CHEMICAL ENGINEERING TRANSACTIONS

VOL. 86, 2021

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Sauro Pierucci, Jiří Jaromír Klemeš

ISBN 978-88-95608-84-6; **ISSN** 2283-9216

Integrating Compost and Biochar towards Sustainable Soil Management

Cassendra Phun Chien Bong[a], Li Yee Lim[a], Chew Tin Lee[a,]*, Pei Ying Ong[b], Yee Van Fan[c], Jiří Jaromír Klemeš[c]

[a]School of Chemical and Energy Engineering, Universiti Teknologi Malaysia (UTM), 81310, Johor, Malaysia
[b]Innovation Centre in Agritechnology for Advanced Bioprocessing, Universiti Teknologi Malaysia, 84600, Pagoh, Johor, Malaysia
[c]Sustainable Process Integration Laboratory – SPIL, NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology - VUT Brno, Technická 2896/2, 616 00 Brno, Czech Republic
ctlee@utm.my

Composting of biowaste to organic fertiliser promotes resource recycling with various environmental co-benefits, including mitigation of nutrient loss, greenhouse gas emissions, and soil enrichment. As produced from the pyrolysis of organic waste, biochar could be added to compost for enhanced performances. The use of either compost or biochar or both has shown a positive effect on the overall soil quality, such as increasing soil pH and electrical conductivity, increasing soil organic matter, promoting soil carbon storage, and reducing the bioavailability of heavy metals. However, studies have reported contradictory observations and varying degree on the positive effect of such amendments on the aspects mentioned above. This review aims to evaluate the effect of biochar on composting towards a greener and cleaner process. The interacting mechanisms among biochar, compost and biochar-compost amendment upon soil application are discussed. The addition of biochar to compost effectively reduces nutrient loss and gaseous emission and promotes humification. The presence of biochar enrich specific groups of microbes that encourage nitrogen immobilisation. Biochar is more effective in improving the soil carbon pool, whereas compost has a more direct and persistent impact on the soil pH and cation exchange capacity. Upon applying mixed compost with biochar in soil, the organic amendments reduced heavy metals' bioavailability through the respective mechanisms. Different effects of compost and biochar on the soil properties and microbial community were observed, depending on the amendment type, soil condition and length of the application period.

1. Introduction

The increasing production of organic waste and its associated environmental impacts calls for effective and sustainable management options. The concept of a circular economy emphasises the re-utilisation of waste as resources to value-added products. Composting is a biological treatment where the organic wastes undergo phases of biological reaction by different microorganisms to produce humus-like compost. The compost is used as an organic amendment to restore soil fertility and promote plant growth and heavy metal immobilisation (Lim et al., 2017).

The composting process's environmental performance is related to the process efficiency in terms of composting time, nutrient loss, gaseous emission, heavy metal immobilisation, and the maturity and quality of the end compost. These factors are closely related to the operational parameters (carbon and nitrogen content, aeration flow, bulk density and pH) and the microbial-mediated process (organic matter mineralisation and passivation of heavy metals). Minimising both N and C losses is essential to reduce its gaseous emission and produce high-quality compost products (Qu et al., 2020). Compost used in agriculture also needs to exhibit a safe heavy metal concentration where a high humification degree could reduce the bioavailability of heavy metals by forming binding complexes (Lim et al., 2017).

Biochar is a highly carbonaceous solid residual produced from the pyrolysis of organic waste at a high temperature (300-700 ˚C) and under the absence of oxygen. Biochar has shown its beneficial role in pollution remediation and nutrient retention, enhancing compost maturity and improving carbon sequestration. These are attributed to its porous structure, large surface area, and anion exchange capacities that increase its high adsorption capacity against targeted substances (Zainudin et al., 2020). There has been a contradictory report on its gas emission-inhibiting capability (Qu et al., 2020). Microbial activity affects the composting process physical and biological parameters (Khan et al., 2014). The addition of biochar to compost could affect the microbial-mediated activities, such as organic matter mineralisation, heavy metal passivation and nutrient immobilisation (Awasthi et al., 2020). More understanding of the transformation mechanisms of organic matter regulated by the shift of microbial community under the presence of compost is essential towards an effective process to produce good quality compost

