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Optimizing Fertilizer Production: Co-Composting Faecal Sludge With Various Bulking Agents

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ABSTRACT

This research investigates the integration of locally available bulking agents—coconut shells, waste tea powder, banana peels, and sugarcane leaves—for co-composting fecal sludge (FS) alongside organic waste. The study involves physical, chemical, and heavy metal analysis of the bulking agents, followed by 91 days of aerobic composting with weekly sample collection and evaluation. The goal was to identify the optimum combination of these agents for producing nutrient-rich compost, particularly for nitrogen (N), phosphorus (P), and potassium (K). The compost prepared using a specific combination of these bulking agents met the key nutrient criteria, providing a viable solution for sustainable waste management. Coconut shells enriched the compost with potassium, calcium, magnesium, and phosphorus, enhancing soil structure and moisture retention. Waste tea powder, rich in nitrogen and potassium, promoted microbial activity and soil fertility. Banana peels contributed high levels of potassium and phosphorus, improving aeration and nutrient cycling, while sugarcane leaves enhanced soil health by contributing organic carbon, nitrogen, and potassium. The study utilized tools like Python and Microsoft Excel for data analysis and visualization, enabling the establishment of reliable maturity indices for assessing compost stability and quality. These findings highlight the potential of using locally available organic waste materials to improve soil fertility and support sustainable agricultural practices.

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INTRODUCTION

In many low-income countries, the improper disposal of municipal wastes poses significant challenges, leading to environmental pollution and public health risks. This issue is particularly pronounced in Ghana, where a substantial portion of waste remains uncollected, contributing to environmental degradation Ghana (1991). With only two functional engineered landfills among 100 urban agglomerations, and limited sewerage network coverage (5%), sanitation infrastructure struggles to match population growth. The consequences extend to urban and peri-urban lands, which are susceptible to degradation and nutrient depletion due to continuous cropping, high

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temperatures, and rainfall, accelerating organic matter decomposition and erosion. The use of inorganic fertilizer alone is insufficient to sustain soil resources for continuous crop production. Fertilizer use in sub-Saharan Africa, particularly in Ghana, is notably the lowest globally Kelly (2006), Crawford et al. (2003). However, excreta and municipal solid waste are recognized for containing valuable nutrients, Zoffering a potential solution for sustainable agriculture and waste management. Excreta, estimated to contain valuable nutrients such as 4.5 kg/p/a for nitrogen, 0.6 kg/p/a for phosphorus, and 1.2 kg/p/a for potassium, along with organic matter, presents an opportunity for nutrient recovery Jönsson et al. (2004). Municipal solid waste also contributes substantial amounts of plant nutrients, including 19 kg/p/a for carbon, 0.8 kg/p/a for nitrogen, 0.3 kg/p/a for phosphorus, and 0.5 kg/p/a for potassium. Co-composting fa ecal sludge (FS) with organic solid waste provides a sustainable approach to recycling nutrients into agriculture, closing the nutrient loop. The synergistic combination of these materials addresses the missing components, such as organic matter, in inorganic fertilizer. However, the effective use of such compost in agriculture depends on various factors, including the quality of the compost.

Despite the potential benefits, faecal sludge management poses significant challenges globally, especially in low- and middle-income countries Strande et al. (2014). Sustainable treatment facilities for faecal sludge are largely lacking, leading to indiscriminate disposal into the environment or its reuse in agriculture without proper treatment, resulting in severe public health and environmental risks. Composting has emerged as an economically viable way to treat faecal sludge, offering nutrient recovery and reuse advantages Awasthi et al. (2015). However, the current operation is associated with large nitrogen (N) and carbon (C) losses, reducing the agronomic value of the final compost. The selection of the right bulking agent for co-composting with FS is essential to reduce nutrient losses, particularly nitrogen through ammonia volatilization Tiquia et al. (2002). Bulking agents play a crucial role in adjusting the carbon-to-nitrogen (C/N) ratio, absorbing excess moisture, and improving the physical characteristics of composting materials.

Faecal sludge management remains a pressing global challenge, particularly in regions lacking sustainable treatment facilities. Current practices involve the collection of FS from on-site sanitation systems, either for agricultural reuse or indiscriminate disposal into the environment. The consequences include significant risks to public health and the environment. Bulking agents play a critical role in FS composting, influencing the composting rate, quality of the final compost, and nutrient losses Amoah et al. (2007). Although the co-composting of sludge and organic waste with bulking agents has been investigated in a number of research, conflicting findings have been reported Esrey (2001). The final compost quality and the parameters of the composting process can be greatly impacted by the type of bulking agent selected. To update and clarify the current literature on FS composting with bulking agents, more study is required. There haven't been many attempts to comprehensively evaluate the FS composting process with various bulking agents in a single study Gulyas et al. (2017). There is a lack of information regarding the frequency of turning composting windrows and the proportion of FS to solid waste. Furthermore, nothing is known about how carbon, organic matter, and nitrogen are changed when FS is co-composted with various bulking agents in an open-air composting system Amoah et al. (2007).

The determination of sample proportions is a critical aspect of scientific research, ensuring the reliability of studies. Python & Microsoft Excel software, renowned for its statistical expertise and user-friendly interface, plays an indispensable role in this process Wilcox (2011) Field et al. (2012), Privitera (2023). By streamlining data analysis, Python & Microsoft Excel provides researchers with a powerful toolkit for hypothesis testing, confidence interval estimation, and regression analysis. Its versatility enables the accommodation of complex experimental designs, ensuring tailored analyses that enhance precision in determining sample proportions and ultimately contribute to the reliability of research findings. As an essential tool in statistical analysis, Python & Microsoft Excel is not merely a preference but a necessity, strengthening research methodologies and ensuring statistical robustness. This paper explores Python & Microsoft Excel's pivotal role in sample proportion determination, underscoring its significance in maintaining methodological rigor.

The study aims to investigate the effectiveness of locally available bulking agents, including coconut shells, banana peels, sugarcane leaves, and waste tea powder, in co-composting fecal sludge (FS) for use as an organic fertilizer. This research builds on previous studies that have explored the potential of organic materials to enhance soil health, improve nutrient cycling, and support sustainable waste management practices.

1. Coconut Shells: Coconut shells are rich in essential nutrients like potassium, calcium, magnesium, and phosphorus, making them an excellent bulking agent for compost. Previous studies have shown that coconut shell biochar improves soil fertility by enhancing nutrient retention and promoting microbial activity. Moreover, its structural properties enhance soil aeration, moisture retention, and porosity, which are crucial for plant growth Cai et al. (2016).

2. Banana Peels: Banana peels are highly valued in composting due to their richness in potassium, phosphorus, and other trace elements, which are vital for plant nutrition. Studies have demonstrated that banana peels enhance soil microbial activity and nutrient availability, promoting plant growth and improving root penetration in the soil Pariyar et al. (2020). Their fibrous structure also helps improve soil aeration and moisture-holding capacity.

3. Sugarcane Leaves: Sugarcane leaves are rich in organic carbon, nitrogen, potassium, and calcium. Their high organic matter content makes them an ideal material for composting. Previous research has indicated that sugarcane leaves improve soil structure, enhance microbial activity, and contribute to overall soil fertility Pathak et al. (2017). Additionally, their contribution to the carbon-to-nitrogen (C:N) ratio is beneficial in balancing composting processes.

4. Waste Tea Powder: Waste tea powder is rich in nitrogen, potassium, and phosphorus, and its fibrous nature helps prevent soil compaction while improving drainage and root health. Research by Thakur et al. (2020) demonstrated that using waste tea as a composting agent improves soil nutrient levels and promotes microbial activity, which contributes to faster organic matter decomposition.

