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Co-composting of food waste and swine manure augmenting biochar and salts: Nutrient dynamics, gaseous emissions and microbial activity

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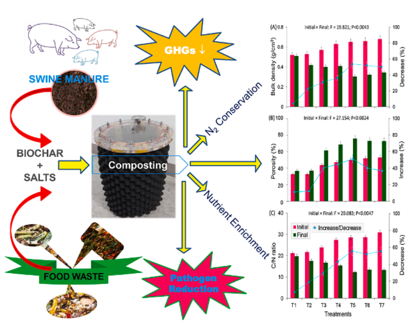
HIGHLIGHTS

- Decomposition process is accelerated by biochar through its affluence of carbon.
- Biochar amendment reduced the emission of greenhouse gases, CO_2 and CH_4.
- Biochar in swine manure + food waste composting increased the nitrogen conservation.
- Biochar addition (6%) and salts to organic wastes eliminate pathogens in compost.

GRAPHICAL ABSTRACT



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ABSTRACT

The prominent characteristics of the biochar, high porosity, sorption capacity with low density improve the aeration, making it a desirable amendment material for composting process. The composting efficiency was analysed by the impact of rice husk biochar amendment (0, 2, 4, 6, 8 and 10%) in the presence of salts for the co-composting of food waste and swine manure, in composting reactors for 50 days. Results revealed that biochar amendment had improved the degradation rates by microbial activities in comparison with control. The final compost quality was improved by reducing the bulk density (29–53%), C/N ratio (29–57%), gaseous emissions

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(CO_2, CH_4, and NH_3) and microbial pathogens (*Escherichia coli* and *Salmonella* sp.). However, 6% biochar amendment had significant improvement in compost quality, degradation rates and nutritional value which is recommended as the ideal ratio for obtaining mature compost from the feedstock, food waste and swine manure.

1. Introduction

The need for home, food, and fuel for the large population will cause resource depletion along with deleterious effects on the health and environment. The resource depletion can be reduced and prevented by circular economy approach in which continuous flow of material will ensure the use of material until the optimal level of consumption is achieved (Liu et al., 2021; Wainaina et al., 2020). This is a move from the methods depending on incineration and landfills, to the cost-effective methods of waste management in which one product serves as raw material for another product, reducing the dependence on incineration and landfills. Livestock wealth contributes substantially in any country's GDP. Pig rearing is an important component of sustainable farm economy and this sector holds a prominent place in global economy. In Korea, the swine manure is significantly increasing as a part of industrialization and development in the livestock sector. Swine manure is rich source of phosphorous, nitrogen and minerals like magnesium, potassium and sodium. Furthermore, microbial load of a variety of pathogenic bacteria, virus and fungi have been documented (Kumari et al., 2015). This manure, if properly managed, can be used as fertilizer due to its rich nutrient contents, whereas improper management can lead to huge impact on the atmosphere creating pollution issues such as malodours and discomfort among the residents around the pig farms. The amount of pig manure generated is exceeding the demand of its application as fertilizer. According to a recent report, per day approximately 173,052 m^3 of swine manure is generated. The swine manure is associated with various health hazards due to its malodours, presence of pathogenic microbes, emission of ammonia and greenhouse gases such as carbon dioxide, methane and nitrous oxide. To overcome these limitations, researchers are concentrating on various treatment strategies such as biogas production, composting, integration of livestock with aquaculture and/or algal culture. However, there are certain limitations such as the difficulties in separation of algae due to its size and density, the pre-treatment steps required in biogas technology, time consuming processes and associated phytotoxicity in composting (Ravindran et al., 2019).

The under-exploited global organic waste material is the food waste which is another issue posed by population growth, urbanization, and rapid economic development. Mismanagement of the indispensable commodity "food" can lead to severe socio-economic and environmental threats. From the farm to plate, the food processing steps generates huge amount of wastage including the processed/cooked leftovers. Recent studies shows that food waste of about 1.3 billion tonnes is generated world-wide annually and is expected to rise more in the next two decades (Petracchini et al., 2018). Although the organic wastes classified under the category food are serving as a source of nutrients and are biodegradable. Food wastes possess various threats due to the greenhouse gas emissions, pathogenic microorganisms and vector borne diseases. As the disease control agencies of various nations have banned the usage of food waste as animal feed, the preferred methods of disposal include composting, landfilling and fermentation which causes substantial emission of greenhouse gases into the environment besides increased administrative costs (Yeo et al., 2019). However, the landfilling of food waste was prohibited in South Korea since 2005, 90% food waste is recycled by composting and converted into feed products and fertilizers. Composting technology is a well-developed technology adopted by various countries due to its robust and easy operations. In composting, the microbes decompose the organic waste into a stable and particulate organic matter. However, the composting of food waste is often unstable and the efficiency is very low due to several disadvantages including its low porosity, high bulk density, poor C:N ratio, easy acidification, and others (Awasthi et al., 2017a). These limitations could be overcome by mixing it with other organic wastes like livestock manure, sludge, and others. The co-composting of two waste matters not only reduces the time and labour but also saves the costs involved during composting the wastes separately.

Owing to large bulk density and low porosity of the raw materials like food waste and swine manure, it is essential to add bulking agent while composting them together to enhance the structure and oxygen diffusion. The physicochemical properties of biochar such as high porosity with low density, high sorption capacity can improve the aeration during composting, modify the microbial community, attenuate heavy metals mobility and reduce nutrient loss and greenhouse gas emissions (Awasthi et al., 2020a,b). About 8–18% of rice straw biochar (Awasthi et al., 2017b), and bamboo biochar (He et al., 2019) have been used for enhancing composting efficiency and to reduce gaseous emissions. Another issue with composting of swine manure and food waste is that, the compost is not much accepted due to the malodours affecting its application. The composting of food waste has caused increased emission of ammonia and volatile fatty acids, sulphides and organic sulphur compounds resulting in high malodours (Qamaruz-Zaman and Milke, 2012); while the addition of biochar to composting substrates enhances volatile fatty acids disintegration and suppress odour generation (Duan et al., 2019a). Several studies have reported that the addition of alkaline materials like magnesium and phosphate salts reduces the acidification and ammonia emission thereby reducing the malodours in the compost. Furthermore, the salts support the microbial activity for decomposition and increases nitrogen and phosphorous conservation. Researchers urge the need for the investigation of co-amendment of salts with biochar like adsorbents to increase the quality of the compost (Wang and Zeng, 2018). Therefore, in this study a treatment strategy involving co-composting of swine manure and food waste in the presence of salts and biochar was evaluated to identify the effect and optimization of biochar ratio on the composting rates its potential ability in retaining the nutritional values of the compost.

2. Materials and methods

2.1. Materials

The feed-stock materials for composting in the present study were collected regionally in South Korea. Food waste was collected from restaurants and hotels. The solid waste, swine manure was collected from pig farm in Yongin, South Korea, transported to laboratory, and stored at 4 °C. The sawdust with a mesh size ranging between 2 and 5 mm was collected from a wood mill in Namwon and the rice husk biochar was purchased commercially from the vendor in Damyang. The rice husk biochar was coarsely powdered to obtain a size of 2–5 mm. The physicochemical parameters such as moisture content, pH, electrical conductivity (EC), bulk density (BD), water holding capacity, porosity, total organic matter, C/N ratio, of all the raw materials used in this study were analyzed using standard protocols (APHA, 2006). All the chemicals used in this study were of analytic grade. Nutrient agar (NA) and xylose lysine deoxycholate agar (XLD agar) were purchased from Oxoid, Potato dextrose agar (PDA) and membrane-fecal coliform agar (m-FC) were purchased from BD Difco™, cellulose agar (CA) and skim milk agar (SMA) were purchased from Sigma-Aldrich.

