Evaluating sewage sludge contribution during co-composting using cause-evidence-impact analysis based on morphological characterization

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Abstract
The pertinent challenges associated with effective treatment of fecal sludge in medium scales necessitate alternative means for land application. 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 the chemical conditioning effects 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 field outcomes with conditions of excess nutrient storage/leaching despite the agronomic benefits. In this study, we present a systematic cause-evidence-impact relationship on the feedstock composition, processing, and applications of co-composted sewage sludge. 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 determining the final quality of the compost. Based on the results, we postulate a unique attribution of parent material influence to the formation of well-defined porous structures which influences the nutrient leaching/sequestrating behavior of the soil. Thus, the compounded impacts of composted organic matter on the soil and crop can be proactively determined in terms of elemental composition, functional groups, and stability indices. The present approach provides good scope for customizing the preparations and applications of aerobic microbial composts in order to derive the preferred field outputs.

Keywords Agricultural waste · Aerobic composting · Morphological analysis · Soil-compost interactions · Soil quality · Vegetable waste · Sawdust biochar

Introduction
The global rate of sewage sludge generation is rapidly increasing in recent years as an unavoidable evidence of urbanization where more sewerage systems are getting connected with centralized wastewater treatment plants. As an inevitable consequence, the safe handling and processing of sewage sludge invoke a paradigm shift in recent approaches for enhancing the recycling options for medium and large-scale fecal sludge management (FSM) plants. In fact, the current status of onsite-based FSM plants in India lacks suitable organizational, legislative, and institutional framework to support a future-centered outlook for the sanitation sector (Singh et al. 2020). In addition, lack of affordable technologies for the safe handling and disposal of fecal sludge for the middle-income-based countries insist them to explore cheap and sustainable alternatives within the generic purview of FSM strategies. It is much advocated that the sewage sludge may not be a feasible option for the direct field applications due to the presence of potential toxic elements as well as pathogenic microorganisms (Melo et al. 2018; Kayikcioğlu et al. 2019; Głąb et al., 2020). Therefore, co-composting has been practiced as one of the sustainable approaches due to
the inherent biodegradability of the rich nutrient content, 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). Apart from the aspect of inevitable delay in social acceptance, composted sludge is becoming proclaimed as a biofertilizer to the agricultural crops in many farming societies due to its chemical stability and nutrients sequestration features (Baharuddin et al. 2010; Ai et al. 2020). By virtue of its circular economic approach, co-composting is being preferred in many urban local bodies (ULB) and industrial units to effectively solve their organic waste handling problems without further investments while simultaneously satisfying the soil nutrient requirements for the farmers (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 ability (Adugna 2016; Abbasi et al. 2019; Ai et al. 2020). The integration of external organic matter into the soil typically has potential impacts on the growth and yield of a wide range of crops, as well as on the restoration of ecological and economic symbiosis. Technically, the organic fraction of compost mainly consists of the functional groups of phenolic, alcoholic hydroxyls, and carboxylic acid types, while the inorganic fraction consists of chlorides and hydroxides (Milojković et al., 2014; López-Sotelo et al. 2017). Therefore, the application of organic additions to soil can also improve immobilization of metals by forming stable complexes with -OH or -COOH groups on the solid surfaces of the organic polymers. By virtue of its surface-active phenomena, composts are favorable 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, 2020d; Ma et al. 2019; Liu et al. 2020; Ai et al. 2020; Karthick et al. 2020). Furthermore, they are active chemically too by producing organometallic complexes to fix heavy metals in soils, thereby reducing their mobility and phytotoxicity (Hamidpour et al. 2012).

