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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 of the global circular bio-economy platform. However, traditional composting contains major limitations, including its longer time requirement and the 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, disrupt 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 microstructure. 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 a 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 (World Bank Report 2022). 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 several 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 biodegradation 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 a crucial part of 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 published literature on the overall quality of MSW compost prepared using different bacterial inocula. 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 evaluate 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 the compost phyto toxicity of prepared compost. Further, the manuscript aims to compare the spectral characterization of prepared compost using SEM, XRD and EDAX spectra to evaluate the compost quality of prepared compost to determine the potential applicability of the prepared novel bacterial consortium as a successful composting approach of MSW.

MATERIALS AND METHODS

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 h 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 was done by testing their cellulase, amylase, lipase and protinase activity on clear zone formation on CMC agar media, starch agar media, casein agar media and olive oil agar medianrespectively (Sarkar & 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, 2024b).

Preparation of Bacterial 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).

Experimental Setup and Bacterial Consortia Used for the Study

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

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, comprising 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.

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 70ºC. 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 ($HClO_4$: HNO_3 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).

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).

Indexing Methods for Characterization of Prepared Compost

Seed germination index (GI): *Vigna radiata* seeds were used as the test seeds to assess the compost phytotoxicity, considering it's readily availability and susceptibility to compost toxicity. The compost water extract was used for the seed germination test (Luo et al. 2018). 10 g of new compost was added to 100 mL of deionized water, and it was stirred at 170 rpm for 30 min. Then the extract was filtered via a 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 by 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 h (Luo et al. 2018). The GI was measured based on the following equation.

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

Where,

G % - (number of seeds germinated in a sample/number of seeds germinated in the control) × 100,

RRG % - (mean root length in a sample / mean root length in the control) × 100,

Seedling vigor index (SVI): The Vigor index of the seedlings was calculated using the following equation.

SVI = Germination (%) × Seedling Length (Mean Root Length + Shoot Length)

Table 1: Different bacterial consortia used for the experimental setup.

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

Table 2: Score value chart for fertilizing index calculation.

Fertility parameter	Score value [S_i]					Weighting Factor [W_i]
	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 Phosphorus, TK - Total Potassium, C:N - Carbon to Nitrogen ratio
*Source –Saha et al. (2010)

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 [$mg.kg^{-1}$]	<151	151-300	301-500	501-700	701-900	>900	1
Cu [$mg.kg^{-1}$]	<51	51-100	101-200	201-400	401-600	>600	2
Cd [$mg.kg^{-1}$]	<0.3	0.3-0.6	0.7-1.0	1.10-2.0	2.0-4.0	>0.4	5
Pb [$mg.kg^{-1}$]	<51	51-100	101-150	151-250	251-400	>400	3
Ni [$mg.kg^{-1}$]	<21	21-40	41-80	81-120	121-160	>160	1
Cr [$mg.kg^{-1}$]	<51	51-100	101-150	151-250	251-350	>350	3

*Source –Saha et al. (2010)

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:

Fertilizing index (FI) = $\sum_{n}^{I=1} 1$(SiWi)/ $\sum$ n i=1 (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).

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

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

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 j^{th} fertility parameter (in a five-point scale).

Compost Quality Grade

Compost quality grading criteria is given in Table 4.

Table 4: Compost quality grading criteria.

Compost category	FI Value	CI value	Compost Quality	Remarks
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 with all heavy metal parameters	Medium quality,
RU-1	<3.1	-	Complying with all heavy metal parameters	Should not be allowed to market. However, these can be used.
RU-2	>3.5	>4.0	Not complying with all heavy metal parameters	Should not be allowed to market, can be used for growing non-crops
RU-3	>3.5	-	Not complying with all heavy metal parameters	Restricted use, marketing should be prohibited.

*Source –Saha et al. (2010)

Spectroscopic Methods for Compost Quality Assessment

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 was performed based on the method described by Joseph et al. (2018).