Compost and biochar have been used as a soil amendment, either alone or combined. The positive effect could be categorised into soil quality restoration (Liu et al., 2020), soil carbon sequestration (Cooper et al., 2020) and heavy metal remediation(Bashir et al., 2020). Contradictory observations were observed where the application of such amendments induce priming effect (D'Hose et al., 2020), inhibit soil microbial enzyme (Tang et al., 2020) and decrease soil pH (Cooper et al., 2020). Compost and biochar have their respective characteristics, where the former derived from biological degradation and the later from thermal degradation. One of the unique characteristics of compost is the high level of humic substances that give rise to its binding capacity and slow nutrient release effect. Biochar is characterised as a porous, high recalcitrant aromatic carbon substance with high adsorption capacity and stability. Incorporating biochar with compost is shown to improve soil aggregate formation that is highly dependent on organic matter availability, with a stronger relationship between the microbial communities and the derived binding agents (Mukherjee and Lal, 2013). The application of such mixed soil enhancer may exhibit a different degree of impact on specific soil parameters. The compound effect of mixed compost with biochar remains unclear towards the soil environment upon application.

This paper first reviews the role of biochar as an additive during the composting process, focusing on nutrient loss, gaseous emission and compost quality, to improve the composting efficiency. The paper further reviews and discuss the effect and mechanisms when compost and biochar are co-applied to the soil. The review aims to achieve a better understanding on the factors concerning the effects and the degree of effects on soil upon the amendments application, and to recommend gaps needed to be addressed towards designing a sustainable soil management system.

2. Integrating compost and biochar for soil application

2.1 Incorporating biochar to composting

This section discusses the effect of incorporating biochar to enhance the process efficiency during composting. One of the main drawbacks of composting is its high N loss, which is often associated with C loss due to affected microbial activity (Tong et al., 2019). N loss happens during composting via NH_3 volatilisation, leaching of nitrification species (NO_2^- and NO_3^-), and gaseous emission (NO, N_2O and N_2) through denitrification (Zainudin et al., 2020). N loss through NH_3 volatilisation could reach 21-77 % of the initial total N (Chan et al., 2020), whereas C loss through CO_2 emission could account for 34-77 % of the initial C (Guo et al, 2012) during composting.

The addition of biochar up to 10 % during the composting of poultry manure leads to a reduction of 394 % for C loss and 40.9 % for N loss (Awasthi et al., 2020). A relatively lower concentration was reported for total NH_3-N loss of 2.1-9.1 % of initial N and CO_2-C loss of less than 20 % of initial C with biochar and gypsum addition during the composting of agricultural waste (Qu et al., 2020). Biochar effectively binds CO_2 to its surface through physisorption (Khan et al., 2014) and preserve N via the adsorption of NH_4^+ or volatile NH_3 (Zainudin et al., 2020). The adsorption of NH_3 also leads to lower toxicity during composting, as indicated by a germination index value of higher than 40, despite a sharp decrease during the thermophilic stage (Khan et al., 2014).