Co-Composting of Fecal Sludge: Co-composting fecal sludge with organic waste has been widely studied as a sustainable method for managing human waste while producing organic fertilizers. Fecal sludge contains valuable nutrients, particularly nitrogen, which complements the carbon-rich bulking agents like coconut shells, sugarcane leaves, and banana peels. Studies have shown that co-composting fecal sludge with organic bulking agents improves compost stability, reduces pathogen levels, and enhances nutrient quality for use as organic fertilizer Vinnerås et al. (2006).

This review presents the findings of previous studies on co-composting fecal sludge with various bulking agents such as coconut shells, waste tea powder, banana peels, and sugarcane leaves. It highlights research gaps and areas that require further investigation to optimize fertilizer production.

1. Coconut Shells: Structural Benefits and Nutrient Enrichment

Coconut shells, being high in potassium, calcium, magnesium, and phosphorus, are widely recognized for improving soil structure and nutrient retention. Studies have shown that the porous nature of coconut shells enhances compost aeration, promotes microbial activity, and improves moisture retention, which aids plant growth.

While the use of coconut shells in general composting is well-studied, there is limited research on their specific application in co-composting with fecal sludge. Most research overlooks how coconut shells affect the balance of nitrogen, phosphorus, and potassium (N-P-K) in combination with fecal matter. Further exploration is needed on microbial interaction and nutrient release dynamics when co-composting fecal sludge with coconut shells. Siregar and Zakaria (2019)

2. Waste Tea Powder: Nitrogen-Rich Agent for Improved Soil Fertility

Tea waste is known for its high nitrogen content, which aids microbial activity and soil fertility. Several studies report that tea waste increases nitrogen levels, supports soil structure by reducing compaction, and improves drainage. The fibrous nature of tea waste also aids in enhancing soil texture and maintaining porosity, which is beneficial for plant growth.

Although the effectiveness of waste tea powder in improving compost quality is known, there is a lack of research on its co-composting potential with fecal sludge. In particular, research on the long-term effects of waste tea on pathogen reduction and microbial stability when combined with fecal matter is scarce. Future studies should also focus on the optimal quantity of tea powder required for maximizing nutrient content in co-composted materials. Kaya (2021).

3. Banana Peels: Potassium-Rich Agent for Nutrient Cycling

Banana peels are rich in potassium, phosphorus, and trace minerals that play a significant role in promoting nutrient cycling and microbial activity during composting. Studies demonstrate that banana peels enhance soil fertility by improving potassium and phosphorus levels and help increase microbial activity, facilitating faster decomposition and enhanced nutrient uptake by plants.

While banana peels have been studied extensively in composting, their application in co-composting fecal sludge remains underexplored. Future studies should examine the specific nutrient ratios (especially potassium) contributed by banana peels when co-composted with fecal sludge. Additionally, more research is needed on how banana peels affect pathogen removal and the stabilization of fecal sludge in the composting process. Pariyar et al. (2020).

4. Sugarcane Leaves: Carbon-Rich Agent for Soil Health

Sugarcane leaves are high in organic carbon, nitrogen, potassium, and calcium, making them suitable for improving soil health. Research indicates that sugarcane leaves can significantly enhance soil structure, moisture-holding capacity, and microbial activity when composted with organic waste. Their contribution to the carbon-to-nitrogen (C:N) ratio ensures a balanced composting process.

Although sugarcane leaves are recognized for their high carbon content, their role in co-composting with fecal sludge is not well studied. The specific effects of sugarcane leaves on nitrogen retention and microbial stability in fecal sludge composting need to be investigated. Studies should also examine the optimal combination of sugarcane leaves with other bulking agents to enhance the quality of compost derived from fecal sludge Jain et al. (2018).

5. Co-Composting Fecal Sludge with Organic Waste: Pathogen Reduction and Nutrient Optimization

Co-composting fecal sludge with organic waste has been studied for its potential to reduce pathogen levels and optimize nutrient content (especially N-P-K). Research shows that combining fecal sludge with organic bulking agents stabilizes the compost, improves microbial activity, and enhances the nutrient profile, particularly nitrogen, phosphorus, and potassium. However, the use of specific locally available materials like coconut shells, banana peels, sugarcane leaves, and tea waste in this context is still limited.

While co-composting is recognized as a promising solution for waste management, there are few studies that specifically address how various locally available bulking agents interact with fecal sludge in terms of pathogen reduction, nutrient balance, and compost maturity. Further studies should aim to identify the optimal ratios of these agents to maximize nutrient content and minimize health risks in co-composted fertilizers Ndungu-Magiroi et al. (2019).

The reviewed literature provides insights into the potential of using coconut shells, waste tea powder, banana peels, and sugarcane leaves as bulking agents in co-composting fecal sludge. While research has demonstrated the benefits of these materials in general composting, specific studies focusing on their use in fecal sludge composting are limited. Future research should focus on optimizing the combination and ratios of these bulking agents to enhance nutrient content, compost maturity, and pathogen safety in co-composted fertilizers.

MATERIALS AND METHODS

Composting Materials

In this study, faecal sludge (FS) obtained from on-site sanitation systems, such as pit latrines and septic tanks, was combined at appropriate ratio. Following this, the mixture underwent dewatering on sand drying beds, achieving a total solids content of approximately 30–40%, as previously detailed by Manga et al. (2021). The selected bulking agents for this investigation included coconut shells, banana peels, sugarcane leaves, and waste tea powder. Coconut shells, banana peels, and sugarcane leaves were obtained from a nearby farm, while waste tea powder was sourced from local restaurants. The weighing, mixing and composting of sample has been carried out as shown in figure 2. To ensure the exclusion of non-biodegradable items, all collected bulking agents underwent meticulous sorting before the construction of composting piles. For a comprehensive overview, Table 1 provides essential physical and chemical characteristics of the raw materials utilized in this research. 3 represents the weighing, mixing and composting process)

For a comprehensive overview, Table 1 provides essential physical and chemical characteristics of the raw materials utilized in this research.

Sample Collection

A representative sample of approximately 1 kg was collected from each composting pile, following the detailed procedure outlined in Manga et al. for obtaining representative samples

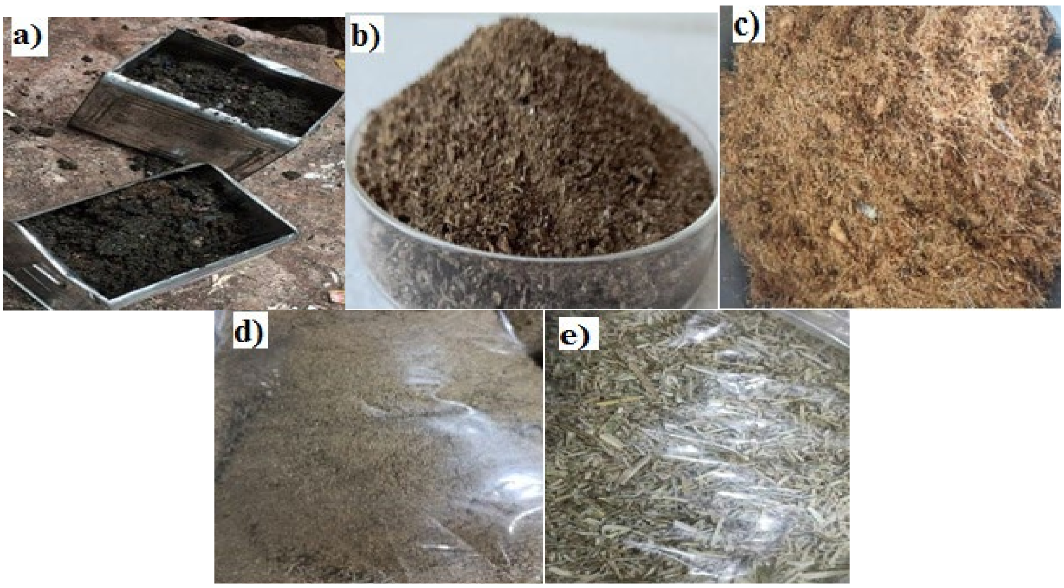

Fig. 1. Materials used for composting a) Faecal Sludge, b) Powdered banana peels, c) Powdered coconut shell, d) Waste tea powder, e) Powdered sugarcane leaf