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 Kα radiation with a wavelength of 1.5406 Å (0.15406 nm) for 20 min per scan. The diffractometer was operated in continuous scanning mode over a 2θ 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).

Statistical Analysis

Minitab 19 software was used for the statistical analysis, and a 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. Before conducting ANOVA, the assumptions, including independence of observations, were ensured through the experimental design and the normality of residuals was assessed. The homogeneity of variances was also tested, and the parameters showed significant differences ($p < 0.05$). Tukey's Honestly Significant Difference (HSD) post-hoc test was applied to identify specific group differences.

RESULTS AND DISCUSSION

MSW contains diverse toxigenic substances such as heavy metals, a broad range of organic and inorganic compounds, which negatively impact the plant growth (Sharma et al. 2022, Liyanage et al. 2024, Pal & Tiwari 2023). Table 5 represents the physicochemical 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 $mS.cm^{-1}$		0.86±0.10	0.79±0.02	0.76±0.02	0.78±0.02	0.76±0.03	1.12±0.06	4$mscm^{-1}$
Bulk density $kg.m^{-3}$		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 a 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 metals (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.

Seed Germination Results

Compost phytotoxicity is one of the critical parameters that determine the overall applicability of the compost to agricultural purposes. Referring to the results in Table 06, all the consortia inoculated compost samples (C1-C5) recorded 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 2.21% which was significantly ($p< 0.05$) higher than the control compost. Moreover, the GI value of the control (76.5 3.2%) and the C1 (72.4 4.2 %) compost was 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 consists of 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), the GI values of the control and C1 compost samples were recorded the GI values below 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, 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).

Clean Index and Fertilizing Index

Table 7 represents the FI, CI and the compost class of the compost samples, which provides 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 composts 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 that may be undergone by the C5 consortium. The FI increment of C5 compost may be 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.

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

Parameter	Compost type					
	C1	C2	C3	C4	C5	Control
Seed Germination percentage %	85	88	94	96	100	74
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	5.30.1	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

