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Review

Restoration of soil quality using biochar and brown coal waste: A review

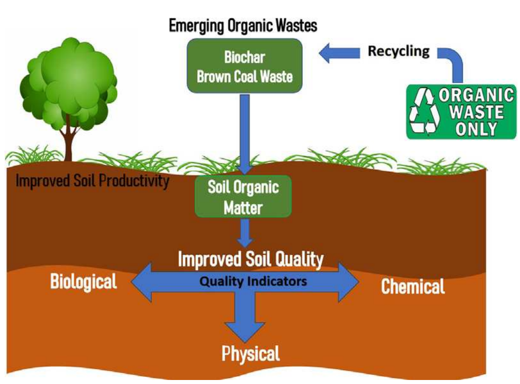
Collins Amoah-Antwi [a,*], Jolanta Kwiatkowska-Malina [a], Steven F. Thornton [b], Owen Fenton [c], Grzegorz Malina [d], Ewa Szara [e]

[a] Faculty of Geodesy & Cartography, Warsaw University of Technology, Poland
[b] Kroto Research Institute, University of Sheffield, Sheffield S10 2TN, UK
[c] Teagasc, Johnstown Castle, Environmental Research Centre, Co., Wexford, Ireland
[d] AGH University of Science and Technology, Krakow, Poland
[e] Warsaw University of Life Sciences, Warsaw, Poland

HIGHLIGHTS

- Organic wastes mitigate degradation, improve soil quality and food security.
- Sustainable soil quality benefits from organic amendment take many years to build.
- Most organic wastes degrade quickly and can be problematic for long-term use.
- Biochar and brown coal waste (BCW) improve soil quality and are stable in soil.
- In-situ technologies can lower production and processing costs of biochar and BCW.

GRAPHICAL ABSTRACT



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ABSTRACT

Soils in intensively farmed areas of the world are prone to degradation. Amendment of such soils with organic waste materials attempts to restore soil quality. Organic amendments are heterogeneous media, which are a source of soil organic matter (SOM) and maintain or restore chemical, physical, biological and ecological functionality. More specifically, an increase in SOM can influence the soil microclimate, microbial community structure, biomass turnover and mineralisation of nutrients. The search is on-going for locally sourced alternatives as many forms may be costly or geographically limiting. The present review focuses on a heterogeneous group of amendments i.e. biochar and brown coal waste (BCW). Both biochar (made from a variety of feedstocks at various temperatures) and BCW (mined extensively) are options that have worldwide applicability.

These materials have very high C contents and soil stability, therefore can be used for long-term C sequestration to abate greenhouse gas emissions and as conditioners to improve soil quality. However, biochar is costly for large-scale applications and BCW may have inherently high moisture and pollutant contents. Future studies should focus on the long-term application of these amendments and determine the physicochemical properties of the soil, bioavailability of soil contaminants, diversity of soil communities and productivity of selected crops.

Abbreviations: Soil quality, SQ; heavy metal(s), HM(s); soil organic matter, SOM; soil organic carbon, SOC; brown coal waste, BCW; organic matter, OM; bulk density, BD; specific surface area, SSA; quality indicator(s), QI(s); compression index, CI; humic acid(s), HA(s); humic substance(s), HSs.; organic carbon, OC; greenhouse gas, GHG.

* Corresponding author at: Warsaw University of Technology, Plac Politechniki 01, 00-661 Warsaw, Poland.
E-mail address: collins.amoah-antwi@pw.edu.pl (C. Amoah-Antwi).

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Furthermore, the development of in situ technologies to lower production and processing costs of biochar and BCW would improve their economic feasibility for large-scale application.

Contents

1. Introduction

Parsimonious tools to alleviate or prevent land degradation are needed as over 30% of the earth is affected and continuing at high rates, i.e. 8–9 × 10^6 ha yr^{-1} (Alam, 2014; Lal, 2015). Four conceptual classes of degradation have been identified as chemical, physical, biological and ecological, which are interlinked by several components such as soil properties and climatic factors (Fig. 1). Loss of ecosystem function through degradation is costly at US$10.6 × 10^{12} each year (ELD, 2015) with subsequent lowSQ and depleted levels of critical soil resources such as OM.

Soil amendment of degraded soils with waste organic materials (e.g. compost, manure, crop residues and straw), can build SOM which aims to restore chemical, physical, biological and ecological functionality. More specifically, an increase in SOM can influence the soil microclimate, microbial community structure, biomass turnover and mineralisation of nutrients (Diacono and Montemurro, 2010; Cheng et al., 2017; Li et al., 2018).