Table 1. Chemical Characteristics of raw material used

No.	Parameter (unit)	Limit as per FCO	Dewatered FS	Coconut shell	Banana peel	Sugarcane leaf	Waste tea powder
1.	Colour	Dark Brown to Black	Dark Brown	Pale Brown	Brown	Yellowish Green	Brown
2.	Foul Odour	Absent	Absent	Absent	Absent	Absent	Absent
3.	Particle Size	Min 90% Material should pass through 4.0 mm IS Sieve	Confirms	Confirms	Confirms	Confirms	Confirms
4.	Bulk Density (g/cm^3)	<1.00	0.69	0.27	0.24	0.19	0.48
5.	Nitrogen (%)	>0.8	02.04	01.12	01.33	00.72	02.61
6.	Phosphorous (%)	>0.4	00.73	00.26	00.13	00.21	00.54
7.	Potassium (%)	>0.4	00.06	01.01	02.11	00.76	00.52
8.	C/N Ratio	<20	11.70	39.74	35.07	66.07	20.41
9.	Organic Carbon (on Dry Basis) (%)	>12	41.40	53.75	49.36	49.86	55.74
10.	Organic Matter (on Dry Basis) (%)	>30	71.38	92.66	85.10	85.95	96.10
11	pH	6.5-7.5	06.27	05.40	07.11	05.81	05.90
12	Electric Conductivity (mmhoms/cm)	<4.0	01.99	03.65	04.88	02.17	01.54
13	Moisture (%)	15-25	42.49	17.40	05.48	04.48	04.60
14	Ash (%)	5-15	16.46	06.06	14.08	13.42	03.72
15	Pathogens	Absent	Present	Present	Absent	Absent	Absent
16	Calcium (%)	<0.5	01.11	01.06	02.19	01.68	01.08
17	Magnesium (%)	>1.2	00.09	00.20	00.45	00.27	00.06
18	Sulphur (%)	>1	00.47	00.08	00.10	00.06	00.08
19	Iron (%)	>19	00.50	328.40	299.53	0.29	133.29
20	Manganese (mg/L)	>2	113.21	19.54	468.92	93.06	112.25
21	Zinc (mg/L)	>0.6	386.61	13.44	28.79	15.99	13.80
22	Copper (mg/L)	>2	79.58	38.78	35.55	10.15	05.05
23	Boron (mg/L)	>0.5	10.15	40.21	36.10	14.09	13.18
24	Molybdenum (mg/L)	<0.2	04.23	01.39	00.36	01.85	00.48
25	Total Plate Count (cfu/g)	>5 X 10^7	16 X 10^7	20 X 10^6	28 X 10^6	65 X 10^6	27 X 10^6
26	Total Fungal Count (cfu/g)	5.21×10^3 to 2.57×10^4	30 X 10^4	23 X 10^4	12 X 10^4	43 X 10^3	15 X 10^4
27	Nitrogen Fixing Organisms (cfu/g)	>5 X 10^7	59 X 10^3	45 X 10^3	70 X 10^3	68 X 10^3	60 X 10^3
28	Phosphorous Solubilizing Organisms (cfu/g)	25 X 10^3 to 550 X 10^3	75 X 10^3	65 X 10^3	60 X 10^3	56 X 10^3	55 X 10^3
29	Escherichia coli (cfu/g)	Absent	Present	Present	Absent	Absent	Absent
30	Actinomycetes (cfu/g)	>5 X 10^7	240	230	190	230	210

from composting piles. This collected sample was then divided into two equal portions. The first portion underwent air-drying, grinding, and sieving through a <2 mm mesh sieve for analyses, including total Kjeldahl nitrogen (TKN), total organic carbon (TOC), micro and macro elements (total potassium (TK), total phosphorus (TP), magnesium (Mg), calcium (Ca), sodium (Na), iron (Fe), manganese (Mn)), and toxic heavy metals (copper (Cu), nickel (Ni), lead (Pb), cadmium (Cd), chromium (Cr), and zinc (Zn)). The second portion of the fresh sample was preserved at 4 ◦C and analyzed within <4 h for pH, electrical conductivity (EC), moisture content, ammonium-nitrogen (NH4+-N), nitrates (NO3−-N), plant growth index (PGI), and CO2-C respiration rate. Compost samples were collected throughout the composting period of 45 days, and these samples were transported to the laboratory for analysis. Figure 1 represents the materials used for composting)

Application of Python in generating random percentage values in specified range:

The Python and Microsoft Excel software has proposed the optimal proportions for achieving the best results with the aforementioned bulking agents. The composting piles were observed over a 60-day period, spanning from November to December, with relative humidity ranging between 69–80% and air temperatures between 19–26 ◦C. To shield the piles from rain, a composting shade roofed with clear polycarbonate roofing sheets was utilized. Regular monitoring of moisture levels in all composting piles ensured that they were adequately moistened to maintain the recommended moisture content range of 50–65% for effective aerobic composting conditions throughout the entire composting process. Daily temperature measurements were taken at the top (approximately 750 mm from the pile base), middle (400 mm from the pile base), and bottom (200 mm from the pile base) of the composting piles using a TFA (D-Wertheim, Model 19.2008, Sandy, UK) stainless steel body compost thermometer. Following python code has been used:

```
import random
i=0
number_of_sample =int(input("Enter number of samples to be generated = "))
while number_of_sample>i:
while True:
col1 = random.randint(30, 40)
col2 = random.randint(10, 20)
col3 = random.randint(10, 20)
col4 = random.randint(10, 20)
col5 = random.randint(5, 10)
if col1+col2+col3+col4+col5 ==100:
print(f"{col1}, {col2}, {col3}, {col4}, {col5}")
i+=1
break
```

Breakdown of code step by step:

1. User Input: The code starts by asking the user to input the number of samples they want to generate.
2. Looping through Samples: The code then enters a loop where it will generate the specified number of samples. (1-20 sample)
3. Inner Loop: Inside this loop, the code continuously generates random values for five different variables (col1, col2, col3, col4, col5) until their sum equals 100.

Random Values: The code uses the random.randint() function to generate random integer values within specified ranges for each of the five variables:

– col1 is between 30 and 40.

–col2, col3, col4 are between 10 and 20.

– col5 is between 5 and 10.

Sum Check: After generating random values, the code checks if the sum of these values equals 100.

4. Print and Increment: If the sum equals 100, the code prints out the values of col1, col2, col3, col4, col5 separated by commas and increments the counter i.
5. Repeat or Exit Inner Loop: The inner loop continues generating random values until a set of values is found that sum up to 100. Once found, the loop breaks and moves on to the next sample.

6. Repeat or Exit Outer Loop: The outer loop repeats the process of generating samples until the specified number of samples have been generated.
7. End of Program: Once the specified number of samples have been generated and printed, the program ends.

In summary, this code generates a specified number of samples where the sum of five random values falls within the range of 100, with each value having its own specified range.

Application of MS Excel for calculation of values:

1. Shortlist Materials According to Units:
- Create a table in Excel listing all materials along with their respective units.
- Filter or sort the materials based on their units to create separate lists for each unit type.