The positive effect of biochar on the gaseous emission and nutrient loss attributes to the microbial community's presence. The microbial utilisation of carbohydrates, carboxylic acids, and polymers increased with biochar, and the presence of various hydrolysis enzymes such as dehydrogenase, protease, cellulase, and xylanase (Awasthi et al., 2020). Biochar addition stimulates microbial activity with higher respiration and decomposition of dissolved organic C, around 12-22.7 % higher than the control sample (Khan et al., 2014). Composting with biochar exhibited higher temperature and extended thermophilic phase than the control sample (Zainudin et al., 2020). Other positive attributes by biochar include the enhanced mineralisation of microbe-mediated organic N (Qu et al., 2020), and as C source to depolymerise high molecular weight nitrogenous compounds (Zhu et al., 2019). Biochar also facilitates the immobilisation of microbe-mediated NO_3^--N, leading to lower NH_4^+-N and total N loss (Qu et al., 2019). The study observed that the composting with biochar recorded 50 % higher NO_2^- and NO_3^- than the control sample. The finished compost recorded a higher amount of NH_4^+ and lower amount of NO_2^- and NO_3- than the control sample (Zainudin et al., 2020). The addition of biochar alters the microbial profiles during composting. The relative abundance of Firmicutes decreased with an increase in Actinobacteria and Proteobacteria with higher biochar loading during composting (Awasthi et al., 2021). The study showed a high correlation with the changes of nutrient cycle, pH and heavy-metal resistant bacteria with biochar addition. The presence of biochar presents a negative effect on the diversity of diazotrophic community but enhanced N fixing during composting due to the increased abundance of *Azobacter* (Wu et al., 2020). It was shown that biochar addition enriched nitrifying and denitrifying bacteria such as *Halomonas*, *Pusillimonas* and *Pseudofulvimonas* (Zainudin et al., 2020).

The biochar addition improves composting's physical parameters, which reduces the gaseous emission and increases organic matter degradation. During swine manure and rice straw composting, a 10 % biochar addition decreased the process bulk density by 45.89 % and increased the free air space by 31.25 % (Guo et al., 2021). N_2O reduction was observed in the composting with biochar where improved oxygenation and higher temperature inhibited the growth of nitrifying microorganisms (Cue et al., 2019). The improved oxygenation due to biochar's porous structure also suppresses the methanogenic activity and promotes methylotroph that reduces CH_4 emission (Wu et al., 2017).

The addition of biochar during composting resulted in higher pH that promoted the passivation of heavy metals. Such immobilisation of heavy metals is attributed to the enhanced microbial-controlled humification such as negative-valence acids and humus substances from organic matter degradation. The improved C/N due to the addition of C-rich biochar facilitate microbial growth and the release of metal cations from unstable organic matter to combine with stable organic to form stable complexes (Cu et al., 2020). Biochar addition facilitates the breakdown of the large aggregates along composting and allow the smaller parts to stick together with the formation of humus colloids to develop final sense particles during the maturation stage (Guo et al., 2021).The role of biochar in composting is depicted in its adsorption capacity, as hosting site to improve microbial-mediated nutrient immobilisation and as a bulking agent facilitating aerobic conditions, as shown in Figure 1.

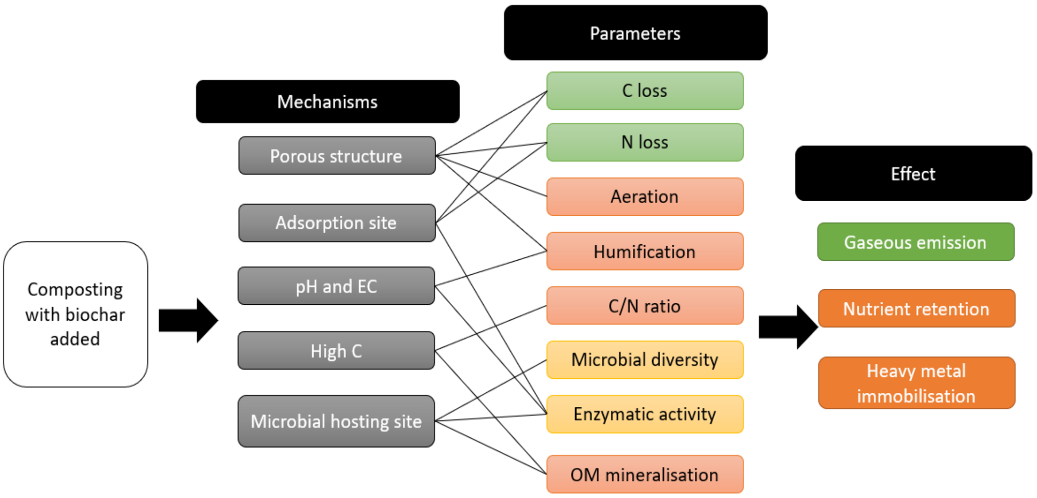

Figure 1: Mechanisms and effect of incorporating biochar to the composting process (Parameters' legend= green: decrease; orange: increase; yellow: both)