Organic amendment types and efficacy vary considerably and can therefore not be used in a homogenous manner. Traditional composts and manures are rich sources of plant macronutrients and have been used extensively as fertilizers, either as partial or full substitutes for mineral fertilizers (Diacono and Montemurro, 2010; Chen et al., 2018). Green manures are rich in N and P with similar fertilizer replacement profiles to inorganic counterparts (Gasser et al., 2012; Meena et al., 2018; Hong et al., 2018). Other organic alternatives such as woody biomass, straw and plant residues are not suitable as fertilizers, but can be used to build C stocks, abate GHG emissions and implemented as soil conditioners to improve soil structure, water-holding capacity, BD, aggregate stability, microbial diversity, microbial biomass, functional enzymes activity, pH, porosity, cation exchange capacity (CEC) and to reduce pollutant bioavailability (Cooperband, 2002;

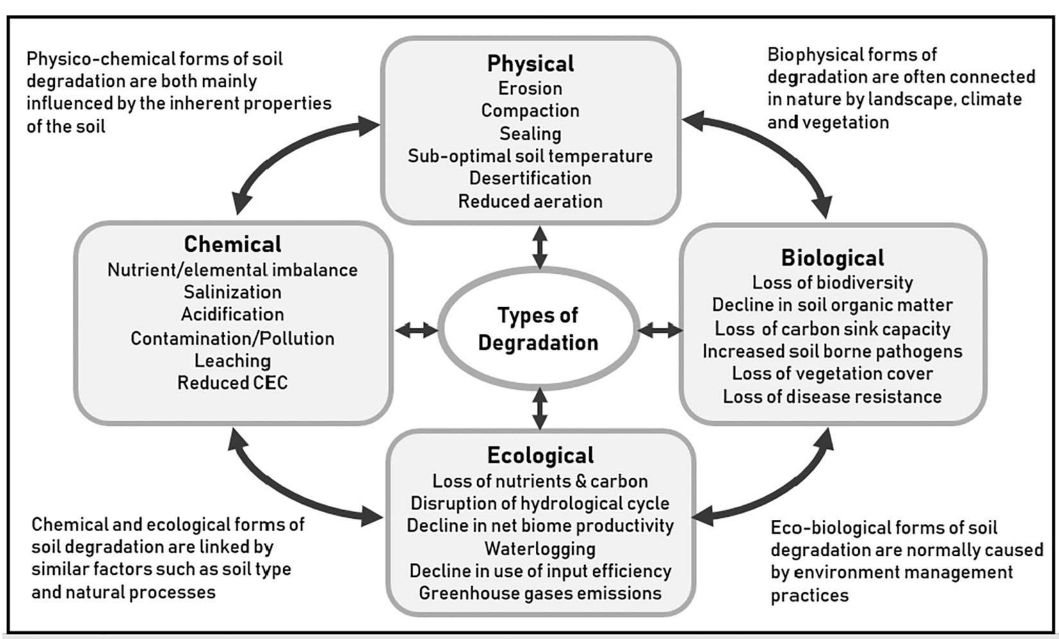

Fig. 1. Conceptual presentation of the types of soil degradation: chemical, physical, biological and ecological – with the various forms in which degradation occurs. Figure shows how the different types of soil degradation are interlinked. Adapted and modified from Lal, 2015 and Gomiero, 2016.

Table 1
Summary of selected experiments investigating the effects of short- and long-term applications of conventional organic materials to soil.