2.2. Preparation of composting substrates and experimental design

The experiment was conducted in a room at temperature 20 ± 2 °C in Kyonggi University, Suwon, Gyeonggi-do, South Korea. The experiment had 7 treatment groups labelled as T1 – T7. T1 contained mixture of food waste, swine manure and saw dust in a ratio of 2:2:1 with a total volume of 8 kg. The mixture ratio was fixed from the study of Lee et al. (2017). The T2 had all the mixtures as in T1 along with 28.462 g of magnesium chloride ~ 0.05 M and 48.7704 g of potassium hydrogen phosphate – 0.1 M. The treatments T3, T4, T5, T7 and T7 had the composition as in T2 with 2, 4, 6, 8 and 10% biochar, respectively. All the raw materials were mixed thoroughly and periodically to attain even distribution. All the experiments were conducted in triplicates in-vessel.

2.3. Physicochemical and gaseous emission analysis

The pH, electrical conductivity (EC) and carbon to nitrogen ratio (C/N ratio) of the mixtures was measured at the beginning (initial) and at the end of the composting. The pH and EC were assessed through shaking the samples for 30 min mechanically using deionized water at 1:10 (w/v) ratio. C/N ratio was evaluated by determining total carbon and total nitrogen contents using a Truspec CN carbon/nitrogen determination (LECO Corporation). The properties such as bulk density (BD), total porosity (TP), ammonium and nitrates were analysed on 0, 3, 7, 14, 21, 31, 41, and 50 days of composting studies. The extractable ammonium and nitrates were analysed with the help of segmented flow analyser (Technicon Autoanalyzer II system, Germany) as described by Ravindran et al. (2019). The emission of NH_3 (indirect greenhouse gas) was assessed employing detector tube method and the CO_2 and CH_4 was evaluated using the GA5000 (Geotech, UK) biogas analyzer, on daily basis for 50 days.

2.4. Microbiological analysis

The variations in microbial population were monitored during the composting treatment. For microbiological analysis, viable microbial count was conducted for total bacteria, total fungi, cellulolytic and proteolytic bacteria, *Escherichia coli* and *Salmonella* sp. For each sample collected on 0, 12, 26, and 47-day periods of composting were serially diluted and spread plated following the procedures described previously (Ravindran et al., 2019). NA, PDA, CA, SMA, m-FC and XLD agar were used as cultivation media for the microbiological studies. The microbiological analysis was conducted in triplicates and expressed as colony farming units (CFU) per gram of dried sample (APHA, 2006).

Table 1
Physicochemical characteristics of raw materials used for composting.

Parameters	Swine manure	Food waste	Biochar	Sawdust
Moisture content (%)	59.88 ± 2.9	65 ± 4.5	12.6 ± 0.8	10.89 ± 0.5
pH	8.9 ± 0.6	5.48 ± 0.3	8.96 ± 0.4	4.15 ± 0.2
EC (mS/cm)	2.58 ± 0.1	1.2 ± 0.07	0.453 ± 0.02	0.23 ± 0.01
Bulk density (g/cm^3)	1.1 ± 0.07	1.06 ± 0.07	0.23 ± 0.01	0.104 ± 0.005
Water holding capacity (g water/g dry sample)	3.21 ± 0.1	4.25 ± 0.2	2.6 ± 0.1	2.76 ± 0.1
Porosity (%)	5.0 ± 0.3	5.5 ± 0.3	72.0 ± 4.3	86.63 ± 4.3
Total organic matter (%)	60.86 ± 3.0	87.11 ± 4.3	22.83 ± 1.5	96.67 ± 6.7
C/N ratio	11.77 ± 0.8	14.6 ± 1.0	51.18 ± 3.5	813.94 ± 48

3. Results and discussion

3.1. Physico-chemical properties of raw materials

The physicochemical properties of all the feed-stock materials were analysed and briefed in Table 1. The pH values of swine manure, food waste, biochar and saw dust were found to be 8.9, 5.48, 8.96, 4.15, respectively. The pH of swine manure and biochar was recorded as slightly alkaline whereas the pH of food waste and sawdust was found as slightly acidic. The EC was found highest in swine manure with 2.58 mS/cm followed by food waste, biochar and sawdust with 1.2, 0.453 and 0.23 mS/cm, respectively. The C/N ratio of the raw material was found to be 11.77, 14.6, 51.18 and 813.94 for swine manure, food waste, biochar and sawdust, respectively indicating difference in C/N ratio among the raw materials. Total organic matter ranged between 22.83 and 96.67% and the moisture content ranged between 12.6 and 65%. These characteristics are acceptable limits and apt to be used for composting. The characteristic changes were monitored when the raw materials were mixed together through the process of composting.

3.2. Effect of biochar amendment on the physicochemical characteristics during composting

During the 50 days of composting, there was a significant change in the physicochemical characteristics indicating the maturity of the treatment and variations were observed between biochar amendment and control groups.

3.2.1. Variations in temperature, pH and electrical conductivity

Temperature is a crucial factor which indicates the successful maturity of composting and an ideal temperature is required for the microbes to carryout bioconversion of the substrate mixtures. The temperature also influences the biogas production rate (Mao et al., 2015). Hence temperature was monitored daily in this study till the 50th day of treatment. At the initial days of composting, the treatments T2 – T7 showed similar drift of high temperature to about 50 – 60 °C for the first week after which it decreased till the completion of the composting experiments (Fig. 1A) indicating entry into the final phase of composting. However, a slight fluctuation in the temperatures was observed while turning the mixtures. The turning of mixtures helps in distributing the microbes and moisture to improve the compost structure. Various studies have reported that temperatures increase significantly in the presence of biochar than during the absence of the same (Ravindran et al., 2019). Similarly, the thermophilic phase in the present study findings during composting was more prevalent and lasted longer in the treatments added with biochar (T3-T7). Treatment added with 6% of biochar (T5) showed maximum temperature of 60 °C. The raise in the temperature is due to the release of high energies in the form of heat from the raw materials especially from swine manure and food waste. The food waste is rich in degradable compounds which upon decomposition in the presence of microbes results in the generation of heat (Cheung et al., 2010). The distinct features of biochar such as high porosity, water holding capacity and aerobic condition that makes the composting faster. The temperature of the T1 (control without salts and biochar) did not rise as high when compared to other treatments with the salts alone and salts with biochar. This also indicates the low activity of microorganisms (Wang et al., 2016a) in the T1 than other treatments. The temperatures achieved in this study is in accordance with the compost hygiene standards and the results correlates with the previous reports of composting in which biochar was added as bulking agent (Waqas et al., 2018).

The increase in temperature can also increase the acidification rate which will inhibit the growth of microorganisms thereby decreasing the composting rates. So, it is important to maintain an ambient temperature for microbial growth to accelerate the composting process. All the treatment processes exhibited a similar trend in the pH variations, where