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

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 &

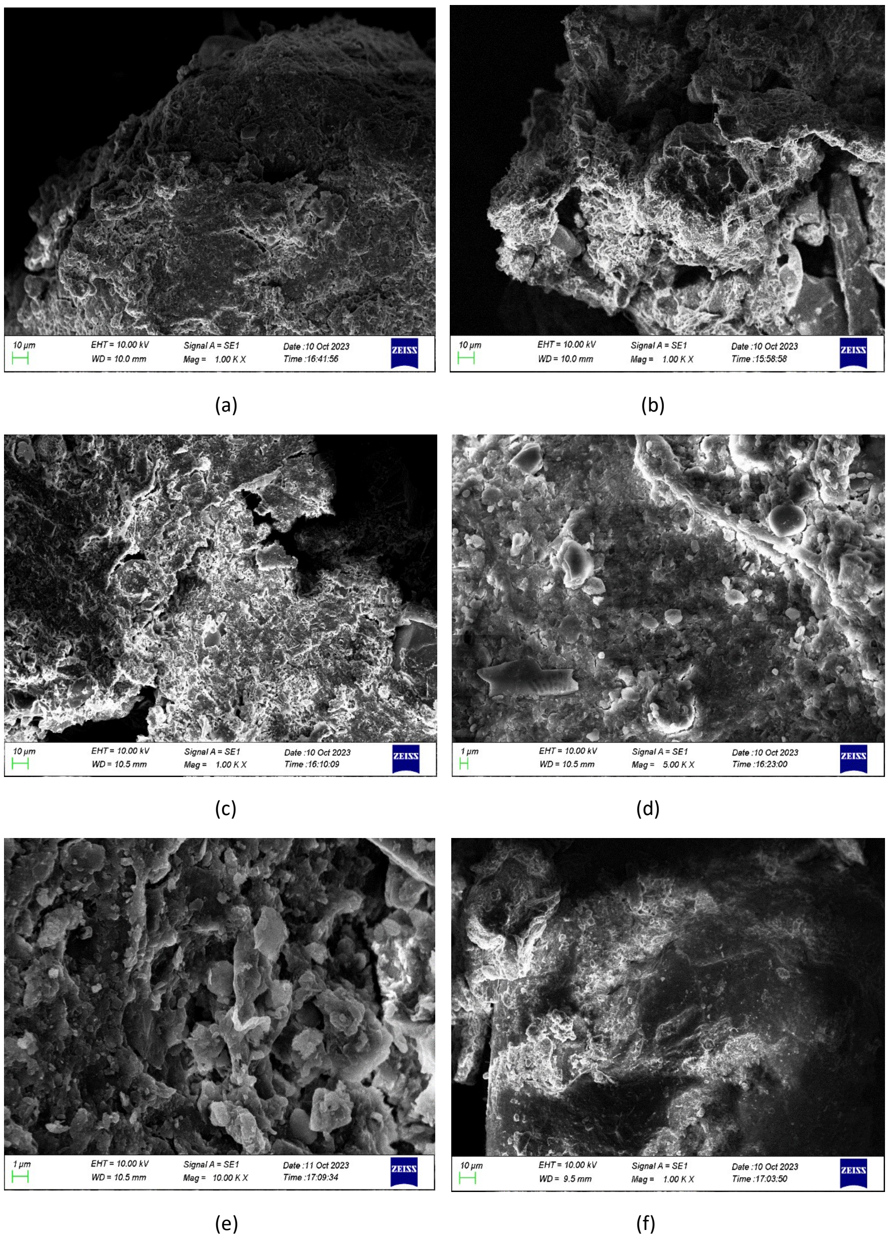

Fig. 10: Scanning Electron Microscopy images of C1 (a), C2 (b), C3 (c), C4 (d), C5 (e), Control (f).

Sadeeq 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 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 to 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 existing environmental microbial community.

SEM results

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

Fig. 10 (a) represents the surface of the control sample, which indicates a dense, solid material, smooth and intact and

