Evaluating Sewage Sludge Contribution During Co-Composting Using Cause-Evidence-Impact Analysis Based on Morphological Characterization

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Research Article

Keywords: Agricultural soil development, Co-composting, Morphological analysis, Sewage sludge, Soil nutrients

Posted Date: August 27th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-675753/v1

Abstract

The methods of compost preparation from sewage sludge and their modes of application to the agricultural fields have profound impacts on the soil ecology and environment. Besides their chemical conditioning effect on soil organic matter, they also impart physical attributes to the soil texture and structure. Though it is expected that compost addition improves water holding capacity and nutrient sequestration, there is lack of clarity in correlating the outcomes with conditions of excess nutrient storage/leaching despite the benefits on crop yield. In this study, we present a systematic cause-evidence-impact relationship on the feedstock, processing and applications of co-composted organic matter. Various analytical tools were compared to elucidate the unique characteristics of co-composted sewage sludge to get a realistic understanding of the complex soil-compost interactions. Results from the spectroscopic characterization reveal the implications of selection of bulking agents and sludge pre-treatment in determination of the final quality of the compost. The results attribute significant parent material influence to the formation of well-defined porous structures. The impacts of compost quality on the soil and crop can be proactively determined in terms of elemental composition, functional groups and stability indices. Thus the present approach provides good scope for customizing compost preparations and applications to get the preferred field outputs.

1. Introduction

Global rate of sewage sludge generation from the wastewater treatment plants is rapidly increasing in recent years. The presence of potential toxic elements as well as pathogenic microorganisms in the sewage sludge may not form a feasible option for the direct applications (Melo et al. 2018; Kayikcioglu et al. 2019; Glab et al. 2020). Co-composting is one of the sustainable approaches aimed at minimizing the burden of waste handling systems while providing numerous advantages for the agricultural sector (Liu et al. 2006; Kong et al. 2006; Singh et al. 2020). Although sewage sludge can be used directly as a bio-fertilizer due to the availability of nutrients and organic matter, composted/co-composted sludge is more preferred in the field due to its chemical stability and nutrients sequestrating features. Many emerging organic wastes have been successfully converted into nutrient-rich composts (Ferrentino et al. 2020; Kujawa et al. 2020). In view of this, co-composting can be addressed as a sustainable management option for the sewage sludge by virtue of its circular economic approach, because it is simultaneously satisfying the nutrient requirements for the crop growth as well as minimizing the waste handling problems (Minamiyama et al. 2008; Abbasi et al. 2019; Ayesha 2020). From the agricultural point of view, the most implicating factors of compost amendment on the soil would be the soil moisture retention capacity, infiltration rate and nutrient sequestration effect (Adugna 2016; Abbasi et al. 2019; Ai et al. 2020). The recirculation of the leachate component during co-composting is also found to provide added advantages such as maintaining the essential nutrients ratio and reducing the issues of seepage and foul odour (Chen et al. 2020; Villamil et al. 2020; Vasudevan et al. 2019; Balaganesh et al. 2020b).

At this point, it is important to realize that the prevailing biogeochemical transformations of the bio-fertilizer in the soil depends largely on the composition and characteristics of the composting materials, especially the sewage sludge, due to the supplementing of essential nutrients and favourable species of micro-organisms (García-Ocampo 2012; Valdez et al. 2020). The organic fraction of composts mainly consists of the functional groups of phenolic, alcoholic hydroxyls and carboxylic acids while the inorganic fraction consists of chlorides and hydroxides (Milojkovic et al. 2014; López-Sotelo et al. 2017). By virtue of surface-active phenomena, composts are the favourable bio-sorbents to attenuate many toxic substances such as heavy metals and excess nutrients when it is mixed with suitable bulking agents (Balaganesh et al. 2019; Ma et al. 2019; Liu et al. 2020; Ai et al. 2020; Karthick et al. 2020). It is to be understood that the stability and bio-geochemical transformations of the compost remains incomprehensible without investigating the cause-effect relationship of the changes in compost properties such as the porous structure, elemental composition and functional groups during the preparation as well as field application (Nguyen et al. 2018). This makes the scope of bio-geochemical interactions between the compost and soil versatile and unique to improve the soil organic matter.

The morphological and spectroscopic studies of compost and soil can play a critical role to reveal the fate, transport and transformation of the nutrients and contaminants in a deeper sense (Cao et al. 2019). Based on the literature review, it is understood that most of the studies are related to the techno-economic feasibility of sludge-amended composts having multiple organic wastes as co-substrates, while detailed information about the prevailing bio-geochemical transformation and their cause-effect relationships unto the functional characteristics are mostly omitted or inadequately represented. The present study attempts to evaluate the morphological and physicochemical analysis of sludge-based compost for explaining the structural variations during the preparation and application, and their implications on the environmental quality. First, we present the details of the experimental work carried out to characterize the contribution of sewage sludge while preparing compost along with other organic wastes by emphasizing on the morphological behaviour. Then, we present categorical descriptions about the plausible connectivity between the feed composition, structural features (based on morphological results) and their field implications in order to derive a cause-evidence-impact relationship of the compost. The findings of this study will enable us to understand the impacts of these transformations on the composted soil for deriving effective management practices to utilize the sludge-based compost in agriculture.

2. Materials And Methods

2.1 Preparation of Compost

The present study was conducted at Bannari Amman Institute of Technology, Sathyamangalam, Erode district, Tamil Nadu (11.4962∘N, 77.2768∘E). In order to prepare the compost, the required quantity of sewage sludge, vegetable waste, agro waste and bulking agents (sawdust and sawdust biochar) were collected from the campus premises and were mixed in three different proportions (Fig. 1). The sewage sludge was collected from the in-house sewage treatment plant (capacity of 7.5 MLD), vegetable wastes were collected from the hostel mess kitchen, while the agro waste such as dry leaves were collected from garden, and the sawdust was gathered from the carpentry workshop.

The composts were prepared in a series of three prototype plastic bins (capacity of 20 L). All the bins were drilled for 10 mm holes to provide sufficient aeration and also attached with a plastic tap at the bottom for leachate collection. The bin 1 was filled with sewage sludge, dry leaves, kitchen waste and sawdust in a pre-determined proportion and kept to serve as a control sample. The bin 2 was filled with the same wastes, but with a provision to recycle the generated leachate from the bottom tap. The specific feature of bin 3 is the addition of biochar as a bulking agent without leachate recirculation (Vasudevan et al. 2019). All the three bins were frequently turned for better aeration. The stabilization and maturity of the composting materials were evaluated periodically based on the preliminary physico-chemical analysis. After a period of 35 days, the compost was found to be sufficiently stabilized and was collected and stored in airtight vessels and shifted to the lab for subsequent experiments.

2.2 Physico-Chemical Characterization of Compost

Initially, the sludge samples from the sewage treatment plant were collected and analyzed for their temporal variation in physico-chemical parameters such as pH, electrical conductivity (EC), chloride, chemical oxygen demand (COD), nitrate, nitrite and ammonium. The regular standard methods prescribed for the analysis are same as those described by Vasudevan et al. (2019). The samples were analysed for EC using digital conductivity meter (M/s Elico India). The aqueous concentration of chloride was estimated by argentometric titration using 0.0141N $AgNO_3$ using $KCrO_4$ as the indicator. Ammonia Nitrogen concentration was estimated using UV-Visible PC based Double Beam Spectrophotometer 2202 (M/s Systronics India) at a wavelength of 640 nm using phenol and sodium nitroprusside as the colouring reagent under strong oxidizing solution (alkaline citrate, sodium hypochlorite). Similarly nitrate-nitrogen concentration was estimated using UV-Visible Spectrophotometer (M/s Systronics India, Double Beam – 2202) at a wavelength of 410 nm using brucine-sulphanilic acid as the colouring reagent under strong acidic digestion medium (H_2SO_4). Chemical oxygen demand (COD) was estimated by closed reflux principle for digesting in the COD reactor (M/s Hanna – HI 839800) by using dichromate versus ferrous ammonium sulphate titration.

2.3 Morphological Characterization of Compost

The structural morphology of the composted sample was characterized by using scanning electron microscope (SEM, EVO18, M/s Carl Zeiss, Germany), Energy Dispersive X-Ray Analysis (EDAX, D8 Advanced ECO, M/s Bruker, India) and Fourier Transform Infrared spectroscope (FTIR, RTracer-100, M/s Shimadzu, Japan). The SEM analysis was performed with EHT = 20.00 kV, WD = 8.00 mm and signal NTS BSD. The image magnifications were in the range of 250 X to 5.00 KX. The range of observed particle size varied from 2 to 100 µm. The spectroscopic observation of compost samples were performed for functional group identification using FTIR with a wavelength ranging from 400 to 4000 cm^{-1}.

