Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Enhancing Okra [Abelmoschus Esculentus (L.) Moench] Yield With Biosolid Mass Derived From Faecal Sludge: A Sustainable Approach

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This study evaluates the effects of biosolid mass (BM) obtained from a faecal sludge treatment plant (FSTP) in Bhongir, Telangana, on Okra (Abelmoschus esculentus (L.) Moench)[1] crop yields. The FSTP, situated in Bhuvanagiri (17.49° N, 78.91° E), has a capacity to treat 15 KLD of faecal sludge and began operations in 2020. The study measured seed germination rates, plant growth, pod length, pod weight, nutrient values and heavy metals (found to be within the limits as per norms). Okra plants grown in an experimental soil bed (ESB) with biomass compost (BMC) exhibited significantly improved growth attributes compared to those grown in a control soil bed (CSB). The germination rates were 37% for CSB and 39 % for ESB. Plants in CSB grew to heights between 0.6 and 0.7 meters, while those in ESB reached 1 to 1.2 meters. The pod weights during the first and second harvests on CSB were 519 g and 830 g, respectively, while they dramatically increased to 1176 g and 1713 g when BM mixed with BMC was used.

The aerobic treatment yielding Aerobically treated Biomass (ABM), and the combination with BMC, significantly enhanced okra yields, doubling and tripling production compared to the control. BMC demonstrated the highest nutrient content across all experiments, with a notable C/N ratio, total nitrogen, and total phosphate levels. Heavy metal analysis confirmed that the concentrations of arsenic, cadmium, and mercury in BMC-treated soil were within permissible limits. The results suggest that BMC is a potent sustainable fertilizer, improving okra yield and ensuring soil safety. This study confirms

[1] Okra (Abelmoschus esculentus) is a nutrient-rich vegetable, high in vitamins A, C, K, and essential minerals, offering health benefits like improved digestion and blood sugar regulation. Economically, it serves as a key cash crop, supporting farmers and the food processing industry. Agriculturally, okra's adaptability, low water requirements, and resilience make it sustainable and valuable in diverse farming systems.

the positive impact of biosolids obtained from stabilized fecal sludge on agricultural productivity, particularly for okra crops.

Keywords: Faecal sludge, Fecal sludge treatment plant, Biosolids, Okra, Macro and micronutrients, Okra crop yield, Heavy metals analysis, Agriculture productivity.

1. Introduction

Various techniques, such as aerobic or anaerobic fermentation, oxidation, dehydration by heating, and stabilization by adding alkaline products, are used to treat and stabilize biosolid mass (Collivignarelli et al. 2019). The sludge is disinfected and composted to prepare it for use as a biofertilizer. Pesticide residues have contaminated agricultural soils across the globe due to the overuse of chemical fertilizers and biocides. Unlike chemical fertilizers, biosolids derived from sewage water are highly beneficial in restoring soil fertility in an environmentally friendly way (Dad et al. 2019). The characteristics of biosolids, such as heavy metals and harmful pathogenic organisms (Kumar et al. 2017), as well as the content of organic and inorganic components, are determined by the composition of the wastewater and the method of treatment. Biosolids are an excellent option for bioremediation of farmlands that have been declared unsuitable for agriculture, as they are rich in essential nutrients like nitrogen and phosphorus, which plants require. They also contain other critical inorganic elements, including potassium, calcium, sulfur, and magnesium, which promote plant growth. Furthermore, biosolids can reclaim previously mined lands by following a systematic agronomic approach. Enriching biosolids with bacteria such as Actinomycetes and Rhizobium can also improve soil structure and fertility by secreting glycoproteins and fixing atmospheric nitrogen, respectively (Gougoulias et al. 2014).

The impact of biosolids on soil enrichment is a complex issue, as various geochemical and biological reactions occur in the agriculture ecosystem. As a result, researchers who undertake bioremediation of agricultural farmlands should consider the soil dynamics during and after the application of biosolids. While biosolids offer a promising alternative to chemical fertilizers, concerns regarding potential heavy metal contamination necessitate a comprehensive assessment of their safety. Excessive accumulation of heavy metals in the soil can lead to phytotoxicity, affecting plant growth and posing risks to human health through the food chain. Therefore, rigorous monitoring of heavy metal concentrations in biosolids and treated soils is crucial to ensure their safe and sustainable use in agriculture. A study by Silva-Leal et al. (2021) found that applying biosolids to sugarcane-cultivated inceptisols increased nitrogen content by 37% and enhanced phosphorus by 277%, leading to decreased uptake of phosphorus by crop plants. Similarly, Sukkariah et al. (2005) observed that after seventeen years of using biosolids to treat clay soil for growing vegetable crops, the uptake of copper and zinc decreased by 58% and 42%, respectively. In contrast, the values of nickel and cadmium showed linear and plateau-like responses, respectively.

The nitrogen, phosphorus, and potassium (NPK) values of soils and manures significantly impact crops' growth characteristics and yield. However, the actual situation in the soil ecosystem depends on various factors, including the direct availability of nutrients to plants and the soil microbiota in the area. While the use of nitrogen and phosphorus chemical fertilizers can increase crop yield and foliage (Ogunlela et al. 1989), prolonged usage can lead to soil pollution and potentially harmful consequences for humans throughout the food chain.

Therefore, finding alternative, environmentally-friendly ways to enrich the soil with the necessary nutrients for healthy plant growth, such as using biosolids, can be a viable option.
Okra is a high-value vegetable crop widely cultivated in tropical and subtropical regions, including India. However, its productivity is often limited by nutrient-deficient soils, particularly in regions with intensive agriculture. Therefore, exploring sustainable and cost-effective methods like biosolid application to enhance okra yield is crucial for ensuring food security and improving farmer livelihoods. The effect of biosolid mass (BM) on vegetables, especially okra yields, is unknown. This study aimed to test the impact of BM recovered from fecal sludge by measuring its N, C, P, and K values compared to regular soil where okra plants were grown. We measured the growth of the plants by analyzing their germination percentage, plant height, pod weight, and pod length.