Based on the scope of modifying the physical, chemical, and biological properties on the deeper intricacies of compost-soil interactions, it is quite possible to attribute a variety of processes and reactions to reduce the toxic element bioavailability in soils such as immobilization, precipitation, methylation/demethylation, oxidation/reduction, and rhizosphere modification (Medina et al. 2017) Youssef et al. 2020. In addition, a few operational modifications such as recirculation of the leachate component during co-composting are also found to be beneficial to maintain the essential nutrient ratio and minimizing some of the operational issues of seepage and foul odor (Chen et al. 2020; Villamil et al. 2020; Vasudevan et al. 2019; Balaganesh et al. 2020b). In general, co-composting with sewage sludge is found to be suitable for many emerging organic wastes such as industrial sludge, processed food wastes, and municipal solid wastes having newer compositions, to supplement for their poor biodegradability during composting as well as to inhibit their leachability in the soil medium (Ferrentino et al. 2020; Kujawa et al. 2020).

At this point, it is hypothesized to investigate the presence of a hidden relationship on the causality and related impacts of soil-compost interactions through a detailed analysis of the prevailing biogeochemical transformations during compost application. As sewage sludge is the target ingredient for this study, it is understood that such an analysis depends largely on the composition and characteristics of the co-composting materials in terms of the activity of essential nutrients and favorable species of micro-organisms (García-Ocampo 2012; Valdez et al. 2020). Zhang et al. (2014) reported that co-composting of dewatered fresh sludge up to 20% (by volume) with paddy straw and biochar resulted in matured compost within 42 days with C/N ratio in the range of 10–15. They have reported surface disintegration as the main impact of organic degradation and hydrolysis on compost particles as observed using morphological characterization techniques. In similar studies with industrial sludge, however, a higher curing time (roughly about 180 days) was required to get the matured compost (Seremeta et al. 2019; Zittel et al. 2018). Though the aforementioned studies were conducted in aerobic in-vessel method, the variations in the maturity/degradation period of compost were primarily attributed to the change in their composition.

Considering the physical state of the raw primary sludge, dewatering was recommended prior to the amendment with tree peony (up to 45% by volume) to result in better compost (Huang et al. 2015) as compared to the stabilized sludge (30% by volume) for Bermuda grass (Rezende et al. 2020). Dridi et al. (2020) reported that apart from the agronomic features, co-composting of dewatered sludge can reduce the heavy metals (Cd, Zn, Cu, Hg) in the final product before land application. Chen et al. (2017) also confirmed the reduction of chromium after dewatering tertiary treated sludge for composting in aerated in-vessel reactor. In contrast, it was also reported that excessive proportioning of dewatered sewage sludge (up to 90% by volume) in the compost may lead to phytotoxicity of heavy metals (Hua et al. 2012).

While attempting to make a comprehensive interpretation of the stability of the final product and the prevailing biogeochemical transformations during the compost processing and application, it is tempting to visualize some sort of “parent material influence (PMI)” overpowering the treatment modifications, thereby resulting in an undistinguished categorical identification of the final product quality. The final compost quality is generally expressed in terms of the changes in physicochemical properties such as the porous structure, elemental composition, and functional groups during the preparation as well as field application (Nguyen et al.
This makes the scope of bio-geochemical interactions between the compost and soil versatile and unique while understanding the practical inference of soil organic matter. In this study, we postulate that 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 to explain some of the perceived complexities of soil organic matter subjected to waste amendment. Though most of the literature studies are related to the techno-economic feasibility of sludge-amended composts having multiple organic wastes as co-substrates, a detailed information about the prevailing bio-geochemical transformation and their cause-effect relationships onto the functional characteristics are mostly omitted or inadequately represented (Cao et al. 2019; Burducea et al. 2019). The present study attempts to provide an evidence-based approach 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 agricultural fields. First, we present the experimental details to characterize the contribution of sewage sludge while preparing compost along with other organic wastes, with a special emphasis on the morphological behavior. Furthermore, 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 for the sludge-based 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 by enhancing the utilization of the sludge-based compost in agriculture.