Experimental summary					Effects of amendment/inference	Reference
Soil type	Experimental type	Soil amendment	Application rate	Yr		
Epileptic and Endoleptic Leptosols (Calcareous sandstones)	Field	Sewage sludge (SS, C/N = 7) Urban organic waste compost (OC, C/N = 11.3)	28 kg m^{-2} 34 kg m^{-2}	N/A	• **Physicochemical properties:** SS and OC increased TP (13,16%), AgS (265, 154%) and CEC (22, 42%), respectively; OC decreased BD (9%) but SS did not affect it. • **Hydrological response:** Increased infiltration rate (~80, 40%); and reduced surface runoff (~87, 43%) and rate of soil loss (~97, 85%). Amendments, especially SS, significantly improved soil AgS, infiltration and other properties which protected the soil against susceptibility to runoff and soil loss.	Luna et al. (2018)
Haplic Yermosol Sandy clay (pH 7.5)	Randomized complete block, field (Maize cultivation)	Sheep manure (SM, C/N = 18) Farmyard manure (FYM, C/N = 19) Poultry manure (PM, C/N = 20)	15 t ha^{-1} 16 t ha^{-1} 13 t ha^{-1}	<0.5	• **Soil properties:** SM, FYM and PM increased SOC (~85–90%), Nt (~100–120%), total P (~25–33%) and total K (~40–65%); decreased pH (~0.3, 0.5, 0.3 units, respectively) and BD (~10%). • **Maize:** Increased leaf area (28, 21, 26%) and grain yield (70, 52, 77%). Manures can substantially improve soil conditions and increase crop yield. The outcomes of amendment with all three manures were comparable and this could be due to their similar C/N profiles.	Mahmood et al. (2017)
Sandy, siliceous, hyperthermic Oxyaquic Alorthods	Randomized complete block (*Stenotaphrum secundatum* grass cultivation)	Dairy manure compost (alone, with aeration and with tillage)	256 Mg ha^{-1}	1	• **Soil properties:** Increased OM (16–21%), extractable P (25–39%) and K (4–24%); reduced pH (7.87) by 0.2–0.4 units. • **Grass:** Increased dry biomass (266–493%) and tissue N (51–62%); reduced P (19–28%). • **Mechanical treatments**: Mixed effect of tillage and aeration on soil and plant properties. Compost amendment can improve coarse-textured soil conditions and promote plant growth even though soil pH remained higher than recommended for *Stenotaphrum secundatum* cultivation (6.5).	Loper et al. (2010)
Typic halaquepts inceptisol (pH 9.0)	Field, Mudflat area (perennial ryegraass cultivation)	Sewage sludge compost (pH 6.3)	30, 75, 150 and 300 t ha^{-1}	<0.5	• **Soil properties::** Increasing amendment rate increased SOM (up to 348%), TP (18%), exchangeable cations, CEC (79%), N (672%) and P (27%); and reduced soil salinity (76%), BD (16%), pH (0.1–0.7) and EC (72%). • **Ryegrass:** Increasing rate of amendment increased ryegrass fresh weight (up to 429%), similar to dry weight increases. • **HMs:** Increased Ni, Cu, Cd, Cr, Zn and Mn accumulation in ryegrass, higher at 150 and 300 t ha^{-1}. Sewage sludge compost can significantly improve physicochemical soil properties and yield of ryegrass, but can lead to increased HM accumulation in plant tissues implying the need to properly treat sewage sludge before applying to soil.	Bai et al. (2013)
Red Typic Plinthdult (pH 6.4)	Rice-tobacco rotation	Humified swine manure compost	15 t ha^{-1}	18	• **Soil properties:** Improved soil structure and macroaggregate formation. Significant increases in SOC and soil Nt. • **Aggregation:** Increased soil macroaggregate content, GMD (~15%) and MWD (~25%); and decreased microaggregate content. Increased SOC from manure compost application improved soil conditions, especially aggregate stability (GMD and MWD) which can decelerate degradation.	Zou et al. (2018)
Three different types	Field (wheat cultivation)	Biosolids (treated by high heat, lime, air drying and anaerobic digestion)	Variable	16–24	• **Soil properties::** Excessively increased water--extractable P in all soils, higher with heat-treated biosolid amendment than lime-treated biosolids. • **HMs:** Increased plant-available Cd, Cu and Zn in soil leading to increased tissue Cd. • **Wheat:** Higher yield in 3 of 5 amended soils; highest yield in anaerobic digestion-treated soils. Excessive water-soluble P in soil could exceed plant requirements and could lead to P run-off into nearby water bodies. Reduced wheat yield from lime-treated biosolids may be due to P sequestration in low-solubility phosphate compounds and Mn deficiency.	Codling and Perry (2013)
Multiple	Multiple Farms	Composts (variable feedstock)	5.7–34 Mg ha^{-1}	2–10	• **Soil properties:** Increases in mean SOC (~300%), microbial activity (~225%), gravimetric water content (~150%); reduction in soil BD (~75%); soil nutrient availability not significantly affected. Increased compost application rates generally resulted in higher positive responses which will also vary according to soil type, compost type or topography.	Brown and Cotton (2011)
Albic paddy (pH 5.7)	Randomized field, wheat-rice rotation (with NPK)	Livestock manure (M) Green manure (G) Straw (S)	22.5 t ha^{-1} 3 t ha^{-1}	<0.5	• **Physicochemical soil properties:** Decreased pH (up to 0.4 units, G > S > M); Increased SOC (up to 55%, S > M > G), Nt (17%, G > S > M), (23%, S > G > M) and	Zhang et al. (2015)

