Potassium	6.75	18.01	15	P	Phosphorus	26.55	22.27
7	N	Nitrogen	13.01	12.43	11	Na	Sodium	2.57	1.60
17	Cl	Chlorine	0.66	1.60	13	Al	Aluminium	1.16	0.84
20	Ca	Calcium	0.39	1.08	12	Mg	Magnesium	1.06	0.69
14	Si	Silicon	0.51	0.98	22	Ti	Titanium	0.34	0.44
13	Al	Aluminium	0.41	0.76	17	Cl	Chlorine	0.23	0.22
22	Ti	Titanium	0.16	0.53	19	K	Potassium	0.00	0.00
15	P	Phosphorus	0.18	0.37	25	Mn	Manganese	0.00	0.00
12	Mg	Magnesium	0.19	0.32	26	Fe	Iron	0.00	0.00
11	Na	Sodium	0.19	0.29	14	Si	Silicon	0.00	0.00
16	S	Sulfur	0.05	0.11	16	S	Sulfur	0.00	0.00
25	Mn	Manganese	0.00	0.00					
26	Fe	Iron	0.00	0.00					

Because of the large amounts of undigested plant material, bedding, and feces, which include organic substances like cellulose and lignin, high carbon levels are expected (Nahm, 2003). The C/N ratio in chicken manure is important for effective composting since it creates the ideal conditions for micro-organisms to break down the organic matter and form compost. Additionally, chicken manure improves soil health, improves aeration, and enhances soil structure, as well as supplying the essential nutrients needed for plant growth (Qasim *et al.* 2018). In addition, chicken manure is a good source of organic nutrients and micronutrients (N, Ca, Cu, Zn, Fe and Mn) (Karthik and Rathinamoorthy, 2017); and P for developing healthy roots (Jastrzebska *et al.* 2016).

3.4.3 Banana peel composition

As presented in Table 3c, banana peels contain macronutrients and micronutrients which help in plant development (El-Awadi *et al.* 2021). Due to their high carbon content, banana peels are suitable for biochar production or composting to generate a bio-fertilizer that releases nutrients gradually (Vinod *et al.* 2023). Potassium is an essential nutrient present in banana peels, required for plant growth (Wang *et al.* 2013; Hariyono *et al.* 2021).

3.4.4 Bone meal composition

As indicated in Table 3d, bone meal is mainly made up of calcium and phosphorus, mostly in the form of hydroxyapatite ($Ca_5(PO_4)3OH$), which is the principal mineral found in animal bones. Because of this composition, bone meal is a valuable source for both phosphorus and calcium for use in agriculture (Piccirillo, 2023). The high level of calcium in bone meal is due to the fact that it comes from bone material which is rich in calcium phosphate compounds. This high concentration of calcium gives the substance soil-amending properties, such as the ability to regulate pH and to supply the essential nutrients needed for the development of plant cell walls (Bayata and Mulatu, 2024). The phosphorus in bone meal is mainly in the form of hydroxyapatite, a substance known for being only slightly soluble. Although this results in the phosphorus being released slowly, it ensures a continuous supply of this essential nutrient, which is important for root development (Castro *et al.* 2024). The trace elements present in bone meal are due to the original composition of the bone and the pyrolysis process; these elements can have an effect on plant nutrition and soil chemistry, even though their concentrations are generally low (Vatansever *et al.* 2017).

3.5 ED-XRF Analysis

The ED-XRF analysis of the elemental oxide content in the feedstocks shows that several major and trace oxides are present, oxides which are important for soil fertility and for the nutrition of plants. These oxides indicate that the feedstocks can be used as a rich nutrient amendment and can also serve as a sustainable element in organic NPK bio-fertilizer formulations.

3.5.1 Biochar composition

Table 4 presents the EDXRF results. The ED-XRF analysis of the biochar obtained from black currant leaves (Table 4a) showed that it had a composition containing a high proportion of mineral oxides which are important for soil fertility and for the development of fertilizers. The main oxides were CaO (66.1%), SiO_2 (6.72%), MgO (6.17%) and P_2O_5 (6.13%), together with P_2O at 4.64%. The study also recorded trace micronutrients such as Fe_2O_3 (3.60%), MnO (0.598%), Zn (370 ppm), Cu (227 ppm) and S (7180 ppm).