However, NO_3^--N was observed in higher concentration (400-1,200 mg/kg) in biochar-treated piles due to stimulation of nitrification and adsorption of NO_3^-, especially at the end of composting when the nitrifier activity was low (Khan et al., 2014). The variation of results with biochar addition might be attributed to the varied intensity of the denitrification process in reducing NO_2^- and NO_3^- into N_2O or N_2 and biochar with various properties. Biochar produced at a temperature greater than 600 ˚C had a lower capacity for NH_4^+-N. Biochar derived from biosolids (D'Hose et al., 2020), manure and food waste (Bong et al., 2020) had higher retention and cation exchange capacity.

2.2 Soil amendment by co-application of compost and biochar

Soil amendment by compost and biochar exert positive effects upon soil application but with different mechanisms. The anoxic and high pH of biochar pores provides a favourable micro-environment for the activities of the N_2O decreasing microbes, and the denitrification products transform from N_2O to N_2 (Liu et al., 2020). The biochar addition can lead to a lower mean turnover rate in the particulate organic matter fraction, allowing storing more organic carbon for a long time (Cooper et al., 2020). The high aromatic C from biochar likely gives rise to the low biodegradation and long residence time in soil. Biochar affects the soil C due to its high stable C content, whereas compost exhibits a stronger effect on soil pH and cation exchange capacity. Aged biochar on applied soil showed lower pH, contrary to the longer-lasting effect of compost in increasing soil pH and cation exchange capacity (Liu et al., 2020). Liu et al. (2020) observed that soil carbon could be improved with low-rate biochar at a high-rate compost application. The study further illustrated that high-rate application of biochar and compost could increase the soil pH, but the compost effect is longer-lasting and on soil with greater depth. A similar observation was reported by Cooper et al. (2020), where both biochar and compost could increase soil C on the topsoil, the effect of compost on soil pH and K lasted for 2-4 y.

Due to soil tillage practices, biochar migrated to subsoil after 2 growing seasons and increase the C sequestration in subsoil where around 50 % of the biochar C is retained in the subsoil area after 2-4 y of application, with a C retention rate of around 83 % (D'Hose et al., 2020). Repeating high dosing of compost may have a high leaching risk, especially if the soil is not depleted of P (Lim et al, 2018). Cooper et al. (2020) observed that bulk organic content was significantly increased by high-rate compost application and by biochar with a low and high-rate application. It increased by 48 % in surface soil and by 71 % in subsurface soil with a high-rate compost-biochar mixture. Less significant improvement was observed with greater soil depth, most likely due to the more limited microbial communities at a greater soil depth, whereas subsurface soil is less affected by environmental conditions that could affect the microbial community structure (Kaiser et al., 2015).

For microbial composition, no significant effect was observed, but there was a shift of microbial community. Studies also showed significant compound effect when compost and biochar are both applied to the soil. Liu et al. (2020) observed that the co-application of biochar and compost can increase the soil physicochemical properties and induce microbial growth while reducing denitrifying activity and altering the microbial nitrogen cycling communities. The soil micro-biomass and community composition remain unchanged following such organic amendments (Cooper et al., 2020). Gram-negative bacteria and actinomycetes decreased significantly, whereas actinomycetes and fungi increased, leading to lower bacteria to fungi ratio after 4 y of application. The changes were more prominent during the early stages of application and dependent on the biochar and compost type (D'Hose et al., 2020).