2. Materials and Methods

2.1.Sample Collection

BM samples were obtained from the Fecal Sludge Treatment Plant (FSTP) at Banka Bioloo Limited's Sanitation Resource Park in Bhongir district, Telangana state, India. For this study, soil samples were collected from farmland in Bhongir by excavating to a depth of 15 centimeters below the ground surface. The soil samples were stored at a temperature of 10°C, following FAO guidelines, to preserve their integrity during transportation to the laboratory.
BM was divided into three experimental variants:

1. **BM:** Untreated BM left in its original form.
2. **ABM:** Aerobically treated bio solid mass.
3. **BMC:** BM mixed with compost powder.

ABM was created through an aerobic bio-treatment using Bacillus and Pseudomonas species. BMC was made by thoroughly mixing BM with compost powder. The three variants were mixed with red soil in a 1:1 ratio to create experimental soil beds (ESB), while red soil alone served as the control soil bed (CSB).

2.2.Microorganisms

Bacillus and Pseudomonas species were isolated from soil samples. Nutrient broth was prepared using standard concentrations and autoclaved to isolate Bacillus. A 10% soil solution was prepared in distilled water and boiled for 15 minutes to ensure that only Bacillus spores survived. After cooling, the upper clear solution was inoculated into the nutrient broth and allowed to grow undisturbed for 48 hours at 37°C. The broth culture was streaked onto nutrient agar plates in a zigzag pattern.
Pseudomonas was isolated from soil and maintained in nutrient broth before streaking onto nutrient agar.

2.3.Treatment of BM

After primary disinfection using UV light, BM was sun-dried in a polyhouse for 10-11 days to eliminate pathogens and helminths. Aerobic treatment reduced sludge volume and odors, allowing for further usage of BM. In a lab-scale bioreactor, powdered sludge was mixed with distilled water, inoculated with Pseudomonas and Bacillus species, and fermented for 21 days at 37°C. Propellers and periodic airflow ensured aerobic fermentation. The sludge was then air-dried and used as ABM.

For BMC, the disinfected sludge was thoroughly mixed with compost powder in a 3:1 ratio and left uncovered in large bins for three weeks.

2.4.Construction of Soil Beds

Following Quintero (1993), the upper 15 centimeters of soil were collected from five farm sites. The beds were constructed to dimensions of 10 ft. x 2 ft. x 1 ft. The primary surface soil from the farmland was excavated to a depth of 1 ft. and mixed 1:1 with BM to create the ESB. 3 experimental beds were built for each experiment and the experiments were repeated for 3 times, consisting of three ABM, three BMC, and three untreated BM beds. Control beds used only red soil.

2.5.Sowing and Watering

The methodology of Rodriguez et al. (1995) was followed to prepare the red soil, ensuring bed depth did not interfere with the okra root depth. Okra seeds, sourced from the Public Distribution System (PDS), were distributed at 16 grams (247 seeds per bed). Each bed was initially flooded with 80 liters of water before seeds were covered with soil. The beds were watered occasionally until sprouts emerged.

2.6. Nutrient Analysis

The Kjeldahl method was used to determine nitrogen and potassium levels in BM and soil samples (Kjeldahl, 1883). Phosphorus content was determined using the Bray method (Bray et al., 1945). Organic carbon was measured following Walkley et al. (1934).

2.7.Metal Analysis

To ensure that the recovered biosolids complied with the Fertilizer (Control) Order (FCO the Fertilizer (Inorganic, Organic or Mixed (Control) Order, 1985 (As Amended upto march 2023)/ (VL/SOP/39/2018 Issue No: 02 11.01.2023).) norms, heavy metal analysis was conducted for each biomass variant. Concentrations of arsenic (AS_2O_3), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), nickel (Ni), lead (Pb), and zinc (Zn) were measured using atomic absorption spectroscopy (AAS) and inductively coupled plasma optical emission spectrometry (ICP-OES). All measurements adhered to the maximum permissible limits specified in the FCO norms.

3. Results

In this study, the biomass variants underwent different treatments: BM was aerobically treated to produce the aerated flocculent mass (ABM), while the mixture of BM with compost powder formed a soft, fine particulate material (BMC). The results of each experiment highlighted significant differences in the chemical properties and performance of these variants.

Table 1: C/N, Nitrogen, and Phosphate Values of Biomass Variants Across Experiments

Experiment	Bio solid	C/N Ratio (%)	Total N (%)	Total Phosphate (%)
Experiment 1	BM	9.57	0.93	1.95
	ABM	10.6	0.97	2.01
	BMC	20.1	1.2	2.5
Experiment 2	BM	9.50	0.98	1.90
	ABM	10.5	0.93	2.09
	BMC	21.11	1.5	3.0
Experiment 3	BM	10.21	0.92	1.98
	ABM	11.57	0.93	2.07
	BMC	19.15	1.0	2.9

Analysis of Table 1

Overview of Nutrient Content:

This table provides a comparative analysis of C/N ratio, total nitrogen (N), and total phosphate (P) across three biomass variants (BM, ABM, BMC) and three experiments. The data reveal several important trends:

BMC consistently displays higher nutrient values across all experiments, particularly in Experiment 2, where the C/N ratio reaches 21.11% and total P hits 3.0%. This indicates superior composting and nutrient stabilization, likely due to the enriched organic material in BMC.

BM and ABM show moderate nutrient levels compared to BMC, with ABM slightly outperforming BM due to the aerobic treatment that enhances nutrient availability.

Statistical Analysis:

A detailed Analysis of Variance (ANOVA) was conducted to evaluate the significance of differences between the biomass variants for the C/N ratio, total nitrogen, and total phosphate values. The key findings from the ANOVA include:

C/N Ratio: A highly significant difference was found between the biomass variants (F-value: 198.69, P-value: 3.29e-06). This indicates that BMC's high C/N ratio, particularly in Experiment 2, is statistically superior to BM and ABM.