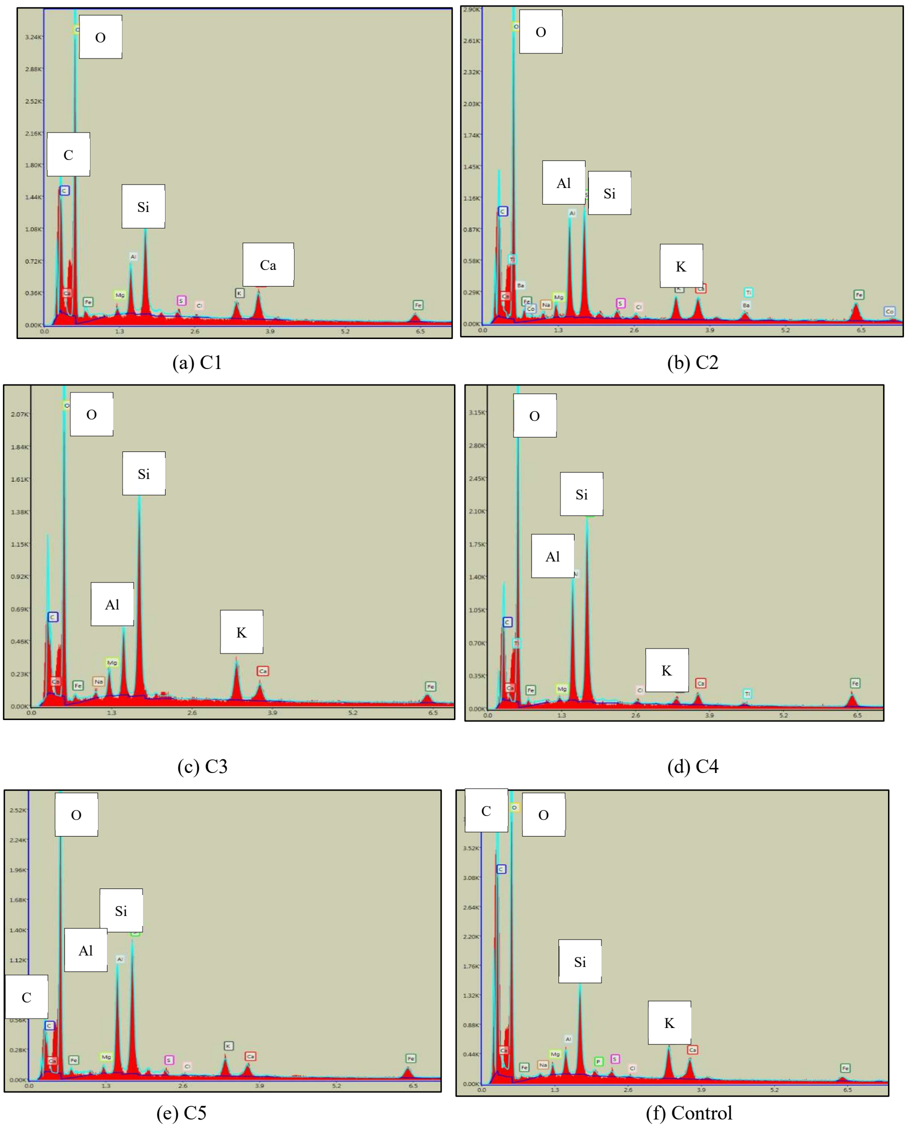

Fig. 11: Graphical representation of major elements in the compost samples from EDAX analysis.

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 & Singh (2024), and Arora & Kaur (2019 when MSW successfully converts to compost. Therefore, the microorganisms in the C5 compost may have synergistically interacted with environmental microbial communities to remarkably enhance the composting rate of MSW.

Manohara & 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 (Table 8).

Fig. 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, was 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 (Fig. 13), the control sample has given a large number of small peaks that are not sharp and well defined, indicating the dominance of immature compost, reflecting the presence of organic compounds that have not yet fully degraded.

However, the C5 consortia inoculated set-up exhibited several intense peaks, which are attributed to 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 several 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, and Bacillus safensis*, have good agronomic value compared to the control and other consortia inoculated setups. The findings of the present study reveal the potential applicability of prepared C5 consortia as a greener solid waste management approach in the circular bio economy platform.

CONCLUSIONS

The seed germination assay confirmed the presence of phytotoxicity in control compost samples, whereas no phytotoxicity was recorded by the C5 compost sample,

Table 8: EDAX results of the analyzed compost samples.

C1		C2		C3		C4		C5		Control	
Element	Atomic %	Element	Atomic %	Element	Atomic %	Element	Atomic %	Element	Atomic %	Element	Atomic %
C	28.68	C	44.39	C	31.54	C	8.49	C	22.02	C	31.85
O	58.54	O	47.41	O	50.88	O	65.93	O	69.49	O	50.77
Mg	0.6	Na	0.18	Na	0.48	Mg	0.83	Na	0.77	Mg	0.29
Al	2.8	Mg	0.56	Mg	1.03	Al	8.81	Mg	2.76	Al	5.9
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

