

Spectral Characterization and Indexing Methods for the Quality Assessment of Municipal Solid Waste Compost Prepared Using Novel Bacterial Consortia

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ABSTRACT

Composting is one of the integral components in the global circular bio-economy platform. However, traditional composting contains major limitations, including it's longer time requirement and formation of odour. Therefore, the inoculation of efficient novel bacterial consortia for compost process modification is a global concern. Furthermore, the assessment of compost quality is crucial because immature compost can cause phytotoxicity, disrtputs soil structure, and damage the natural ecological balance when used in agriculture. Conversely, there is no universally applicable procedure to determine compost quality, maturity, and stability. This study focuses on assessing the quality of compost produced by five novel microbial consortia using indexing and spectroscopic methods. Clean Index (CI) Fertilizing Index (FI), Germination Index (GI) and Vigor Index (VI) were used as indexing methods to assess the phytotoxicity and compost quality. Scanning Electron Microscopy (SEM), X Ray Diffraction spectroscopy (XRD) and Energy

Dispersive X-ray Spectroscopy (EDS) techniques were used for spectroscopic analysis of compost micro structure. The results revealed that out of all compost samples (including the control) the compost made by Consortium 5 (C5) recorded a significantly greater ($p < 0.05$) GI, VI, FI and CI compared to the control and other treatments. Further, the GI value of C5 was recorded as 110.2 ± 2.2 %, demonstrating the possible usage of C5 compost as a phytonutrient soil amendment. Importantly, SEM, XRD and EDS spectrograms also confirmed the rapid waste degradation pattern and elemental composition alteration by the C5 consortium. Consequently, the compost by the C5 consortium was categorized into the compost quality “A” category, whereas the control compost belonged to the compost quality “D” category. In contrast, the findings of the present study confirm that the potential applicability of prepared novel bacetrail consortium as a rapid greener waste management approach in the circular bio-economy.

INTRODUCTION

The generation of solid waste has become a burning issue in the world, owing to rapid urbanization and industrialization (The World Bank Report 2020a). Currently, around 33% of the 2 billion tonnes of solid waste generated each year worldwide is not collected and treated by municipalities (Valavanidis, 2023; Wijerathna et al., 2024a). Consequently, about 90% of this waste is used for uncontrolled dumping, which leads to severe ecological and public health implications. Nevertheless, the approximate global operational cost for waste management was USD 252 billion in the year 2020, and it could double to a staggering USD 640.3 billion by the year 2050 (World Bank, 2022 ; Roy et al., 2023).

Composting is an effective, environment-friendly, integral component of waste management in the circular bio-economy platform. Further, it is a biological process influenced by a number of physicochemical conditions and enzymatic degradation of different microbial communities in the environment (Sarsaiya et al., 2019; Wijerathna et al., 2023). However, traditional composting processes still have several limitations, including the prolonged time required and the difficulty in assessing compost maturity and quality. Inoculation of microbial consortia with greater extracellular hydrolytic enzyme activity (cellulase, amylase, protease, pectinase, and lipase) is a rapid biological method to facilitate the efficient transformation of Municipal Solid Waste (MSW) to valorized compost (Valavanidis, 2023).

However, the final quality of MSW compost depends on its stability and maturity. Compost maturity describes how much organic matter has stabilized in composts throughout the bio-degradation processes (Azim, et al., 2018). Poor maturity compost can threaten soil quality and inhibit crop growth (Sarsaiya et al., 2019). Furthermore, by releasing harmful compounds and competing for oxygen in the rhizosphere, spreading premature compost may limit the growth of plants. Therefore, evaluation of compost maturity is crucial part of the composting. Several European and North American countries have adopted specific standards mainly to regulate the marketing of desirable quality composts (Esteves.2021). However, such quality control guidelines have been unable to identify different quality grades of marketable compost (Esteves.2021).

Compost maturity can be assessed using a variety of techniques. However, there is no universal method to define it. Among these methods, the Vigour Index (VI) and Seed Germination Index (GI) have been extensively employed as biological parameters to assess the compost's maturation and phytotoxicity (Yang et al., 2019). Additionally, the overall quality of compost in agriculture is assessed based on the Fertilizing Index (FI) and Clean Index (CI). The Fertilizing Index is a quantitative measure used to assess compost's fertilizing potential or nutrient content. It commonly involves analyzing the nutrient composition of the material. This analysis includes measuring key elements such as nitrogen (N), phosphorus (P), potassium (K), and other essential micronutrients (Ji et al., 2023). The fertilizing index can incorporate various parameters and factors, such as nutrient ratios, bioavailability of nutrients, and their release rates in soil, to assess the material's ability to enhance soil fertility and support plant growth. Additionally, the CI indicates a quantitative number to represent the amount of heavy metal available in the compost samples (Yang et al., 2019).

Additionally, several spectroscopic techniques, including Scanning Electron Microscopy (SEM), X Ray Diffraction Spectroscopy (XRD), and Energy-Dispersive X-ray Spectroscopy (EDS) analysis, have recently been utilized to assess compost age. These techniques can successfully acquire complementary, comparative data and a description of compost maturity. While EDS and SEM are evident methods used for the material's elemental identification and to obtain information about its quantitative composition, XRD analysis of compost evaluates the molecular and atomic composition of compost (Kataki, 2017).

In Sri Lanka there is a lack of publish literature on the overall quality of MSW compost prepared using different bacterial inoculum. Therefore, the application of immature compost and compost with phyto toxicity can negatively affect the agricultural plants (Yang et al., 2019). The objective of the present study evaluates systematic comparison and quality assessment of MSW compost prepared from five indigenous novel bacterial consortia using the indexing methods including GI, VI, FI and CI by evaluating compost phyto toxicity of prepared compost. Further, the manuscript aims to compare spectral characterization of prepared compost using SEM, XRD and EDAX spectrum to evaluate the compost quality of prepared compost to determine the potential applicability of prepared novel bacterial consortium as a successful composting approach of MSW.

2. MATERIALS AND METHODS

2.1 Isolation and screening of bacteria

For the study the bacteria were isolated from the three different dump sites in Sri Lanka including Karadiyana, Meethotamulla and Sundarapola dump sites. Leachate, solid waste and soil samples were collected from these dump sites and standard pour plate and streak plate methods on nutrient agar were used for the isolation of bacteria. The culture plates were incubated at 30 °C for 24 hours under steady conditions (Wijerathna et al., 2024a; Gunaratne et al., 2024). The screening of bacteria was done based on the extracellular enzyme secretion potential of these bacteria to degrade cellulose, starch, lipids and protein substrates contained in the solid waste. The primary screening of these bacteria were done by testing their cellulase, amylase, lipase and proteinase activity on clear zone formation on CMC agar media, starch agar media, casein agar media and olive oil agar media respectively (Sarkar and Chourasia, 2017). The secondary screening was done for the positive isolates to select the best potential bacteria to degrade the solid waste by quantifying their enzyme activity following the standard enzyme assays (Wijerathna et al., 2024a; Wijerathna et al., 2024b).