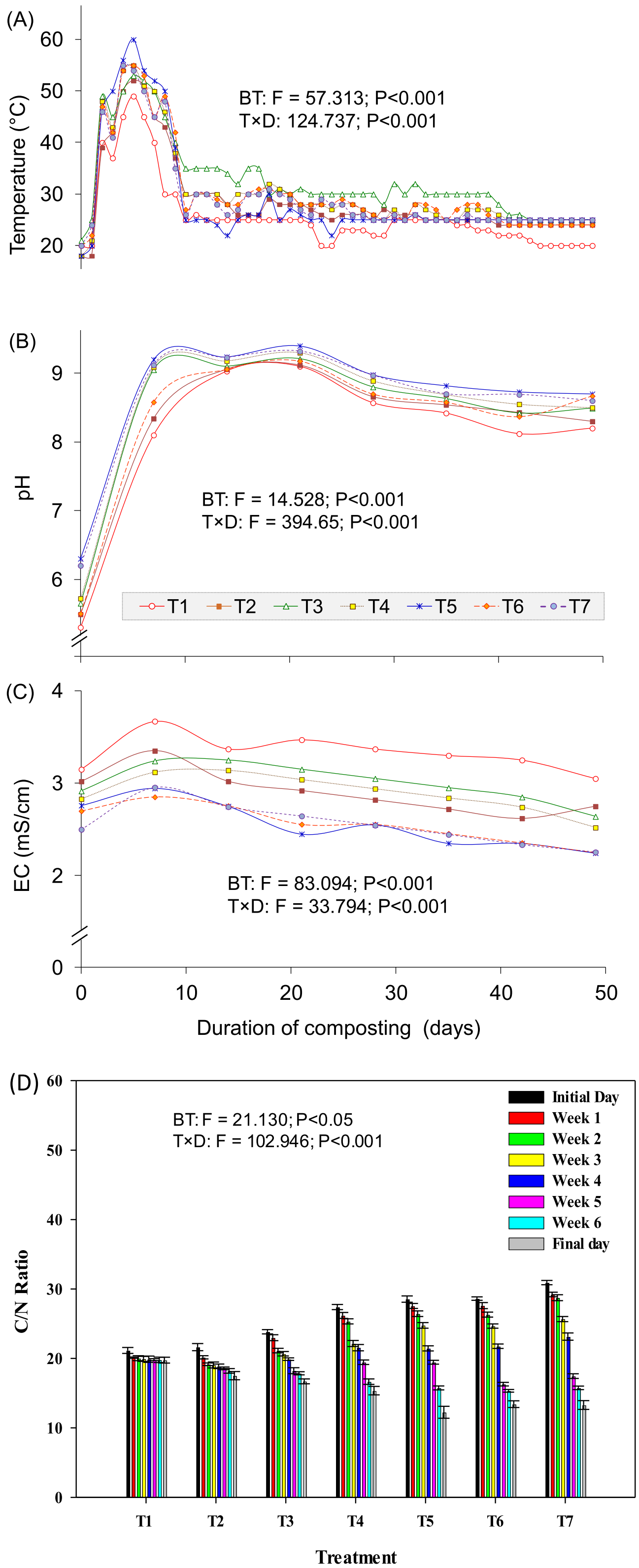

Fig. 1. Dynamics of temperature (A), pH (B), electrical conductivity (C) and C/N ratio (D) among different composting treatment groups (Values are representation of mean of the triplicates). Significant interaction of parameters between treatments (BT) and treatment × duration (T × D) of composting is derived using ANOVA. P ≤ 0.05 indicates significant difference by ANOVA.

the pH increased to about 9.0 – 9.5 on the 21st day and got stabilized to about 8.0 – 8.5 in the final compost (Fig. 1B). The increase of pH in treatment groups is probably because of the ammonization process occurring during the biodegradation (Janczak et al., 2017) and volatilization with subsequent release of greenhouse gases (Chung et al., 2021). The bulking agent, biochar has affected the pH values of the treatment by maintaining an alkaline pH; whereas the treatments without biochar (T1 and T2) were comparatively less alkaline than other treatments (T3-T7). However, the alkaline nature of the swine manure (T1) and the presence of salts (T2) have maintained the pH within alkaline ranges. The results of the current study are in consistent with the earlier reports (Li et al., 2020). The decrease in pH in all the treatments is mainly due to ammonia striation and H^+ ions liberation during microbial nitrification indicating that the final compost is mature (Wang et al., 2017). Recent findings of Awasthi et al. (2017b) suggests that pH value of 7.0 – 8.5 and 12% biochar serve as a propeller for microbial degradation of organic matter favouring the composting. While in the present study, 6% biochar itself was sufficient to attain the suggested pH value favouring the microbial activity for the degradation of organic matter. This could also be due to the co-amendment of biochar with salts. The co-amendment of biochar with salts not only reduces the salinity but also slows the redissolution of the struvite formed which increases the value of the final compost (Wang and Zeng, 2018).

The EC is considered as the sign of salinity during composting which shows the levels of salt toxicity. It also indicates whether the compost is suitable for agricultural purposes (OCQS, 2012). The variations in EC are shown in Fig. 1C. In the present study, all the treatments experienced similar increase in the EC values at the initial stage as a result of rapid degradation of organic substances into simpler compounds with the release of numerous ions and water loss by evaporation. Then the EC gradually decreased from 14th day due to the salts precipitation and ammonia volatilization (Waqas et al., 2018). The EC values reached to 3.05, 2.75, 2.64, 2.52, 2.24, 2.25, and 2.25 for T1 – T7, respectively in the final compost. Although mild fluctuations were found, the EC values obtained for the final composts (T5, T6 and T7) were well within the limits suitable for agronomic applications. The values obtained in the present study are consistent with the previous results of Ravindran et al. (2019) as well as with Jain et al. (2018).

3.2.2. Bulk density and total porosity changes

The importance of physical properties like bulk density, porosity, particle size and moisture content has been reported to regulate the composting process. Bulk density is considered as one of the essential properties to be evaluated during composting (Jain et al., 2018) and it should decrease over the composting duration as it reaches maturity. In this study, during the initial stages, the treatments with biochar showed maximum BD as the biochar occupies a considerable part of the weight (Wang et al., 2018). However, the BD decreased significantly ($P \leq 0.001$) towards the completion of composting in all biochar treated groups (Fig. 2A). BD values in all the treatments were found to be decreased by 1.92 (T1), 21.13 (T2), 29.64 (T3), 35.07 (T4), 53.07 (T5), 51.21 (T6) and 49.41% (T7), respectively. While comparing the BDs of all the treatments, the treatment with 6% biochar (T5) showed maximum decrease of about 53% and reached 0.305 g/cm^3 at the final stage of treatment. Whereas the increase of biochar % in T6 and T7, had no significant difference with the T5 treatment. The BD for T5, T6 and T7 were 0.305, 0.322 and 0.344 which is well within the ideal range (<0.400 g/cm^3). Similar reduction in BD was reported in previous studies with biochar amended composting treatments (Zhang and Sun, 2016). The reduction in BD can be due to water evaporation, which is in agreement with the temperature trends of this study (Fig. 1A) and degradation of organic matters. The changes in the BD reduction in T6 and T7 can be due to the elongated thermophilic days of T5 treatment (6 days) which was only 3 days in T6 and T7. Several studies suggest the addition of bulking agents like biochar helps in maintaining the bulk density which facilitates the gaseous exchange and increases the

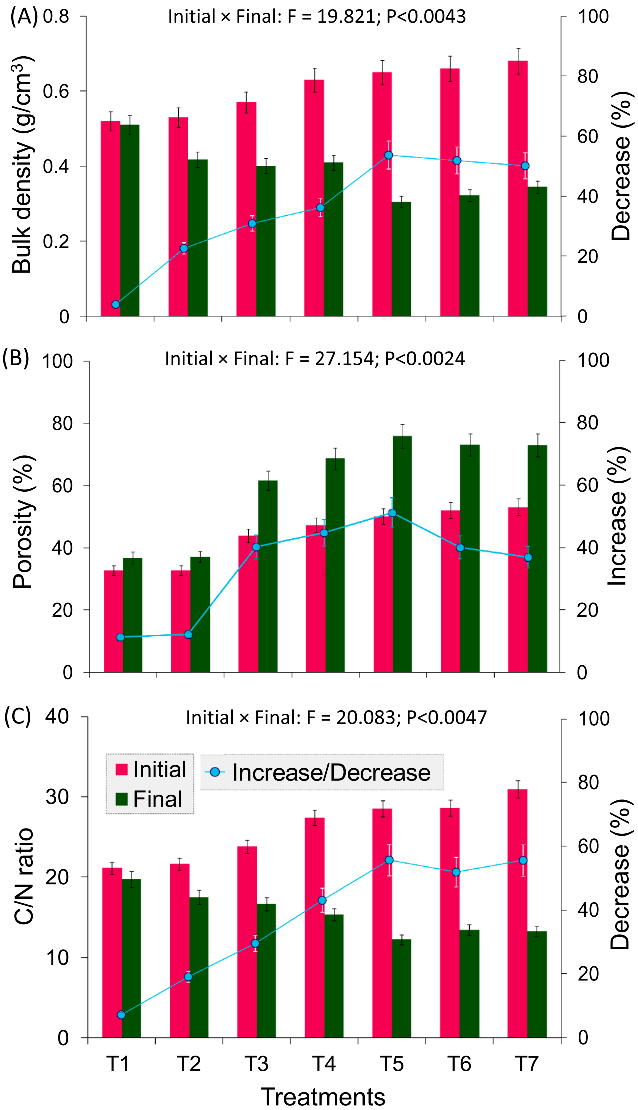

Fig. 2. Profile of bulk density (A), porosity (B) and C/N ratio (C) variations among different composting treatment groups (Values are representation of mean of the triplicates; error bars indicate ± standard deviation; $P \leq 0.05$ indicates significant difference by ANOVA).