(continued on next page)

Table 1 (*continued*)

Experimental summary					Effects of amendment/inference	Reference
Soil type	Experimental type	Soil amendment	Application rate	Yr		
					available P (55%, M > G > S) and K (37%, S > M > G). • **Soil microbial biomarkers:** Increased monounsaturated and cyclopropane FAs (M and S) and straight chain FAs (G). • **Enzyme activity:** Increased with amendments, highest in M (Phosphatase, β-Glucosidase, β-Cellobiosidase, L--leucine aminopeptidase) and S (N-Acetyl-glucosamine, Urease, phenol oxidase, β-Xylosidase). • **Rice yield:** Increased with M (24%) and S (8%), no yield response from G. Different manures enhance different microbial and biochemical soil properties. Increased monounsaturated and cyclopropane FAs from M and S imply they promote growth of fungi and gram-negative bacteria, while straight chain FAs indicate abundant gram-positive bacteria from G application. Albic paddy soil amendment was most effective with M and S leading to increased yield.	
Loamy silt	Randomized field crop rotation (maize cultivation)	Urban organic waste compost (OWC) with N Cattle manure compost (MC) Sewage sludge compost (SC) Green waste compost (GC)	175 kg N ha^{-1} (annual)	12	• **Soil properties**: Increased Nt (7–21%; OWC > GC > SSC > MC), OC (3–14%; SSC > GC > OWC > MC) and MicB (3–8%; GC > OWC > SSC > MC). • **Maize yield**: Increased yield (20–30%), higher for compost+N amendments (60–70%); no significant differences between treatments in both sets. Amendment with GC provided best outcome whereas MC had least effect. Combining compost and N can improve soil conditions in the long-term. This will provide readily available nutrients for microorganisms and plants which can increase MicB and crop yield.	Ros et al. (2006)
Zn smelter-polluted soil (ZS) and Unpolluted mine soil (UM)	Phytotron chamber, pot (Giant Miscanthus and Scots Pine cultivation)	Biodegradable municipal waste compost (MWC) Sewage sludge compost (SSC)	15 Mg ha^{-1}	1.5	• **SOC:** Increased from MWC and SSC in the UM (up to ~40%), but no significant increases in ZS. • **HMs:** MWC reduced Cd and Zn bioavailability in both soils, but Pb increased over 10-folds in UM; SSC increased bioavailability of Cd, Zn and Pb in both soils. • **Plants:** Increased respective root biomass of Giant Miscanthus and Scots Pine from MWC in UM (100 and 35%, respectively) but no change in ZS; no significant effect from SSC in both soils. MWC can reduce HMs in soil and promote plant growth in unpolluted soils but may be a high source of Pb. SSC may not be effective for reducing plant available HMs, which could be due to its low metal binding capacity or an inherently high HM content, therefore may not promote plant growth.	Placek et al. (2017)
Cultivated soil	Field pot (maize cultivation)	Manure compost (pH 7.2)	150 kg N ha^{-1}	0.5–1	• **Soil properties**: Increased SOM, humus and available N (strong positive correlations with microbial indices); minimal impact on soil pH, Nt, and available P. • **Microbial:** Increased soil MicB C (~25%) and N (140%), and respiration rate (~55%) at mature stage of maize. • **Enzyme activity**: Increased soil activities of urease (~55%), invertase (~17%), catalase (~40%) and cellulase (~50%). Manure compost can enhance SOM accumulation which supports soil activities of functional microorganisms and enzymes	Zhen et al. (2014)

Note: Percent expressions of amendment-induced changes are with respect to control treatments unless otherwise specified.
BD – bulk density, TP – total porosity, SOM – soil organic matter, OM – organic matter, AgS – aggregate stability, EC – electrical conductivity, CEC – cation exchange capacity, SOC – soil organic carbon, HM(s) – Heavy metal(s), OC – organic carbon, MicB - microbial biomass, FAs – fatty acids, MWD – Mean weight diameter, GMD – Geometric mean diameter, Nt – total nitrogen.