2.2 Preparation of bacteria consortia and identification of bacteria

The best potential bacteria were used for the consortia preparation by evaluating their antagonistic effects. Out of all prepared consortia the best five consortia (table 1) were used for the field application based on their total enzyme production potential (Wijerathna et al., 2024a).

The molecular identification of bacteria was done by using the 16s rRNA molecular identification. The DNA extraction of bacteria was done by using the freeze-thaw manual method and the sequencing was done from Macrogen Korea (Wijerathna et al., 2024b).

2.3 Experimental setup and bacterial consortia used for the study

Table 1 represents the developed five different bacterial consortia for the composting field experiment.

Table 1: Different bacterial consortia used for the experimental set-up

Bacterial consortium	Bacteria in the consortium
C1	<i>Bacillus haynesii</i> BHC1 (PP391133), <i>Bacillus haynesii</i> (PP438760), <i>Bacillus licheniformis</i> (CP027791)
C2	<i>Bacillus haynesii</i> BHC1 (PP391133), <i>Bacillus licheniformis</i> (CP027791) , <i>Bacillus subtilis</i> (CP007800)
C3	<i>Bacillus haynesii</i> BHC1 (PP391133), <i>Bacillus safensis</i> (PP391033) , <i>Bacillus velezensis</i> (CP 026533)
C4	<i>Bacillus haynesii</i> BHC1 (PP391133), <i>Bacillus amyloliquefaciens</i> BAC1 (PP391056), <i>Bacillus subtilis</i> (CP007800)
C5	<i>Bacillus haynesii</i> BHC1 (PP391133), <i>Bacillus amyloliquefaciens</i> AMWC (PP391615), <i>Bacillus safensis</i> (PP391033)

For the composting experiment, 18 standard compost containers (each 150 cm high and 45 cm in diameter) were used in triplicate for the control and experimental groups comprised with five different bacterial consortia configurations. All the MSW samples were collected from the Maharagama Municipal council; Sri Lanka from their daily organic waste collection and all the waste samples were collected at the same time from the same location. Considering the bin's capacity, 95 kg of mixed organic municipal solid trash and 2% (volume/ weight) inoculum of bacteria (depending on the waste's weight) were introduced to each bin. No additional microbial consortia were added to the control group. The spectral and indexing approaches assessed the final composts' quality.

2.4 Analysis of Compost Physicochemical Properties

The moisture content of the compost was analyzed by measuring the weight loss at 105°C. Before being examined for chemical properties, the samples were ground up, sieved through a 4 mm sieve, and dried at 70°C. A 100 mL measuring metal core was used to calculate the bulk density (Sharma et al., 2019). The formula for total organic carbon is $\% C = (\% VS)/1.8$. Analysis for pH, total N and Total P were carried out using standard methods (Santos et al., 2020). The pH was measured using a portable pH meter and the total nitrogen was measured following the Kjeldahl method (Santos et al., 2020). The organic carbon was measured using the dichromate wet oxidation method. Total phosphorus was determined by total digestion of the compost in the di-acid mixture (HClO₄: HNO₃ at 9:4 ratio) with subsequent analysis by spectrophotometer after colour development using the vanadomolybdate yellow colour method (Sharma et al., 2019 ; Santos et al., 2020).

2.5 Determination of trace metals

Metal analysis for Cd, Zn, Cr, Pb and Cu in prepared compost samples was performed using the Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES Agilent 720) (Fathabad, et al., 2018).

2.6 Indexing methods for characterization of prepared compost

2.6.1 Seed Germination Index(GI)

Vigna radiata seeds were used as the test seeds to assess the compost phytotoxicity considering its readily availability and susceptibility to compost toxicity. The compost water extract was used for the seed germination test (Luo et al., 2018). A 10 g of new compost was added to 100 mL of deionized water and it was stirred at 170 rpm for 30 minutes. Then the extract was filtered via 0.45 µm filter paper and the filtrate was gathered onto several petri dishes. The seeds were subjected to surface sterilization by dipping in 70% alcohol for 30 seconds followed an immediate washing with distilled water five times (Luo et al., 2018). Each petri dish contained 10 *Vigna radiata* seeds, water instead of compost extract which were then incubated for 48 hours (Luo et al., 2018). The GI was measured based on the following equation.

$$GI = (G\% \times RRG\%) \times 100$$

*Note

G% - (number of seeds germinated in a sample / number of seeds germinated in the control) \times 100;

RRG% - (mean root length in a sample / mean root length in the control) \times 100;

2.6.2 Seedling Vigour Index (SVI)

The Vigour index of the seedlings was calculated using the following equation.

$$SVI = \text{Germination (\%)} \times \text{Seedling Length (Mean Root Length + Shoot Length)}$$

2.6.3 Fertilizing index (FI)

The Fertilizing Index (FI), was used as an indicator to determine the fertilizing potential and the economic worth of the prepared compost. A rating system from 1 to 5, where 5 represents the best fertilization possibility, was used to calculate the FI.

The FI is measured based on the following formula:

$$\text{Fertilizing index (FI)} = \sum_{i=1}^n 1 (SiWi) / \sum_{i=1}^n (Wi)$$

where "Si" is the statistically calculated rating associated with total organic carbon content, Total Nitrogen content, Total Phosphorus, Total Potassium, and C: N and "Wi" is the ranking variable 5-1, which represents the quality of compost in descending order (Table 2).