2. Calculate Mean of Ingredients for Shortlisted Materials:
- Identify the ingredients associated with each shortlisted material.
- Use Excel's AVERAGE function to calculate the mean (average) of the ingredients for each shortlisted material.

3. Multiply Mean by Percentage to Get Percentage Amount:
- For each shortlisted material:
- Multiply the mean of its ingredients by the corresponding percentage value obtained from the Python code.
- Use a formula like =Mean * Percentage in Excel to perform this calculation.
- Repeat this calculation for each material in the shortlisted materials list.

4. Compare with the limit as per FCO column.
- Compare the sum of all ingredients in the material percentage taken and compare it with the FCO limits if it matches the range of FCO limit, we can consider it as the best percentage quantity of ingredients should be taken to form a best sample of material. If it does not match, recalculate the python readings.

Stepwise Procedure to identify the quantity of materials:

1. Generated Random Percentage Samples for Ingredients:
- Utilize Python code or any random number generation method to create 20 samples of percentages for five ingredients in a material.
- Ensure that each sample set sums up to 100%, representing the total composition of the material.

2. Shortlisted Materials Based on Units:
- In Excel, create a table listing materials along with their respective units.
- Filter materials based on units to create separate lists for each unit type.
- For instance, if materials have units like grams, milliliters, or percentages, create separate lists for each unit type to facilitate analysis.
- This step helps organize materials for further analysis based on their units, making it easier to manage and analyze data.

3. Calculated Ingredient Values Based on Percentage Samples:
- For each material in the shortlisted lists:
- Use the generated percentage samples to calculate ingredient values.
- Multiply each percentage by the mean or average value of the corresponding ingredient.
- Repeat this process for all five ingredients in each material.

4. Analyzed Ingredient Values and Compare to Limits:

- Sum up the ingredient values calculated for each material.
- Compare the total ingredient value to the limits provided by the Fco (Food Chemicals Codex) or any other relevant standards or specifications.
- For instance, if the Fco specifies limits for each ingredient in a material, compare the total ingredient value to these limits to determine if the material meets the specified standards.
- Determine if the material meets the specified limits or if adjustments are needed based on the analysis.
- If the total ingredient value exceeds the limits, adjustments may be needed to ensure compliance with standards.

5. Findings:

- Analyze the results obtained from comparing ingredient values to limits.
- Based on the analysis, draw conclusions regarding the suitability of the materials.
- Consider factors such as compliance with standards, potential adjustments needed, and implications for material selection.
- Summarize the findings and implications of the analysis to provide a clear conclusion.
- Based on the analysis and conclusions, make recommendations regarding the selection of ingredients for optimal material composition.
- Consider factors such as ensuring compliance with standards, meeting desired specifications, and optimizing material properties.
- Provide specific recommendations based on the analysis to guide decision-making regarding material selection and formulation.

Composting Process and Sampling:

The proportions for raw materials, including FS, coconut shell, banana peel, sugarcane leaf, and waste tea powder, were determined based on their availability, with a specified threshold range for each. The thresholds were set as follows in Table 3:

Mixing dewatered FS containing approximately 30–40% total solids with various sorted bulking agents was a meticulous process. Compost static piles, each with a volume of 3 m3, were carefully constructed utilizing the following proportions in Table 2:

The Table 3 encapsulates a comprehensive array of parameters meticulously analyzed within organic fertilizer samples, crucial for evaluating their efficacy and potential implications on soil fertility and crop yield. Each parameter provides insights into various aspects of the fertilizer's composition and characteristics, contributing to a holistic understanding of its suitability for

Table 2. Threshold range of materials

Raw Material	FS	Coconut shell	Banana peel	Sugarcane leaf	Waste Tea powder
Threshold range	30-40	5-20	5-10	5-10	5-10

Table 3. Proportions of materials

Sample No.	FS (70-100)	Coconut shell (5-20)	Banana peel (5-10)	Sugarcane leaf (5-10)	Waste Tea powder (5-10)
1	38	17	16	19	10
2	38	15	20	18	9
3	38	17	18	20	7
4	39	20	20	14	7
5	40	18	19	17	6
6	40	14	19	17	10
7	39	15	19	18	9
8	38	20	15	20	7
9	40	19	20	13	8
10	39	15	19	20	7

agricultural use. Total 10 samples have been analyzed using 33 parameters. Due to space limitations, 2 representative samples has been presented in Table 4.

Analytical Methods

The moisture content was determined by calculating the difference between the initial and final weights of the sample after oven drying at 105 ◦C for 24 hours, following the procedure outlined in Okalebo et al. (2002). The oven-dried samples (at 105 ◦C for 24 hours) were then ashed in a muffle furnace for 8 hours at 550 ◦C to quantify the total organic matter content, which was calculated as the difference between the sample weight before and after combustion

Table 4. Values of samples using various parameters

Parameter (unit)	Sample No.									
	R-1	R-2	R-3	R-4	R-5	R-6	R-7	R-8	R-9	R-10
pH	6.13	6.19	6.16	6.17	6.17	6.19	6.18	6.10	6.18	6.18
Electric Conductivity (mmhoms/cm)	2.72	2.81	2.80	2.89	2.84	2.76	2.78	2.76	2.87	2.79
Moisture (%)	21.29	21.07	21.31	22.10	22.21	21.69	21.44	21.67	22.35	21.44
Ash (%)	12.46	12.73	12.76	12.59	12.85	12.76	12.75	12.52	12.59	12.95
Organic Carbon (on Dry Basis) (%)	47.81	47.66	47.63	47.65	47.43	47.51	47.58	47.76	47.59	47.46
Organic Matter (on Dry Basis) (%)	82.43	82.16	82.11	82.15	81.78	81.91	82.03	82.34	82.04	81.82
C/N Ratio	31.41	31.15	32.16	30.20	30.95	30.18	30.92	32.30	29.47	31.83
Nitrogen (%)	1.58	1.57	1.53	1.57	1.55	1.61	1.58	1.53	1.60	1.54
Phosphorous (%)	0.44	0.43	0.42	0.43	0.43	0.44	0.43	0.43	0.44	0.43
Potassium (%)	0.73	0.78	0.76	0.79	0.77	0.75	0.76	0.73	0.78	0.76
Bulk Density (g/cm^3)	0.44	0.43	0.43	0.44	0.44	0.45	0.44	0.43	0.44	0.43
Calcium (%)	1.38	1.42	1.41	1.39	1.40	1.40	1.41	1.37	1.39	1.42
Magnesium (%)	0.20	0.21	0.21	0.21	0.21	0.20	0.20	0.20	0.20	0.21
Sulphur (%)	0.23	0.23	0.23	0.23	0.24	0.24	0.23	0.23	0.24	0.23
Iron (%)	117.33	121.40	119.32	135.15	124.27	116.47	118.41	120.19	133.20	115.75
Manganese (mg/L)	150.2	166.5	157.22	162.73	160.45	164.16	163.03	143.74	163.86	162.65
Boron (mg/L)	20.46	20.83	20.93	22.12	21.34	20.26	20.57	21.05	21.81	20.59
Molybdenum (mg/L)	2.30	2.26	2.31	2.29	2.35	2.32	2.30	2.34	2.31	2.33
Total Plate Count (cfu/g)	8.37E+07	8.35E+07	8.41E+07	8.30E+07	8.56E+07	8.59E+07	8.49E+07	8.39E+07	8.40E+07	8.56E+07
Total Fungal Count (cfu/g)	195470	193740	193800	203520	200510	197310	195540	197100	205290	193400
Nitrogen Fixing Organisms (cfu/g)	60190	60810	60470	59730	60160	60760	60700	59720	59790	60860
Phosphorous Solubilizing Organisms (cfu/g)	164740	153030	164850	182940	171220	147420	153180	182550	177180	153200