3. Results And Discussion

3.1 Observation of the Physico-Chemical Behaviour of Compost

The quantitative evaluation of compost quality showed significant variations for the three treatment options. The composting process attained three different phases (mesophilic, thermophilic, cooling/curing) primarily due to the temperature variation caused by biological variations. The temperature increased rapidly during first week in all the three bins and then decreased slowly during the second and third week and gradually reached an asymptote at the end of 30th day (Fig. 2). The average temperature of the matured compost (shown as ‘final’) is observed to be lower than the average value during the first week of composting (shown as ‘initial’). The samples from bin 2 started with a lower temperature value (30^oC) compared to the other two treatments (40^oC each), but resulted in a higher temperature (45^oC) for the final samples. This is due to the enhanced microbial activity caused by the recirculation of sewage sludge during co-composting. Similarly, the moisture content increased marginally for the final compost for all the three treatments (as representatives from bin 1, bin 2 and bin 3). Although one would normally expect to attain a lower value of final moisture content in bin 3 due to the presence of biochar as a bulking agent, the destruction of micro-pores due to the aggregation has retained the moisture content in the final product. Hence, it is to be understood that apart from increasing the porosity, the particle size distribution of the bulking agent plays a significant role is reducing the moisture content.

The physical modifications in temperature and moisture content are depicting the change in biochemical reaction rates, thus resulting in more prominent variations in the chemical concentration profiles. The Total Organic Carbon (TOC), Total nitrogen (TN) and Carbon to Nitrogen Ratio (C/N ratio) showed significant variations during the composting with similar rate of reduction for all the three treatments. However, since the values of temperature and moisture content are quite dissimilar to begin with, the degree of reduction also resembled the same trend. Higher values of TOC and C/N ratio were observed for samples from bin 3 owing to the increased surface activity of sawdust biochar thus contributing more labile carbon to the humification process.

After dewatering, when the sludge is mixed with other ingredients in fixed proportion, the contribution of sludge is highlighted in terms of increased moisture content and reduced temperature. The typical chemical parameters such as TOC, TN and C/N ratio of the matured compost were also modified according to the sludge treatment. For example, the sludge recirculation has resulted in higher reduction in carbonaceous and nitrogenous compounds (Fig. 2). This is also expected from other treatments where the composition of compost changed only in the preparation of bulking agent.

3.2 Unveiling the Role of Morphological Analysis for Compost Characterization

Recent developments in the biometric instrumentation has widened the scope of qualitative observations as a quick assessment protocol in understanding the surface and chemical modifications occurring in various biochemical reactors (López-Cano et al. 2016; Liu et al. 2020). The implementation of real-time monitoring tools in the operation and maintenance of large-scale wastewater treatment plants serves as a good example for this statement (Singh et al. 2020). In a similar way, a detailed understanding of the biochemical transformations occurrign during the composting is necessary to unveil for its various in-field applications (Burducea et al. 2019). The conventional approach of deriving substrate-level mass transfer kinetics becomes inevitably impractical to deal with the complex interactions of multi-species degradation reactions; quite often resulting in dealing with many unintentionally released unknown intermediate by-products. One practical approach to explain the internal reactions undergoing in a heterogeneous environment (such as composted soil) could be to visualize (directly or indirectly) the changes in physical (surface morphology) and chemical (elements/compounds/functional groups) characteristics during the process (Table 1). In this aspect, morphological analysis has been widely accepted as an essential characterization tool for studies involving material preparations and modifications (Huang et al. 2015; Zhang et al. 2014; Chen et al. 2017).

Table 1
Details of Physico-Chemical Characterization of Sludge-based Compost using Morphological Features

Physical state of sludge	Sludge proportion (%)	Composting type	Composting time (days)	Physical modifications	Physical status of matured compost	Morphological characterization technique used	Implications	Reference
Dewatered, fresh municipal	Paddy straw (20% of sludge); Biochar (6–18% of sludge)	Aerated, in-vessel, rectangular reactor (12.5L)	42	Intermittent air circulation (0.03 $m^3/h/kg$); turning – once in a week	C/N = 10–15; H/C = 1–2; Oxygen uptake rate = 1–4 mg/g/h	Extraction-emission matrix (Fluorescent spectrometer); Composition (Elemental analyser, FTIR); Structural (SEM)	Distinctive fractions of FA & HA – using FRI-EEM spectra; surface disintegration due to organic degradation and hydrolysis	Zhang et al. 2014
Dewatered, tertiary treated	Adjusted to get a C/N ratio of 30:1	Aerated, in-vessel, rectangular reactor (31.25L)	55	Turning thrice a week	C/N = 30:1; used as adsorbent for Cr(VI) removal	BET, SEM, FTIR, EDX	Surface area – using BET; porous structure – SEM; hydroxyl, carbonyl and amino groups (FTIR) to verify Cr(III) production	Chen et al. 2017
Dewatered	90% sewage sludge with bamboo charcoal	—	—	—	C/N = 12.1	FTIR, SEM	Phyto-availability of heavy metals (FTIR); soil aggregation (SEM)	Hua et al. 2012
Anaerobic digested sludge	—	—	—	—	Stabilized phosphorous	XRD, SEM-EDAX	Crystallization of stabilized sludge	Huang et al. 2015
Fresh, municipal	Sewage: green = 3:1	Aerobic	30–40	—	Dissolved organic matter fractions	FTIR	Mineral compounds in soil	Fang et al. 2016
Oil palm effluent anaerobic sludge		Anaerobic digester ($500m^3$)	40	—	C/N = 12.4	SEM	Degraded porous structure	Baharuddin et al. 2010
Fresh, municipal	Adjusted to get a C/N ratio of 22:1	Aerobic reactor (34L)	42	Turning thrice a week	C/N = 22:1; dissolved organic matter extraction	SEM	Effect of microbial community in bio-transformation	Zhao et al. 2018
Stabilized sludge	30%	Aerobic in-vessel				Digital image analysis	30g/l SS addition best suitable for Bermuda grass	Rezende et al. 2020
Dewatered sewage sludge	50% (1:3:4)	Aerobic in-vessel				FTIR, XRD, XANES		Wang et al. 2020
Industrial sewage sludge	23.81%	Aerobic in-vessel	180	Passive aeration		FTIR, EDX		Seremeta et al. 2020
Industrial sewage sludge	23.81%	Aerobic in-vessel	180	Passive aeration	8.3 pH, 52°C -62°C Temperature	UV VIS, FTIR, ^{13}C NMR		Zittel et al. 2018
Activated sludge	75% (2:1)	Heap composting	135			FTIR, ^{13}C NMR		Amir et al. 2010
Dewatered fresh sludge	60%	Aerobic in-vessel	18	Forced aeration	6.8–7.1 pH, 30°C -35°C	XRD		Wang et al. 2019

Physical state of sludge	Sludge proportion (%)	Composting type	Composting time (days)	Physical modifications	Physical status of matured compost	Morphological characterization technique used	Implications	Reference
Dewatered digested	33.33(1:1:1)	Windrow	200	Forced aeration in box for 20 days + mixing	34% MC, 7.8 pH, 39.1% OM			Albrecht et al. 2010
Dewatered	33.33(1:1:1)		120		24ºC Temperature, 7.3 pH, 2.2 MC		Study confirmed the reduction of heavy metals (Cd, Zn, Cu, Hg) in SS after composting	Dridi et al. 2020
5 days oxygen Stabilized, dewatered	0.15 in (1:0.15, 1:0.15:0.1)	Open system, container	140	Aerated 6 times/day and Mixed every 10 days		SEM		Glab et al. 2020
Dewatered primary sludge	70%		45	Forced ventilation system			Sludge compost amendment performed better up to 45% for tree peony	Huang et al. 2015
Direct	50 (1:1)	Windrow	45	Turned when temperature above 65ºC				Silva et al. 2019
Dewatered primary sludge		Aerobic in-vessel		Daily turning			BSFL composting less suitable for SS	Lalander et al. 2019
Undigested sludge		Aerobic in-vessel		Daily turning			BSFL composting less suitable for SS	Lalander et al. 2019
Digested sludge		Aerobic in-vessel		Daily turning			BSFL composting less suitable for SS	Lalander et al. 2019
		Cylinder compost reactor	55	Forced aeration				Wang et al. 2020