Table 2 Score value chart for fertilizing index calculation

Fertility parameter	Score value (Si)					Weighting Factor (Wi)
	5	4	3	2	1	
TOC (% dm)	>20.0	15.1-20.0	12.1-15	9.1-12	<9.1	5
TN (% dm)	>1.25	1.01-1.25	0.81-1.00	0.51-0.080	<0.51	3
TP (% dm)	>0.60	0.41-0.060	0.21-0.40	0.11-0.20	<0.11	3
TK (% dm)	>1.00	0.76-1.00	0.51-0.75	0.26-0.50	<0.26	1
C:N ratio	<10.10	10.1-15	15.1-20	20.1-25	>25	3

Note

* TOC - Total Organic Carbon, TN - Total Nitrogen, TP - Total phosphorous, TK - Total Potassium, C:N - Carbon to Nitrogen ratio

*Source –Saha et al. (2010)

2.6.4 Clean index

Clear index According to the procedure shown in Table 3, rankings values were allocated to each metal based on its high toxicity to mammals. The clean index was calculated based on the following formula.

$$\text{Clean Index (CI)} = \frac{\sum_{j=1}^n S_j W_j}{\sum_{j=1}^n W_j}$$

Where ‘S_j’ is the score value of analytical data for heavy metal (in a five-point scale), and ‘W_j’ is the weighing factor of the jth fertility parameter (in a five-point scale)

Table 3 Score value chart for clean index calculation

Heavy metal	Score Value (S _j)						Weighting Factor (W _j)
	5	4	3	2	1	0	
Zn (mgKg ⁻¹)	<151	151-300	301-500	501-700	701-900	>900	1
Cu (mgKg ⁻¹)	<51	51-100	101-200	201-400	401-600	>600	2
Cd (mgKg ⁻¹)	<0.3	0.3-0.6	0.7-1.0	1.10-2.0	2.0-4.0	>0.4	5
Pb (mgKg ⁻¹)	<51	51-100	101-150	151-250	251-400	>400	3
Ni (mgKg ⁻¹)	<21	21-40	41-80	81-120	121-160	>160	1
Cr (mgKg ⁻¹)	<51	51-100	101-150	151-250	251-350	>350	3

*Source –Saha et al. (2010)

2.5 Compost quality grade

Table 4 Compost quality grading criteria.

Compost category	FI Value	CI value	Compost Quality	Remarks
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A	>3.5	>4.0	Complying with all heavy metal parameters	Excellent quality, with very low heavy metal contaminants content, strong potential for manurial value, and suitable for organic agriculture
B	3.1-3.5	>4.0	Complying with all heavy metal parameters	Good quality, relatively lower heavy metals, medium fertilizing ability
C	>3.5	3.1-4.0	Complying with all heavy metal parameters	Good quality High fertilizing potential
D	3.1-3.5	3.1-4.0	Complying for all heavy metal parameters	Medium quality,
RU-1	<3.1	-	Complying for all heavy metal parameters	Should not be allowed to market, However these can be used
RU-2	>3.5	>4.0	Not complying for all heavy metal parameters	Should not be allowed to market, can be used for growing non crops
RU-3	>3.5	-	Not complying for all heavy metal parameters	Restricted use; marketing should be prohibited.

*Source –Saha et al. (2010)

2.7 Spectroscopic methods for compost quality assessment

2.7.1 SEM /EDS spectroscopy

SEM-EDS analysis of compost samples produces high-quality pictures of solid materials. The current study used SEM and element detection by EDS (SEM-EDS) to investigate the structural

modifications of the composting samples. The analysis were performed based on the method described by Joseph et al. (2018).

2.7.2 XRD spectroscopy

An XRD device (Philips X-ray diffractometer) was used to get the spectra of the various compost specimens after they had been compressed into a fine powder. 200 mg of the specimen was used, and the specimens were exposed to Cu K α radiation with a wavelength of 1.5406 Å (0.15406 nm) for 20 minutes per scan. The diffractometer was operated in continuous scanning mode over a 2 θ range of 5° to 80°, with a step size of 0.02° and a counting time of 1 second per step (Sharma et al., 2019).

2.8 Statistical Analysis

Minitab 19 software was used for the statistical analysis and one-way ANOVA test was conducted to evaluate the effects of different compost treatments (Control, C1, C2, C3, C4, and C5) on various parameters, which were analyzed independently. Prior to conducting ANOVA, the assumptions including independence of observations, ensured through the experimental design and normality of residuals were assessed. The homogeneity of variances also were tested and the parameters showing significant differences ($p < 0.05$), Tukey's Honestly Significant Difference (HSD) post-hoc test was applied to identify specific group differences.

3. RESULTS AND DISCUSSIONS

MSW contains diverse toxigenic substances such as heavy metals, broad range of organic and inorganic compounds which negatively impact the plant growth (Sharma, et al., 2022; Liyanage et al., 2024; Pal and Tiwari, 2023). Table 5 represents the physico chemical results of the compost samples. Referring to the data, the pH, conductivity, bulk density and moisture of the C5 compost sample ranged between 7.2-9.5, 0.76-1.12 mscm⁻¹, 325-680 kgm⁻³, 40.5 %-44.6 % respectively showing a significant difference ($p < 0.05$) compared to the control and other samples.

Table 5 Compost quality characterization.

Parameters	Compost sample						Sri Lankan Standard
	C1	C2	C3	C4	C5	Control	
pH	7.6±0.2	7.2±0.3	7.3±0.2	7.4±0.1	7.2±0.1	9.5±0.2	6.5-8.5
Conductivity mscm⁻¹	0.86±0.10	0.79±0.02	0.76±0.02	0.78±0.02	0.76±0.03	1.12±0.06	4mscm ⁻¹
Bulk density kgm⁻³	580±10	490±10	660±12	680±10	660±10	325±12	NA
Moisture %	44.6±0.5	42.5±0.45	44.5±1.5	40.5±0.2	42.5±0.5	45.2 ± 0.5	NA
Total P %	0.60±0.05	0.40±0.10	0.40±0.10	0.98±0.10	1.1 ±0.10	0.95±0.05	0.5%
Total N%	0.9±0.1	0.9±0.2	0.9±0.2	1.2±0.2	0.9 ±0.2	0.8±0.1	1%
Total organic C %	22±0.5	24±0.5	26±0.5	30±0.5	25±0.2	34±0.2	20%
C:N	24	26	29	25	27	42.5	10-25
Total Potassium%	0.6±0.0	0.8±0.1	0.7±0.1	0.5±0.1	0.6±0.1	0.5±0.1	1%
Faecal coliform	5	6	5	0	0	45	0
Salmonella spp.	0	0	0	0	0	5	0
Shigella spp.	0	0	0	0	0	0	NA
Sand content%	12±1	12±1	11±1	11±2	10±1	12±2	20%
Particle size (Residue particles when passing through 2 mm sieve)	3.8±0.1%	4.2±1.2%	3.4±0.5%	1.8±0.2%	1.4±0.2%	15.2±0.1%	2%