Okalebo et al. (2002). pH and electrical conductivity (EC) measurements were conducted in a water-soluble extract with a 1:10 (w/v) ratio, using a pH electrode and EC probe of a HACH multi-meter (sensION MM374), respectively. Compost samples were analyzed for organic carbon by oxidation using potassium dichromate Liu et al. (2011), Manga et al. (2021). Nitrogen content was analyzed following the Kjeldahl method for total Kjeldahl nitrogen (TKN), while nitrate ($NO3^{-}$-N) and ammonium ($NH4^{+}$-N) were extracted with 0.5 K2SO4 in a 1:10 (w/v) ratio from fresh compost samples and determined by spectrophotometric methods according to procedures reported in the literature Liu et al. (2011), Pariyar et al. (2020). Organic matter (OM), nitrogen, and total organic carbon (TOC) losses were computed according to Equations (1)–(3) Bernal et al. (1998).

$$OM\,loss(\%)=100-100\left[X1(100-X2)\right]/\left[X2(100-X1)\right] \quad (1)$$

$$NT\,loss(\%)=100-100\left[(X1Nf)/(X2/Ni)\right] \quad (2)$$

$$TOC\,loss(\%)=100-100\left[(X1TOCf)/(X2/TOCi)\right] \quad (3)$$

Where X1 and X2 are the initial and final ashes content (%); Ni and Nf are the initial and final content of total nitrogen ($\boldsymbol{TKN+NO3--N}$).$\boldsymbol{TOCi\ and\ TOCf}$ are the initial and final content of TOC.

The microbial respiratory activity in compost samples was measured through the evolution rate of CO2-C in closed bottles, following Öhlinger's soil respiration techniques, with modifications based on similar procedures reported in the literature. In this method, CO2-C was captured in an alkaline solution (KOH) and titrated with a HCl solution (0.5M). The resulting CO2-C production rate was expressed as mg CO2-C per mass of organic matter (as Volatile Solids–VS) per day. For the analysis of toxic elements/heavy metals (Cu, Ni, Pb, Cd, Cr, and Zn), air-dried samples underwent digestion using a mixed acid solution (HClO4 + HNO3 + H2SO4), and the wet-digest was used to determine the concentrations of each element via atomic absorption spectrophotometry. Macro and micronutrients (K, TP, Mg, Ca, Na, Fe, Mn) analysis involved digestion with sulfuric acid-hydrogen peroxide, with subsequent determination of Mg, Ca, Mn, and Fe content using atomic absorption spectrophotometry. K and Na concentrations were determined using a flame photometer. Total phosphorus was assessed on wet digests using the ascorbic acid method.

Statistical Analysis

The reported results are presented as average values with standard deviation, derived from duplicate measurements. Statistical analyses were performed using the Python & Microsoft Excel Trial version software, which can be accessed at https://www.Python & Microsoft Excel.com/en-us/support/downloads/. The data underwent analysis utilizing the design of experiment to determine the significance of differences among mean values. Design Mixture was utilized to explore relationships between variables, with a significance level set at $p < 0.05$.

RESULTS AND DISCUSSION

pH Evolution

The figure 1 showcases pH values for ten samples, ranging from 6.1041 to 6.1926. The specific pH readings for each sample are as follows: 6.1321, 6.1914, 6.1554, 6.1737, 6.1726, 6.1926, 6.183, 6.1041, 6.1833, and 6.1812 as shown in figure 4. These readings suggest

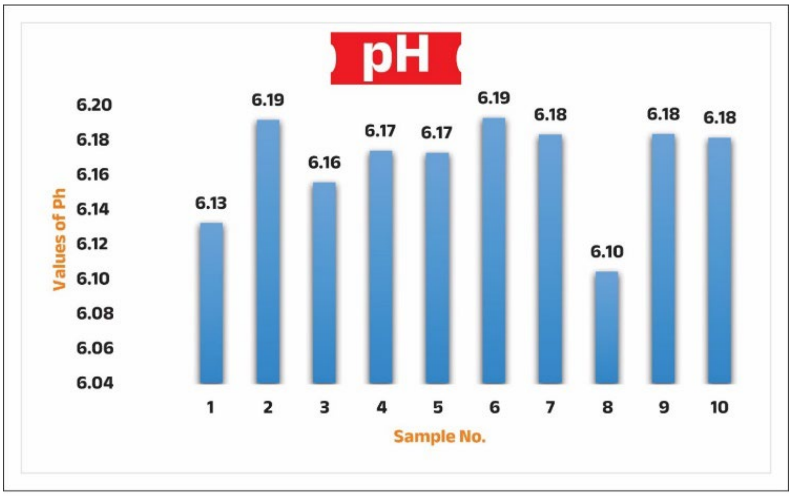

Fig. 4. pH evolution during composting period

a relatively narrow pH range, with an average pH of approximately 6.17, indicating a close clustering of individual values around this central figure. Such consistency in pH levels may imply uniformity or stability within the system or environment from which the samples were obtained. However, further analysis would be required to discern the specific context and implications of these pH measurements, including whether they reflect natural variations or responses to experimental conditions.

In Figure 4 pH evolution during composting of faecal sludge-FS with: (a) brewery waste-SBW; error bars represent the standard deviation of the bottom, centre, left side, and right-side pile temperatures.

During the thermophilic phase, all composting piles demonstrated decreases in pH values. This trend can be attributed to ammoniacal nitrogen volatilization and the precipitation of carbonate in the form of calcium carbonate Eklind et al. (2000), as observed during the composting of pig manure with sawdust. Our study findings suggest that the three tested bulking agents have a significant effect ($p = 0.0001$) on the pH evolution during faecal sludge composting.

In our study, we noted that piles exhibited a longer duration of the thermophilic phase due to their water retention capacity, high carbon content, and availability of a higher specific surface for microbial attack, all of which support microbial activities for an extended period. This observation aligns with findings by Leconte et al. (2009) during the co-composting of sawdust with poultry manure. The prolonged thermophilic phase can be attributed to the intensive microbial activities during the early stages of composting, which may have led to the faster consumption and depletion of easily biodegradable carbon in the piles, resulting in a decrease in microbial activities and temperatures during the later stages. Previous research has also found microbial activities to be influenced by the presence of easily biodegradable carbon sources during composting Liu et al. (2011), Cáceres et al. (2006).

In our study, we considered the composting process complete once the composting temperatures reached ambient levels, which was observed to occur over a composting period of 37 days. A detailed discussion on the temperature evolution of these composting piles is presented in a separate note elsewhere Manga, et al. (2021). We observed evidence indicating that the types of bulking agents have a statistically significant effect ($p = 0.0001$) on the evolution of composting temperatures of faecal sludge. Furthermore, all composting piles achieved and maintained the optimum conditions recommended for effective and complete sanitization of the composting material.