Total Nitrogen: Although BMC exhibited higher nitrogen values, the ANOVA result for total nitrogen was not statistically significant (F-value: 3.89, P-value: 0.0826), suggesting that nitrogen levels between the variants are relatively comparable.

Total Phosphate: The differences in phosphate levels were highly significant (F-value: 26.56, P-value: 0.0010), with BMC consistently showing the highest levels, particularly in Experiment 2.

Post-Hoc Tukey's HSD Analysis:

Following the ANOVA, Tukey’s HSD (Honestly Significant Difference) test was applied to determine which biomass variants differ significantly from each other:

C/N Ratio: BMC significantly outperformed both BM and ABM, confirming its superior decomposition and nutrient content.

Total Nitrogen: The differences between BM, ABM, and BMC were not statistically significant, indicating that while BMC had slightly higher nitrogen levels, they were not substantially different from the other variants.

Total Phosphate: BMC again showed significant differences from BM and ABM, particularly in Experiments 2 and 3, where phosphate levels were much higher.

Growth Comparison and Yield:

The higher C/N ratio and phosphate content in BMC is reflected in the superior plant growth and yield attributes observed in subsequent experiments on Okra growth. BMC consistently produced:

Higher germination rates, increasing from 50% in Experiment 1 to 55% in Experiment 2.

Taller plant heights and heavier pod weights, supporting the conclusion that BMC’s enriched nutrient profile boosts overall crop productivity.

Heavy Metal Analysis:

Heavy metal concentrations, including arsenic (AS_2O_3), cadmium (Cd), and mercury (Hg), remained well within the safe limits specified by the Fertilizer (Inorganic, Organic, or Mixed) (Control) Amendment Order, 2021. Other metals, such as copper (Cu), chromium (Cr), nickel

(Ni), and zinc (Zn), also stayed below threshold values, ensuring the safety of all biomass variants for agricultural use.

Conclusion:

The comprehensive analysis highlights BMC as the most nutrient-dense and effective biomass variant. Its ability to enhance plant growth, increase yield, and remain within safe heavy metal concentrations makes it an excellent candidate for sustainable fertilizer use. ABM, while beneficial, falls short of BMC in nutrient content and crop enhancement. BM, being untreated, shows the lowest nutrient availability and growth potential.

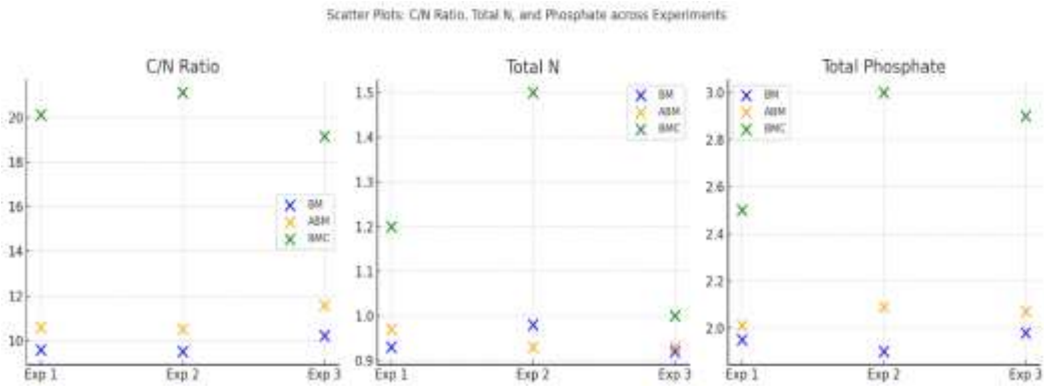

Figure 1: Scatter Plots

Scatter plots illustrate the variation in C/N ratio, total nitrogen, and total phosphate across the different biomass variants in each experiment. These plots reveal correlations and trends, enabling a clearer comparison of changes between BM, ABM, and BMC over time.

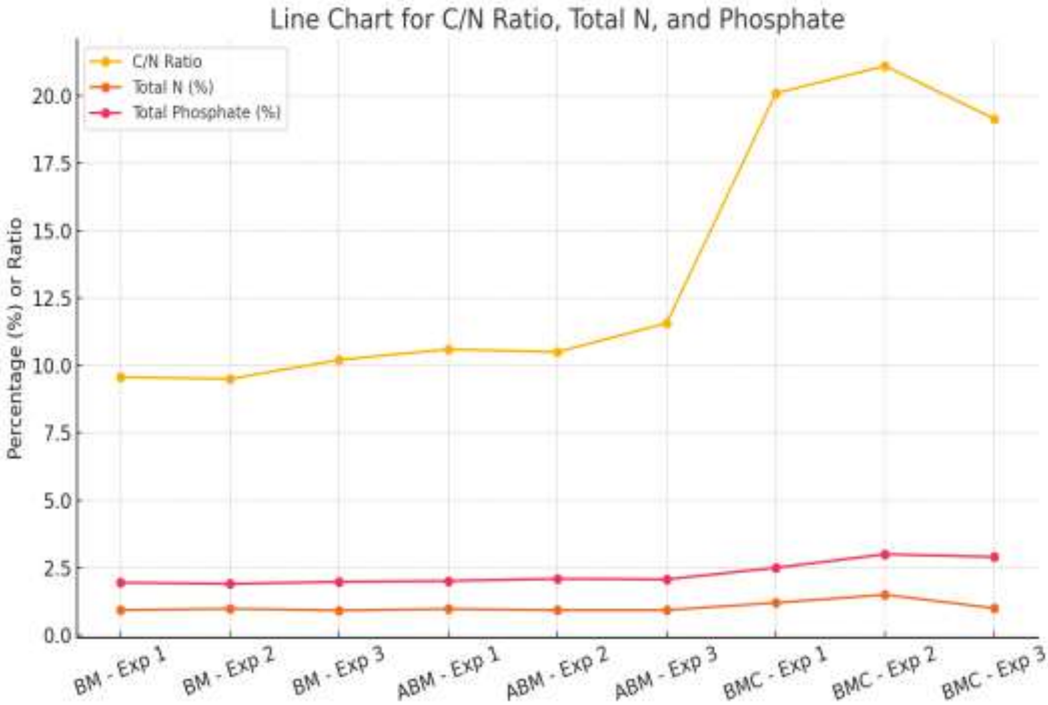

Figure 2: Line Chart

The line chart provides a longitudinal perspective, mapping the trends in C/N ratio, total nitrogen, and total phosphate for BM, ABM, and BMC. This visualization highlights overall patterns, making it easier to identify consistent trends or significant deviations in the composition of each biomass variant throughout the experiments.