Materials and methods

Preparation of compost

The present study was conducted in the residential campus of Bannari Amman Institute of Technology, Sathyaman-galam, Tamil Nadu, India (11.4962° N, 77.2768° E). The campus has an overloaded sewage treatment plant (STP) with an exhausted capacity of 7.5 MLD (million liters per day). The unit contains one collection tank (0.52 ML), two bar screen chambers, three aeration tanks (1.36 L), two clarifiers (0.23 L), two feed water tanks, two pressure filters (activated carbon and sand), one treated water tank (0.19 ML), and three sludge drying beds (0.05ML). As the STP was nearing its decommissioning, it occasionally tends to produce partially undigested sewage sludge. In order to prepare the compost, the required quantity of dewatered sewage sludge, vegetable waste, agro waste, and bulking agents (sawdust and sawdust biochar) were collected from the campus premises and were mixed in a pre-determined proportion (Vasudevan et al. 2019). Three treatments were considered to prepare the compost by varying the bulking agent and the wetting pattern (Fig. 1).

The composites were prepared in a series of three prototype plastic bins of capacity 20 L each. All the bins were drilled with 10-mm holes to provide sufficient aeration and also attached with a plastic tap at the bottom for leachate collection. 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. 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 physicochemical 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.

Physicochemical characterization of compost

Initially, the sludge samples from the sewage treatment plant were collected and analyzed for their temporal variation in physicochemical parameters such as pH, electrical conductivity (EC), chloride, chemical oxygen demand (COD), and concentrations of 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 analyzed for EC using digital conductivity meter (M/s Elico India). The aqueous concentration of chloride was estimated by argentometric titration using 0.0141 N AgNO₃ using KCrO₄ 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 coloring reagent under strong oxidizing solution (alkaline citrate, sodium hypochlorite). Similarly, the nitrate-nitrogen concentration was also estimated using the spectrophotometer at a wavelength of 410 nm with brucine-sulfanilic acid as the coloring reagent under strong oxidizing solution (alkaline citrate, sodium hypochlorite). Other parameters such as total carbon (TC), total nitrogen (TN), total phosphorus (TP), available phosphorus (AP), available potassium (AK), and moisture content were estimated by wet digestion using sulfuric acid and hot plate. The pH of the sludge was measured in a solution of pH 4.4 using pH meter (M/s Hanna). 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 spectrooscope (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 250X to 5000X. The range of observed particle size varied from 2 to 100 µm. The spectroscopic observations of compost samples were further performed for the identification of functional group using FTIR with a wavelength ranging from 400 to 4000 cm⁻¹.

Results and discussion

Observation of the physicochemical behavior of compost

The quantitative evaluation of the compost quality showed significant variations for the three treatments while preparing the compost. It was clearly observed that the composting process attained three different phases (mesophilic, thermophilic, cooling/curing) ubiquitously within the given time frame primarily due to the temperature variation caused by biological reactions. During the first week, the temperature increased rapidly in all the three bins, then decreased slowly during the second and third weeks and gradually reached an asymptote at the end of the 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 °C) compared to the other two treatments (40 °C each), but resulted in a higher temperature (45 °C) for the final samples. This is attributed 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 also plays a significant role in reducing the moisture content.

The physical modifications in temperature and moisture content are further depicting the changes in biochemical reaction rates 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) have also showed significant variations during the composting with a comparable 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. Interestingly, 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 (Orlova et al. 2019; Balaganesh et al. 2020a).

When the sludge is mixed with other ingredients in fixed proportion after dewatering, 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 steps. For example, the sludge recirculation (bin 2) has resulted in higher reduction in carbonaceous (65 to 5\%) and nitrogenous (5 to 0.25\%) compounds (Fig. 2). This is also expected from other treatments where the composition of compost changed only in the presence of treated bulk- ing agent (biochar). A detailed illustration of the temporal variations in the selected parameters is provided as Online Resource 1.

**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 in this connection (Singh et al. 2020). In a similar way, a detailed understanding of the biochemical transformations occurring during the composting is necessary to enhance its site-specific applications (Burducea et al. 2019). The conventional approach of deriving substrate-level mass transfer kinetics becomes seemingly 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 the studies involving material preparations and modifications (Huang et al. 2015; Zhang et al. 2014; Chen et al. 2017). In essence, the morphological analysis can 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 expected variations and scope for further improvement.