Heavy metal s (mg/kg)	Zn	64±2	72±1	45±1	40±2	42±1	46±0	N/A
	Cu	42±1	32±1	38±1	44±0	24±0	40±0	N/A
	Cd	0.52± 0.02	0.48± 0.15	0.32± 0.15	0.24± 0.05	0.26± 0.15	0.93± 0.12	3
	Pb	20±1	16±1	14±1	18±2	14±2	20±2	50
	Ni	10±1	10±2	13±2	10±2	15±1	47±4	50
	Cr	24±1	30±1	22±1	24±1	20±1	52±4	50

Further, total phosphate, total nitrogen, total organic carbon and C: N ratio were significantly different ($p < 0.05$) compared to the control. Importantly, the heavy metal content of Zn, Cu, Cd, Pb, Ni and Cr ranged 40-72 mg kg^{-1} , 24-44 mg kg^{-1} , 0.24-0.93 mg kg^{-1} , 14-20 mg kg^{-1} , 10-50 mg kg^{-1} , 20-52.4 mg kg^{-1} resulting a significant different ($p < 0.05$) compared with the control sample. Similar studies done by Sharma et al. (2022) and Kutu. (2019) also recorded the compost physicochemical values in the same range.

3.1 Seed germination results

Table 6. Seed germination and Vigour index of the prepared compost

Parameter	Compost type					
	C1	C2	C3	C4	C5	Control
Seed						
Germination percentage %	85± 1	88 ± 2	94 ± 2	96 ± 2	100 ± 0	74 ± 2
Germination Index (GI)	72.4 ± 4.2 %	80.1 ± 3.1 %	84.5 ± 2.2 %	84.5 ± 2.3 %	110.2 ± 2.2 %	76.5 ± 3.2 %

Total root and shoot length (cm)	5.1 ± 0.2	5.2 ± 0.1	5.3 ± 0.1	5.4 ± 0.1	5.5 ± 0.4	4.9 ± 0.2
Vigour index (VI)	437.7	462.0	502.9	521.3	551.0	364.8

Compost phytotoxicity is one of the critical parameters which determine the overall applicability if the compost to the agricultural purposes. Referring to the results in table 06, all the consortia inoculated compost samples (C1-C5) recorded with a greater VI than was in the control compost showing a significant difference ($p < 0.05$) between the treatments. The GI value of C5 compost, was recorded as $110.25 \pm 2.21 \%$ which was significantly ($p < 0.05$) higher than the control compost. Moreover, the GI value of the control ($76.5 \pm 3.2 \%$) and the C1 ($72.4 \pm 4.2 \%$) compost were recorded below 80% which represents the presence of phytotoxic compounds in the compost. The GI values which are less than 80% represent the presence of phytotoxicity in the compost as evidenced by the published studies conducted by Humaira et al. (2016) and Selim et al. (2012). Further, the GI values which are greater than 100% represent that compost consist no phyto toxicity showing the potential applicability of compost as a phytonutrient (Humaira et al., 2016). Based on the results of the GI values (table 6), of the control and C1 compost samples were recorded the GI values the below the 80% indicating the plant phytotoxicity. Further, C2 to C4 compost samples were within the acceptable range indicating no phytotoxicity. The VI of green gram for the prepared five compost types ranged from 364.8 – 551 while the control compost sample (consortium not added) recorded the lowest VI value. This may be due to the detoxification mechanisms carried out by particularly C5 consortium which may rapidly degrade the toxic secondary metabolites and complex compounds available in the MSW (Meena et al., 2019; Benavente et al., 2018).

Similarly, Liu et al. (2019) also reported a high level of toxicity among samples of fresh MSW compost due to the presence of heavy metals including Cu, Cd, Pb, Ni and Cr. Even in the present study, the inoculated microbial consortium (C4 and C5) may efficiently convert the MSW into matured compost while reducing the phytotoxic effect. Moreover, the generation of short-term daughter

compounds (short-chain organic fatty acids, phenols) during the initial phases of composting may also link to the record of a lower GI value in compost particularly, which may be attributed to slower composting of the control treatment (Marouani et al., 2019; Mahongnao et al., 2024). Besides, the seed VI represents the compost maturity, the availability of nutrients and the presence of toxic substances in the compost. Referring to the VI values of the present study (table 4), the overall greatest VI value was recorded in the C5 consortium inoculated compost while indicating the formation of quality compost. Furthermore, high seed vigor in compost often correlates with high microbial activity and a healthy microbial community (Bu et al., 2022).

3.2 Clean index and Fertilizing index

Table 7. Compost grade of prepared compost based on the clean index and fertilizing index.

Compost type	Fertilizing index	Clean index	Compost class
C1	3.2 ± 0.5	4.0 ± 0.3	C
C2	3.4 ± 0.3	4.6 ± 0.2	B
C3	3.3 ± 0.3	4.6 ± 0.5	B
C4	3.6 ± 0.2	4.6 ± 0.2	A
C5	4.5 ± 0.2	5.0 ± 0.5	A
Control	3.0 ± 0.2	4.2 ± 0.2	D

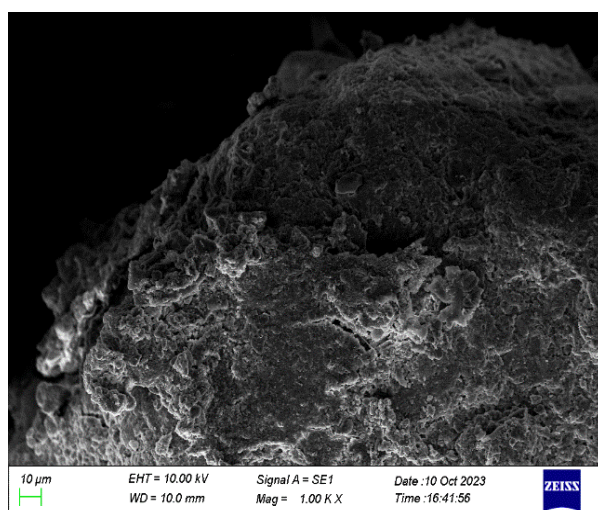
Table 7 represents the FI, CI and the compost class of the compost samples which provide a comprehensive idea of compost stability and maturity. Based on the data, the FI and CI of the C5 compost samples were significantly different ($p < 0.05$) compared to the control and to the other treatments. Moreover, the greatest FI was recorded in the C5 control sample which indicates high fertilizing potential whereas the lowest FI was recorded in the control compost sample indicating the lower availability of nutrients. Only the C4 and C5 compost were categorized to compost class “A” which has good quality whereas the control compost remained within the compost class “D” which has a lower quality index. Furthermore, the significant ($p < 0.05$) increment of CI in the C5 inoculated compost may be attributed to the particular heavy metal detoxification mechanisms which may be undergone by C5 consortium. The FI

increment of C5 compost may cause due to the complete and faster degradation of MSW to compost by the C5 consortium which may increase the available nutrient composition in the compost.