Chemical Composition

As detailed in Table 1, the chemical composition of the biomass variants varied across three experiments. In Experiment 1, BM had a C/N ratio of 9.57%, total nitrogen of 0.93%, and total phosphate of 1.95%. ABM displayed improved values due to the aerobic treatment, with a C/N ratio of 10.6%, 0.97% nitrogen, and 2.01% phosphate. BMC exhibited the highest values overall, with a C/N ratio of 20.1%, total nitrogen of 1.2%, and total phosphate of 2.5%.

In Experiment 2, BM showed consistent chemical characteristics, maintaining a C/N ratio of 9.50%, nitrogen at 0.98%, and phosphate at 1.90%. ABM remained relatively steady, while BMC demonstrated an increase in nutrient levels, reaching a C/N ratio of 21.11%, total nitrogen of 1.5%, and total phosphate of 3.0%.

In **Experiment 3**, BM exhibited a slight increase in its chemical composition, showing a C/N ratio of 10.21%, nitrogen at 0.92%, and phosphate at 1.98%. ABM maintained stable nutrient levels, with a C/N ratio of 11.57%, nitrogen at 0.93%, and phosphate at 2.07%. BMC, though it decreased slightly from Experiment 2, remained dominant with a C/N ratio of 19.15%, total nitrogen of 1.0%, and total phosphate of 2.9%.

Growth Attributes

The growth parameters of okra plants grown with different biomass variants were analyzed across three experiments (Tables 4-6). In Experiment 1, BMC achieved a germination rate of 50% and attained the greatest plant height of 2.5 meters. The plants grown with BMC also had the highest weights during the first and second harvests, at 1455 g and 2100 g, respectively. Similarly, root and shoot lengths were significantly greater, reaching 34 cm and 18.98 cm, respectively. In contrast, ABM and BM showed lower but consistent values, while the control soil bed (CSB) performed the worst.

Experiment 2 reflected similar trends, where BMC led with a germination rate of 55% and a plant height of 2.8 meters. The plants achieved the highest yields during the first and second harvests, at 1460 g and 2200 g, respectively. Their root and shoot lengths reached 36 cm and 19.18 cm. In Experiment 3, BMC maintained dominance with a 55% germination rate and a plant height of 2.7 meters. First and second harvest weights were 1555 g and 2130 g, respectively, while root and shoot lengths reached 36 cm and 19.78 cm.

The consistent patterns across the three experiments highlighted BMC's superior nutrient composition and its positive impact on plant growth.

Table 4: Okra growth attributes with different BM variants –**Experiment-1**

Growth parameter	**ABM**	**BMC**	**BM**	**CSB**
Germination (%)	42±1.12	50±1.16	39.0±0.98	37.0±1.08
Plant height (Meters)	1.8±0.03	2.5±0.04	1.2±0.01	0.7±0.02
Plant weight during 1st yield (g)	1200±1.12	1455±2.81	1176±3.98	519±3.28
Plant weight during 2nd yield (g)	1785± 4.96	2100±610	1713±4.67	830±5.46
Root length (cm)	23±1.18	34±1.11	27±0.91	21±1.16
Shoot length (cm)	16.18±0.08	18.98±1.01	16.72±0.04	14.54±1.02
Total Plant Biomass (g)	8.1±1.16	14.2±0.72	9.6±0.10	7.5±0.28

Table 4: In Experiment 1, okra plants grown with the BMC variant exhibited the most favorable growth attributes overall. They had a germination rate of 50% and achieved the greatest plant height at 2.5 meters. They also had the highest plant weights during the first (1455 g) and second (2100 g) yields. Root and shoot lengths were similarly substantial, with the highest root length (34 cm) and a shoot length of 18.98 cm. The total plant biomass was 14.2 g. ABM and BM variants showed lower but consistent values across growth parameters. CSB consistently underperformed compared to the biomass variants.

Table 5: Okra growth attributes with different BM Variants-**Experiment-2**

Growth parameter	ABM	BMC	BM	CSB
Germination (%)	40±1.12	55±1.16	39.±0.98	37±1.08
Plant height (Meters)	1.8±0.03	2.8±0.04	1.2±0.01	0.8±0.02
Plant weight during 1st yield (g)	1100±1.12	1460±2.81	1170±3.98	520±3.28
Plant weight during 2nd yield (g)	1790± 4.96	2200±610	1720±4.67	850±5.46
Root length (cm)	22±1.18	36±1.11	25±0.91	20±1.16
Shoot length (cm)	16.25±0.08	19.18±1.01	15.72±0.04	14.64±1.02
Total Plant Biomass (g)	7.89±1.16	15.2±0.72	9.8±0.10	6.99±0.28

Table 5: Experiment 2 produced similar trends, with the BMC variant leading again in germination (55%), plant height (2.8 m), and plant weights (1460 g first yield, 2200 g second yield). BMC had a root length of 36 cm and a shoot length of 19.18 cm. The total biomass reached 15.2 g, indicating consistent superiority. ABM and BM variants maintained steady growth, but BMC outperformed them. CSB continued to show the lowest results across all metrics.