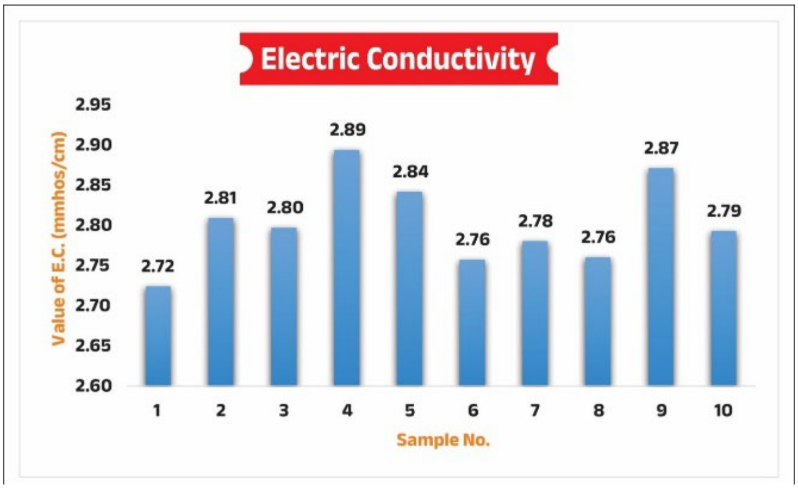

Fig. 5. Changes in Electric Conductivity

Fluctuation in electric conductivity

The dataset's oscillations are visible in the electric conductivity values shown in figure 2, which range from 2.7238 to 2.8937 milliohms per centimetre. According to figure 5, the samples' exact values are 2.7238, 2.8089, 2.7969, 2.8937, 2.8415, 2.7571, 2.78, 2.76, 2.8708, and 2.7926. These variations in conductivity levels could be a sign of shifts in the ions dissolved in the solution or changes in the conductivity characteristics of the soil. When properly balanced, higher conductivity readings may indicate a larger concentration of ions and, consequently, a higher quantity of dissolved salts or nutrients, which could be advantageous for plant growth.

To maintain soil fertility and restore vital nutrients, lower conductivity levels may suggest a reduction in ion concentration and the need for organic fertiliser addition. In order to ensure healthy plant growth and maximize agricultural productivity, it is crucial to monitor changes in electric conductivity in order to measure soil nutrient levels and determine the optimum application of organic fertilisers.

In figure 2, the Evolution of: (A) pH; and (B) electrical conductive (EC) during the composting of Faecal Sludge-FS with different bulking agents. Error bars represent the standard error of n = 2.

Changes in moisture content

Ten samples' moisture levels are shown in the dataset that is provided. The percentages of the samples' values range from 21.0726% to 22.3484%. Each sample shows a slightly varying amount of hydration, according to these readings, which show variations in moisture content throughout the samples. As illustrated in Figure 6, the moisture values for each sample are specifically 21.2922%, 21.0726%, 21.3086%, 22.0963%, 22.2068%, 21.6948%, 21.4427%, 21.6662%, 22.3484%, and 21.4403%. Despite the relatively small range of moisture levels, the differences that are seen within this range may have a big impact on environmental or agricultural management.

Since moisture content directly affects soil fertility, plant growth, and overall crop health, it is imperative to monitor it in agricultural activities. For plants to establish their roots, germination of seeds, and uptake of nutrients, the ideal moisture content is required. Consequently, successfully determining and controlling moisture levels is essential to guaranteeing successful crop yields and sustainable agricultural methods.

Additionally, the amount of moisture in an ecosystem has a significant impact on things like

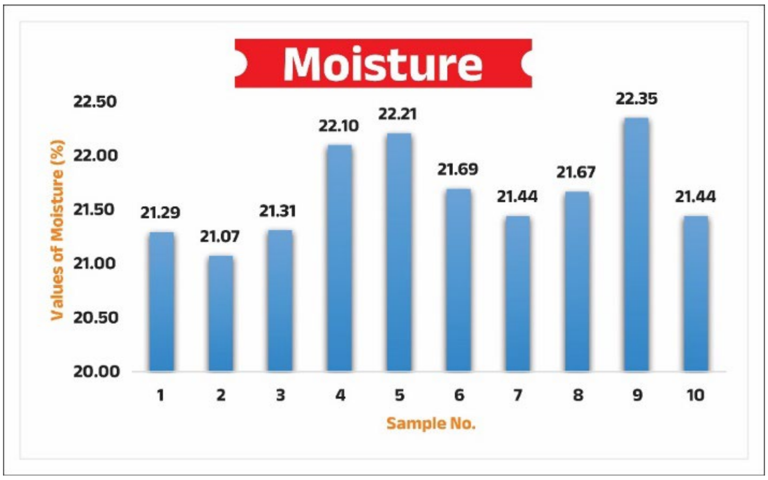

Fig. 6. Fluctuation in Moisture content

soil erosion, groundwater recharge, and the viability of a habitat for different kinds of creatures. Variations in moisture content can impact an ecosystem's plant and animal species distribution, water resource availability, and slope stability.

In conclusion, the moisture data presented emphasises how critical it is to keep an eye on and regulate moisture levels in environmental and agricultural contexts. Stakeholders can ultimately increase agricultural output and ecosystem health by conserving habitat, managing soil, and deciding on irrigation strategies by having a clear grasp of the differences in moisture content between samples.

Changes in Ash content

The percentages ranging from 12.4596% to 12.948% are shown by the ash content statistics for organic fertiliser samples that have been submitted. According to figure 7, the specific ash content readings for each sample are 12.4596%, 12.7302%, 12.7638%, 12.5866%, 12.8546%, 12.761%, 12.754%, 12.5232%, 12.5936%, and 12.948%. Understanding the mineral makeup of organic fertilisers is essential for determining their quality and applicability for agricultural use, and these readings provide that knowledge. Ash content analysis aids farmers in determining the purity and nutrient content of organic fertilisers made from organic waste materials like compost, manure, and plant leftovers.

An ideal ash concentration indicates a well-balanced mineral composition, which improves soil fertility and supports long-term crop production. Superior organic fertilisers usually have a moderate ash content, which guarantees sufficient amounts of vital nutrients and reduces the possibility of contaminating the soil. On the other hand, an abnormally high ash concentration could indicate contamination or low-quality organic inputs, which could result in nutritional imbalances in the soil and have a negative impact on crop health. In order to ensure that organic fertilisers are effective in enhancing crop yields, supporting ecologically responsible farming practices, and encouraging soil health, it is imperative to monitor the ash content of these fertilisers.

Evolution of organic carbon

Ten samples of organic fertiliser are included in the dataset, with the organic carbon values reported as percentages on a dry basis. The range of values is 47.434% to 47.8145%. The individual readings for each sample are as follows: as illustrated in figure 8, 47.8145%,