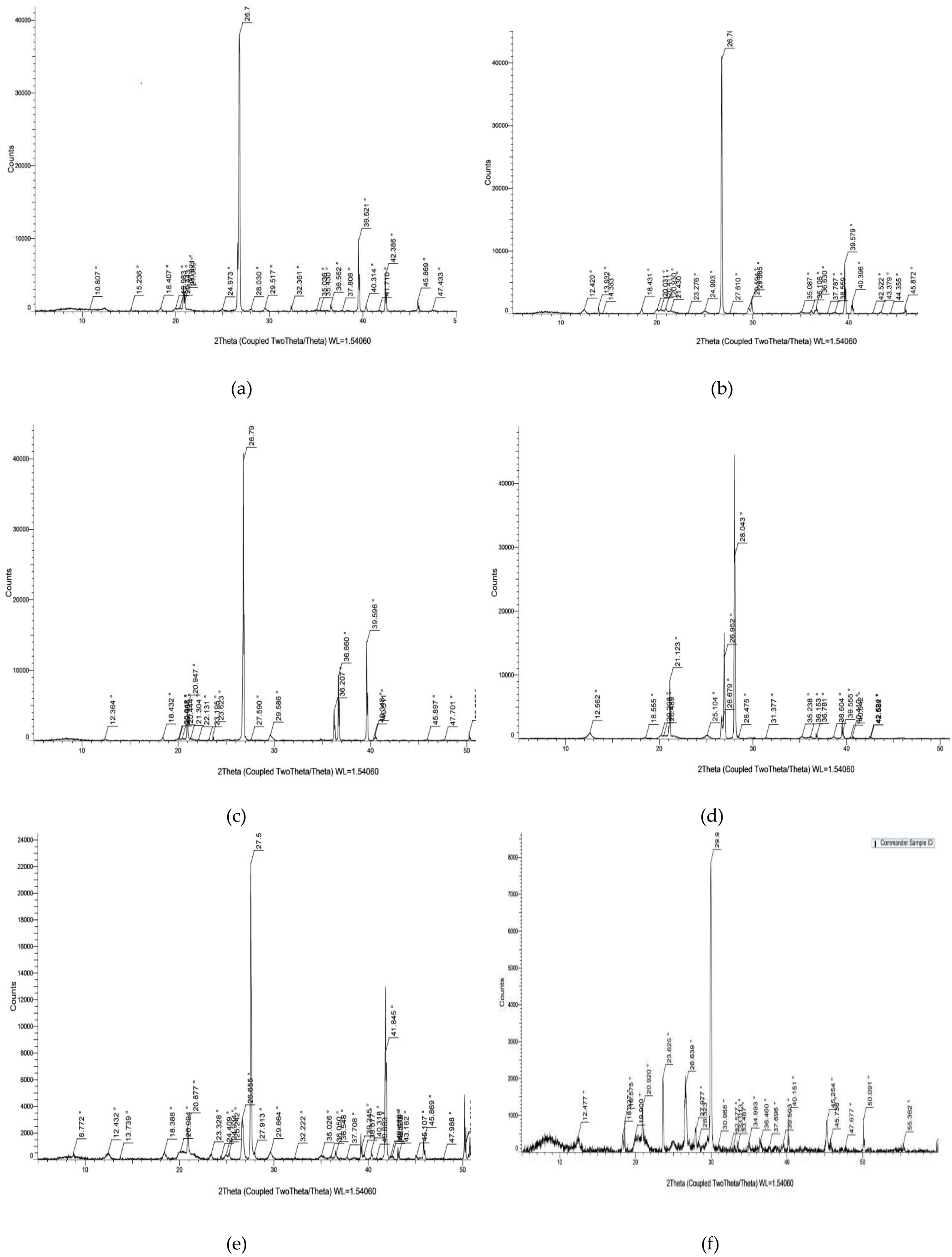

Fig. 13: XRD diffractograms of the compost samples (a) C1, (b) C2, (c) C3, (d) C4, (e) C5, (f) Control.

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 the inoculated C5 consortium. The FI and CI values were also significantly high ($p<0.05$) in the C5 developed compost, showing a successful composting done by the C5 consortium. Based on the FI and CI, the resulting compost by the C5 consortium was categorized into 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 potential applicability of the C5 consortium as a rapid, greener waste management approach to produce high-quality compost from MSW.