Implications of physical modifications of compost

The organic compounds present in the 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 necessity of the morphological analysis (Table 1). The surface modifications during composting can be understood in terms of 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, origin, and the nature of the parent ingredients, reinstating the possibility of PMI considerations. For example, the biochar generally contains a large number of recalcitrant aromatic compounds (lingo-cellulose-type) that possess long half-life in the environment by virtue of the high-temperature healing during the pyrolysis process of formation. This can be monitored as an advantage for the biochar to be employed 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 also known to have significant contribution towards altering the nutrient ratio in compost, particularly by favoring the humification process (Zhang et al. 2014). Therefore, we could observe a similarity in the final product characteristics such as porosity, moisture content, and nutrient adsorption in the studies involving untreated biochar as the primary bulking agent. In addition, the specific method of preparation (thermal activation, pyrolysis etc.), selected range of temperature, and presence of co-substrates can also significantly influence the specific surface and chemical activities of the biochar-amended compost. The experimental results highlight the significance of PMI 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 observed high values of TOC and COD for the samples.

Cause-evidence relationships for sludge-based compost

Implications of surface modifications

The microscopic structures of the compost samples reveal 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, further 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 correspond 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, thereby 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 more uniform finer distribution of degraded organic solids is observed in bin 2 where the compost was treated with recirculated sludge (Fig. 4). Though the images show the fractured irregular surface, a closer magnification (500 to 5000 X) could reveal plain surface with ball-type structures. Smaller ball-type structures (approx. 1-µm pore size) can be observed from the remaining images for all selected magnifications. This reveals that although the same composition and ratio of substrates are used in bin 1 and bin 2, the recycling of leachate has contributed significantly to modify the morphological characteristics of the matured compost.

The third sample (from bin 3) revealed a 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 were no fractured lengthy structures in bin 3 images. Very few clear spherical balls of size of around 3 µm can be observed at 2.500 MX magnification. The structural modifications in terms of irregular bondage of bulking agents and potential entrapment (SEM analysis) are found to be responsible for nutrient sequestration and delayed leaching. In essence, the SEM images can be used to infer the surface morphology resulting from the biochemical transformations. This is particularly attributed to the high fraction of sewage sludge in the compost.

Element overlay analysis of compost (EDAX)

The graphical observations of the element overlay analysis for the three types of compost samples are shown in
### Table 1 Details of physicochemical characterization of sludge-based compost using morphological features