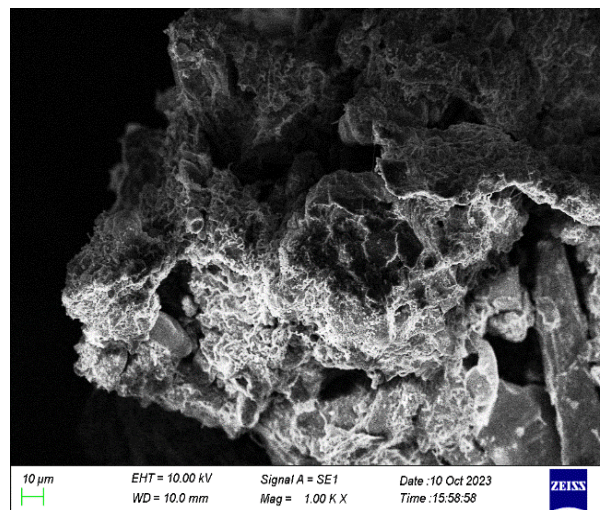
The C2 and C3 compost types belonged to the compost class “B” whereas the control compost sample which prepared without addition of consortium belonged to the compost class “D”. Importantly the overall quality of C5 compost were notably high which may be due to the synergistic interaction of C5 consortium which contains *Bacillus haynesii* (strain BHC1 -PP391133), *Bacillus amyloliquefaciens* (strain BAC1 -PP391056) and *Bacillus safensis* (Strain-PP391033). Several studies have been conducted on the FI and the CI of the MSW compost in the world (Bello et al., 2023; Aweez et al., 2019; Hameed et al., 2022; Wijerathna et al., 2024b). However, Kabasiita et al. (2022) have reported the FI and CI of MSW compost in Uganda which was ranged from 1.9- 2.9 and 3.8 - 4.9 respectively. However, all the compost types generated in the present study had a greater FI, CI and compost class compared to those reported by Kabasiita et al. (2022) which may be attributed the initial composition and MSW and the excellent performance of the inoculated consortium.

In the present study the final compost quality of each treatment may have depended on the applied microbial consortia which synergistically act with the environmental existing microbial community.

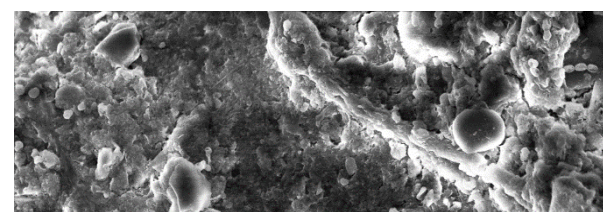
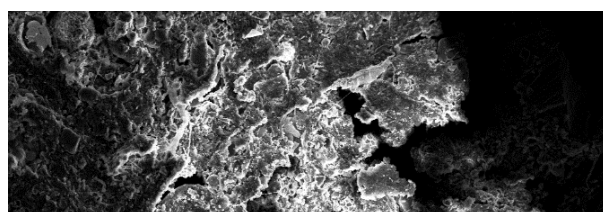
3.3 SEM results



(a)



(b)



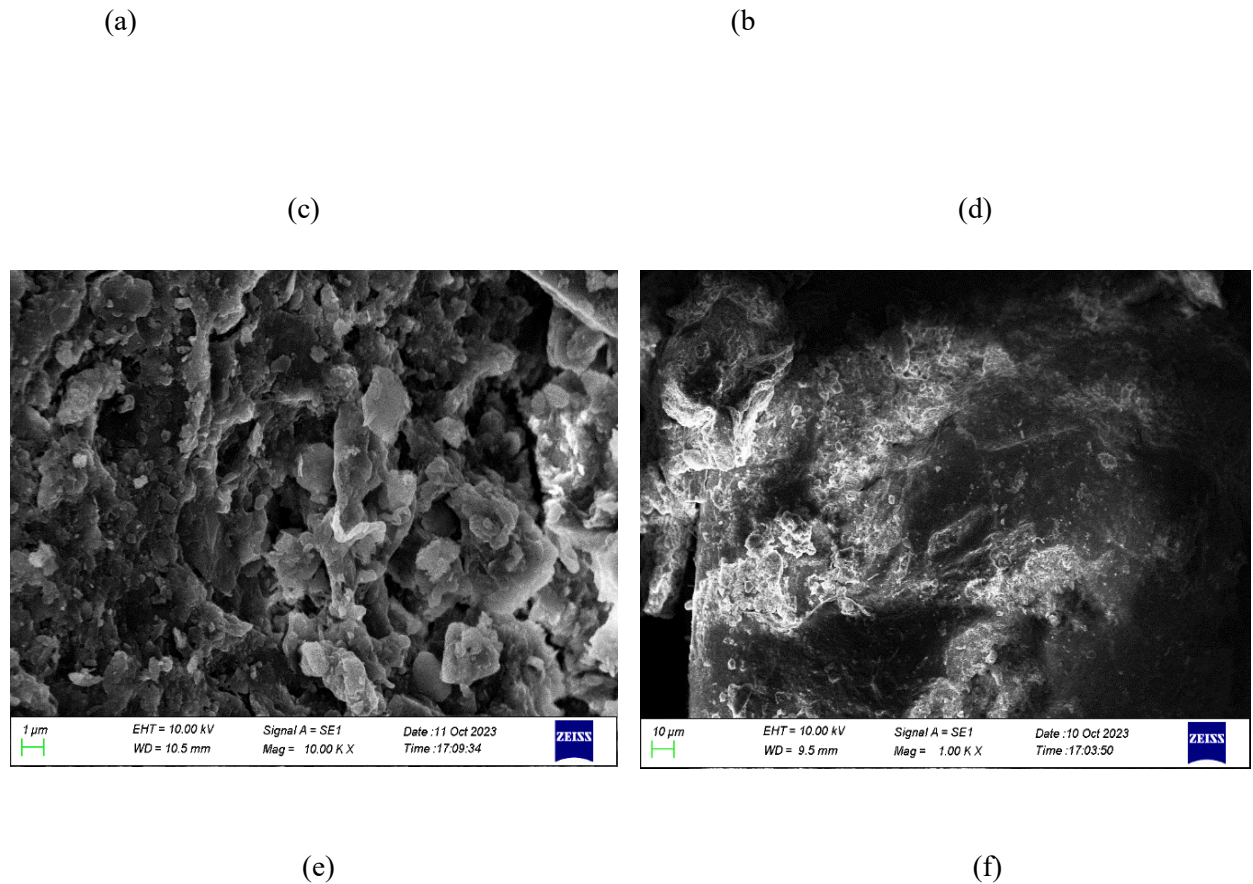
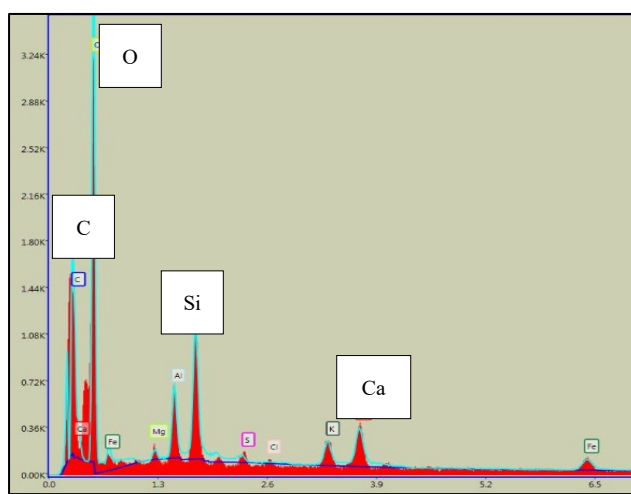