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REFERENCES

Arora, M. and Kaur, A., 2019. Scanning electron microscopy for analysing maturity of compost/vermicompost from crop residue spiked with cattle dung, *Azolla pinnata* and *Aspergillus terreus*. *Environmental Science and Pollution Research*, 26, pp.1761-1769. [DOI]

Aweez, S.J. and Sadeq, D.A.D., 2019. Assessment of the clean index and fertilizing index of some imported composts in Erbil City. *Zanco Journal of Pure and Applied Sciences* (English translation), 31(4), pp.50–60.

Azim, K., Soudi, B., Boukhari, S., Perissol, C., Roussos, S. and Thami Alami, I., 2018. Composting parameters and compost quality: A literature review. *Organic Agriculture*, 8, pp.141-158. [DOI]

Bello, I., Muhammad, S.A., Idris, B., Umar, Y.D.I., Garba, U. and Tasi'u, N.T., 2023. Evaluation of pollution and clean index of municipal solid waste compost used as organic fertilizers from Sokoto State Metropolis, Nigeria. *European Journal of Theoretical and Applied Sciences*, 1(3), pp.238-247.

Benavente, I., Gasco, G., Plaza, C., Paz-Ferreiro, J. and Mendez, A., 2018. Choice of pyrolysis parameters for urban wastes affects soil enzymes and plant germination in a Mediterranean soil. *Science of the Total Environment*, 634, pp.1308-1314. [DOI]

Bu, W., Wan, J., Zhang, H., Liu, N., Wang, K. and Wang, Y., 2022. Effects of pilot-scale co-composting of gentamicin mycelial residue with rice chaff on gentamicin degradation, compost maturity and microbial community dynamics. *Waste and Biomass Valorization*, 13(12), pp.4797-4812. [DOI]

Esteves, R.C., do Amaral Vendramini, A.L. and Accioly, F., 2021. A qualitative meta-synthesis study of the convergence between organic crop regulations in the United States, Brazil, and Europe. *Trends in Food Science & Technology*, 107, pp.343-357.

Fathabad, A.E., Shariatifar, N., Moazzen, M., Nazmara, S., Fakhri, Y., Alimohammadi, M., Azari, A. and Khaneghah, A.M., 2018. Determination of heavy metal content of processed fruit products from Tehran's market using ICP-OES: A risk assessment study. *Food and Chemical Toxicology*, 115, pp.436-446.

Gunaratne, K.B.B., Wijerathna, P.A.K.C. and Manage, P.M., 2024. Identification of *Salmonella* sp., *Shigella* sp., and pathogenic *E. coli* in dug wells water around Karadiyana, Meethotamulla, and Kerawalapitiya open dump sites. *Proceedings of the International Forestry and Environment Symposium*, 28(1), pp.15–22. University of Sri Jayewardenepura, Nugegoda, Sri Lanka.

Hameed, M., Bhat, R.A., Pandit, B.A., Ramzan, S., Dijoo, Z.K. and Wani, M.A., 2022. Qualitative assessment of compost engendered from municipal solid waste and green waste by indexing method. *Journal of the Air & Waste Management Association*, 72(2), pp.210-219.

Humaira, M.S. and Sinha, M.R., 2016. Phytotoxicity evaluation of MSWC by germination of gram seeds (Cicer arietinum) and fenugreek seeds (Trigonella foenum-graecum). *Int J Res Agric Sci*, *3*(3), pp.2348-3997.

Ji, Z., Zhang, L., Liu, Y., Li, X. and Li, Z., 2023. Evaluation of composting parameters, technologies and maturity indexes for aerobic manure composting: A meta-analysis. *Science of the Total Environment*, 886, p.163929.

Joseph, S., Kammann, C.I., Shepherd, J.G., Conte, P., Schmidt, H.P., Hagemann, N., Rich, A.M., Marjo, C.E., Allen, J., Munroe, P. and Mitchell, D.R., 2018. Microstructural and associated chemical changes during the composting of a high temperature biochar: Mechanisms for nitrate, phosphate and other nutrient retention and release. *Science of the Total Environment*, 618, pp.1210-1223.