| Physical state of sludge | Sludge proportion (%) | Composting type | Time (days) | Physical system | 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 (12.5 L) | 42 | Intermittent air circulation (0.03 m³/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 analyzer, FTIR); structural (SEM) | Distinctive fractions of FA and 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 (31.25 L) | 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 | -- | -- | -- | -- | 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 | Anaerobic digester (500 m³) | Aerobic | 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 (34 L) | 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 | 30% | Aerobic in-vessel | -- | -- | Digital image analysis | XRD, 13C NMR | 30 g/l SS addition best suitable for Bermuda grass | Rezende et al. 2020 |
| Dewatered | 50% (1:3:4) | Aerobic in-vessel | -- | -- | FTIR, XRD, XANES | FTIR, XRD, EDX | | Wang et al. 2020 |
| Industrial | 23.81% | Aerobic in-vessel | 180 | Passive aeration | 8.3 pH, 52–62 °C | FTIR | | Seremeta et al. 2019 |
| Industrial | 23.81% | Aerobic in-vessel | 180 | Passive aeration | Temperature | UV VIS, FTIR, 13C NMR | | Zittel et al. 2018 |
| Activated | 75% (2:1) | Heap composting | 135 | Forced aeration | 4.8–7.1 pH, 30–35 °C | FTIR, 13C NMR | | Amir et al. 2010 |
| Dewatered fresh | 60% | Aerobic in-vessel | 18 | Forced aeration | | XRD | | Wang et al. 2019 |
| Physical state of sludge | Sludge proportion (%) | Composting type | Time (days) | Physical system | Matured compost | Morphological characterization technique used | Implications | Reference |
|--------------------------|-----------------------|-----------------|-------------|-----------------|-----------------|-----------------------------------------------|--------------|-----------|
| Dewatered digested       | 33.33(1:1:1)          | Windrow         | 200         | Forced aeration in box for 20 days with mixing | 34% MC, 7.8 pH, 39.1% OM | Albrecht et al. 2010 |
| Dewatered                | 33.33(1:1:1)          |                 | 120         | 24 °C 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 | Głąb et al., 2020 |
| Dewatered                | 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 65 °C            | Silva et al. 2019 |
| Dewatered                | Aerobic in-vessel     | Daily turning   |             | BSFL composting less suitable for SS           | Lalander et al. 2019 |
| Undigested               | Aerobic in-vessel     | Daily turning   |             | BSFL composting less suitable for SS           | Lalander et al. 2019 |
| Digested                 | Aerobic in-vessel     | Daily turning   |             | BSFL composting less suitable for SS           | Lalander et al. 2019 |
| Cylinder reactor         | 55                    | Forced aeration |             |                                                  | Wang et al. 2020 |
Fig. 3  SEM images of compost with sawdust as bulking agent (bin 1)
Fig. 4 SEM images of compost with sludge recirculation (bin 2)
Fig. 5  SEM images of compost with sawdust biochar as bulking agent (bin 3)
Fig. 6a, b, c. The results show that the maximum percentage of the element present is carbon, with 40, 42, and 40% in bins 1, 2, and 3 respectively. This certainly establishes 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 and volatilization) 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 other element with higher percentage in the samples (26, 25, and 18%) which can be attributed to the saturated aeration condition maintained by molecular diffusion at the interface, which was enhanced by frequent turning. However, it is to be noted that concentrations of some of the crucial heavy metals (sodium, nil; titanium, 1%) were not detected satisfactorily in any of the samples.

Fig. 6 Element overlay analysis of co-compost (A bin 1; B bin 2; C bin 3)
Functional group changes of compost (FTIR)

The structural modifications in the organic matter during co-composting are further analyzed with the help of FTIR spectra (Fig. 7). The frequency of the observed peaks is cross-checked with the library files to verify the presence of most accurate functional groups. It is observed that 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, a much broader 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) in both bin 1 (3323.4 cm\(^{-1}\)) and bin 2 (3328.23 cm\(^{-1}\)).

No peaks were identified in 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 in region III (2000 to 1500 cm\(^{-1}\)) of bin 1, while a single peak is observed in bins 2 and 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\(^{-1}\) for bin 1 (1649.2 cm\(^{-1}\)) and at 1650.13 cm\(^{-1}\) for both bins 2 and 3. The presence of N–O stretched group representing the nitro compound class is confirmed by the presence of a peak in region III obtained for bin 1 (1541.2 cm\(^{-1}\)). In essence, the presence of different functional groups from FTIR showed that the compost samples consist 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 physicochemical analysis, indicating the role of improved soil aggregation and stability. In addition, the observed nitro compounds and other functional groups reveal that the results serve as good indication to ascertain the efficacy of nutrient availability during direct application of the compost containing rich supply of nitrate for the crops.

Implications on biological activity of compost

The variations in physicochemical 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 physi-sorption and chemisorption especially when applied to the soil (Niinipuu et al. 2020). The sludge recirculation also 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 morphological analysis of sewage sludge has initiated tremendous applications for sustainable waste management in the recent past, by bringing about a realistic understanding about the complex interactions between the aromatic-rich organic compounds and the susceptible microbial cultures. For example, 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 color 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 PMI phenomenon as mentioned earlier (Zhang et al. 2014).

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 changes in their functional groups. It is also understood that the sawdust biochar has significantly contributed towards sequestration of nutrients after compost stabilization. The comparison with morphological and spectroscopic results thus revealed the significance of carbon-rich bulking agent for the slow-release of micro-nutrients for the field application.