3.2.1 Implications of Physical Modifications of Compost

The organic compounds present in compost undergo biochemical transformation owing to their water-soluble nature, thus causing distinctive surface and micro-structural features to exhibit as a function of time. A detailed observation of the micro-structure can throw more light on the phase-transformations occurring during the preparation, thus highlighting the popularity of the morphological analysis (Table 1). The surface modifications during composting can be identified as the improved specific surface area, pore volume, cation exchange capacity, evolution of volatile organic compounds and sequestration of nutrients and toxic compounds. In addition, the specific surface features and subsequent biochemical transformations of organic compounds during composting rely very much on the initial composition and the origin and nature of the parent ingredients (known as parent material influence). For example, the biochar generally contains large number of recalcitrant aromatic compounds (lingo-cellulose-type) that possess long half-life in the environment by virtue of the high temperature during the pyrolysis process of formation. Thus, biochar is a preferred amendment as an effective bulking agent for co-composting to achieve 70–85% degradation of labile organic matter from the raw materials (Balaganesh et al. 2020a). Biochar is known to have significant contribution towards altering the nutrient ratio in compost, particularly by favoring the humification process (Zhang et al. 2014). In addition, the specific method of preparation (thermal activation, pyrolysis etc.), selected range of temperature and presence of co-substrates also significantly influence the specific surface and chemical activity of the biochar-amended compost.

3.2.2 Implications on Biological Activity of Compost

The variations in physico-chemical properties of compost can be primarily attributed to the subsequent biochemical transformation of the water-soluble organic compounds during the composting period. This is quite evident from the increasing level of humification during the decomposition of easily degradable organic constituents such as aliphatic chains, polysaccharides, alcohols and proteins (Albrecht et al. 2010). Similarly, the presence of functional groups (carbonyl, phenolic and aromatic) on the projected edges of the base molecules has facilitated the surface activity of the matured compost through physisorption and chemisorption especially when applied to the soil (Niinipuu et al. 2020).

The morphological analysis of sewage sludge has initiated tremendous applications for sustainable waste management in the recent past, by bringing about a realistic understanding on the complex interactions between the aromatic-rich organic compounds and the susceptible microbial cultures. The separation of humic-acid-like compounds (HA fraction) and fulvic-acid-like compounds (FA fraction) can be easily visualized using the fluorescent excitation-emission spectra of the dissolved organic matter. Many times, the image comparison studies overlay with some quantitative approach such as estimation of colour intensity, image area and volumetric fluorescence using the fluorescence regional integration (FRI) approach (Zhang et al. 2014). Based on the observation of high FA fraction in the wood biochar-based compost using FRI-EEM spectra in corroboration with the selected proportion of raw materials, the physical structure of the stabilized product can be well attributed to a phenomenon called parent material influence (PMI) (Zhang et al. 2014).

3.3 Cause-Evidence Relationships for Sludge-based Compost

3.3.1 Implications of Surface Modifications

The microscopic structure of the compost samples reveals the visible surface modifications in size, shape and porosity. As observed in Fig. 3, there are multiple irregularities in the micro-structure of samples from Bin-1 indicating the significance of PMI on the compost quality. The irregular clumpy structures (Fig. 3) correspond to the bulking agent (sawdust in Bin-1), while the finer layers of construction corresponds to the combination of greens which are more easily degradable and can change their shape invariably. However, the rod-like fraction remains more or less uniform indicating the structural stability of the bulking agent during the compost preparation. It is to be understood that the humification and aromatization has improved the overall distribution of sludge particles resulting in a decrease in the macro-pores availability in the stabilized compost. In essence, the structural features of the final product are observed to carry forward the inherent PMI as their characterizing features.

A finer distribution of degraded organic solids is more uniformly present in bin 2 where the compost was treated with recirculated sludge (Fig. 4). Though the images show the fractured irregular surface, a closer magnification (500X-5000X) could reveal plain surface with ball structures. Similar ball structures (approx. 1 µm pore size) can be observed from remaining images with all observed magnifications. This reveals that although the same composition and ratio of substrates are used in bin 1 and bin 2, the recycling of leachate varies the morphological characteristics of the matured compost.

The third sample (from bin 3) showed the largest distribution of fine particles on the surface where the sludge is amended with biochar as bulking agent instead of plain saw dust (Fig. 5). A coarse grained structure was observed at a magnification of 250X where all particles are found to be of less than 50 µm size. Unlike the previous samples, there was no fractured lengthy structure in bin 3 images. Very few clear spherical balls of size around 3 µm can be observed at 2.500MX magnification. These SEM images can be used to infer the surface activity resulting from the biochemical transformations.

3.3.2 Element Overlay Analysis of Compost (EDAX)

The analysis of element overlay, smart quantum and graphical observations are shown in Figs. 6 (a, b, c). The results show that maximum percentage of element present in the sample is carbon, which is 40, 42 and 40% in bins 1, 2 and 3 respectively. This proves the optimum feasibility of carbon degradation/transformation during the co-composting, and its utility for the direct land application. As the carbon is deployed from both organic and inorganic origins, the elemental fraction mentioned here ascertains the proportion of fixed carbon remaining after sufficient aeration during co-composting. While the values of TOC and Chemical Oxygen Demand (COD) describe the oxidizable carbon remaining during the preparation, the elemental analysis can be confronted with the possible removal of labile fraction of organic carbon from the matured compost. This, in effect, reflects the soil-adsorption capacity of the carbon when applied directly to the organic-deficient soils. Furthermore, it is found that oxygen is the next element with higher presence in the samples (26, 25 and 18%). This can be attributed to the saturated aeration condition maintained by molecular diffusion at the interface and by frequent turning. The concentration of some of the crucial heavy metals (sodium – nil, titanium – 1%) were not detected satisfactorily in any of the samples.

3.3.4 Functional Group Changes of Compost (FTIR)

The structural modifications in the organic matter during co-composting can be better understood with the help of FT-IR spectra (Fig. 7). The frequency of the observed peaks is crosschecked with the library files to verify the presence of most accurate functional groups. There is a clear evidence of peak shift in the region around 1000 cm^{-1} for the sample collected from bin 1 indicating the sequential degradation of polysaccharide-like materials which are removed during the co-composting process. Similarly, the broad distribution of peaks in the region 600–1200 cm^{-1} shows the presence of large number of Si-O bonds which indicates the presence of complex interactions between HA fractions and silica impurities (present as clay minerals). A single large peak in the region I of IR spectrum (4000 to 2500 cm^{-1}) reveals the presence of C-H, N-H and O-H single bonds in both the bins (bin 1 and bin 2). This also represents the possibility of absorption of O-H group (alcohol compound) for both bin 1 (3323.4 cm^{-1}) and bin 2 (3328.23 cm^{-1}). No peaks were identified in the region II (2500 to 2000) cm^{-1} in any of the bins indicating the absence of triple bond structures in the matured compost. Two peaks were observed from bin 1 in region III (2000 to 1500) cm^{-1} while a single peak is observed in bin 2 and bin 3, indicative of the presence of C = N, C = O and C = C double bonds as the functional groups in the composts. The presence of C = N stretching group and imine/oxime compound class is observed in the range 1690–1640 cm^{-1} from bin 1 (1649.2) cm^{-1} and at 1650.13 cm^{-1} for both bin 2 and bin 3. The presence of N-O stretched group representing the nitro compound class is confirmed by the presence of peak in the region III obtained from bin 1 (1541.2 cm^{-1}). The results serve as good indication to ascertain the efficacy of nutrient availability during direct application of the compost containing sufficient nitrates for the crops.

The series of minor peaks observed in the fingerprint region (IV region) reveals the presence of S = O stretching, C-N stretching and C-Br stretching groups at 1369.5, 1225.8, 1029, 665.45 and 562.26 (in cm^{-1}), indicating the presence of sulfonamide, amine, and halo compounds. However, sulfoxide and 1, 2, 4 tri substituted compound class were present only in bin 3. The expected variations in the compost nutritional properties are thus found to be easily correlated with the change in functional groups.