Table 6: Okra growth attributes with different BM Variants-**Experiment-3**

Growth parameter	ABM	BMC	BM	CSB
Germination (%)	41±1.12	55±1.16	39.6±0.98	37.0±1.08
Plant height (Meters)	1.78±0.03	2.9±0.04	1.2±0.01	0.7±0.02
Plant weight during 1st yield (g)	1230±1.12	1555±2.81	1166±3.98	525±3.28
Plant weight during 2nd yield (g)	1765± 4.96	2130±610	1715±4.67	835±5.46
Root length (cm)	26±1.18	36±1.11	29±0.91	22±1.16
Shoot length (cm)	16.28±0.08	19.78±1.01	16.8-±0.04	14.59±1.02
Total Plant Biomass (g)	8.1±1.16	15.8±0.72	9.7±0.10	7.9±0.28

Table 6: In Experiment 3, BMC remained dominant, achieving a germination rate of 55%, a plant height of 2.9 meters, and the highest weights during the first (1555 g) and second (2130 g) yields. The root length was 36 cm, the shoot length reached 19.78 cm,

and the total biomass was 15.8 g. ABM and BM variants were consistent with previous results, while CSB had the lowest performance, lagging in every growth attribute.

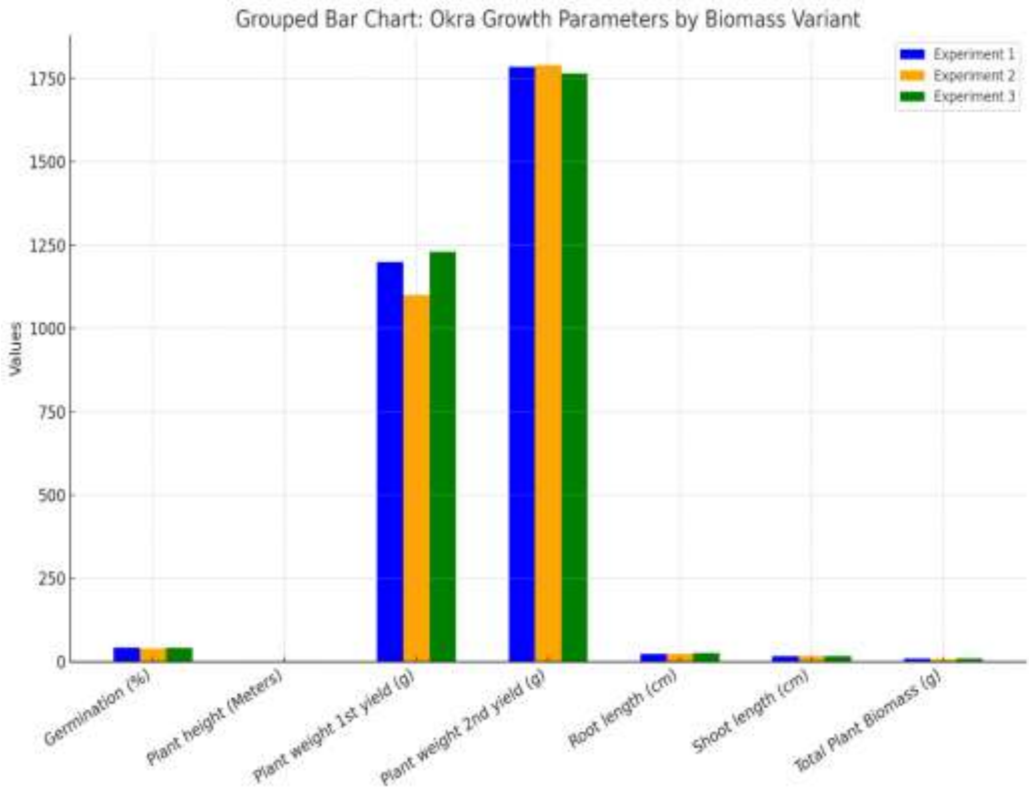

Figure 3: Grouped Bar Chart

The grouped bar chart visually depicts the differences in okra growth parameters across the experiments, highlighting BMC's consistently superior performance. Key insights include:

- **Germination and Plant Height:** BMC consistently has higher values than ABM and BM, maintaining a clear advantage.
- **Plant Weight (1st and 2nd Yield):** BMC leads, followed by ABM, while BM remains slightly behind.
- **Root and Shoot Lengths:** BMC outperforms particularly in root length.
- **Total Plant Biomass:** BMC consistently achieves the highest biomass.