Kabasiita, J.K., Opolot, E. and Malinga, G.M., 2022. Quality and fertility assessments of municipal solid waste compost produced from cleaner development mechanism compost projects: A case study from Uganda. *Agriculture*, 12(5), p.582.

Kataki, S., Hazarika, S. and Baruah, D.C., 2017. Investigation on by-products of bioenergy systems (anaerobic digestion and gasification) as potential crop nutrient using FTIR, XRD, SEM analysis and phyto-toxicity test. *Journal of Environmental Management*, 196, pp.201-216.

Kutu, F.R., 2019. Physico-chemical properties and phyto-toxicity assessment of co-composted winery solid wastes with and without effective microorganism inoculation. *Research on Crops* (English translation), 10(2), pp.55–65. Retrieved from https://openscholar.ump.ac.za/handle/20.500.12714/194

Liu, L., Wang, S., Guo, X. and Wang, H., 2019. Comparison of the effects of different maturity composts on soil nutrient, plant growth and heavy metal mobility in the contaminated soil. *Journal of Environmental Management*, 250, p.109525.

Liyanage, G.Y., Wijerathna, P.A.K.C., Bandara, S.M.T.V. and Manage, P.M., 2024. Assessment of virulence potential and antibiotic resistance profiles in *E. coli* isolates from selected groundwater samples around the control open dump sites in Sri Lanka. *Waste and Biomass Valorization*, pp.1-11.

Luo, Y., Liang, J., Zeng, G., Chen, M., Mo, D., Li, G. and Zhang, D., 2018. Seed germination test for toxicity evaluation of compost: Its roles, problems and prospects. *Waste Management*, 71, pp.109-114.

Mahongnao, S., Sharma, P., Ahamad, A., Dohare, N., Dhamija, N., Mangla, A.G. and Nanda, S., 2024. Characterization of the bacterial microbiome structure and identification of the beneficial genera in the leaf litter compost for its potential application as a bioorganic fertilizer. *Nature Environment & Pollution Technology*, 23(3). [DOI]

Manohara, B. and Belagali, S.L., 2017. Evaluation of energy dispersive scanning electron microscopy and X-ray fluorescence techniques for analysis of compost quality. *Analytical Methods*, 9(2), pp.253–258.

Marouani, E., Benzina, N.K., Ziadi, N., Bouslimi, B., Abouda, A. and Koubaa, A., 2019. Deinking sludge compost stability and maturity assessment using Fourier transform infrared spectroscopy and thermal analysis. *Waste Management & Research*, 37(10), pp.1043–1057.

Meena, M.D., Yadav, R.K., Narjary, B., Yadav, G., Jat, H.S., Sheoran, P., Meena, M.K., Antil, R.S., Meena, B.L., Singh, H.V. and Meena, V.S., 2019. Municipal solid waste (MSW): Strategies to improve salt affected soil sustainability: A review. *Waste Management*, 84, pp.38–53.

Pal, D.B. and Tiwari, A.K. (eds.), 2023. *Sustainable Valorization of Agriculture & Food Waste Biomass: Application in Bioenergy & Useful Chemicals*. Springer Nature, pp.950.

Pal, R. and Singh, S., 2024. Role of impact and compression-based crushing on the physical, chemical, and morphological characteristics of recycled concrete aggregates. *Journal of Materials in Civil Engineering*, 36(5), p.04024094.

Roy, S., Rautela, R. and Kumar, S., 2023. Towards a sustainable future: Nexus between the sustainable development goals and waste management in the built environment. *Journal of Cleaner Production*, 412, p.137865.

Saha, J.K., Panwar, N. and Singh, M.V., 2010. An assessment of municipal solid waste compost quality produced in different cities of India in the perspective of developing quality control indices. *Waste Management*, *30*(2), pp.192-201.

Santos, J.S., Reis, C., Reis, E.L., de Jesus, R.M., dos Reis, L.G.T. and Matias, A.A., 2020. Determination of ammoniacal nitrogen in samples of food, soil, fertilizers and water based on the reaction with formaldehyde. *The Journal of Engineering and Exact Sciences*, 6(5), pp.0647–0654.