3.4 Cause-Evidence-Impact Relationships for Compost

The basic approach for evaluating the cause-evidence-impact relationships relies on sensibly estimating the direct/indirect implications of feedstock proportion on the maturity and stabilization of the compost. Achieving an adequate range of common physico-chemical parameters can, however, provide the background information about the feedstock proportion. But the differences in the preparation/processing can only be understood by evaluating the micro-structural modifications with the help of morphological analysis. Once applied to the field, the compost-soil interactions will be further modified according to the prevailing soil environment, and the final implications will be further studied on (i) soil quality, (ii) crop productivity and (iii) alleviating potential risks of pollution. Hence, based on the present study results, a summary of the cause-evidence-relationship is provided in Fig. 8.

3.4.1 Implications on Physico-Chemical Properties of Soil

The incorporation of stabilized compost can impart high humic fraction with less reactive compounds leading towards improvements in soil structure and aggregation. The evidence of biochar-amended compost on improving soil texture is also reported in a few literatures. Many researchers reported significant improvements in soil bulk density (reduction), water holding capacity, and soluble concentrations of total carbon and mineralizable nitrogen (Aggelides and Londra 2000; Celik et al. 2004; Evanylo et al. 2008; Sax et al. 2017; Kakabouki et al. 2021). As the nutrients find limited scope for migrating pathways (such as volatilization and leaching), there is good scope of nutrient sequestration. This is particularly significant in case of mobility reduction of nitrate in agricultural soils to improve the plant availability. Hence, it can be understood that proportioning the C/N ratio of the feedstock has a direct impact on the final soil chemical quality (EC, pH and CEC) while optimization of the physical interactions (such as aeration and mixing) can influence the formation of macro-aggregates with increased stability (Logsdon et al. 2017). It is also reported that the reduction in bulk density is rather a slow result that can be effectively manifested over a period of cultivation practices (Table 2). But the most intricating role of compost in agriculture can be thought to be its simultaneous effects on soil water retention as well as infiltration capacities. The moisture retention capacity is generally observed to be high for compost amended soils in proportion to the porous nature of the amendments while the infiltration rate is attributed to the increased porosity, reduced bulk density and soil microbial activity (Zemánek 2011). Thus, the selection of suitable composting proportion can impart a long-time effect on the agricultural soils.

Table 2
Comparative evaluation of different composting materials and methods on the impact of agriculture in terms of soil quality and crop yield

S. No	Compost feed stock	Experimental conditions	Effect	Reference
Improvements in Soil Quality				
1.	Sewage sludge, town waste, sawdust	Aerated pile method, (3x6)m plot	Reduction in soil bulk density; increased soil porosity; increased hydraulic conductivity	Aggelides and Londra (2000)
2.	Different organic wastes	5 years @ 30–50 m^3 in a year in plots of 25x12m	Soil erosion reduced by 67%; runoff by 60%; bulk density by 8%; and 21% higher organic matter	Strauss et al. (2001)
3.	Manure organic waste	5years @ 25 t/ha	Increased soil water (86%) due to the increase in micro- and macro-porosity	Celik et al. (2004)
4.	Dairy waste	5 years @ 100 t/ha	Increased organic carbon (143 times); total carbon pool (115%)	Habteselassie et al. (2006)
5.	Poultry litter, yard waste	Turned windrow method, four months	Improved porosity, bulk density, water holding capacity; corn yield high	Evanylo et al. (2008)
6.	Cattle manure	5 years	Organic carbon (2.02t C/ha.Y) & total nitrogen (0.24t N/ha. Y)	Whalen et al. (2008)
7.	Leguminous plant residues	trapezoidal pile composting; 10 days once turning; ptimum moisture, 179 days	Improved soil structural stability and biological activity; reduced bulk density	Tejada et al. (2009)
8.	Digestates and compost	4 years @ 100 m^3/ha	Increased pH; improved biological activity	Fuchs et al. (2014)
9.	Mixed domestic and yard wastes	5 years @ 40% (v/v)	Increased hydraulic conductivity (22 times), but reduced for the incorporated yard waste compost (5 years)	Cannavo et al. (2014)
10.	Mixture of food waste, animal bedding and manure	12 years composting (33% v/v)	Improved (reduced) bulk density, increased carbon and nitrogen	Sax et al. (2017)
11.	Green waste	5, 10 and 15 kg/ tree	Improved soil NPK at high rate	Tong et al. (2018)
12.	Quail manure	Chicken manure and quail manure	Harvested mushrooms chicken manure compost preserved the whiteness for a longer time	Ranjbar et al. (2019)
13.	Agro-industrial waste compost	*5* levels to grow *Allium cepa* L	Improved the soil pH, TOC, TKN, field capacity; permanent wilting point; available water content; cultivable bacterial count and fungi No significant effect on electrical conductivity and phosphorus	Erana et al. (2019)
14.	Municipal solid waste compost	Three doses of compost (0, 30 and 60 Mg compost ha^{-1} soil) or inorganic fertilization (~ 140 N: 120 P2O5: 240 K_2O kg ha^{-1} soil) after 5 months	Improved soil pH, total organic C and N, cation exchange capacity and available P, Ca, Mg and K; no effect on NH^+4-N and NO^-3-N	Dominguez et al. (2019)
15.	Solid organic waste, urban greening	30 t / ha dosage, mesocosm (20x30x10)cm	Soil organic matter, enzymatic activities and microbial community increased	Picariello et al. 2020
16.	Sludge-based compost	Pilot-scale application on slopy land	Reduced erosion, improved infiltration and water retention	Vasudevan et al. 2018
Improvements in Crop Yield				
1.	Municipal solid waste	5years @ 80 t/ha	Wheat grain yield increased (246%)	Cherif et al. (2009)
2.	Sheep manure and wheat straw	5 years @ 60:40 (v/v)	High crop productivity (21.4%)	Jindo et al. (2016)
3.	Municipal waste compost and nitrogen fertiliser	Municipal waste compost rates (0, 1, 2, 4% on the basis of soil dry weight) and 4 N levels (0, 50, 100, 200 mg kg^{-1} soil)	C-N improved growth of tomatoes Uptake of nutrients	Rajaie and Tavakoly (2016)

S. No	Compost feed stock	Experimental conditions	Effect	Reference
4.	Press-mud compost	5 levels 0.00, 1.25, 2.50, 3.75 and 5.00 t ha-1	Incorporation of 1.25 t ha^{-1} in three splits	Kalaivanan and Hattab (2016)
5.	Sugarcane byproducts and pressmud	Literature survey	Press mud recycling can helps in saving of costly chemical fertilizers	Dotaniya et al. (2016)
6.	Organo-mineral fertiliser (OMF) compost	Six organo-metallic samples @ 10, 20 and 30 ton ha^{-1}	50% saving of the recommended dose of NPK fertilisers; decreased the concentration of Cd^{2+} and NO^{-}_{3}	Rady et al. (2016)
7.	Onion waste and bovine manure mixture as compost	pH 8.3; 2.2% organic matter; compost dosages (20,40,60,80 Mg ha^{-1})	Positive effect on the fresh weight of the plant; doses of 6 kg m^{-2}	Pallejero et al. (2017)
8.	Faecal sludge co-composted with oil palm empty fruit bunches (EFB) and cocoa pod husks (CPH)	Mixing ratio of 1:1:1, 2:1:1 and 2:2:1 @ 3 months	Suitable growing medium for tomato	Nartey et al. (2017)
9.	Cow manure co-composted with poplar leaf litter	1:0, 1:1, 1:2 and 1:3; rate of 20 t ha^{-1}; 8 weeks	High bioavailability	Anwar et al. (2017)
10.	Sewage sludge fertiliser compost	Green beans and white radish	Increase in yield, TOC and chlorophyll contents of green beans	Khaliq et al. (2017)
11.	Date palm waste compost	Three levels	Palm compost at 30 t ha^{-1} high yield	Benabderrahim et al. (2018)
12.	Rock phosphate (RP) enriched compost	5 mixing ratio; max 1 month; @ (100–1000 kg ha^{-1})	Ratio of 50:50 (RP:Compost) and application rate of 800 kg ha^{-1} showed maximum growth	Datta et al. (2018)
13.	Compost with jatropha cake on maize yield	@ 1.5 t/ha (30% grade B + 70% JC); 2 t/ha (30%grade B + 70% JC); 2.5 t/ha (50% grade B + 50%JC	Positive effect on soil fertility after harvesting of maize	Olowoake et al. (2018)
14.	Composted kitchen waste and poultry manure	8 weeks @ 0, 5, 1 and 150 t ha^{-1}	Promoted the growth and yield of Corchorus; Accumulation of heavy metals within the allowable limit	Oguntade et al. (2019)
15.	Daily household green waste	Inorganic fertiliser blended with crop residues, farm yard manure, compost	Highest yield of 53.33 ± 2.09 Q/ha; lowest yield of 32.71 ± 3.09 Q/ha	Ghosh and Devi (2019)
16.	Recycled organic fraction of municipal solid waste, pruning materials of ornamental trees and garden biomass	3 months; amended dose (5 to 10)t DW/ ha/ year	Dosage not increased soil pollution risks; increased micro-nutrients	Baldi et al. (2021)