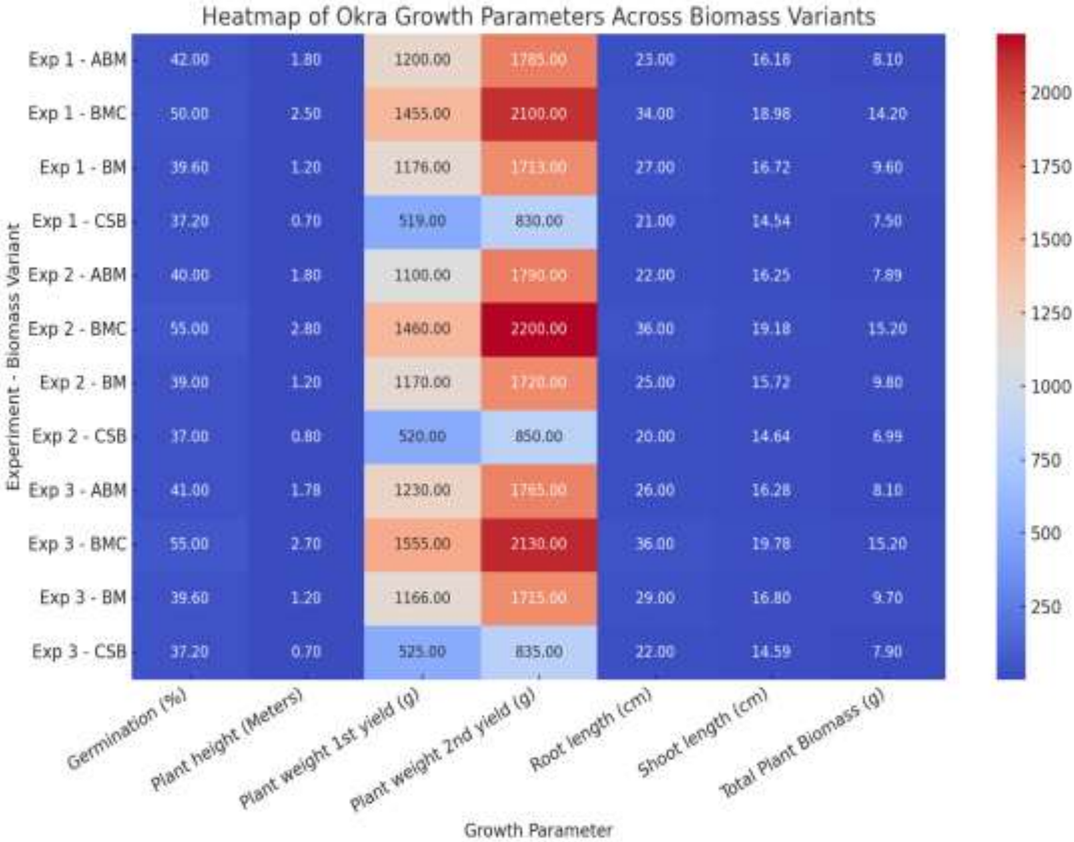

Figure 4: Heatmap

The heat map provides a comprehensive overview of growth parameters across experiments and variants. Key insights include:

- **Germination & Plant Height:** BMC remains the strongest performer in the second and third experiments.
- **Plant Weight (1st and 2nd Yield):** BMC consistently leads, followed closely by ABM, while CSB lags.
- **Root and Shoot Lengths:** BMC maintains strong performance, especially in root length, while CSB remains the weakest.
- **Total Plant Biomass:** BMC achieves the highest values, with ABM consistently in second place.

Heavy Metal Analysis

Heavy metal concentrations across the three experiments are presented in Tables 7-9. All variants remained within the permissible limits specified by the Fertilizer (Inorganic, Organic or Mixed (Control) Order, 1985 (As Amended upto march 2023)/ (VL/SOP/39/2018 Issue No: 02 11.01.2023). Arsenic (AS_2O_3), cadmium (Cd), and mercury (Hg) were significantly below their respective maximum allowable levels. Copper (Cu), chromium (Cr), and nickel (Ni) were also well within the safe ranges. Zinc (Zn), although showing relatively high levels, remained under the limit.

Table 7: Heavy metal Analsysis-Experiment-1

Heavy metals(mg Kg^{-1})	**Test Results**	**Specifications as per FCO(Maximum)**
Arsenic (AS_2O_3)	1.05	10
Cadmium (Cd)	0.79	5
Chromium (Cr)	12.31	50
Copper (Cu)	65.23	300
Mercury (Hg)	0.008	0.15
Nickel (Ni)	9.23	50
Lead (Pb)	11.35	100
Zinc (Zn)	214.93	1000

Table 7: In Experiment 1, heavy metal concentrations across the biomass variants remained within the permissible limits specified by the Fertilizer (Inorganic, Organic, or Mixed) (Control) Amendment Order, 2023. Arsenic (AS_2O_3) was recorded at 1.05 mg/kg, well below the maximum allowable limit of 10 mg/kg. Similarly, cadmium (Cd) measured 0.79 mg/kg, and mercury (Hg) was at 0.008 mg/kg, both significantly under their respective limits of 5 mg/kg and 0.15 mg/kg. Copper (Cu) and chromium (Cr) were 65.23 mg/kg and 12.31 mg/kg, respectively, while nickel (Ni) and lead (Pb) stayed below their thresholds at 9.23 mg/kg and 11.35 mg/kg. Zinc (Zn) was the most abundant at 214.93 mg/kg, still well under the limit of 1000 mg/kg.

Table 8 Heavy metal Analsysis-Experiment-2

Heavy metals(mg Kg^{-1})	**Test Results**	**Specifications as per FCO(Maximum)**
Arsenic (AS_2O_3)	1.08	10
Cadmium (Cd)	0.86	5
Chromium (Cr)	13.31	50
Copper (Cu)	60.12	300
Mercury (Hg)	0.005	0.15
Nickel (Ni)	8.23	50
Lead (Pb)	11.40	100
Zinc (Zn)	250.93	1000

Table 8: In Experiment 2, heavy metal concentrations showed similar trends, with most staying within the acceptable range. Arsenic (AS_2O_3) was 1.08 mg/kg, and cadmium (Cd) was 0.86 mg/kg. Mercury (Hg) was present in trace amounts (0.005 mg/kg). Chromium (Cr) was recorded at 13.31 mg/kg, copper (Cu) at 60.23 mg/kg, nickel (Ni) at 8.23 mg/kg, and lead (Pb) at 11.40 mg/kg. Zinc (Zn) showed a slight increase to 250.93 mg/kg but remained within permissible limits.

Table 9 Heavy metal Analsysis-Experiment-3

Heavy metals(mg Kg^{-1})	**Test Results**	**Specifications as per FCO(Maximum)**
Arsenic (AS_2O_3)	1.10	10
Cadmium (Cd)	0.89	5
Chromium (Cr)	12.39	50
Copper (Cu)	59.23	300
Mercury (Hg)	0.006	0.15
Nickel (Ni)	8.23	50
Lead (Pb)	12.65	100
Zinc (Zn)	250.93	1000

Table 9: In Experiment 3, arsenic (AS_2O_3) was at 1.10 mg/kg, cadmium (Cd) at 0.89 mg/kg, and mercury (Hg) at 0.006 mg/kg, all within acceptable ranges. Copper (Cu) and chromium (Cr) concentrations were at 59.23 mg/kg and 12.39 mg/kg, respectively. Nickel (Ni) was consistent at 8.23 mg/kg, and lead (Pb) was recorded at 12.65 mg/kg. Zinc (Zn) maintained its levels from Experiment 2 at 250.93 mg/kg.