Compost application is associated with heavy metals' immobilisation in soils due to its high humus content and neutral pH (Lim et al., 2017). The bioavailability of heavy metal is the most important parameter. Such soil amendment works by reducing the metal bioavailability in the soil and their root to shoot transportation (Chen et al., 2016). Biochar-compost application increased the plant photosynthetic pigments, where drought and Cd stress declined photosynthesis rate, transpiration rate and chlorophyll content (Bashir et al., 2020). Application of compost and biochar can change the Cd species and reduce its bioavailability (Liu et al., 2017). These could be due to the water exchangeable organic carbon that binds to free metal ions (Zeng et al., 2015) and higher pH (> 6) that decreases the mobility of heavy metal by forming a stable insoluble complex between organic matter (negative sorption sites) and heavy metals (Lim et al., 2017). Soil enzyme activities were activated by compost and inhibited by biochar but showed a highly variable response to their combination. Electric conductivity and available K showed the greatest influence on metal availability and soil enzyme activity, whereas the availability of As Cu, Cd and Zn can affect dehydrogenase, catalyse and urease (Tang et al., 2020). Increase in metal available such as As and Cu lead to activation of soil enzyme activities as cofactor, but Cd and Zn availability led to inhibition of soil enzyme due to chelating with enzymes sulfhydryl group (Hu et al., 2014). Figure 2 shows an overall superstructure on the effect of biochar, compost and biochar-compost blend on soil-related activities.

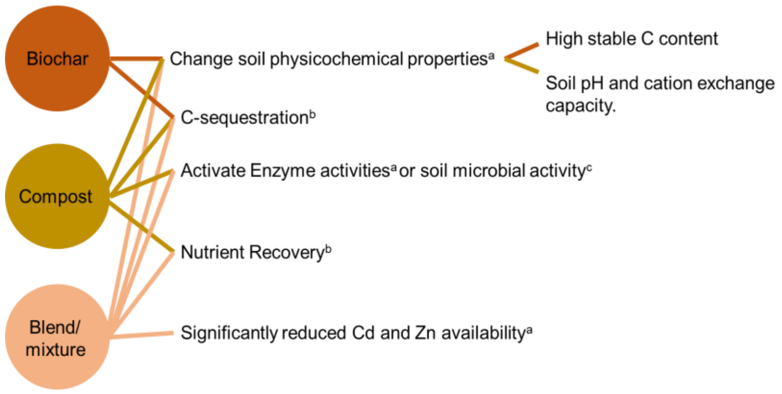

Figure 2: Superstructure on the application of organic amendments on soil activities ([a]Tang et al., 2020; [b]Oldfield et al., 2018; [c]Sánchez-Monedero et al., 2019)

3. Conclusions

The effect of biochar was discussed when incorporated during the composting process and co-application with the compost in soil. The addition of biochar enables a greener and efficient process due to reduced gaseous emission through improved aeration and microbial-mediated mechanism. The biochar's adsorption capacity reduces NH_3 and CO_2, immobilises the leaching of NH_4^+ and acts as a hosting site for microbial community. Studies showed that biochar enriched specific genera of microorganisms instead of the whole community. Further studies on such selective mechanisms of the biochar can help engineers target specific microorganisms with desirable functional genes to optimise the composting process. Co-application of compost and biochar in soil generally show a positive effect. For compost application, the preferable application rate could be more dependent on the product maturity and stability due to its comparative higher nutrients composition than the carbonaceous biochar. Although various mechanisms have been observed, there are still limited quantitative information. Techniques such as correlation and regression analysis could contribute in mapping the trade-offs among the qualities and quantities of amendments used for different soils under different conditions. This can shed some light towards an optimal utilisation of waste-derived products for sustainable soil management.

Acknowledgments

The authors would like to acknowledge the research grants from the Ministry of Education (MOE) Malaysia with grant no. R.J130000.7809.5F147. The authors also acknowledge the funding and support by the EU project Sustainable Process Integration Laboratory – SPIL, funded as project No. CZ.02.1.01/0.0/0.0/15_003/0000456, by Czech Republic Operational Programme Research and Development, Education, Priority 1: Strengthening capacity for quality research under collaboration agreement with UTM, Malaysia.

References

Abbas T., Rizwan M., Ali S., Adrees M., Mahmood A., Rehman M.Z., Ibrahim N., Arshad M., Qayyum M.F., 2018, Biochar application increased the growth and yield and reduced cadmium in drought stressed wheat grown in an aged contaminated soil, Ecotoxicology and Environment Safety, 148, 825-833.