Fließbach et al., 2007; Li et al., 2012; Hattab et al., 2015; Tran et al., 2015; Costantini et al., 2016; Mahmood et al., 2017; Zhang et al., 2017; Adekiya et al., 2019; Onagwu, 2019; Ren et al., 2019). More examples of the effects of the application of selected conventional organic wastes on soil properties have been summarised in Table 1.

Long term studies are needed to examine positive and negative aspects of any organic soil amendment. A holistic approach is required to investigate the impact, and this should especially be the case where new or emerging organic amendments are being considered. In addition, knowledge transfer and education are important as it can take many years of committed organic amendment for positive measurable outcomes. On the one hand, long term studies (from 14 selected field trials in Europe and North America ranging from 20 to 120 years) which investigated the long-term effects of manures and fertilizers on SQ and productivity suggested that improvement in SQ beyond the supply of nutrients is only possible after many years of OM accumulation (Edmeades, 2003). On the other hand, a meta-regression analysis of data from 47 studies in Europe showed that landowners become sceptical of soil management tools where no benefits are gained in the short term (Van den Putte et al., 2010). In addition, Hijbeek et al. (2019) found that "farmers' perception" with respect to the short term efficacy of a measure was more important than the cost of implementing that measure or whether the measure protected the crop in question in the long term or not. Elsewhere, Wright et al. (2007) initially found increases in OC and extractable P, S and Ca in soil after a one-time compost amendment, but no continued increases were observed after three months, with C and macronutrient contents exhibiting temporal variability throughout the observation period (29 months). However, some long-term residual effects from compost amendment do exist and have been reported (Diacono and Montemurro, 2010; Adugna, 2016). In a study evaluating the long-term effects of compost, farmyard manure and sewage sludge on the chemical and microbial properties of a luvisol, Scherer et al. (2011) found increases in soil N, OC and microbial biomass across all treatments after 45 years, with benefits more pronounced in compost treated soils. Due to the high turnover rates of conventional organic materials, long-term or repeated field application of conventional organic inputs may be problematic. For example, their excessive use may increase the risk of eutrophication from N leaching and P runoff, or P leaching in soils with low P retention (Edmeades, 2003; Chen et al., 2018; Horta et al., 2018). Conventional organic materials, especially manure, are also sources of GHG emissions (Petersen, 2018), while others such as sewage sludge are documented sources of HMs (Bai et al., 2013). Manure and slurry are usually applied to a field without prior treatment, and may contain a broad range of bacterial, viral and parasitic pathogens. For example, Nolan et al. (2018) and Nag et al. (2020) found that even when treated by anaerobic digestion, one of the cleanest producers of green energy, manure digestate may still have significant levels of pathogens (e.g. *Cryptosporidium parvum, Salmonella spp., Norovirus, Streptococcus pyogenes, enteropathogenic E. coli (EPEC), Mycobacterium* spp. and *Salmonella typhi*) of public health relevance.

Highly processed organic materials with high soil stability are gradually emerging as alternative soil amendments to offset the limitations of conventional organic amendments. This has placed high carbonised, bio-energy organic materials such as biochar and BCW into research focus, as they represent opportunities to bridge the gap between biowaste recycling and sustainable agriculture. Therefore, the primary objective of the current review is to examine biochar and BCW as emerging soil organic waste amendment options. Specifically, this review examines how their incorporation into soil affects physical, chemical and biological indicators of SQ. These effects will be reviewed from analysing a broad range of applications in low-fertility arable, marginal and degraded soils.

2. Soil management with biochar and BCW

2.1. Biochar

Biochar is a black carbon-rich solid produced by thermal decomposition of biomass under oxygen-limited conditions at temperatures typically between 300 and 700 °C (Lehmann et al., 2011; Shin et al., 2014; Peng et al., 2018). Feedstock for biochar production may comprise purpose-grown biomass or diverse waste materials from industry including agriculture, e.g. manure, on-farm vegetation such as ruches and clippings from hedgerows, hard- and soft-woods, biosolids and municipal wastes (Beesley et al., 2014; Rey-Salgueiro et al., 2016; Peng et al., 2018). Biochar is mainly produced by pyrolysis (fast, intermediate or slow), but also by other methods including hydrothermal carbonisation and gasification, with all three processes involving aromatic condensation which leads to a characteristically high C product (Fischer and Glaser, 2012; Nsamba et al., 2015; Wang et al., 2017). In plant biomass, the compounds of interest for biochar production comprise lignin, cellulose and hemicellulose, because of their high recalcitrance at high temperatures. Lignin especially, is the most stable, containing high levels of polyaromatic compounds, and is resistant to degradation even at temperatures above 300 °C, and may vary depending on biomass type (Kavitha et al., 2018; Supanchaiyamat et al., 2019).