aeration thereby enhancing the composting process and retaining the nutrients to improve the quality of the product (Zainudin et al., 2020). Final compost product with low BD implies high porosity. This suggestion matches with the total porosity results obtained in the present study.

In contrast to the BD, the total porosity of the treatments increased. Especially in the biochar amended treatments, the total porosity increased greatly. The porosity values of the final composts recovered from T1, T2, T3, T4, T5, T6 and T7 were 36.77, 37.11, 61.62, 68.69, 77.38, 73.15 and 73.00% respectively (Fig. 2B). The acceptable ranges (Zhang and Sun, 2016) of total porosity were attained in the treatments T5 – T7. Although porosity values of these 3 treatment groups were high compared to other treatments with and without biochar, there was a non-significant variation within the three treatments. High moisture content of the organic matter especially the food waste can cause leachate, decrease the porosity and other adverse effects on the biological activity. The increased total porosity observed in this study by the end of the experiment indicates the availability of moisture content (Sánchez-García et al., 2015) and avoids leachate loss helpful for the degradation of organic matters.

3.2.3. Changes in C/N ratio

During composting, microbes need some macronutrients such as carbon and NPK for their growth. Amongst, organic carbon and the forms of nitrogen are very important for their growth and energy production. This leads to significant C/N ratio changes in the substrates which can be measured to assess the maturity of the compost (Chung et al., 2021). A significant portion of carbon is discharged as CO_2 during composting and the remaining combines with nitrogen to serve as energy source for microbial growth. Thus, carbon content will be decreasing whereas the nitrogen is continuously recycled by the microbes which lead to decrease of C/N ratio in final compost. Similarly, in the present study at the initial stages, all the treatments showed high C/N ratios and eventually decreased at the final stages (Fig. 1D and Fig. 2C). The treatments added with biochar and salts (T3 – T7) showed very high initial ratio of C/N than the treatments without biochar (T1 and T2). The maximum decrease of 57.10% was seen in the final compost obtained from T5. The maximum percentage decrease in the T5 treatment signifies the rapid decomposition of organic matters. Generally, biochar addition provides extra carbon to the swine manure and food waste which is the reason for initial high C:N ratios in biochar amended groups (Sánchez-García et al., 2015). In most of all the treatments, the C/N ratio was found < 20 denoting the compost maturity. This result coincides with the results of earlier studies (Yang et al., 2020).

3.2.4. Changes in gaseous emissions and nitrogen conservation

Levels of gaseous emissions such as CO_2 and O_2 can be used as indicators of compost approaching stability. In the event of successful mineralization of organic matters owing to the increased action of microbes, the CO_2 level remains high. However, as the compost pile achieves the maturity and microbial activity decreases, the CO_2 level also decreases (Jeong et al., 2019). The highest CO_2 emission in all the treatments was observed on the 5th day (Fig. 3A). Then till the treatment reaches the stability, the CO_2 levels were decreasing with fluctuations during turning up of the mixtures. The CO_2 emission increased with the increase in biochar up to 6% in the presence of Mg and P salts, but further increase in the biochar concentration decreased the CO_2 emission. This indicates that the addition of biochar and salts together accelerates the decomposition process which can be endorsed by the richness of carbon in the biochar whereas addition of only salts and absence of both salts and biochar could not match the composting rates of the former. On the other side this phenomenon can also be explained by the aeration provided by porosity and large surface area ratio providing maximum microbial growth for easy degradation of organic matters and CO_2 emissions (Awasthi et al., 2017b). The trend observed in the increase and decrease of CO_2 levels was in consistent with the trend of temperature of the piles. This agrees with the recent reports of Chung et al. (2021) and Duan et al. (2019b).

CH_4 is produced by methanogens at anaerobic condition indicating that the pile is supplied with insufficient oxygen. IPCC reported that CH_4 is likely to cause global warming 28 times over CO_2 (IPCC, 2014). CH_4 is one of the greenhouse gases released during composting process. In the current study, CH_4 emissions in all the treatments were observed to be increasing during earlier composting stages (Fig. 3B). The CH_4 evolution increased rapidly and attained its peak on the 8th day [reaching up to 550 (T4), 130 (T5), 450 (T6), and 500 ppm (T7)], and 9th day [reaching up to 2300 (T1), 1750 (T2) and 950 ppm (T3)] of composting. This again illustrates the rapid degradation of organic matters which consumes oxygen and creates an anaerobic condition. As the degradation rates decreases the aerobic condition returns back. However, the increase in CH_4 emission of biochar amended groups (T4, T5, T6 and T7) was significantly ($P \leq 0.001$) very low compared to that without biochar (T1 and T2) and the treatment with 2% biochar (T3). The treatments with the presence of biochar could cope up with this anaerobic condition and was able to reach the minimum CH_4 emission within a short period (day 9 – 17); whereas in other treatments, the reduction in CH_4 emissions