Summary of heavy metals. *The Ministry of Agriculture and Farmers Welfare has issued the Fertilizer (Inorganic, Organic or Mixed (Control) Order, 1985 (As Amended upto march 2023)/ (VL/SOP/39/2018 Issue No: 02 11.01.2023)

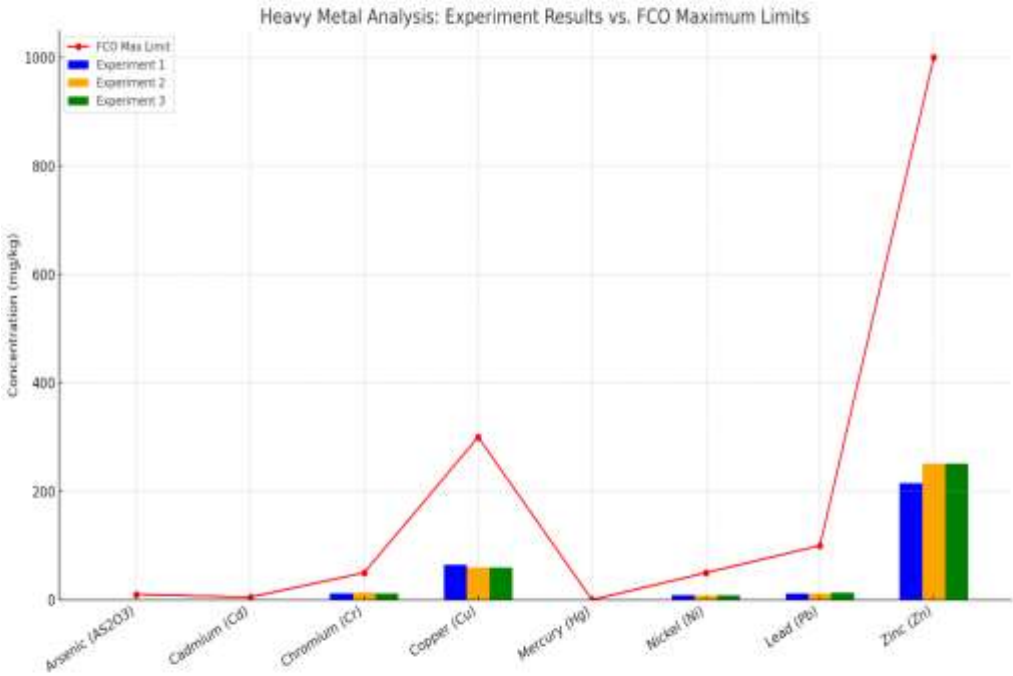

Figure 5: Grouped Bar Chart

The grouped bar chart effectively compares heavy metal concentrations across the experiments relative to the FCO maximum permissible limits (red line). Key insights include:

Below Limits: Arsenic (AS_2O_3), cadmium (Cd), and mercury (Hg) remained well below their respective maximum allowable limits across all experiments.

Noticeable Variation: Copper (Cu) exhibited slight variations between experiments but consistently remained well within permissible limits.

Consistent Results: Lead (Pb) and nickel (Ni) displayed consistent results across all experiments.

Near the Limit: Zinc (Zn) concentrations were relatively high but stayed within the permissible range.

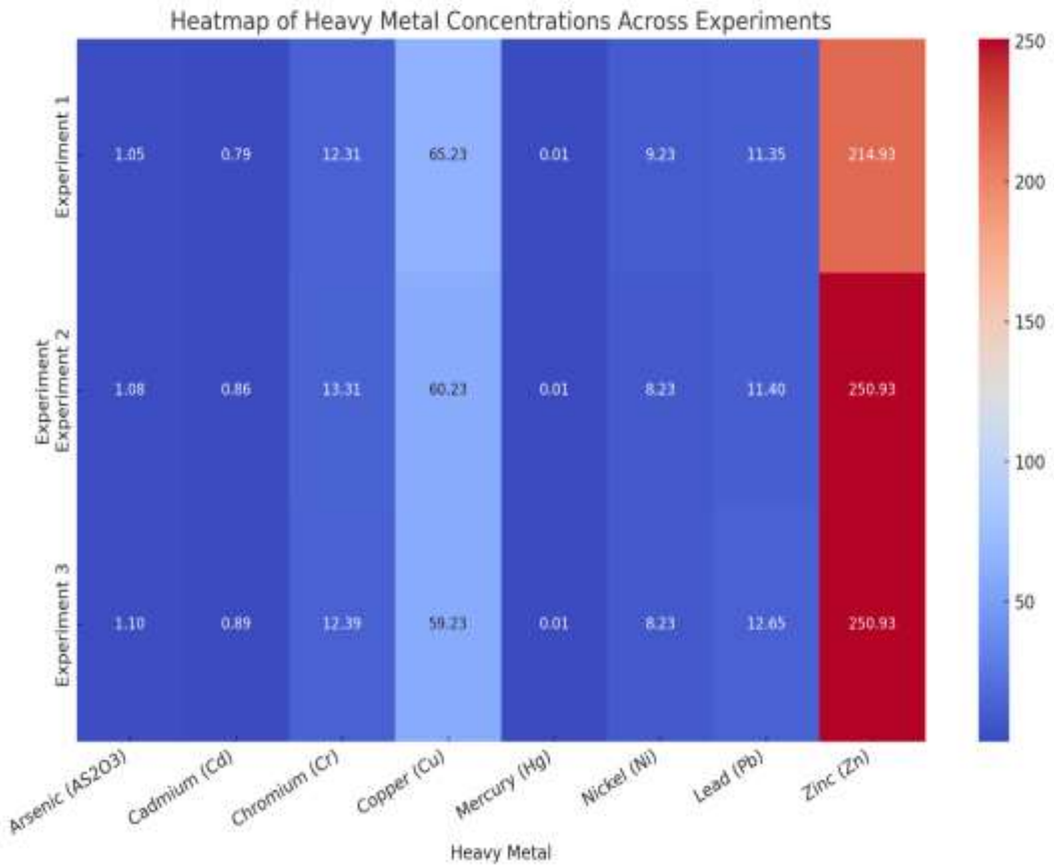

Figure 6: Heatmap

The heat map visually summarizes the concentration of heavy metals across the three experiments, highlighting key observations:

- **High Contrast: Zinc (Zn) is the most prominent in concentration compared to the other metals.**
- **Moderate Levels: Copper (Cu) and chromium (Cr) were present at moderate levels but well below the FCO limits.**
- **Lower Concentrations: Arsenic (AS_2O_3), cadmium (Cd), and mercury (Hg) were observed at minimal concentrations.**

Overall Trends and Patterns

Scatter plots and line charts (**Figures 1 and 2**) illustrate the variations in C/N ratio, nitrogen, and phosphate levels across the three biomass variants, revealing consistent correlations and trends. Grouped bar charts (Figure 3) and heatmaps (Figure 4) emphasize the growth attributes, reinforcing the dominance of BMC in promoting plant germination, growth, and yield attributes. The heavy metal analysis visualizations (Figures 5 and 6) confirm that all variants are safe for agricultural use.

In summary, BMC consistently demonstrated superior performance in terms of chemical composition and growth attributes, making it the most effective and sustainable fertilizer option. ABM provided reasonable benefits over untreated BM, while the heavy metal concentrations in all variants remained well within safe limits, ensuring agricultural viability.

4. Discussion

This study thoroughly investigated the effects of different biomass treatments derived from fecal sludge on the growth of okra plants, comparing the performance of untreated BM, aerobically treated ABM, and compost-enriched BMC. The detailed analysis of the chemical properties (Tables 1-3) and okra growth attributes (Tables 4-6) provided critical insights into the superior efficacy of BMC as a sustainable fertilizer.

Nutrient Content:

The C/N ratio, total nitrogen, and phosphate values were consistently higher in BMC than in ABM and BM. BMC showed a C/N ratio ranging from 19.15% to 21.11% across experiments, while ABM hovered between 10.5% and 11.57%, and BM fluctuated around 9.50% to 10.21%. These differences were reflected in the improved plant growth and productivity observed with BMC. The compost-enriched BMC variant proved to be markedly superior, delivering the highest germination rates (up to 55%) and demonstrating significant gains in nutrient availability. This aligns with the findings of Silva-Leal et al. (2021) and Aukour et al. (2018), who observed enhanced nitrogen content and improved crop yields when biosolids were used.

Growth Attributes and Yield:

The growth of okra plants varied significantly across the three biomass treatments. BMC consistently yielded higher germination rates and taller plants (up to 2.8 meters), as well as heavier pod weights, reaching up to 2200 g during the second yield in Experiment 2. Root and shoot lengths were also substantially longer in BMC compared to ABM and BM. While ABM provided moderate improvements over BM, BMC's dominance was evident in every growth parameter, indicating its ability to significantly enhance plant growth and productivity.

Heavy Metal Analysis:

The heavy metal concentrations were analyzed across the three experiments (Tables 7-9), revealing that all variants remained within the permissible limits set by the Fertilizer (Inorganic, Organic or Mixed (Control) Order, 1985 (As Amended upto march 2023)/(VL/SOP/39/2018 Issue No: 02 11.01.2023).

Arsenic (AS_2O_3), cadmium (Cd), and mercury (Hg) were well below the allowable limits, while copper (Cu), chromium (Cr), nickel (Ni), and zinc (Zn) also stayed within safe ranges. Although zinc concentrations were relatively high, they remained under the acceptable threshold, affirming the safety of all biomass variants for agricultural use.

Visual Trends and Patterns:

The scatter plots and line charts (Figures 1 and 2) highlighted consistent trends in the C/N ratio, nitrogen, and phosphate values among BM, ABM, and BMC. The grouped bar charts (Figures 3 and 5) and heat maps (Figures 4 and 6) illustrated the advantages of BMC over the other variants in terms of superior germination, growth, and biomass accumulation. These visualizations reinforced the reliability of BMC in improving plant growth and productivity.

Overall Insights:

In summary, this study confirms that BMC, enriched with compost powder, promotes superior plant growth and yield. Aerobic treatment of BM into ABM enhanced its properties but did not match the efficacy of BMC. Both treatments showed significant improvements over untreated BM, validating the positive impact of these methods. The consistently safe levels of heavy metals in all variants further assure their viability as sustainable fertilizers.

5. Conclusion

In conclusion, this study demonstrates the effectiveness of compost-enriched bio solid mass (BMC) derived from fecal sludge as a sustainable fertilizer for okra cultivation. The superior nutrient composition of BMC, particularly its higher carbon-to-nitrogen ratio, nitrogen, and phosphate content, resulted in significant improvements in okra growth, including higher germination rates, increased plant height, and greater pod weight compared to untreated biosolids and aerobically treated variants (ABM). Additionally, the heavy metal content in all biosolid variants remained well within permissible limits, reinforcing their environmental safety for agricultural applications. These findings suggest that BMC holds great potential as a viable alternative to chemical fertilizers, offering not only enhanced crop yields but also a safer and more sustainable farming solution. **Future research should expand to include diverse soil types and crop varieties to further validate the utility of biosolids in sustainable agriculture. Raising awareness and securing certifications for biosolids as a trusted fertilizer option will be key to promoting adoption among farmers.**

6. Acknowledgments

The researchers duly acknowledge M/s Banka Bio Limited, Hyderabad, Telangana, India, for all the support provided on the sampling of Bio solids from the FSTP. The researchers also duly acknowledge the support and guidance provided by Ms. Namita Banka, Executive Director, Banka Bio Limited, Dr. Mahalakshmi K and Mr. Atun Roy Choudhury.

7. Conflict of interest

The authors declare no conflict of interest. All authors have read and approved the manuscript.

8. Data availability

Data are available with the corresponding author.

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