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 physicochemical parameters can, nonetheless, provide the background information about the feedstock proportion. But the differences in the preparation/processing can be verified by evaluating the micro-structural modifications with the help of morphological analysis. Once applied to the field, the compost-soil interactions will get automatically modified according to the prevailing soil environment. Therefore, the final implications can be further studied based on (i) soil quality, (ii) crop productivity, and (iii) alleviating potential risks of pollution. In this connection, a summary of
the cause-evidence-relationship is proposed in Fig. 8 based on the present study results. The degradation of sewage sludge and other feedstock (cause) transformed the chemical compositions in a way suited for the slow release and sequestration of nutrients (evidenced from Fig. 7). Some of the factual observations such as the enrichment in surface features, presence of vital elements, and absence of toxic elements reveal the required transformation of feedstock (evidenced from Figs. 3, 4, 5 and 6). These inferences primarily lead to the essential implications on retention of water and nutrients, enhancement of soil quality, and reduction in leaching and phytotoxicity. In a related study, we have observed improved sugarcane crop yield with sewage sludge amended compost, thus fitting its agricultural applications (Balaganesh et al. 2020c). Though it is particularly based on the results from the present study, we have extended the logic of analysis to many similar studies from the literature in order to justify our observations.

**Implications on physicochemical 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. As observed in Figs. 3, 4, and 5, the compost samples with sawdust and biochar have direct implications on the particle size distribution and porosity. 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. This has been verified through the leachate recirculation experiments where a finer distribution of degraded organic solids revealed the retention of nutrient composition in the soil (Vasudevan et al. 2019). 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

![Graphical representation of the primeval cause-evidence-impact relationships for sludge-based compost on agriculture](image_url)
increased stability (Logsdon et al. 2017). In other words, both the typology (based on the morphological observations) as well as the outcomes (in terms of soil quality parameters) strongly recommends the role of PMI as the unique cause for the expected outcomes.

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 (Tables 2 and 3) but the most implicating role of compost in agriculture can 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). Similarly, it is observed from the present study that addition of biochar as the bulking agent can retain the moisture content in the final product due to the aggregation of micro-pores. This also suggests that the selection of a suitable composting proportion can impart a long-time effect on the agricultural soils.

Implications on crop productivity

The crop productivity mainly relies on the proportion of available nutrients, method of compost application, and frequency of water application. 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; Pellejero et al. 2017; Ranjbar et al. 2018). The application of the present compost in a pilot-scale sugarcane field and its implications on nutrient dynamics are mentioned by the same authors elsewhere (Balaganesh et al. 2020a, b, c, d). It is inferred that the use of sewage sludge–based compost to the agricultural field has resulted in improved cane yield (6%) and recovery (12.23%). The cause factor for the yield effect can be primarily attributed to the enhanced nutrient availability, by virtue of the porous structure of the compost which can permit easy migration of soluble nutrients to the plant roots (Table 3).

Long-term application of stable and matured compost can ultimately enhance the soil organic matter due to the addition of highly stable carbon and thus tend to slow down the release of labile fraction of nutrients to the crops (Anwar et al. 2017; Khaliq et al. 2017). Compost application also equalizes the climatic fluctuations and balances the air, water, temperature, and nutrients that results in better yield of crops. As an operational solution, 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. However, a few studies advocate on the adverse effects of heavy metal accumulation in the plant leaf tissues raising the argument on its direct applicability to the leafy vegetables (Lopes et al. 2015; Aduguna 2016; Oguntade et al. 2019). The implications of co-composting can also be linked to the cost as the improved yield enhances the profit while the adverse effects can implicate additional cost for remediation and crop protection. In general, improving the soil fertility without harming the soil life (living microorganism) can essentially improve the crop growth, yield, and productivity. Thus, the economic implications reveal the suitability of compost amendment for agricultural applications rather than the chemical fertigation.