Agegnehu G., Srivastava A.K., Bird M.I., 2017, The role of biochar and biochar-compost in improving soil quality and crop performance: a review, Applied Soil Ecology, 119, 156-170.

Awasthi M.K., Duan Y., Awasthi S.K., Liu T., Zhang Z., 2020, Influence of bamboo biochar on mitigating greenhouse gas emissions and nitrogen loss during poultry manure composting, Bioresource Technology, 303, 122952.

Awasthi S.K., Duan Y., Liu T., Zhang Z., Pandey A., Varjani S., Awasthi M.K., Taherzadeh M.J., 2021, Can biochar regulate the fate of heavy metals (Cu and Zn) resistant bacterial community during the poultry manure composting?Journal of Hazardous Materials, 406, 124593.

Bashir A., Rizwan M., ur Rehman M.Z., Zubair M., Riaz M., Qayyum M.F., Alharby H.F., Bamagoos A.A., Ali S., 2020, Application of co-composted farm manure and biochar increased the wheat growth and decreased cadmium accumulation in plants under different water regimes. Chemosphere, 246, 125809.

Bong C.P.C., Lim L.Y., Lee C.T., Ong P.Y., Klemeš J.J., Li C., Gao Y., 2020, Lignocellulosic biomass and food waste for biochar production and application: a review, Chemical Engineering Transaction, 81, 427-432.

Chan M.T., Selvam A., Wong J.W., 2016, Reducing nitrogen loss and salinity during 'struvite' food waste composting by zeolite amendment, Bioresource Technology, 200, 838-844.

Chen H., Awasthi S.K., Liu T., Duan Y., Ren X., Zhang Z., Pandey A., Awasthi M.K., 2020, Effects of microbial culture and chicken manure biochar on composting maturity and greenhouse gas emissions during chicken manure composting, Journal of Hazardous Material, 389, 121908.

Cooper J., Greenberg I., Ludwig B., Hippich L., Fischer D., Glaser B., Kaiser M., 2020, Effect of biochar and compost on soil properties and organic matter in aggregate size fractions under field conditions, Agriculture, Ecosystems and Environment, 295, 106882.

Cui E., Wu Y., Zuo Y., Chen H., 2016, Effect of different biochars on antibiotic resistance genes and bacterial community during chicken manure composting, Bioresource Technology, 203, 11-17.

Cui H., Ou Y., Wang L., Yan B., Li Y., Ding D., 2020, The passivation effect of heavy metals during biochar-amended composting: Emphasise on bacterial communities, Waste Management, 118, 360-368.

D'Hose T., Debode J., De Tender C., Ruysschaert G., Vandecasteele B., 2020, Has compost with biochar applied during the process added value over biochar or compost for increasing soil quality in an arable cropping system? Applied Soil Ecology, 156, 103706.

Dias B.O., Silva C.A, Higashikawa F.S, Roig A, Sánchez-Monedero M.A., 2010, Use of biochar as bulking agent for the composting of poultry manure: effect on organic matter degradation and humification, Bioresource Technology, 101, 1239-1246.

Guo R., Li G., Jiang T., Schuchardt F., Chen T., Zhao Y., Shen Y., 2012, Effect of aeration rate, C/N ratio and moisture content on the stability and maturity of compost, Bioresource Technology, 112, 171-178.

Guo X., Wu S., Wang X., Liu H., 2021, Impact of biochar addition on three-dimensional structural changes in aggregates associated with humus during swine manure composting, Journal of Cleaner Production, 280, 124380.

Hu X.F., Jiang Y., Shy Y., Hu X., Liu L., Luo F., 2014, Effects of mining wastewater discharges on heavy metal pollution and soil enzyme activity of the paddy fields, Journal of Geochemistry Exploration, 147, 139-150.

Kaiser M., Kleber M., Berhe A.A., 2015, How air-drying and rewetting modify soil organic matter characteristics: an assessment to improve data interpretation and inference, Soil Biology and Biochemistry, 80, 324-340.

Khan N., Clark I., Sánchez-Monedero M.A., Shea S., Meier S., Bolan N., 2014, Maturity indices of co-composting of chicken manure and sawdust with biochar, Bioresource Technology, 168, 337-344.