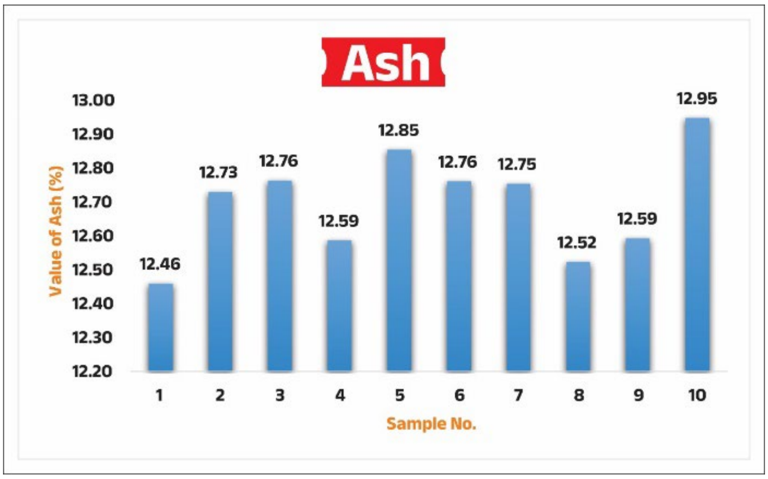

Fig 7. Change in ash content

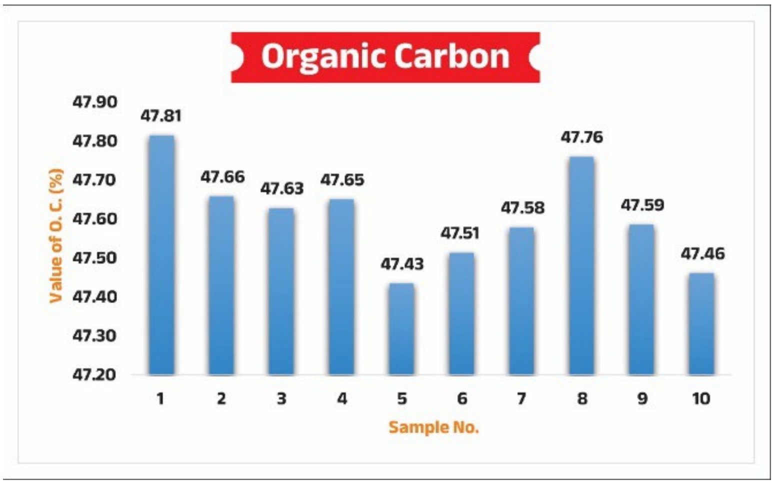

Fig. 8. Evolution of organic carbon

47.6579%, 47.6281%, 47.6502%, 47.434%, 47.5136%, 47.5783%, 47.7598%, 47.5855%, and 47.4607%. Since it indicates the quantity of organic matter available to support soil microbial activity and nutrient cycling, organic carbon content is an essential indicator of the quality and nutrient composition of organic fertilisers. Increased soil organic matter buildup can lead to better soil structure, moisture retention, and nutrient availability. This is indicated by higher amounts of organic carbon in the soil.

By decreasing the need for synthetic fertilisers and minimising their negative effects on the environment, organic fertilisers with a higher percentage of organic carbon can improve soil fertility and support sustainable agricultural practices. The fertilizer's ability to promote plant development and enhance soil health may be compromised if its levels of organic carbon are reduced, as this could indicate a decrease in the amount of nutrients present or a breakdown of the organic matter. In order to ensure that organic fertilisers are efficient in improving crop yields, enhancing soil fertility, and promoting long-term soil sustainability in agricultural systems, it is imperative to measure the amount of organic carbon in the fertilisers

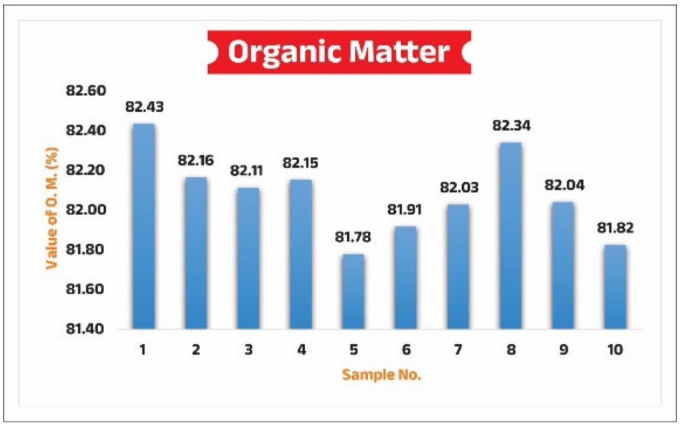

Fig. 9. Fluctuation in organic matter

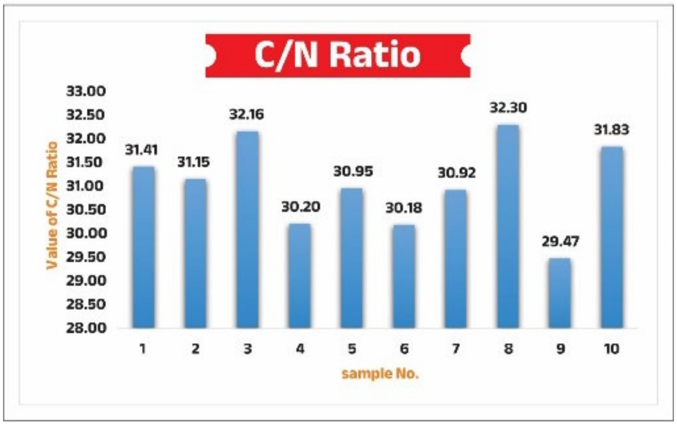

Fig. 10. Rise and fall in carbon to nitrogen ratio

Changes in Organic matter content

Ten samples of organic fertiliser are included in the dataset, with the organic matter levels reported as percentages on a dry basis. 81.7773% to 82.4331% are the range of these values, and figure 9 shows the specific readings for each sample: 82.4331%, 82.1634%, 82.1116%, 82.1502%, 81.7773%, 81.9149%, 82.0262%, 82.3384%, 82.0389%, and 81.8232%. The concentration of decomposed plant and animal leftovers in organic fertilisers is reflected in their organic matter content, which is a crucial factor in determining their quality and nutrient composition. Elevated levels of organic matter indicate increased potential for the build-up of soil organic carbon, which in turn promotes improvements in soil structure, moisture retention, and nutrient availability.

By lowering dependency on synthetic inputs and reducing environmental degradation, organic fertilisers with higher organic matter content can effectively improve soil fertility, stimulate microbial activity, and support sustainable farming practices. Lower amounts of organic matter, on the other hand, can be a sign of a decreased nutrient content or organic material breakdown in the fertiliser, which could have an effect on how well it works to improve soil health and promote plant development. In order to ensure that organic fertilisers are efficient in enhancing soil fertility, increasing crop yields, and promoting long-term sustainability in agricultural systems, it is imperative to monitor the amount of organic matter in them.

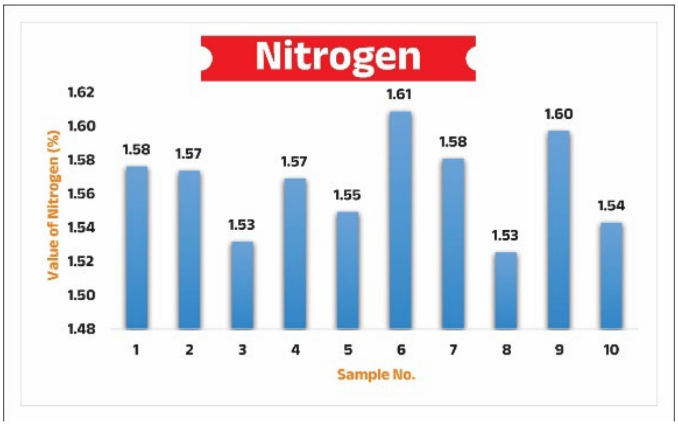

Fig. 11. Changes in Nitrogen content

Changes in Carbon to Nitrogen ratio

Ten samples of organic fertiliser are shown with their C/N ratio values in the dataset that is provided. The range of these ratios, which show differences in the carbon-to-nitrogen ratio among the samples, is 29.4665 to 32.2972. As illustrated in figure 10, the C/N ratio measurements for each sample are specifically 31.4073, 31.1505, 32.1571, 30.2035, 30.953, 30.1798, 30.9168, 32.2972, 29.4665, and 31.83. Because it affects soil fertility, microbial activity, and nutrient availability, the carbon-to-nitrogen ratio is a crucial metric in the analysis of organic fertilisers. For optimum plant growth and soil health, a balanced C/N ratio is necessary to support effective nutrient cycling and decomposition processes.

Higher C/N ratio organic fertilisers might contain more carbon-rich organic matter, which improves soil over time and sequesters organic carbon in the soil. On the other hand, lower C/N ratios could indicate a higher nitrogen content than carbon, which could have an impact on soil fertility by causing nitrogen to be lost by volatilization or leaching. In order to evaluate organic fertilisers' quality, nutrient composition, and suitability for sustainable farming methods, it is imperative to keep an eye on their C/N ratio. Farmers can optimise the application of organic fertiliser, improve soil productivity, and promote ecologically responsible farming practices by comprehending and controlling the C/N ratio.