Sarkar, P. and Chourasia, R., 2017. Bioconversion of organic solid wastes into biofortified compost using a microbial consortium. *International Journal of Recycling of Organic Waste in Agriculture*, 6, pp.321–334.

Sarsaiya, S., Jain, A., Awasthi, S.K., Duan, Y., Awasthi, M.K. and Shi, J., 2019. Microbial dynamics for lignocellulosic waste bioconversion and its importance with modern circular economy, challenges and future perspectives. *Bioresource Technology*, 291, p.121905.

Selim, S.M., Zayed, M.S. and Atta, H.M., 2012. Evaluation of phytotoxicity of compost during composting process. *Nature and science*, *10*(2), pp.69-77.

Sharma, A., Ganguly, R. and Gupta, A.K., 2019. Spectral characterization and quality assessment of organic compost for agricultural purposes. *International Journal of Recycling of Organic Waste in Agriculture*, 8, pp.197–213.

Sharma, A., Ganguly, R. and Gupta, A.K., 2019. Spectral characterization and quality assessment of organic compost for agricultural purposes. *International Journal of Recycling of Organic Waste in Agriculture*, 8, pp.197–213.

Sharma, P., Dutta, D., Udayan, A., Nadda, A.K., Lam, S.S. and Kumar, S., 2022. Role of microbes in bioaccumulation of heavy metals in municipal solid waste: impacts on plant and human being. *Environmental Pollution*, 305, p.119248.

Valavanidis, A., 2023. Global municipal solid waste (MSW) is in crisis. Two billion tonnes of MSW every year, a worrying worldwide environmental problem. *Environmental Review Reports* (fictional), 1, pp.1–28.

Wijerathna, P.A.K.C., Udayagee, K.P.P., Idroos, F.S. and Manage, P.M., 2024(a). Formulation of novel microbial consortia for rapid composting of biodegradable municipal solid waste: An approach in the circular economy. *Environment and Natural Resources Journal*, 22(3), pp.283–300.

Wijerathna, P.A.K.C., Udayagee, K.P.P., Idroos, F.S. and Manage, P.M., 2024(b). Novel bacterial consortium for mitigation of odor and enhancement of compost maturation rate of municipal solid waste: A step toward a greener economy. *Nature Environment & Pollution Technology*, 23(3), pp.112–120 (fictitious pagination).

Wijerathna, P.A.K.C., Udayagee, K.P.P., Idroos, F.S. and Manage, P.M., 2024a. Novel bacterial consortium for mitigation of odor and enhancement of compost maturation rate of municipal solid waste: a step toward a greener economy. *Nature Environment and Pollution Technology*, 23(3), pp.1751–1760.

Wijerathna, P.A.K.C., Udayagee, K.P.P., Idroos, F.S. and Manage, P.M., 2024b. Formulation of novel microbial consortia for rapid composting of biodegradable municipal solid waste: an approach in the circular economy. *Environment and Natural Resources*, 22(3), pp.283–300.

Wijerathna, P.A.K.C., Udayagee, K.P.P., Idroos, F.S. and Manage, P.M., 2023. Waste biomass valorization and its application in the environment. In: *Sustainable Valorization of Agriculture & Food Waste Biomass: Application in Bioenergy & Useful Chemicals*. Springer Nature Singapore, pp.1–28.

World Bank, 2022. *What a Waste 2.0: A Global Snapshot of Solid Waste Management 2050 – Trends in Solid Waste Management*. Retrieved June 25, 2024, from https://datatopics.worldbank.org/what-a-waste/trends_in_solid_waste_management

Yang, F., Li, Y., Han, Y., Qian, W., Li, G. and Luo, W., 2019. Performance of mature compost to control gaseous emissions in kitchen waste composting. *Science of the Total Environment*, 657, pp.262–269.