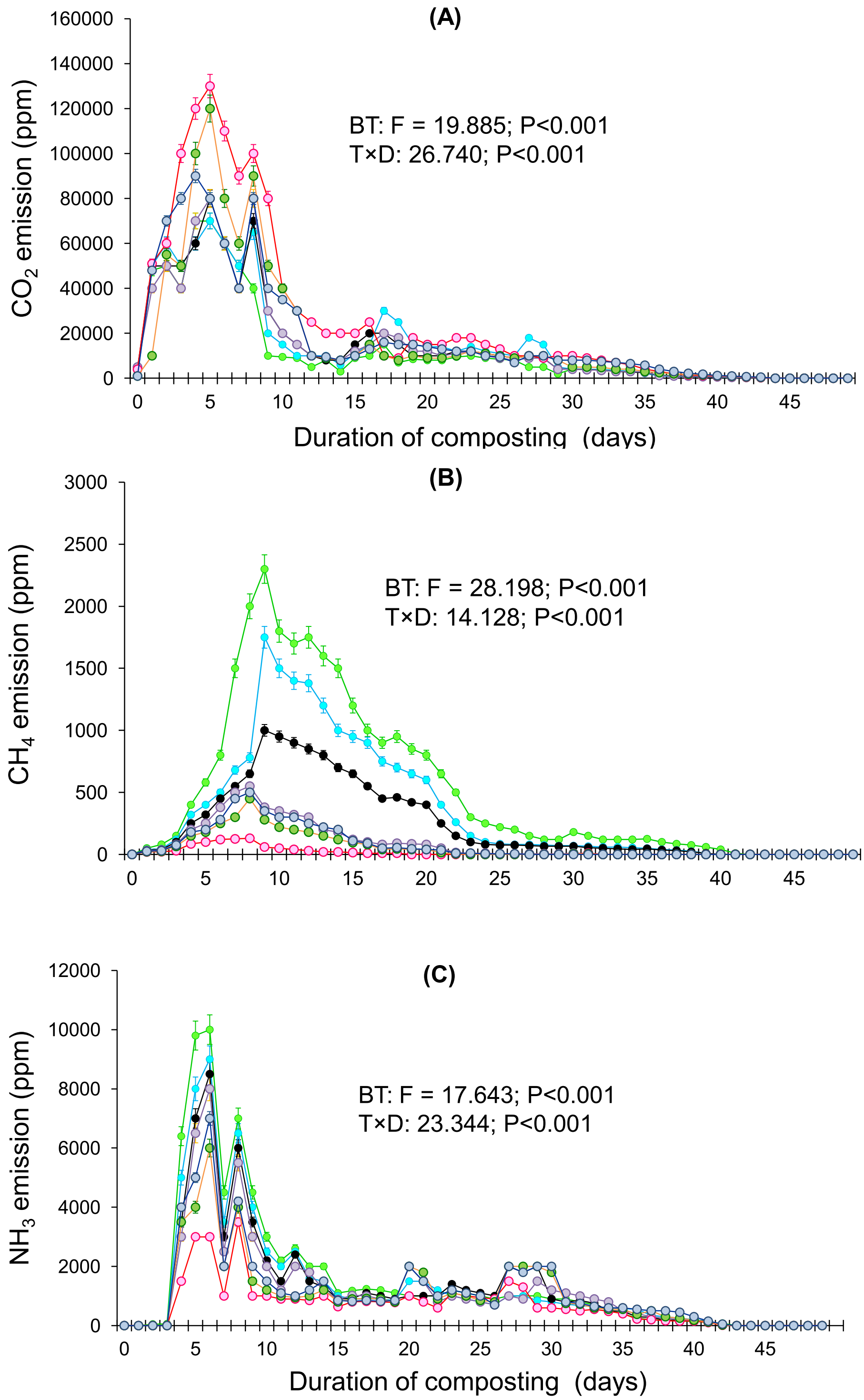

Fig. 3. Profile of CO_2 (A), methane (B), and ammonia (C) emission variations among different composting treatment groups (Values are representation of mean of the triplicates; error bars indicate ± standard deviation; $P \leq 0.05$ indicates significant difference by ANOVA).

took a longer duration. Most of all the treatments tended to zero CH_4 emission towards the final phase of composting. Jiang and co-workers suggested that the addition of Mg and P salts to the swine manure can reduce the CH_4 emission (Jiang et al., 2016); whereas in the present study the CH_4 emission reduction was not as high when compared to those treatments added with salts and biochar. This may be due to the co-composting of swine manure and food waste altogether. It has been reported that the addition of biochar to composting mixture has a significant effect to reduce gaseous emissions (He et al., 2019). Results of the study by de la Rosa et al. (2014) concluded that the biochar addition alleviates the methanogens activity and escalates methane oxidizing bacterial functioning. The present study results are in agreement with the previous findings (Chen et al., 2017).

The agronomical value and the quality of compost is dependent on the nitrogen content of the final product. During composting of livestock wastes, nitrogen fractions are converted continuously and a significant amount of nitrogen loss is accompanied by ammonia emission (Luo et al., 2014). The emission of NH_3 results in the loss of nitrogen and also environmental pollution as it is considered as an indirect greenhouse gas (Wang et al., 2016b). The NH_3 emission dynamics are depicted in Fig. 3C. With the aim of retaining the nutrients, different strategies are used to prevent nitrogen loss during composting of livestock wastes. Adding of biochar has several advantages including prevention of nutrient loss. NH_3 emission was very high at the initial stages of composting and it follows the trends of pH and temperature variations observed in this study. The obtained results indicate that salts and biochar amendment has reduced the NH_3 emission to a greater extent which is in agreement with the suggestion that biochar addition reduces NH_3 volatilization (Yang et al., 2020). Maximum emission was observed in T1 (without biochar and salts) and the results are in agreement with the findings of Duan et al. (2019b) and the minimum emission was observed in the T5 (with salts and 6% biochar). Addition of 6% biochar has reduced the NH_3 emission by 75% indicating 75% nitrogen loss is prevented which is higher than the earlier reports of Wang et al. (2016a) for food waste composting and Yang et al. (2020) for swine manure composting. Further increase in biochar percentage, contrastingly did not reduce NH_3 emission further as anticipated which is not desirable for good quality compost. However, after 8th day of composting, a gradual decline in the NH_3 emission was observed in all the treatments and tending toward non-detectable limits. Multiple functions of biochar such as reduced volatilization, the surface characteristics and porosity of biochar adsorbing NH_3, the role of salts in mitigating NH_3 emissions, favorable conditions for nitrifying bacteria facilitating microbial metabolism all together is considered as the reason for reduced emission of NH_3 (López-Cano et al., 2016).

Due to decomposition, organic nitrogen is converted into NH_4^+, which at alkaline condition undergoes ammonia volatilization, emitting gaseous NH_3 consequently lower the compost quality (Chen et al., 2017). Ammonia volatilization is also increased at temperatures above 45 °C. Initially the NH_4^+-N contents in most of all the biochar amended substrates rose quickly reaching the peak on 7th day and reduced gradually and stabilized by the end of composting (Fig. 4A). Whereas, NH_4^+-N concentrations peaked in the treatments without biochar was attained on the 14th day. The raise of NH_4^+-N content is because of the mineralization of nitrogen and ammonification; while the decrease is due to the nitrification and denitrification processes and ammonia emissions. In addition, the amendment of diatomite reduced the emission of NH_3 (8.63–35.29%) and N_2O (14.34–73.21%) during co-composting of pig manure which favours nitrogen conservation (Ren et al., 2021). The NH_4^+-N concentration was very high in T1, high in T2 and comparatively low in biochar amended compost treatments. This indicates the high absorption efficiency of biochar provides a good compost product and greatly reduces the release of environmental polluting greenhouse gases (Duan et al., 2019b). Although not much change was observed in the treatment added with salts alone, there was difference when compared to the control. Similarly, it had reflected in the current results by reduced emission of ammoniacal nitrogen compared to control. However, the combined effects of both biochar and salts had more positive composting effects.

The nitrate nitrogen content in all the treatments underwent a slight decline in the course of thermophilic composting stage. The inhibition of nitrifying bacterial growth at high temperatures is known to affect the nitrification process. After the thermophilic stage, enhancement in the NO_3^--N concentration was noticed in all the treatments (Fig. 4B).