3.4.2 Implications on Crop Productivity

The crop productivity mainly relies on the available nutrients proportions, compost application method and water application frequency. Aerated composting units based on sewage sludge showed significant improvements in the crop yield (and productivity) in many pilot-scale studies (Jindo et al. 2016; Pallejero et al. 2017; Ranjbar et al. 2019). The cause is attributed to the enhanced nutrient availability by virtue of the porous structure of the compost which allowed easy migration of soluble nutrients to the plant roots (Table 2). However, a few studies are pertinent to the adverse effect of heavy metal accumulation in the plant leaf tissues raising the argument on its direct applicability to the leafy vegetables (Oguntade et al. 2019). The provision for recirculation of leachate (compost tea) can also enhance the plant growth and yield due to the enhanced availability of essential elements and nutrients. Anwar et al. (2017) reported that co-composting of cow manure with leaf litter could enhance the bioavailability of plant nutrients for growing spinach. Khaliq et al. (2017) also studied the applicability of sewage sludge proportionated for nitrogen, phosphorous and potassium for improving the yield of beans and radish corps. Long term application of stable and matured compost can enhance the soil organic matter due to the addition of highly stable carbon and thus tends to slow the release of available nutrients to the crops. Compost application also equalizes the climatic fluctuations and balances the air, water, temperature and nutrients that results in better yield of crops (Lopes et al. 2015; Aduguna 2016). In general, improving the soil fertility without harming the soil life (living microorganism) can essentially improve the crop growth, yield and productivity.

3.4.3 Implications on Soil Bioremediation

The applicability of compost in agricultural soil also has trivial limitations, especially when dealing with plant pathogens and problematic soils. Hence, a fare justification is volunteered before encountering such application strategies for achieving multiple targets such as improved soil fertility and enhanced crop productivity. The primary role of compost in such conditions, however, is observed to be in enhancing the immobilization (through adsorption) and precipitation of heavy metals and trace organics. The encapsulated toxic compounds inside the humic matter can be further sequestrated for a longer period, thus minimizing the risks on the consumer health and environmental pollution.

Similarly, the toxicity caused by the improper method of compost application can also cause detrimental effects to the soil quality as well as crop yield. These are mainly caused by the high salinity (due to the increased concentration of chlorides), heavy metal accumulation (direct toxic effects), and potential leaching of nutrients (such as nitrate). In particular, sludge-derived composts are more susceptible to such issues if not proctored during the proportioning stage and preparation stage. It is essential therefore that the stabilized compost should meet the minimum quality requirements for safe and sustainable application to the agricultural field.

4. Conclusion

The present study highlighted a coherent approach to evaluate the physico-chemical characteristics of sewage sludge-amended compost in order to evaluate the implications on its application, by using morphological analysis as a supporting technique. Three types of compost samples were prepared for the study by varying the bulking agent and employing leachate recirculation as a unique treatment. The conventional approach for quantifying the physico-chemical parameters was verified with the corresponding morphological analysis. The study also comprehended an intuitive approach to relate the cause-evidence-impact connections in the compost applications. The major inferences from the study are given below:

- Morphological analysis could impart better pathway to define the intricacies involving in composting- from preparation to application. This paves for a scientific methodology to correlate the defining parameters in terms of their expectations and achievements.
- The experimental results highlight the significance of parent material influence as a crucial factor for proportioning the raw materials in terms of the element overlay analysis. The maximum percentages of carbon (42%) and oxygen (26%) are in confirmation with the high values of TOC and COD for the samples.
- The structural modifications in terms of irregular bondage of bulking agents and potential entrapment (SEM analysis) were found to be responsible for nutrient sequestration and delayed leaching. This is particularly attributed to the high fraction of sewage sludge in the compost.
- The presence of different functional groups from FTIR showed that the compost samples consists of C-H, N-H and O-H single bonds and C=N, C=O and C=C double bonds as the functional groups. This is in accordance with the results from elemental analysis and conventional physico-chemical analysis, indicating the role of improved soil aggregation and stability.
- The sludge recirculation has played an important role in stabilizing the compost by maintaining the moisture and temperature profiles with sufficient nutrient enrichment. This is further proved by the presence of more finely porous structure of the matured compost.
- The sawdust biochar has significantly contributed towards sequestration of nutrients after compost stabilization. The comparison with morphological and spectroscopic results revealed the significance of carbon-rich bulking agent for the slow-release of micro-nutrients for the field application.
- The present study attempted to provide the connecting links between quantitative and qualitative measurements based on the structural and morphological behaviour of the biochemical transformations during co-composting. The results from this study will help in deriving a cause-evidence-impact model to compare the significance of concentration (mass/volume), dimension (micro-structure) and composition/orientation (elements/ functional groups) in similar bio-processing systems. Hence, these findings suggest the suitability of morphological analysis in supplementary to the conventional physico-chemical analysis to justify the suitability of sewage sludge-amended compost for enhancing soil fertility.

Declarations

Acknowledgement

This research was funded by Science and Engineering Research Board, Department of Science and Technology, Government of India under Swachh Bharat Mission (ECR/2016/001114/ES). The authors would like to acknowledge the support rendered by the management, staff and students of Bannari Amman Institute of Technology, Sathyamangalam.

Data availability statement:

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Ethics approval and consent to participate – Not applicable

Consent for publication – Not applicable

Availability of data and materials – Not applicable

Competing interests – The authors declare that they have no competing interests

Authors' contributions – PBG contributed in performing experimental study and writing the manuscript, MV contributed in interpretation of the results and writing the manuscript, NN contributed in in interpretation of the results and reviewing the manuscript. All the authors read and approved the final manuscript.