CaO was the most plentiful oxide, accounting for 66.1%, a figure which shows a strong capacity to facilitate physico-chemical interactions between organic compounds and minerals. Elevated levels of calcium lead to improved carbon use (Dang *et al.* 2024). Calcium helps in the formation of organo-mineral associations with the microbial by-products of plant litter (Shabtai *et al.* 2023). The high level of calcium is in agreement with the EDX results that show 11.66% elemental calcium.

ED-XRF analysis showed a moderate nitrogen content of 6.85%, which means that the biochar's slow release of nitrate can reduce nitrate leaching and allow plants to receive nitrate much longer (Hagemann *et al.* 2017). Because the biochar contains 6.13% P_2O_5, it provides a moderate contribution to phosphorus availability. This is important since crop residues and woody biochar generally have lower phosphorus content than animal-based feedstocks (Hossain *et al.* 2020), although this result is due to the retention of mineral phosphorus during the carbonisation process. The K_2O content of 4.64% indicates that the biochar can in part meet potassium requirements and increase K availability when used together with other materials that are rich in potassium, such as banana peel.

3.5.2 Chicken manure composition

The ED-XRF analysis of chicken manure (Table 4b) showed that it contains a high proportion of oxide forms of macro- and micronutrients which are important for soil fertility and for the production of organic fertilizers. The main oxides present were SiO_2 (52.7%), CaO (11.9%), K_2O (9.61%), P_2O_5 (7.14%) and Al_2O_3 (5.21%). Other oxides and trace elements found were Fe_2O_3 (8.61%), MgO (0.758%), TiO_2 (1.79%) and MnO (0.224%). The study also recorded micronutrient elements such as Zn (908 ppm), Cu (240 ppm) and S (10,100 ppm). Chicken manure is well known for providing a wide range of nutrients, and therefore makes a good base for organic fertilizers (Verner, 2023). The nitrogen content, particularly when the manure is dried, can act as a slow-release source and thus improve nitrogen use efficiency while reducing leaching losses (Purnomo *et al.* 2017).

Furthermore, the largest amount of oxide in this sample was SiO_2 (52.7%), which possibly came about due to soil contamination or from the residual feed additives. Even though it is not a main nutrient, SiO_2 helps to improve canopy photosynthesis and decreases transpiration losses (Vatansever *et al.* 2017).

Moreover, liming increases the pH levels of soil, calcium, CEC, and base saturation, while at the same time decreasing the concentration of aluminium and improving the availability of phosphorus (Peter *et al.* 2018). The amount of K_2O was 9.61%, which shows that chicken manure can be used to supply the potassium element in NPK mixes. Potassium is a necessary macronutrient that promotes growth and yield, particularly under drought conditions (Ahmad *et al.* 2018a). The P_2O_5 content (7.14%) shows that chicken manure is a source of phosphorus. Other essential elements present in significant amounts include Fe_2O_3 (8.61%), which is important for chlorophyll synthesis and for redox activity (Khanizadeh *et al.* 2024). Copper and zinc are important metals for plants since they aid in protein synthesis; they are also essential for photosynthesis and respiration, for the electron transport chains, for ethylene detection, for cell wall processes, for protection against oxidative damage, and for the formation of the molybdenum cofactor (Abou Seeda *et al.* 2020). The high sulfur content (10,100 ppm) helps in the synthesis of amino acids and improves the efficiency with which nitrogen and phosphorus are taken up. Plants are unable to form these amino acids in the absence of sulfur, which thus limits their capacity to convert nitrogen into usable proteins (Bawaliya *et al.* 2023).

Table 4: EDXRF Analyses of Feedstocks

(a) Biochar

Serial No	Component	Result	Unit
1	S	7180	ppm
2	Cl	18500	ppm
3	V	272	ppm
4	Ni	215	ppm
5	Cu	227	ppm
6	Zn	370	ppm
7	Br	72.0	ppm
8	Rb	107	ppm
9	Sr	3780	ppm
10	Y	10.4	ppm
11	Zr	390	ppm
12	Ag	26.3	ppm
13	Ba	1040	ppm
14	MgO	6.17	mass%
15	Al2O3	1.59	mass%
16	SiO2	6.72	mass%
17	P2O5	6.13	mass%
18	K2O	4.64	mass%
19	CaO	66.1	mass%
20	TiO2	0.538	mass%
21	MnO	0.598	mass%
22	Fe2O3	3.60	mass%
23	Sc	6820	ppm