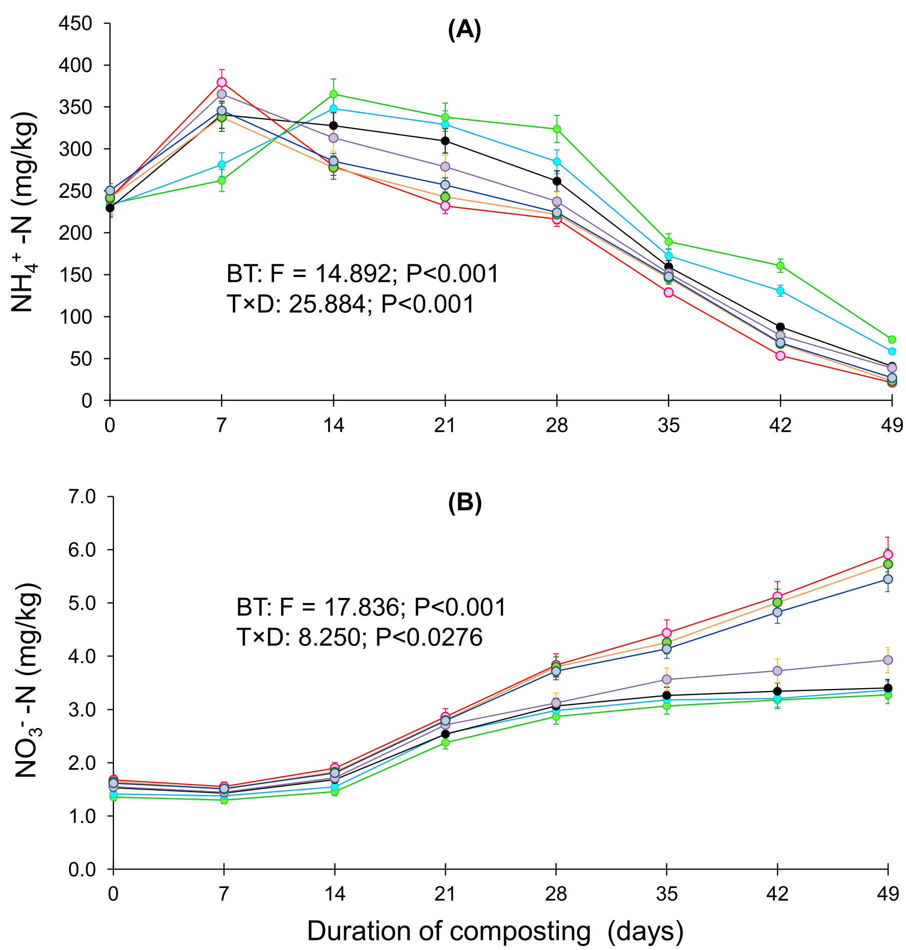

Fig. 4. Profile of NH_4^+-N (A), and NO_3-N (B) variations among the treatment groups (Values are representation of mean of the triplicates; error bars indicate ± standard deviation; P ≤ 0.05 indicates significant difference by ANOVA).

However, the biochar and salts added groups experienced a larger raise in the NO_3^-N concentrations. By the end of maturation phase, the NO_3^-N contents (mg/kg) increased from 1.358, 1.41, 1.53, 1.54, 0.68, 1.64, 1.61 to 3.27, 3.36, 3.40, 3.92, 5.12, 5.00, 4.82 for the treatments from T1 to T7, respectively. The NO_3^-N content in T1 (without biochar and salts) at the final phase was found to be 45% lower than the T5 (with 6% biochar and salts) treatment indicating the retention of nitrogen availability in the compost. The increase in NO_3^-N in biochar and salts co-amended treatments was significantly different ($P \leq 0.01$) from the treatments without biochar which clearly indicates that the addition of biochar plays a vital role in nitrogen conservation. This could be attributed to the enhanced nitrification process by biochar addition (Zhou et al., 2021).

3.3. Microbial population analysis

The microbial population was markedly improved in all the salt and biochar treated composting compared to control set-up. The treatment with 6% biochar (T5) showed the highest increase in total bacterial and total fungal population at 26 days, accounting to 8.9 and 6.8 log_{10} CFU/g of microbial load, respectively. The T1 showed the lowest increase in both total bacterial (6.8 log_{10} CFU/g) and total fungal (5.2 log_{10} CFU/g) population at 26 days (Fig. 5A and 5B). The cellulolytic bacterial population reached the highest load at 26 days of composting in all the treatments. The prominent increase (6.0 log_{10} CFU/g) in the cellulolytic population was observed in T5 treatment. The proteolytic bacterial population was reported the highest in T5 (7.8 log_{10} CFU/g) and the lowest in T1 (6.1 log_{10} CFU/g) after 47 days of treatment (Fig. 5C and 5D). These alterations in the microbial load during the composting period revealed increased activities of microorganisms and decomposition of swine manure and food waste. The biochar and inorganic salt amendment affect the microbial activities during composting which resulted in the improvement of their survivability. The previous literatures have illustrated that the amendment of manures and wastes with the biochar and various salts during composting increase degradation and maturation of manures and wastes, improve microbial activities, and ameliorate physico-chemical parameters (Hwang et al., 2020). After 26 days of composting, the microbial population observed to be declined. The microbiological analysis of the sample collected at 47 days of composting showed decrease in viable microbial population. The decline in the viable microbial load indicates the reduction of nutrient rich substances (organic and nitrogen containing compound) within the composting vessel (Ravindran et al., 2019). Food waste and swine manure contains highly nutrient-rich organic and inorganic compounds which are crucial for the growth of microorganisms and metabolic activities in the course of composting processes (Hwang et al., 2020). But, these nutrients rich materials get depleted as the composting process extend which halt microbial proliferation in the composting vessel. The decrease in both nutrient-rich materials and viable microbial load signifies the wastes and manures under composting acquire maturity and stability (Ravindran et al., 2019).

The pathogenic bacterial population such as *E. coli* and *Salmonella* sp. investigated during composting showed that the populations (log_{10} CFU/g) were in the maximum range of 1.6–1.8 and 0.6–0.9, respectively during the first week of composting. However, these pathogenic bacterial populations in composting substrates showed a declining trend after first week of the treatments with and without biochar and salts (Fig. 5E and 5F). The elimination of pathogenic bacteria might be due to the

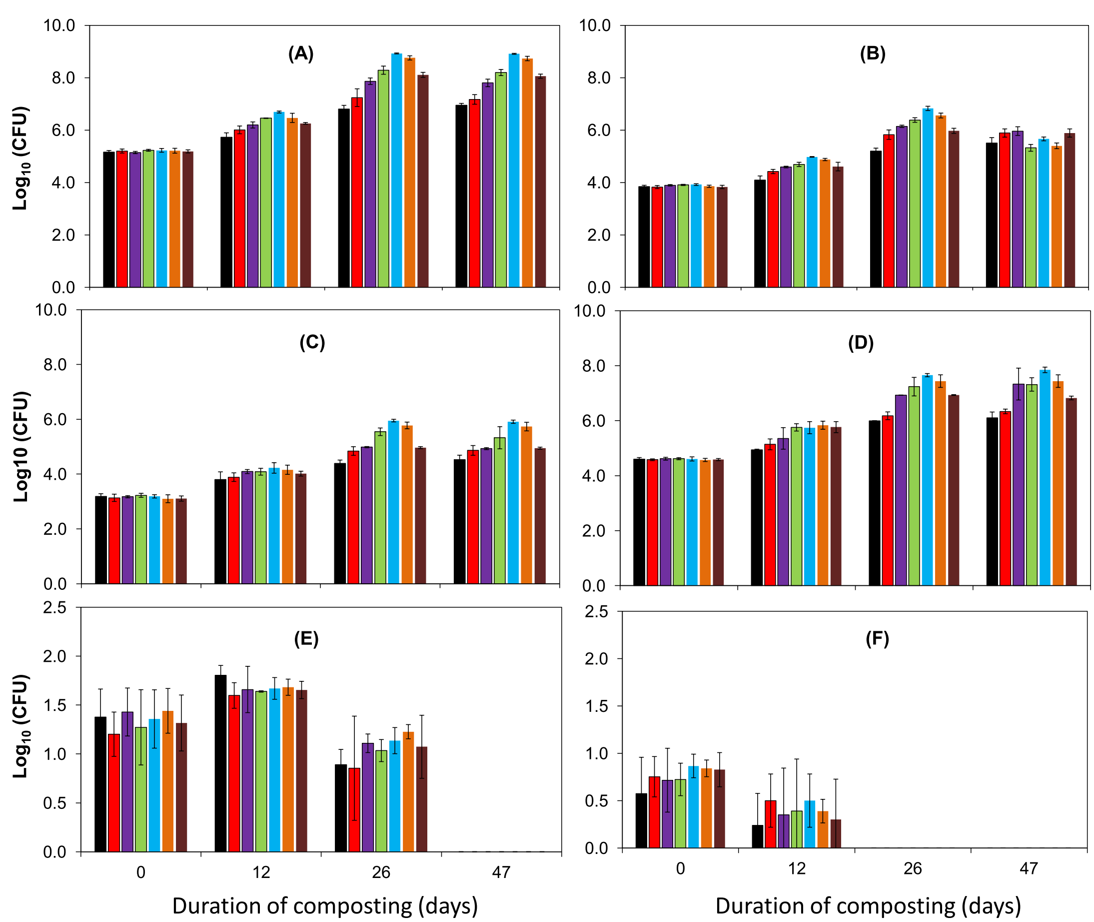

Fig. 5. Population dynamics of (A) total bacteria, (B) total fungi, (C) cellulolytic bacteria, (D) proteolytic bacteria, (E) *Escherichia coli*, and (F) *Salmonella* sp. (Values are representation of mean of the triplicates; error bars indicate ± standard deviation; $P \leq 0.05$ indicates significant difference by ANOVA).

severe environmental conditions that prevailed in the composting vessel. The alteration in the pH, temperature, oxygen level, and nutrients level create harsh condition for the microbial growth. Therefore, the composting technique amended with biochar is deemed to be beneficial and safe to remove pathogens from food wastes and manures.