Figure 10 Scanning Electron Microscopy images of C1 (a), C2 (b), C3 (c), C4 (d), C5 (e), Control (f)

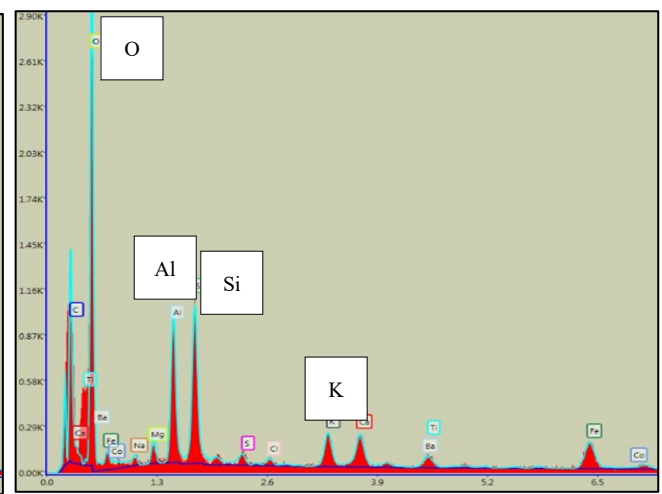
Figure 10 represents the SEM microstructural images of the prepared compost samples. The obtained SEM images represent nature of the compost surface changes occur when the solid waste degradation takes place by producing compost with inoculated five different consortia and control. The formation of cavities and the destructed morphology represent the bacterial breakdown of solid waste into compost. The SEM images represents the surface and degradation of the MSW by inoculated microbial consortia.

Figure 10 (a), represents the surface of the control sample which indicated a dense solid material, smooth and intact and compacted surface indicating a relatively lower degradation of MSW. Compared to the control, the micrographs of all the bacteria inoculated samples indicated more porous surface structures indicating the faster degradation rate of solid waste by inoculated bacterial consortia. Furthermore, the C5

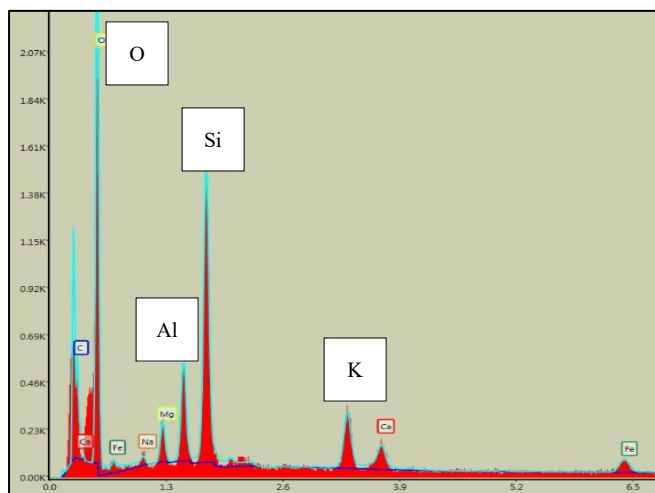
consortia inoculated sample (f) resulted from a noticeable surface degradation demonstrating a very porous surface and a larger number of cavities represented by gaps and holes; a faster solid waste degradation and fragmentation of MSW. Porosity is an important factor of the compost which is closely associated with the water holding capacity of compost. A similar porosity pattern was recorded for the studies carried out by Pal and Singh, (2024), and Arora and Kaur, 2019 when MSW successfully converts to compost. Therefore, the microorganisms in the C5 compost may have synergistically interacted with environmental microbial communities for remarkably enhance the composting rate of MSW.