(b) Chicken Manure

Serial No	Component	Result	Unit
1	S	10100	ppm
2	Cl	9680	ppm
3	V	ND	ppm
4	Ni	59.9	ppm
5	Cu	240	ppm
6	Zn	908	ppm
7	Br	7.56	ppm
8	Rb	334	ppm
9	Sr	539	ppm
10	Y	71.9	ppm
11	Zr	2320	ppm
12	Ag	20.1	ppm
13	Ba	1000	ppm
14	Ce	162	ppm
15	Pb	101	ppm
16	MgO	0.758	mass%
17	Al2O3	5.21	mass%
18	SiO2	52.7	mass%
19	P2O5	7.14	mass%
20	K2O	9.61	mass%
21	CaO	11.9	mass%
22	TiO2	1.79	mass%
23	MnO	0.224	mass%
24	Fe2O3	8.61	mass%
25	Co	(62.3)	ppm
26	Ga	25.8	ppm
27	Nb	39.4	ppm

(c) Banana Peel

Serial No	Component	Result	Unit
1	S	4760	ppm
2	Cl	41700	ppm
3	Cu	207	ppm
4	Zn	585	ppm
5	Br	938	ppm
6	Rb	1330	ppm
7	Sr	711	ppm
8	Y	48.1	ppm
9	Zr	147	ppm
10	SiO2	5.20	mass%
11	P2O5	3.89	mass%
12	K2O	71.0	mass%
13	CaO	14.1	mass%
14	MnO	0.109	mass%
15	Fe2O3	0.661	mass%

(d) Bone Meal

Serial No	Component	Result	Unit
1	S	3520	ppm
2	Cl	3750	ppm
3	Ni	(17.5)	ppm
4	Cu	79.0	ppm
5	Zn	327	ppm
6	Br	48.5	ppm
7	Rb	11.2	ppm
8	Sr	1210	ppm
9	Y	ND	ppm
10	Zr	136	ppm
11	Ba	1010	ppm
12	Na2O	1.21	mass%
13	Al2O3	0.520	mass%
14	SiO2	1.13	mass%
15	P2O5	26.0	mass%
16	K2O	0.236	mass%
17	CaO	68.8	mass%
18	MnO	(0.0065)	mass%
19	Fe2O3	0.276	mass%
20	Sc	7700	ppm

3.5.3 Banana peel composition

The ED-XRF analysis of banana peel (as shown in Table 4c) shows that it has a nutrient-rich composition, with the main components being K_2O (71.0%), CaO (14.1%), P_2O_5 (3.89%) and SiO_2 (5.20%), together with some beneficial micronutrient oxides such as MnO (0.109%) and Fe_2O_3 (0.661%). Trace metals detected include Zn (585 ppm), Cu (207 ppm) and S (4760 ppm), all of which are important for crop nutrition and for soil fertility. Banana peel is a valuable source of potassium as a feedstock (Khanyile *et al.* 2024), while P_2O_5 is a better indicator of plant-available phosphorus.

3.5.4 Bone meal composition

The EDXRF analysis of the bone meal (see Table 4d) revealed significant amounts of CaO at 68.8% and P_2O_5 at 26.0%, a result that is in agreement with the known composition of hydroxyapatite, the main mineral found in bone. This corresponds to the usual Ca/P molar ratio of about 1.67 in natural bone, as stated by Herpandi *et al.* (2024).

3.6 Proximate and Ultimate Analysis of the Formulated Bio-Fertilizer

Table 5 presents the properties of the formulated bio-fertilizer.

Table 5: Proximate and ultimate composition of formulated bio-fertilizer (g/100g)

Parameter	Formulated Bio-Fertilizer
Moisture	2.79
Ash	41.17
Volatile Matter	41.83
Fixed Carbon	14.21
Carbon	47.85
Hydrogen	1.87
Nitrogen	3.15
Sulfur	0.14
Oxygen	6.20

The analysis shown in Table 5 showed a moisture content of 2.79%, a figure that is good for the stability of the fertilizer and for long-term storage. The ash content was 41.17%, showing that the formulation is rich in minerals. With volatile matter amounting to 41.83% and fixed carbon at 14.21%, there is a balance between organic matter that can decompose. As presented in Table 5, the carbon content was 47.85%, a level which improves soil structure, promotes microbial activity and increases the retention of organic matter (Zhou *et al.* 2023). Nitrogen content was 3.15%, an amount adequate for supporting early vegetative growth and protein synthesis. Hydrogen, at 1.87%, and sulfur, at 0.14%, play a role in plant biochemical functions (Fuentes-Lara *et al.* 2019), while oxygen, at 6.20%, shows the presence of oxidized organic matter, something that is advantageous for soil aeration and biological activity (Li *et al.* 2022).