Variation of Nitrogen content

Ten samples of organic fertiliser are included in the dataset, and the nitrogen content values are shown as percentages. These figures, which reflect variability in nitrogen concentration throughout the samples, vary from 1.5254% to 1.6089%. As illustrated in figure 11, the nitrogen content measurements for each sample are specifically 1.5762%, 1.5737%, 1.5317%, 1.5691%, 1.5493%, 1.6089%, 1.5808%, 1.5254%, 1.5972%, and 1.543%. An essential component of organic fertiliser, nitrogen is necessary for protein synthesis, plant development, and total crop yield.

In order to maximise agricultural production, improve soil fertility, and encourage healthy plant development, organic fertilisers must include the ideal amounts of nitrogen. While lower nitrogen levels may require supplementing to meet plant nutritional requirements, higher nitrogen content in organic fertilisers can promote vigorous plant development and increase crop production. Thus, it is essential to keep an eye on the nitrogen level of organic fertilisers to guarantee a balanced nutrient composition, efficient soil management, and environmentally friendly farming methods. Farmers may optimise fertiliser application techniques, reduce

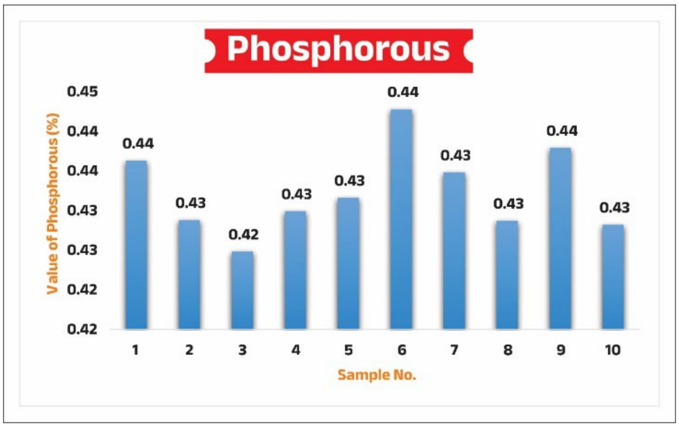

Fig. 12. Change in Phosphorous content

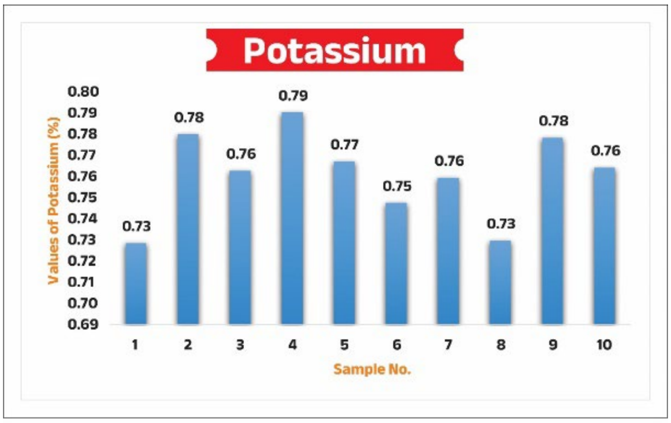

Fig. 13: Changes in Potassium content

negative environmental effects such nitrogen runoff, and promote long-term soil health and productivity by knowing and controlling nitrogen levels.

Transformation of Phosphorous content

Ten samples of organic fertiliser are included in the collection, and the phosphorus content measurements are shown as percentages of P2O5. These figures, which show variability in phosphorus concentration throughout the samples, vary from 0.4248% to 0.4428%. The phosphorus content values for each sample are as follows, as indicated in figure 12: 0.4363%, 0.4288%, 0.4248%, 0.4299%, 0.4316%, 0.4428%, 0.4348%, 0.4379%, and 0.4282%. An essential component of organic fertilisers, phosphorus helps plants expand their roots, bloom, and bear fruit.

To maximise crop output, improve plant vigour, and raise overall agricultural production, organic fertilisers must have the ideal amount of phosphorus. Increased yields and improved crop quality can result from stronger root development, better flowering and fruit set, and higher phosphorus concentration in organic fertilisers. However, in order to meet the nutrient requirements of plants and avoid indications of phosphorus deficiency, such as stunted growth and poor fruit development, lower phosphorus levels may require supplementation. In order to ensure a balanced nutrient composition, efficient soil management, and sustainable agricultural practices, it is imperative to check the phosphorus level of organic fertilizers. Farmers may enhance soil fertility, optimize fertilizer application techniques, and promote healthy plant growth by monitoring and controlling phosphorus levels. These actions will ultimately increase agricultural output and sustainability over the long run.

Evolution of Potassium (K2O)

Ten samples of organic fertiliser with potassium content values reported as percentages of K2O are supplied in the dataset. These figures, which reflect variability in potassium concentration throughout the samples, vary from 0.7285% to 0.7902%. The potassium content values for each sample are as follows, as seen in figure 13: 0.7594%, 0.7297%, 0.7783%, 0.7671%, 0.7475%, 0.7799%, 0.7627%, 0.7902%, and 0.7642%. In organic fertilisers, potassium is an important nutrient that controls plant water uptake, enzyme activity, and general health.

In order to maximise agricultural output, improve crop quality, and increase resilience to diseases and environmental challenges, organic fertilisers must have optimal potassium levels. Increased yield, better fruit quality, and stronger stems can all be facilitated by more potassium content in organic fertilisers, especially in crops that need more potassium, including fruits and vegetables. On the other hand, low potassium levels could require supplementation to avoid indications of potassium deficiency such crop output reduction, foliage yellowing, and poor fruit quality. For this reason, keeping an eye on the potassium concentration of organic fertilisers is essential to maintaining a balanced nutrient composition, efficient soil management, and environmentally friendly farming methods. Farmers may optimise fertiliser application techniques, improve soil fertility, and promote healthy plant growth by monitoring and controlling potassium levels. These actions will ultimately contribute to the productivity and sustainability of agriculture over the long run.

CONCLUSION

This study highlights the effectiveness of co-composting faecal sludge (FS) with locally sourced bulking agents such as coconut shells, banana peels, sugarcane leaves, and waste tea powder. The research fills a significant gap by addressing the challenges of composting FS, including managing high moisture content, nitrogen loss, and slow decomposition rates, which are prevalent issues in rural and decentralized waste management systems.

A critical finding from this pilot-scale study is the superior performance of coconut shell as a bulking agent. It not only accelerates compost maturity but also significantly reduces nitrogen loss and enhances the compost's agronomic value, making it a potential game-changer in optimizing FS compost for agricultural applications. This finding is particularly innovative compared to other studies that have predominantly focused on more conventional bulking agents like sawdust and rice husk, which do not offer the same nutrient retention or structural benefits during composting.

The comparative analysis with existing composting studies reveals that while many efforts have succeeded in producing compost from organic waste, few have explored the specific integration of FS with bulking agents readily available in tropical regions. This research underscores the potential of such materials to address key composting challenges, particularly in resource-constrained settings where conventional materials might not be accessible.

Moreover, the use of Python for rigorous statistical analysis and Excel for data visualization allowed for the precise optimization of raw material proportions. The results indicated that the combination of coconut shell with banana peels and sugarcane leaves consistently maintained ideal temperature and pH levels, crucial for pathogen reduction and nutrient stabilization, outperforming other bulking agents.

This study not only contributes to the field of FS management by demonstrating a practical, low-cost approach to producing high-quality compost, but it also offers a scalable solution that aligns with the principles of the circular economy. It promotes the recycling of waste into valuable fertilizer, with substantial implications for enhancing soil health and sustainable agricultural practices in rural and semi-urban contexts. This research, by focusing on the specific challenges of FS composting and presenting novel solutions, marks a step forward in sustainable waste management.

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CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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