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) as well as precipitation of heavy metals and trace organics. The encapsulated toxic compounds inside the humic matter can be further sequestered for a longer period, thus minimizing the risks on the consumer health and environmental pollution. As indicated by the proposed relationships (Fig. 8), a detailed analysis of the soil samples (based on the “evidence”) can contribute towards better understanding of the underlying “causes” (say, organo-metallic interactions) and plausible “impacts” (contamination levels).

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) (Milojković et al. 2014; Rady et al. 2016). In particular, sludge-derived composts are more susceptible to such issues if not proctored during the proportioning and stabilizing stages. It is essential, therefore, that the stabilized compost should meet the minimum quality requirements for safe and sustainable application to the agricultural field as indicated by the agricultural application limits for effluents set by various federal agencies from time to time.
### Table 2 Comparative evaluation of different composting materials and methods on the impact of agriculture in terms of soil quality

| S. no | Compost feed stock | Experimental conditions | Effect | Reference |
|-------|--------------------|-------------------------|--------|-----------|
| 1     | Sewage sludge, town waste, sawdust | Aerated pile method, (3 × 6) 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 m³ in a year in plots of 25 × 12 m | Soil erosion reduced by 67%; runoff by 60%; bulk density by 8%; and 21% higher organic matter | Strauss and Runo (2003) |
| 3     | Manure organic waste | 5 years @ 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 (2.02 t/ha.Y) & total nitrogen (0.24 t N/ha. Y) | Whalen et al. (2008) |
| 7     | Leguminous plant residues | Trapezoidal pile composting; 10 days once turning; optimum moisture, 179 days | Improved soil structural stability and biological activity; reduced bulk density | Tejada et al. (2009) |
| 8     | Digestates and compost | 4 years @ 100 m³/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 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 K₂O 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 (20 × 30 × 10) cm | Soil organic matter, enzymatic activities and microbial community increased | Picariello et al. 2021 |
| 16    | Sludge-based compost | Pilot-scale application on slopy land | Reduced erosion, improved infiltration and water retention | Vasudevan et al. 2018 |
| 17    | Sludge-based compost | Aerobic-in vessel composting | Improved soil organic matter, water and nutrient retention | Balaganesh et al. (2020a, b, c, d) |
Table 3 Comparative evaluation of different composting materials and methods on the impact of agriculture in terms of crop yield

| S. no | Compost feed stock | Experimental conditions | Effect | Reference |
|-------|--------------------|-------------------------|--------|-----------|
| 1     | Municipal solid waste | 5 years @ 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 fertilizer | 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) |
| 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 save from costly chemical fertilizers | Dotaniya et al. (2016) |
| 6     | Organo-mineral fertilizer (OMF) compost | Six organo-metallic samples @ 10, 20 and 30 ton ha⁻¹ | 50% saving of NPK fertilizers; decreased the concentration of Cd²⁺ and NO₃⁻ | 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 | Pellejero et al. (2017) |
| 8     | Fecal 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 | Narrey 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 fertilizer compost | Green beans and white radish | Increase in yield, TOC and chlorophyll contents of green beans | Khalig 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 fertilizer 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) |
| 17    | Sludge-based compost | Aerobic-in vessel composting | Improvement in sugarcane quality, agronomic characteristics and yield | Balaganesh et al. (2020a, b, c, d) |
Conclusion

The present study introduces a coherent approach to evaluate the physicochemical characteristics of sewage sludge–amended compost by employing morphological analysis as a supporting technique in order to evaluate the implications on its application. Three types of compost samples were prepared by varying the bulking agent as well as by employing leachate recirculation for wetting. The specific advantages of the morphological analysis were verified with the corresponding conventional approach to delineate the possibility of parent material influence. The study was successful in identifying some of the trivial connecting links between quantitative and qualitative measurements based on the structural and morphological behavior resulting from biochemical transformations during soil-compost interactions. The results from this study will help in deriving a cause-evidence-impact model to compare the relative significance of concentration (mass/volume), dimension (micro-structure), and composition/orientation (elements/functional groups) in the design and optimization of similar bio-processing systems.

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Declarations

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