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Figures

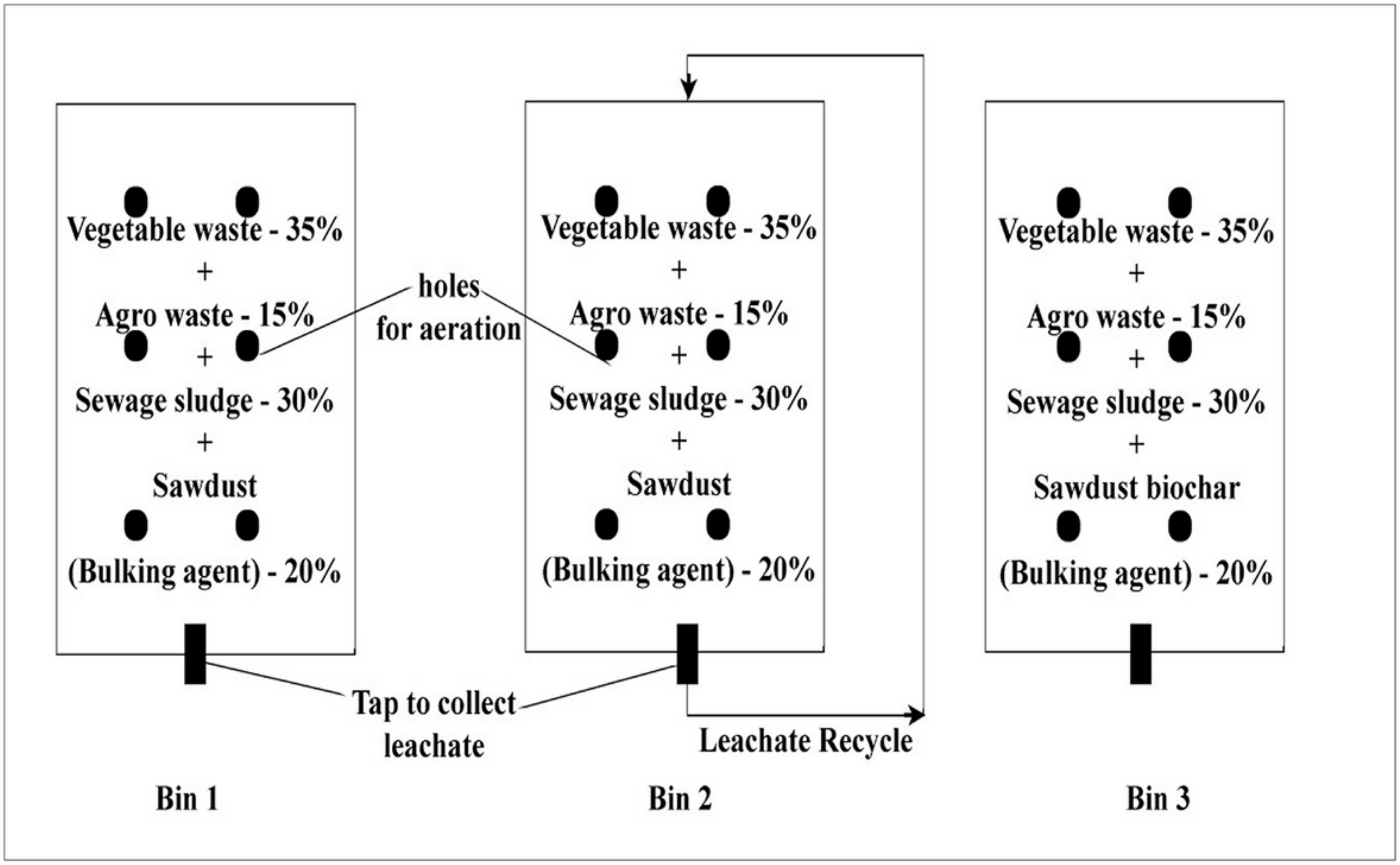

Figure 1

Scheme and compositions of composting bins amended with sewage sludge

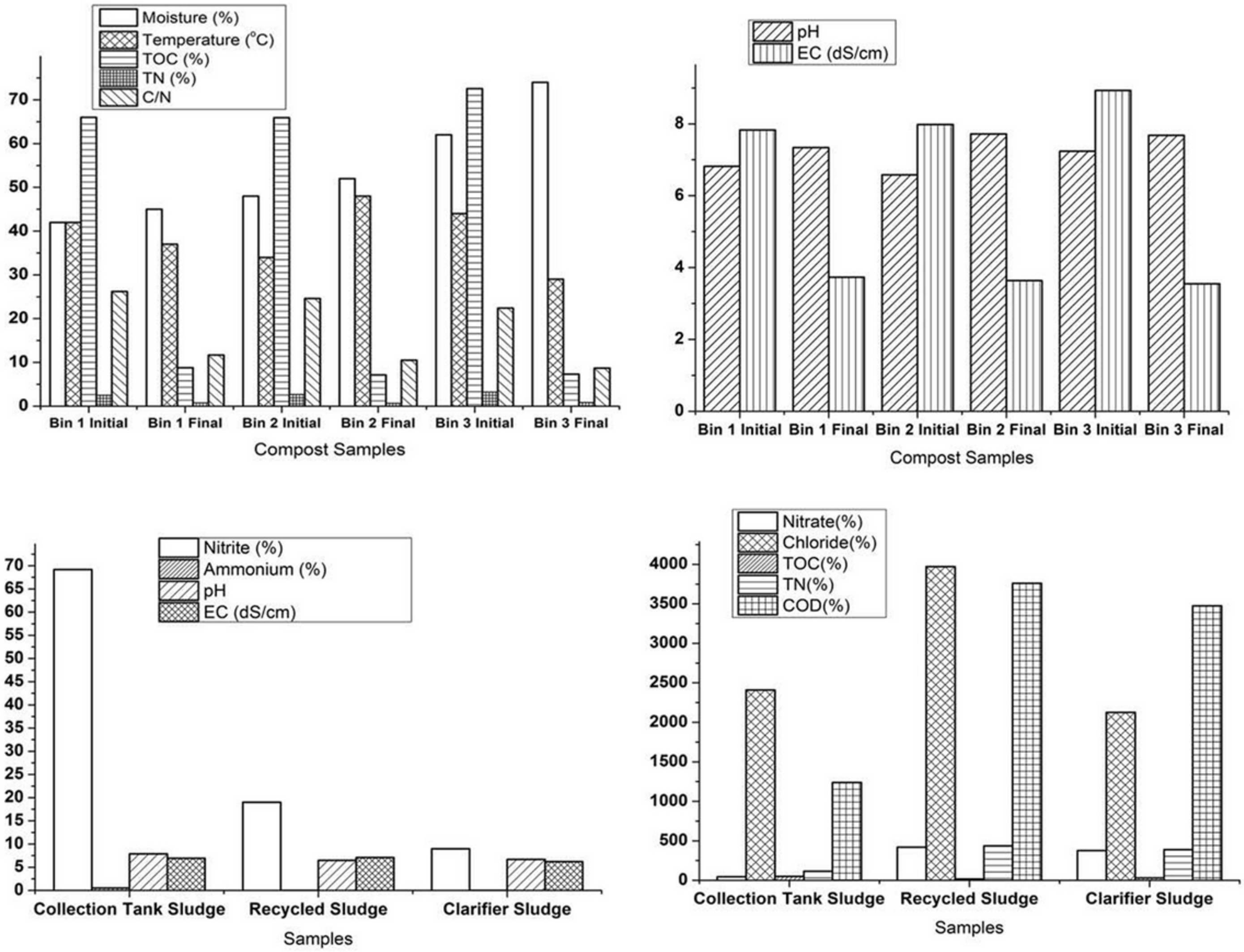

Figure 2

Physico-chemical observations of compost and the sewage sludge samples

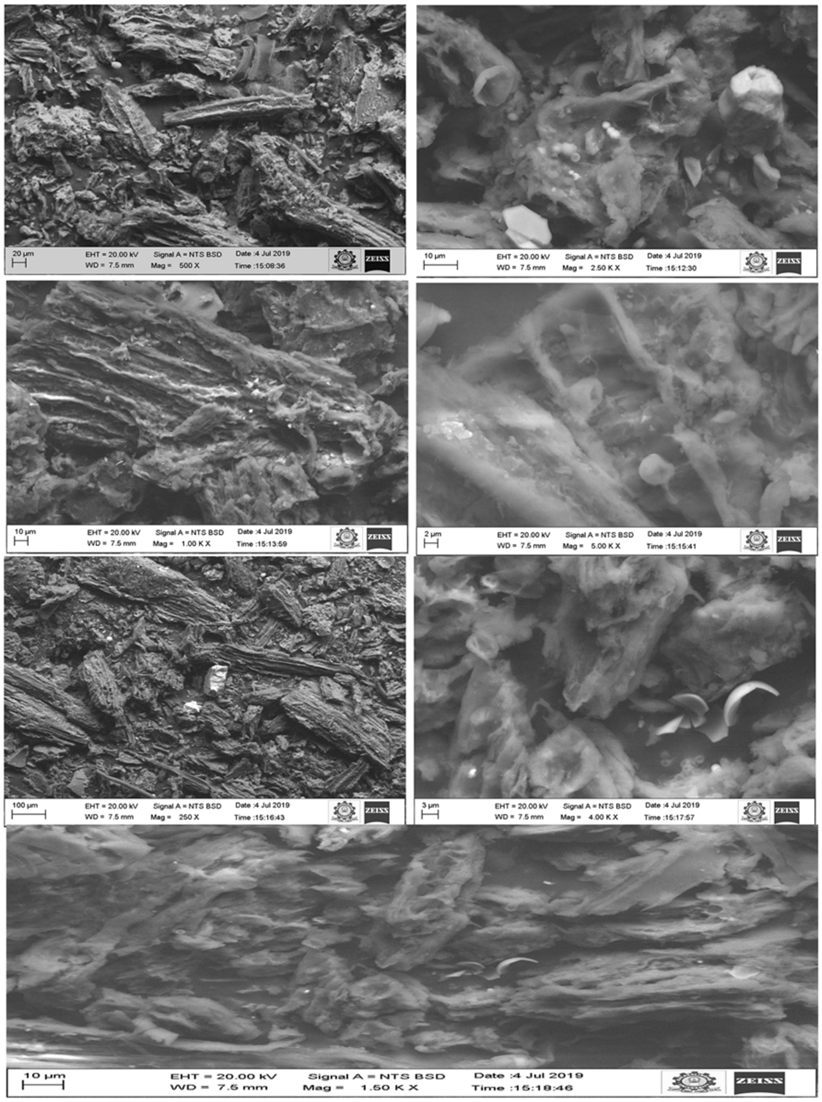

Figure 3

SEM images of compost with sawdust as bulking agent (Bin 1)