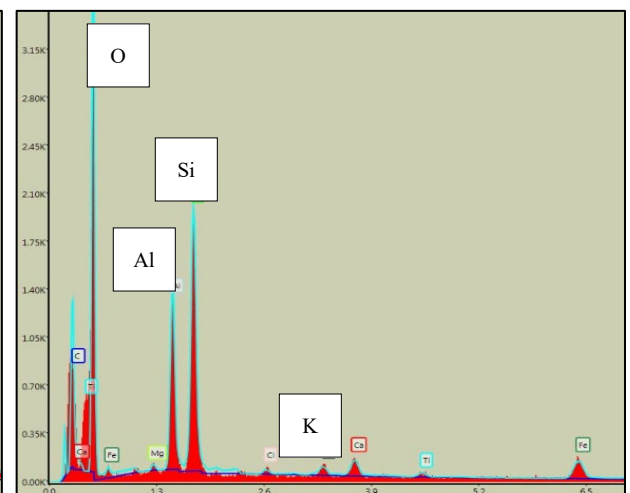
(a) C1



(b) C2



(c) C3



(d) C4

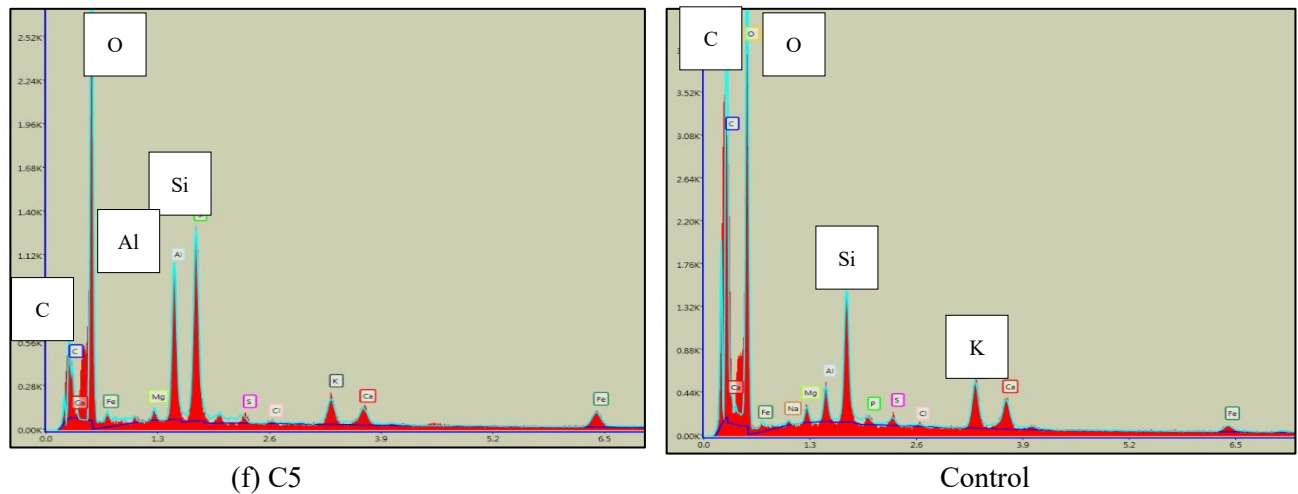


Figure 11. Graphical representation of major elements in the compost samples from EDAX analysis

Table 8. EDAX results of the analyzed compost samples

Manohara and Belagali, (2017) have recorded a 41.51% carbon content in the compost samples collected from various composting sites in India when analyzed through EDX. The MSW compost includes various metals since municipal trash contains paints, electronic equipment, paper and plastic-based waste substances, chemicals, personal care products, and medications. The study revealed a decrease in these peaks as a result of a faster rate of breakdown that produced mature compost.

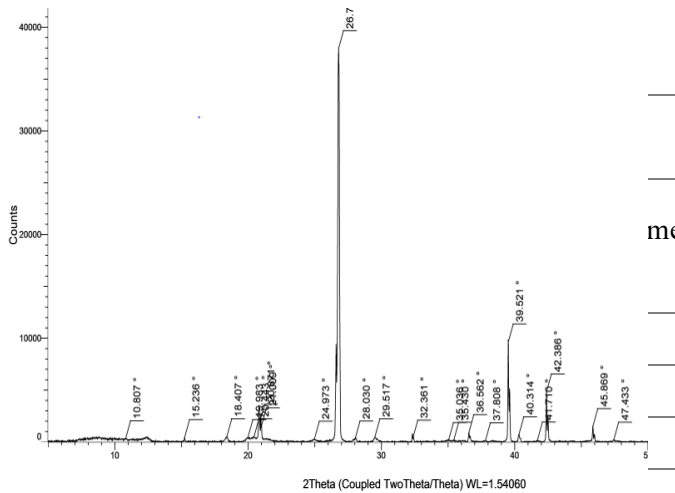
Element

C

O

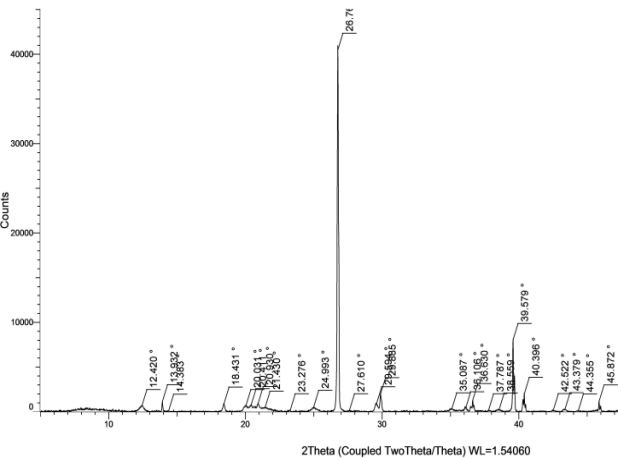
Mg

Al



Counts

2Theta (Coupled TwoTheta/Theta) WL=1.54060

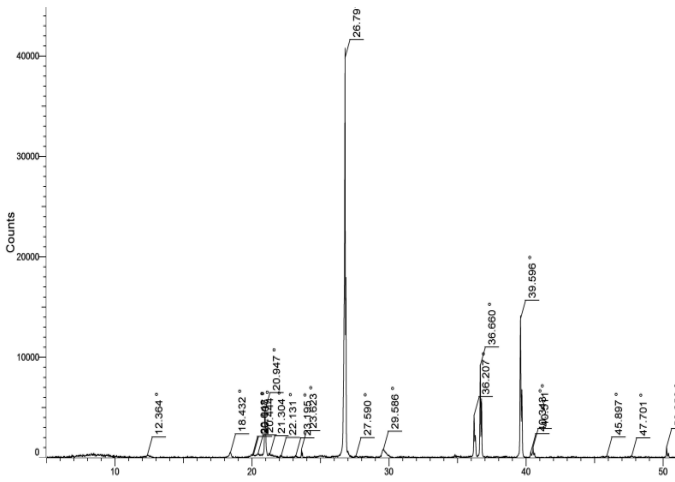


Counts

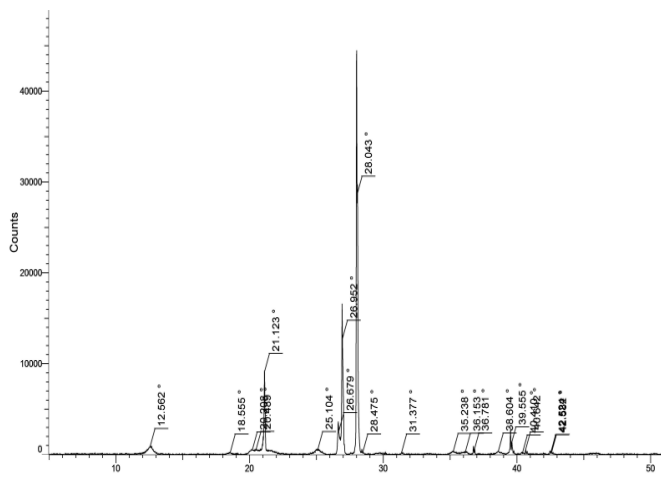
2Theta (Coupled TwoTheta/Theta) WL=1.54060