3.7 ED-XRF Analysis of Formulated NPK Bio-Fertilizer

The results of the EDXRF analysis of the formulated NPK bio-fertiliser are given in Table 6.

Table 6: ED-XRF characterisation of the formulated NPK bio-fertilizer

S/N	Compound Name	Mass Concentration (%)
1	SiO_2	20.625
2	P_2O_5	10.172
3	K_2O	8.508
4	CaO	26.595
5	MgO	1.43
6	Al_20_3	0.936
7	SO_3	0.3746
8	ZnO	0.02132
9	CuO	0.00280
10	MnO	0.05676

The ED-XRF examination of the final NPK bio-fertilizer mixture (see Table 6) showed that it contained a high proportion of oxide forms of both macronutrients and micronutrients which are important for soil fertility and plants growth. In particular, the phosphorus content, determined as P_2O_5, was found to be 10.17%, this demonstrating that bone meal functions as an effective source of phosphorus. The potassium content, given as K_2O, was 8.51%, which shows how much banana peel has contributed to the formulation. Potassium is a necessary macronutrient needed in various plant physiological processes, such as drought tolerance, root development and flowering (Ahmad et al. 2018b).

CaO was found to be present in a high amount of 26.60%, which shows that the material contains a considerable quantity of bone meal. Ca is important for plant growth since it helps to reduce soil acidity, improves the structure of the soil, and increases both microbial and root activity (Thor, 2019). SiO_2 and MgO were present at 20.63% and 1.43%, respectively. These minerals help to increase a plant's ability to withstand stress and aid in the production of chlorophyll (Abbas *et al.* 2024; Wei *et al.* 2025). The amount of SO_3 at 0.375% has a role in the assimilation of nitrogen and in the synthesis of amino acids in crops (Giordano and Raven, 2014). Micronutrients such as ZnO (0.021%), CuO (0.0028%), and MnO (0.057%) were identified and are important for the activation of enzymes, for photosynthesis, and for plant immune responses.

4. Conclusion

The following conclusions can be drawn from this study:

1. The black currant leaves were carbonised in such a way that biochar was obtained with very desirable physical and chemical properties. According to BET analysis, the biochar had a mesoporous structure (with a mode pore diameter of 3.02 nm) and a large surface area, features which are important for improving nutrient adsorption. ED-XRF and SEM-EDX showed that there were significant amounts of Ca, Mg, and K, and the ultimate analysis indicated a high carbon content (71.87%), showing that the material is appropriate for bio-fertilizer production.
2. The banana peel, bone meal, and chicken manure were found to make complementary contributions of nutrients. According to ED-XRF analysis, the banana peel had a dominance of potassium (K_2O: 71.0%), bone meal contained the majority of phosphorus (P_2O_5: 26.0%), and chicken manure was rich in nitrogen (N: 20.25%). This was further confirmed by SEM-EDX and ultimate analyses, which showed that it is feasible to use these agricultural wastes as targeted sources of nutrients in the formulation of organic fertilizer.
3. The bio-fertiliser mixture which included chicken manure (1000 g), bone meal (500 g), banana peel (200 g) and biochar (300 g) had an NPK ratio of 2.4:5.1:2.1. By using biochar the formulation helps to enhance the retention of nutrients and reduces losses through leaching. According to the analysis the mixture contained 13.89% nitrogen, 14.31% phosphorus (as P_2O_5) and 17.90% potassium (as K_2O). The product conforms to the standards for conventional organic fertilizers and has the promise to improve soil fertility, in particular in soils that are nutrient-deficient or are managed organically.

Research in the future should involve carrying out optimization studies using response surface methodology (RSM) in order to accurately adjust the nutrient ratios to meet the specific requirements of different crops. It is also necessary to carry out storage stability assessments in order to examine how well the nutrients are retained over time under a variety of environmental conditions. Furthermore, field trials are required to asses the agronomic performance of the fertilizer formulation across a range of crop species and soil types.

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