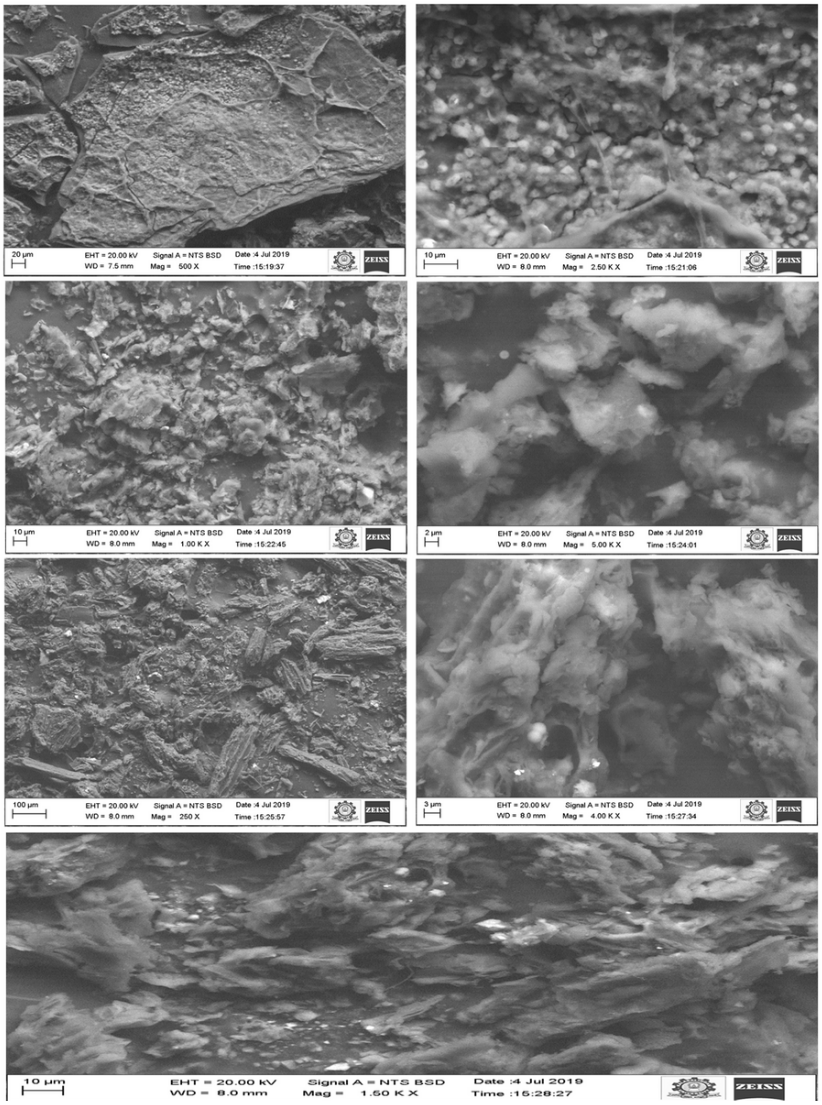

Figure 4

SEM images of compost with sludge recirculation (Bin 2)

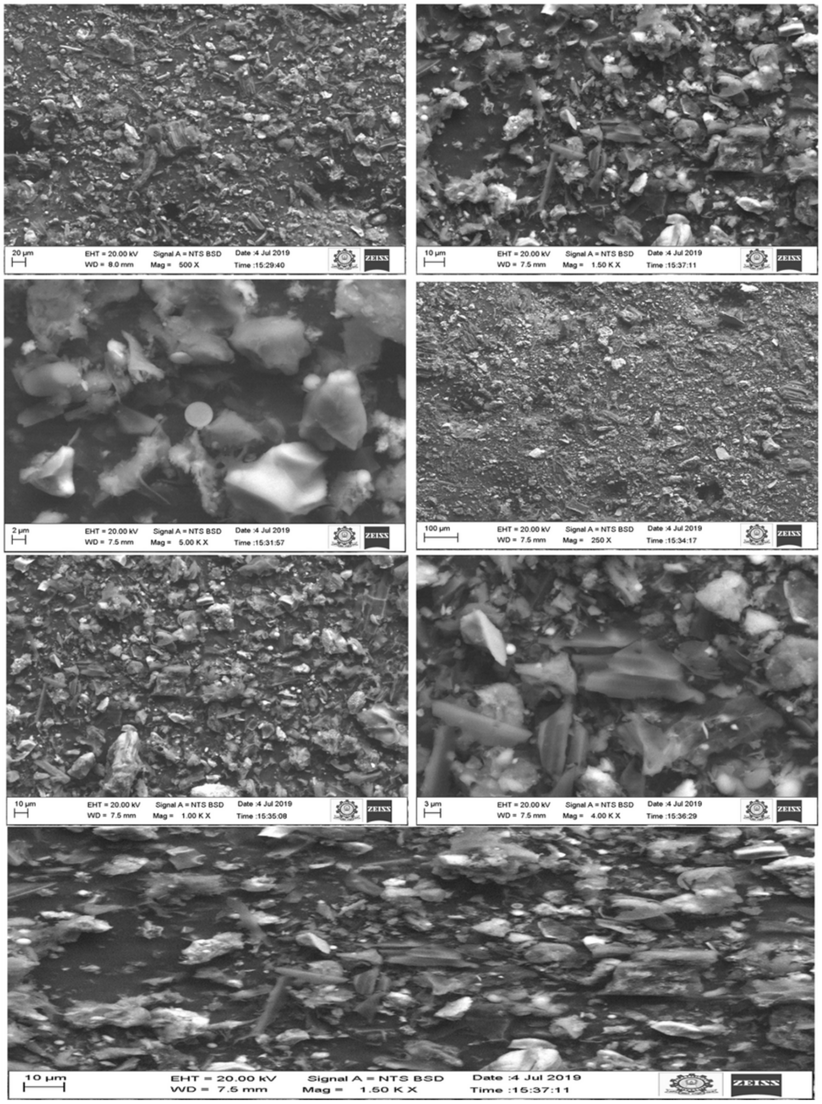

Figure 5

SEM images of compost with sawdust biochar as bulking agent (Bin 3)