4. Conclusions

Co-composting food waste and swine manure demonstrated a positive trend with increase in biochar concentration up to 6%, while further increase affected the compost quality. Thus, 6% biochar amendment is sufficient which has positively influenced the overall composting process by accelerating the degradation of organic matters and in producing a nutrient rich end product apart from preventing greenhouse gases emission and nitrogen losses. The decrease in viable pathogenic microbial growth also signifies its safe application. Hence biochar amendment for food waste and swine manure composting can be considered as a superior option for nutrient conservation.

CRediT authorship contribution statement

Balasubramani Ravindran: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing, Project administration, Supervision, Resources, Funding acquisition. **Mukesh Kumar Awasthi:** Methodology, Software, Validation, Data curation, Writing – review & editing. **Natchimuthu Karmegam:** Methodology, Software, Validation, Data curation, Writing – review & editing. **Soon Woong Chang:** Methodology, Software, Validation, Data curation, Writing – review & editing. **Dhiraj Kumar Chaudhary:** Formal analysis, Data curation. **Ammaiyappan Selvam:** Methodology, Software, Validation, Data curation, Writing – review & editing. **Dinh Duc Nguyen:** Writing – review & editing. **Ashequr Rahman Milon:** Formal analysis, Data curation. **Ganesh Munuswamy-Ramanujam:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

APHA, 2006. Standard Methods for the Examination of Water and Wastewater —Section 9222D Thermotolerant (fecal) coliform membrane filter procedure, American Water Works Association. Water Environment Federation, Washington, D.C.

Awasthi, M.K., Duan, Y., Awasthi, S.K., Liu, T., Chen, H., Pandey, A., Zhang, Z., Taherzadeh, M.J., 2020a. Emerging applications of biochar: Improving pig manure composting and attenuation of heavy metal mobility in mature compost. J. Hazard. Mater. 389, 122116. https://doi.org/10.1016/j.jhazmat.2020.122116.

Awasthi, M.K., Duan, Y., dduan, T., Awasthi, S.K., Zhang, Z., 2020b. Relevance of biochar to influence the bacterial succession during pig manure composting. Bioresour. Technol. 304, 122962. https://doi.org/10.1016/j.biortech.2020.122962.

Awasthi, M.K., Selvam, A., Lai, K.M., Wong, J.W.C., 2017a. Critical evaluation of post-consumption food waste composting employing thermophilic bacterial consortium. Bioresour. Technol. 245, 665–672. https://doi.org/10.1016/j.biortech.2017.09.014.

Awasthi, M.K., Wang, M., Chen, H., Wang, Q., Zhao, J., Ren, X., Li, D.-S., Awasthi, S.K., Shen, F., Li, R., Zhang, Z., 2017b. Heterogeneity of biochar amendment to improve the carbon and nitrogen sequestration through reduce the greenhouse gases emissions during sewage sludge composting. Bioresour. Technol. 224, 428–438. https://doi.org/10.1016/j.biortech.2016.11.014.

Chen, W., Liao, X., Wu, Y., Liang, J.B., Mi, J., Huang, J., Zhang, H., Wu, Y.u., Qiao, Z., Li, X., Wang, Y., 2017. Effects of different types of biochar on methane and ammonia mitigation during layer manure composting. Waste Manag. 61, 506–515. https://doi.org/10.1016/j.wasman.2017.01.014.

Cheung, H.N.B., Huang, G.H., Yu, H., 2010. Microbial-growth inhibition during composting of food waste: Effects of organic acids. Bioresour. Technol. 101 (15), 5925–5934. https://doi.org/10.1016/j.biortech.2010.02.062.

Chung, W.J., Chang, S.W., Chaudhary, D.K., Shin, JoungDu, Kim, H., Karmegam, N., Govarthanan, M., Chandrasekaran, M., Ravindran, B., 2021. Effect of biochar amendment on compost quality, gaseous emissions and pathogen reduction during in-vessel composting of chicken manure. Chemosphere 283, 131129. https://doi.org/10.1016/j.chemosphere.2021.131129.

de la Rosa, J.M., Paneque, M., Miller, A.Z., Knicker, H., 2014. Relating physical and chemical properties of four different biochars and their application rate to biomass production of *Lolium perenne* on a Calcic Cambisol during a pot experiment of 79 days. Sci. Total Environ. 499, 175–184. https://doi.org/10.1016/j.scitotenv.2014.08.025.

Duan, Y., Awasthi, S.K., Liu, T., Zhang, Z., Awasthi, M.K., 2019a. Response of bamboo biochar amendment on volatile fatty acids accumulation reduction and humification during chicken manure composting. Bioresour. Technol. 291, 121845. https://doi.org/10.1016/j.biortech.2019.121845.

Duan, Y., Awasthi, S.K., Liu, T., Zhang, Z., Awasthi, M.K., 2019b. Evaluation of integrated biochar with bacterial consortium on gaseous emissions mitigation and nutrients sequestration during pig manure composting. Bioresour. Technol. 291, 121880. https://doi.org/10.1016/j.biortech.2019.121880.

He, X., Yin, H., Han, L., Cui, R., Fang, C., Huang, G., 2019. Effects of biochar size and type on gaseous emissions during pig manure/wheat straw aerobic composting: Insights into multivariate-microscale characterization and microbial mechanism. Bioresour. Technol. 271, 375–382. https://doi.org/10.1016/j.biortech.2018.09.104.

Hwang, H.Y., Kim, S.H., Shim, J., Park, S.J., 2020. Composting process and gas emissions during food waste composting under the effect of different additives. Sustain. 12, 7811. https://doi.org/10.3390/SU12187811.

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (The Intergovernmental Panel on Climate Change), Kristin Seyboth (USA). IPCC, Geneva, Switzerland.

Jain, M.S., Jambhulkar, R., Kalamdhad, A.S., 2018. Biochar amendment for batch composting of nitrogen rich organic waste: Effect on degradation kinetics, composting physics and nutritional properties. Bioresour. Technol. 253, 204–213. https://doi.org/10.1016/j.biortech.2018.01.038.

Janczak, D., Malińska, K., Czekała, W., Cáceres, R., Lewicki, A., Dach, J., 2017. Biochar to reduce ammonia emissions in gaseous and liquid phase during composting of poultry manure with wheat straw. Waste Manag. 66, 36–45. https://doi.org/10.1016/j.wasman.2017.04.033.

Jeong, S.T., Cho, S.R., Lee, J.G., Kim, P.J., Kim, G.W., 2019. Composting and compost application: Trade-off between greenhouse gas emission and soil carbon sequestration in whole rice cropping system. J. Clean. Prod. 212, 1132–1142. https://doi.org/10.1016/j.jclepro.2018.12.011.

Jiang, T., Ma, X., Yang, J., Tang, Q., Yi, Z., Chen, M., Li, G., 2016. Effect of different struvite crystallization methods on gaseous emission and the comprehensive comparison during the composting. Bioresour. Technol. 217, 219–226. https://doi.org/10.1016/j.biortech.2016.02.046.