Lim L.Y., Lee C.T., Lim J.S., Klemeš J.J., Ho C.S., Abu Mansor N.N., 2017, Feedstock amendment for the production of quality compost for soil amendment and heavy metal immobilisation, Chemical Engineering Transactions, 56, 499-504.

Liu B., Ai S., Zhang W., Huang D., Zhang Y., 2017, Assessment of the bioavailability, bioaccessibility and transfer of heavy metals in the soil-grain-human systems near a mining and smelting area in NW China, Science of the Total Environment, 609, 822-829.

Liu N., Liao P., Zhang J., Zhou Y., Luo L., Huang H., Zhang L., 2020, Characteristics of denitrification genes and relevant enzyme activities in heavy-metal polluted soils remediated by biochar and compost, Science of the Total Environment, 739, 139987.

Oldfield T.L., Sikirica N., Mondini C., López G., Kuikman P.J., Holden N.M., 2018, Biochar, compost and biochar-compost blend as options to recover nutrients and sequester carbon, Journal of Environmental Management, 218, 465-476.

Rizwan M., Ali S., Abbas T., Rehman M.Z., Hannan F., Keller C., Al-Wabel M.I., Ok Y.S., 2016, Cadmium minimisation in wheat: a critical review, Ecotoxicology and Environment Safety, 130, 43-53.

Sánchez-Monedero M.A., Cayuela M.L., Sánchez-Garcia M., Vandecasteele B., D'Hose T., López G., Martínez-Gaitán C., Kuikman P.J., Siicco T., Mondini C., 2019, Agronomic evaluation of biochar, compost and biochar-blended compost across different cropping systems: Perspective from the European project FERTIPLUS, Agronomy, 9, 225.

Tang J., Zhang L., Zhang J., Ren L., Zhou Y., Zheng Y., Luo L., Yang Y., Huang H., Chen A., 2020, Physicochemical features, metal availability and enzyme activity in heavy metal-polluted soil remediated by biochar and compost, Science of the Total Environment, 701, 134751.

Tong B., Wang X., Wang S., Ma L., Ma W., 2019, Transformation of nitrogen and carbon during composting of manure litter with different methods, Bioresource Technology, 293, 122046.

Qu J., Zhang L., Zhang X., Gao L., Tian Y., 2020, Biochar combined with gypsum reduces nitrogen and carbon losses during agricultural waste composting and enhances overall compost quality by regulating microbial activities and functions, Bioresource Technology, 314, 123781.

Wu X., Sun Y., Deng L., Meng Q., Jiang X., Bello A., Sheng S., Han Y., Zhu H., Xu X., 2020, Insight to key diazotrophic community during composting of dairy manure with biochar and its role in nitrogen transformation, Waste Management, 105, 190-197.

Zeng G., Wu H., Liang J., Guo S., Huang L., Xu P., Liu Y., Yuan Y., He X., He Y., 2015, Efficiency of biochar and compost (or composting) combined amendments for reducing Cd, Cu, Zn and Pb bioavailability, mobility and ecological risk in wetland soil, RSC Advances, 5, 34543-34548.

Zhu L., Yang H., Zhao Y., Kang K., Liu Y., He P., Wu Z., Wei Z., 2019, Biochar combined with montmorillonite amendments increased bioavailable organic nitrogen and reduce nitrogen loss during composting, Bioresource Technology, 294, 122224.

Wu X., Sun Y., Deng L., Meng Q., Jiang X., Bello A., Sheng S., Han Y., Zhu H., Xu X., 2020, Insight to key diazotrophic community during composting of dairy manure with biochar and its role in nitrogen transformation, Waste Management, 105, 190-197.

Zeng G., Wu H., Liang J., Guo S., Huang L., Xu P., Liu Y., Yuan Y., He X., He Y., 2015, Efficiency of biochar and compost (or composting) combined amendments for reducing Cd, Cu, Zn and Pb bioavailability, mobility and ecological risk in wetland soil, RSC Advances, 5, 34543-34548.