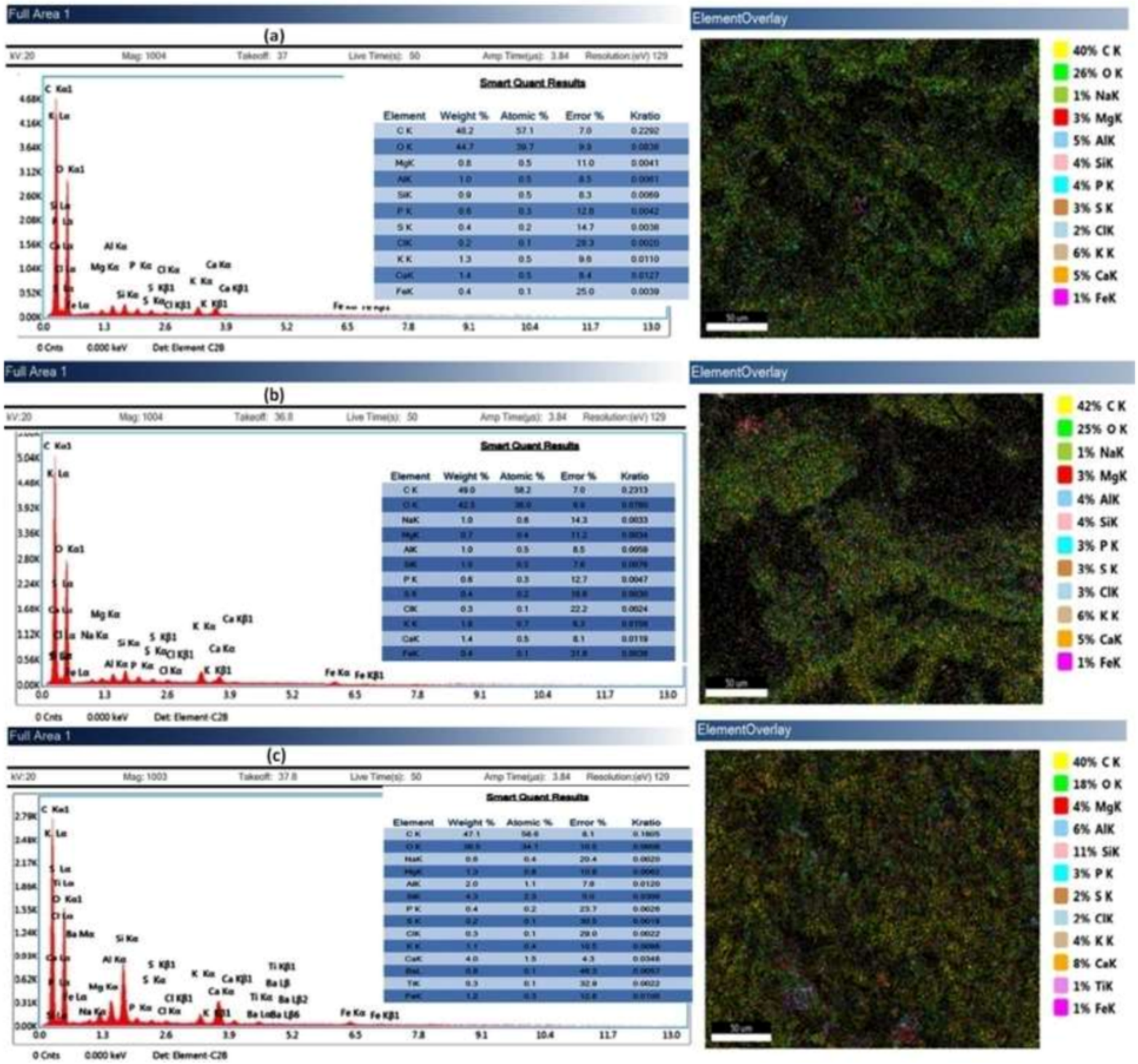

Figure 6

Element overlay analysis of co-compost (A-Bin 1, B-Bin 2, C-Bin-3)

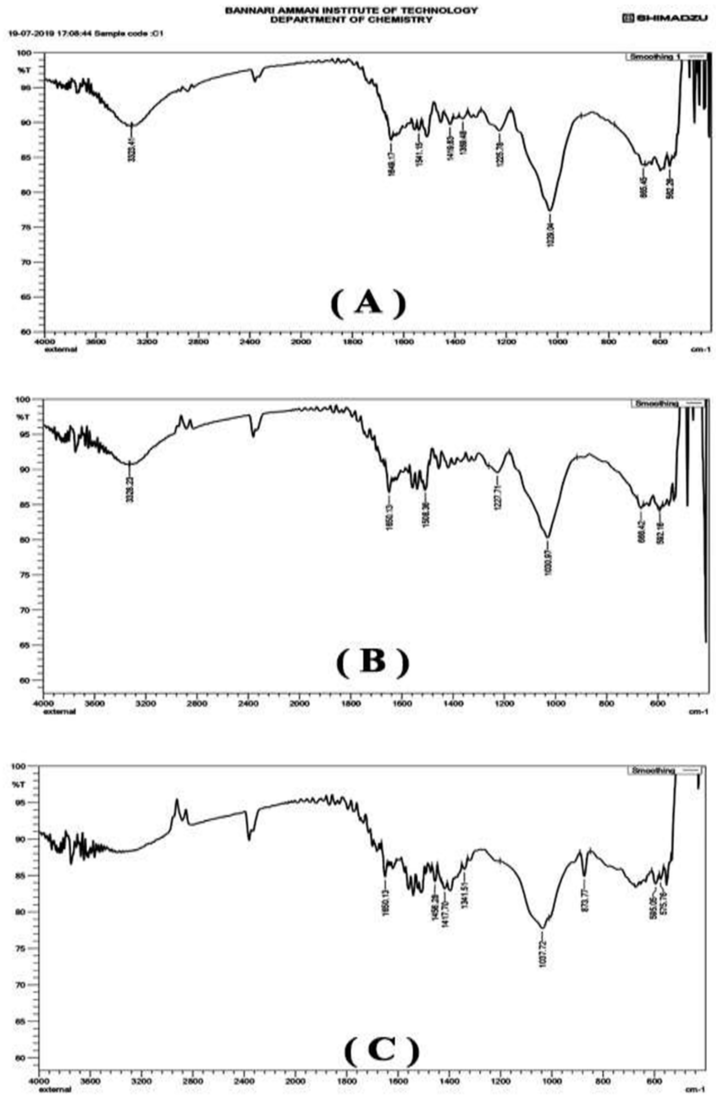

Figure 7

Functional group changes of co-compost (A-Bin 1, B-Bin 2, C-Bin-3)

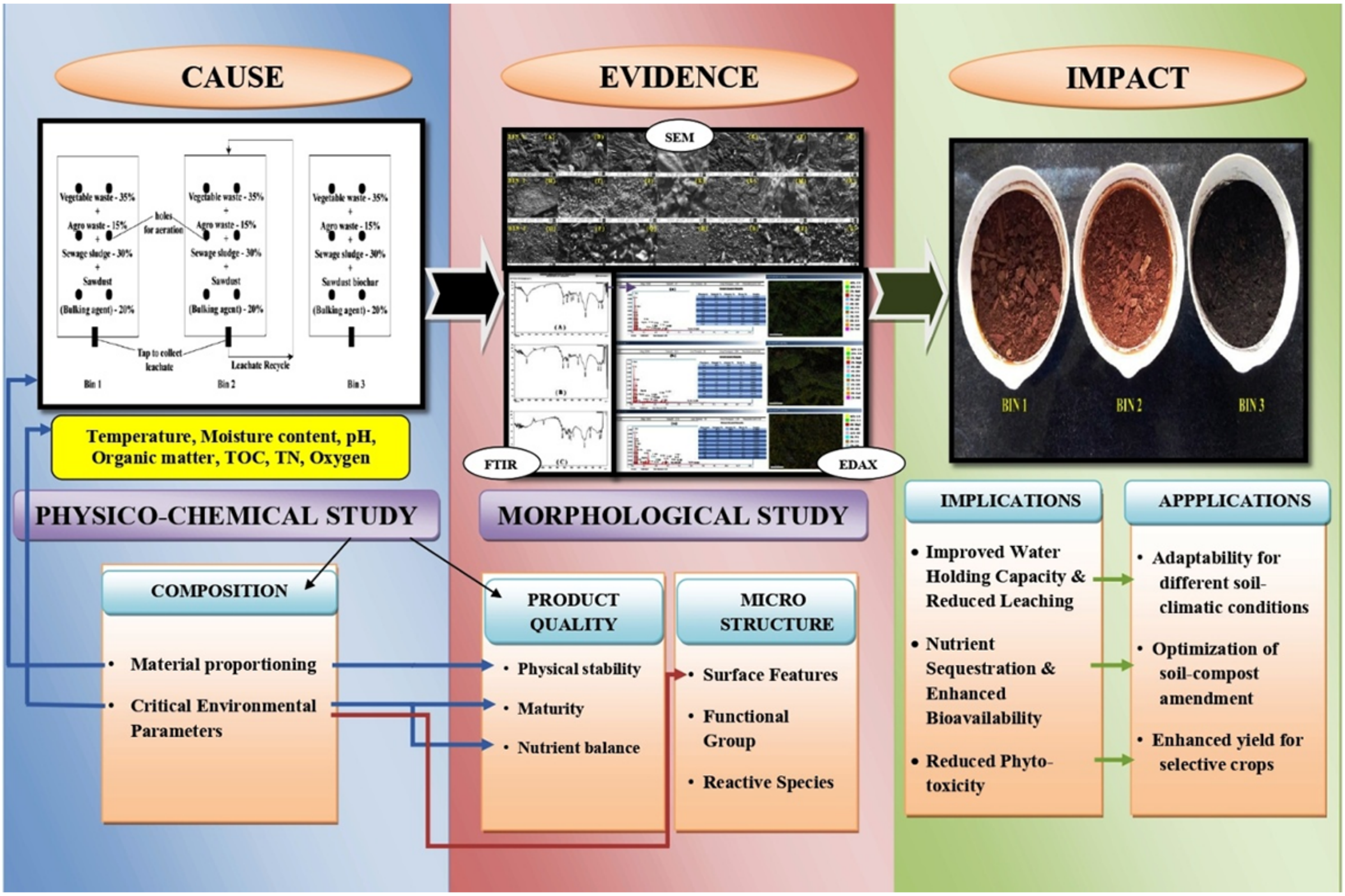

Figure 8

Graphical representation of the primeval cause-evidence-impact relationships for sludge-based compost on agriculture