Si	4.53	Al	0.94	Al	4.97	Si	10.19	Al	5.41	Si	8.06
S	0.34	Si	3.03	Si	4.73	S	0.36	Si	8.37	Cl	0.2
Cl	0.11	P	0.07	S	0.38	Cl	0.15	K	3.73	K	0.4
K	1.17	S	0.23	Cl	0.25	K	1.91	Ca	1.85	Ca	0.82
Ca	2.2	Cl	0.06	K	1.36	Ca	1.37	Fe	1.59	Ti	0.21
Fe	1.04	K	1.54	Ca	1.52	Fe	1.97			Fe	1.51

(a)



(b)



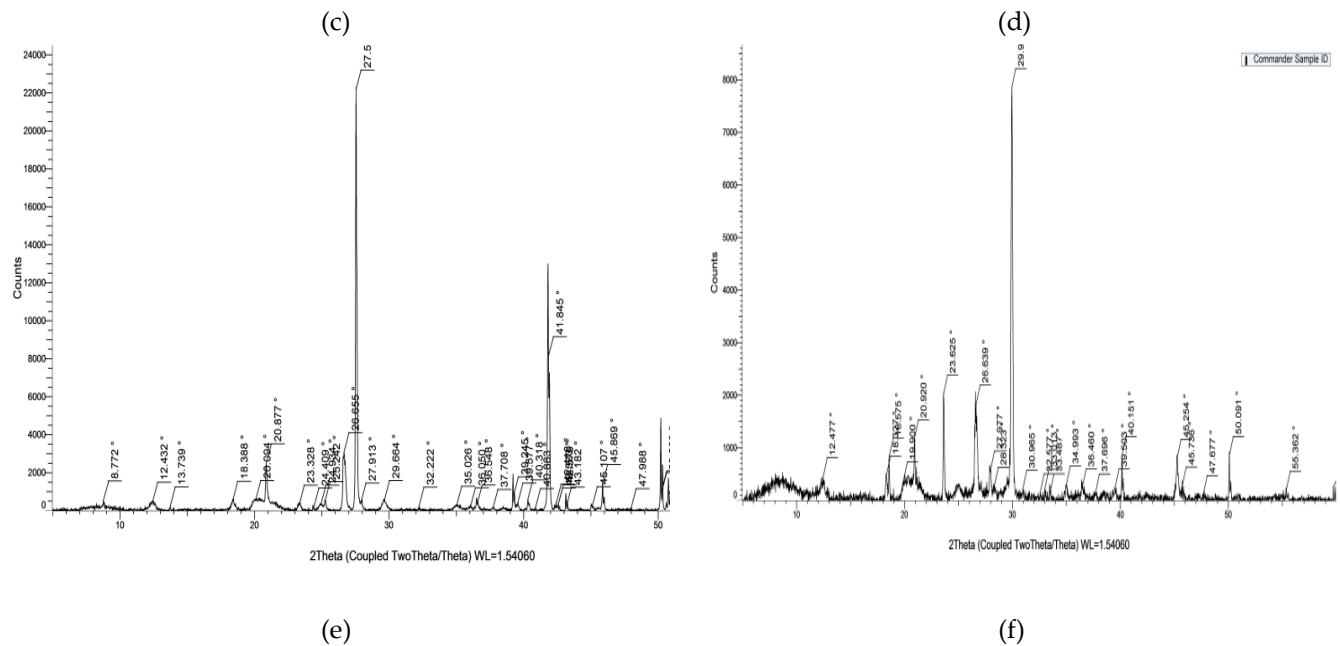


Figure 13 XRD diffractograms of the compost samples (a) C1, (b) C2, (c) C3, (d) C4, (e) C5, (f) Control

Figure 13 shows the compost specimens' XRD diffractograms. The existence of several important substances, such as the carbonate of calcium and silicon oxide as well as minerals, such as quartz, calcite, and dolomite, which were indicated by the strong peaks that appeared on the spectra of the XRD examination of compost material. The XRD pattern of immature compost is characterized by broad, diffuse peaks indicative of high amorphous content. In contrast, mature compost exhibits sharper, well-defined peaks corresponding to stable crystalline minerals, indicating a more advanced state of decomposition and stabilization (Benavente et al., 2018). In the XRD figures (figure 13), the control sample has given a large number of small peaks which are not sharp and well defined indicating the dominance in immature compost, reflecting the presence of organic compounds that have not yet fully degraded.

However, the C5 consortia inoculated set-up exhibited a several intense peaks which is attributed to the certain minerals (Calcite - CaCO_3 , Quartz- SiO_2 , Phosphates detected by XRD can serve as indicators of

compost maturity, which is important for determining its suitability for agricultural use. Furthermore, As compost matures, the transformation of organic matter into humic substances and the precipitation of inorganic minerals become more pronounced which is indicated by C5 compost. Sharma et al. (2019) have also noted a number of diffuse peaks indicative of high amorphous content in poorly matured compost produced in two different municipal solid waste dumpsites located in the cities of Solan and Mandi in Himachal Pradesh. However, the results of the C5 compost which was produced from the novel bacterial consortia consisting of *Bacillus haynesii*, *Bacillus amyloliquefaciens*, *Bacillus safensis* has good agronomic value compared to the control and other consortia inoculated set ups. The findings of the present study reveals the potential applicability of prepared C5 consortia as a greener solid waste management approach in the circular bio economy platform.

5. CONCLUSIONS

The seed germination assay confirmed the presence of phytotoxicity in control compost samples whereas no phytotoxicity was recorded by the C5 compost sample evidencing the potential applicability of C5 compost as a phyto nutrient. The indexing parameters and SEM, XRD and EDS spectrograms analysis confirmed the rapid waste degradation pattern and elemental composition alteration by inoculated C5 consortium. The FI, and CI values also were significantly high ($p < 0.05$) in the C5 developed compost showing a successful composting done by C5 consortium. Based on the FI and CI, the resulting compost by the C5 consortium was categorized in to compost quality “A” category which has high quality whereas the control compost belonged to the compost quality “D” category which has low quality. The results of this study evidence that the the potential applicability of C5 consortium as rapid greener waste management approach a to produce high quality compost from MSW.

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