Kumari, P., Choi, H.L., Sudiarto, S.I.A., Moreno-Hagelsieb, G., 2015. Assessment of bacterial community assembly patterns and processes in pig manure slurry. PLoS One 10 (9), e0139437. https://doi.org/10.1371/journal.pone.0139437.

Lee, C.H., Kim, S.-C., Park, S.-J., Kim, M.-S., Oh, T.-K., 2017. Effects of animal waste addition on food waste compost under co-composting. Korean J. Soil Sci. Fertil. 50, 623–633. https://doi.org/10.7745/KJSSF.2017.50.6.623.

Li, H., Zhang, T., Tsang, D.C.W., Li, G., 2020. Effects of external additives: Biochar, bentonite, phosphate, on co-composting for swine manure and corn straw. Chemosphere 248, 125927. https://doi.org/10.1016/j.chemosphere.2020.125927.

Liu, H., Kumar, V., Yadav, V., Guo, S., Sarsaiya, S., Binod, P., Sindhu, R., Xu, P., Zhang, Z., Pandey, A., Awasthi, M.K., 2021. Bioengineered biochar as smart candidate for resource recovery toward circular bio-economy: A review. Bioengineered. https://doi.org/10.1080/21655979.2021.1993536.

López-Cano, I., Roig, A., Cayuela, M.L., Alburquerque, J.A., Sánchez-Monedero, M.A., 2016. Biochar improves N cycling during composting of olive mill wastes and sheep manure. Waste Manag. 49, 553–559. https://doi.org/10.1016/j.wasman.2015.12.031.

Luo, W.H., Yuan, J., Luo, Y.M., Li, G.X., Nghiem, L.D., Price, W.E., 2014. Effects of mixing and covering with mature compost on gaseous emissions during composting. Chemosphere 117, 14–19. https://doi.org/10.1016/j.chemosphere.2014.05.043.

Mao, C., Feng, Y., Wang, X., Ren, G., 2015. Review on research achievements of biogas from anaerobic digestion. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2015.02.032.

OCQS, 2012. Ontario Compost Quality Standards [WWW Document]. Ontario Minist. Environ. Waste Manag, Policy Branch.

Petracchini, F., Liotta, F., Paolini, V., Perilli, M., Cerioni, D., Gallucci, F., Carnevale, M., Bencini, A., 2018. A novel pilot scale multistage semidry anaerobic digestion reactor to treat food waste and cow manure. Int. J. Environ. Sci. Technol. 15 (9), 1999–2008. https://doi.org/10.1007/s13762-017-1572-z.

Qamaruz-Zaman, N., Milke, M.W., 2012. VFA and ammonia from residential food waste as indicators of odor potential. Waste Manag. 32 (12), 2426–2430. https://doi.org/10.1016/j.wasman.2012.06.023.

Ravindran, B., Nguyen, D.D., Chaudhary, D.K., Chang, S.W., Kim, J., Lee, S.R., Shin, JoungDu, Jeon, B.-H., Chung, SeokJoo, Lee, JaeJoung, 2019. Influence of biochar on physico-chemical and microbial community during swine manure composting process. J. Environ. Manage. 232, 592–599.

Ren, X., Wang, Q., Chen, X., He, Y., Li, R., Li, J.i., Zhang, Z., 2021. Pathways and mechanisms of nitrogen transformation during co-composting of pig manure and diatomite. Bioresour. Technol. 329, 124914. https://doi.org/10.1016/j.biortech.2021.124914.

Sánchez-García, M., Alburquerque, J.A., Sánchez-Monedero, M.A., Roig, A., Cayuela, M. L., 2015. Biochar accelerates organic matter degradation and enhances N mineralisation during composting of poultry manure without a relevant impact on gas emissions. Bioresour. Technol. 192, 272–279. https://doi.org/10.1016/j.biortech.2015.05.003.

Wainaina, S., Awasthi, M.K., Sarsaiya, S., Chen, H., Singh, E., Kumar, A., Ravindran, B., Awasthi, S.K., Liu, T., Duan, Y., Kumar, S., Zhang, Z., Taherzadeh, M.J., 2020. Resource recovery and circular economy from organic solid waste using aerobic and anaerobic digestion technologies. Bioresour. Technol. 301, 122778. https://doi.org/10.1016/j.biortech.2020.122778.

Wang, M., Awasthi, M.K., Wang, Q., Chen, H., Ren, X., Zhao, J., Li, R., Zhang, Z., 2017. Comparison of additives amendment for mitigation of greenhouse gases and ammonia emission during sewage sludge co-composting based on correlation analysis. Bioresour. Technol. 243, 520–527. https://doi.org/10.1016/j.biortech.2017.06.158.

Wang, Q., Awasthi, M.K., Ren, X., Zhao, J., Li, R., Wang, Z., Wang, M., Chen, H., Zhang, Z., 2018. Combining biochar, zeolite and wood vinegar for composting of pig manure: The effect on greenhouse gas emission and nitrogen conservation. Waste Manag. 74, 221–230. https://doi.org/10.1016/j.wasman.2018.01.015.

Wang, S., Zeng, Y., 2018. Ammonia emission mitigation in food waste composting: A review. Bioresour. Technol. 248, 13–19. https://doi.org/10.1016/j.biortech.2017.07.050.

Wang, X., Selvam, A., Wong, J.W.C., 2016a. Influence of lime on struvite formation and nitrogen conservation during food waste composting. Bioresour. Technol. 217, 227–232. https://doi.org/10.1016/j.biortech.2016.02.117.

Wang, Q., Wang, Z., Awasthi, M.K., Jiang, Y., Li, R., Ren, X., Zhao, J., Shen, F., Wang, M., Zhang, Z., 2016b. Evaluation of medical stone amendment for the reduction of nitrogen loss and bioavailability of heavy metals during pig manure composting. Bioresour. Technol. 220, 297–304. https://doi.org/10.1016/j.biortech.2016.08.081.

Waqas, M., Nizami, A.S., Aburiazaiza, A.S., Barakat, M.A., Ismail, I.M.I., Rashid, M.I., 2018. Optimization of food waste compost with the use of biochar. J. Environ. Manage. 216, 70–81. https://doi.org/10.1016/j.jenvman.2017.06.015.

Yang, Y., Kumar Awasthi, M., Du, W., Ren, X., Lei, T., Lv, J., 2020. Compost supplementation with nitrogen loss and greenhouse gas emissions during pig manure composting. Bioresour. Technol. 297, 122435. https://doi.org/10.1016/j.biortech.2019.122435.

Yeo, J., Chopra, S.S., Zhang, L., An, A.K., 2019. Life cycle assessment (LCA) of food waste treatment in Hong Kong: On-site fermentation methodology. J. Environ. Manage. 240, 343–351. https://doi.org/10.1016/j.jenvman.2019.03.119.

Zainudin, M.H., Mustapha, N.A., Maeda, T., Ramli, N., Sakai, K., Hassan, M., 2020. Biochar enhanced the nitrifying and denitrifying bacterial communities during the composting of poultry manure and rice straw. Waste Manag. 106, 240–249. https://doi.org/10.1016/j.wasman.2020.03.029.

Zhang, L., Sun, X., 2016. Influence of bulking agents on physical, chemical, and microbiological properties during the two-stage composting of green waste. Waste Manag. 48, 115–126. https://doi.org/10.1016/j.wasman.2015.11.032.

Zhou, S., Wen, X., Cao, Z., Cheng, R., Qian, Y., Mi, J., Wang, Y., Liao, X., Ma, B., Zou, Y., Wu, Y., 2021. Modified cornstalk biochar can reduce ammonia emissions from compost by increasing the number of ammonia-oxidizing bacteria and decreasing urease activity. Bioresour. Technol. 319, 124120. https://doi.org/10.1016/j.biortech.2020.124120.