The feedstock type, production method and temperature are key determinants of the physicochemical characteristics of biochar (Sun et al., 2014; Yu et al., 2019). Biochar feedstock influences its liming capacity, whereas pyrolysis temperature affects the pH, CEC and C content of biochar (Chen et al., 2008; Yuan and Xu, 2011; Yuan et al., 2011). High temperature (>550 °C) biochars have a high SSA (> 400 $m^2\ g^{-1}$), more condensed polyaromatic structures and significantly higher pH, and hence are very good adsorbents (Yao et al., 2012; Angın and Şensöz, 2014; Luo et al., 2018). Biochars produced by low temperature pyrolysis (<550 °C) thus have a higher concentration of labile OM and macronutrients (Keiluweit et al., 2010; Luo et al., 2018), and are more suitable for amending nutrient-deficient soils. Diverse forms of biochar exist as a result of the different feedstock, methods and conditions available for its production. Consequently, the efficacy of biochar use may vary widely implying the need for characterisation and the application of specific dosages (O'Connor et al., 2018).

Addition of biochar to arable soil closes the nutrient loop and increases C sequestration, potentially forging a carbon-negative cycle. Due to the high C content (60–80%) and the C sequestration potential of biochar, it has become the focus of many studies which have shown it to be a viable tool for climate change abatement. The calculation of C stocks and the stability of this store has become important (Simo et al., 2019). Preventing the decline of C stocks and indeed building C stocks through incorporation of organic amendments is a new research area. The sequestered C remains in soil for a long time, with many studies suggesting mean residence times >1000 years (Cheng et al., 2008; Rakshit et al., 2012), even though key proponents in this area insist that the length of time will depend on various factors including the type of soil, climate, feedstock and pyrolysis temperature. There is, however, a wide consensus that the incorporation of biochar in soil induces many changes in soil properties much earlier than a few tens or hundreds of years. Most observations made from biochar use have been reported from short- to medium-term experiments. This is because aside from its highly recalcitrant OM, biochar may also contain significant quantities of labile material that could be mineralised in the short term.

Regular biochar amendment will ensure a steady build-up of C in soil, which is the largest terrestrial reservoir of OC at global scale (2344 Gt) (Stockmann et al., 2013), while reducing the accumulation of GHGs in the atmosphere and hydrosphere. Biochar is also widely known to alter the main microbial N-transforming processes responsible for nitrous oxide (N_2O) gas production: nitrification, denitrification and dissimilatory nitrate (NO_3^-) reduction (Cayuela et al., 2014; Fuertes-Mendizábal et al., 2019). This reportedly leads to reduction of N_2O gas emission which has a global warming potential about 298 times higher than carbon dioxide (CO_2) (Fuertes-Mendizábal et al., 2019). As a direct approach to mitigating global warming, biochar has sometimes failed to offset, or even in some cases, stimulated GHG emissions from soil (Pereira et al., 2016; Case et al., 2018; Duan et al., 2018).

These results, however, may be highly contextual as biochar may not be the same across studies, hence making comparison difficult. Future studies will need to include standard and analogous experimental data to improve mechanistic understanding of biochar's interaction in soil. The large pore volumes of biochar, especially of the smaller particle-sized (≤1 mm) types which also improve soil aggregation while reducing soil BD (Munoz et al., 2016; Omondi et al., 2016), are effective for increased water retention (Batista et al., 2018; Kameyama et al., 2019). The dark colour of biochar increases absorption of solar radiation by soil, hence stimulating several biological processes including mineralisation of nutrients (Maroušek et al., 2018). Thus, increased soil temperature and water retention promote plant growth and dynamics of soil microorganisms (Grunwald et al., 2017; Suliman et al., 2017). There is evidence that biochar induces shifts in the enzymatic activities (e.g. lowered for glycosyl hydrolases, while increased for phenol oxidase and arylesterase) of some soil microbial communities which could eventually result in enzymatic modifications of recalcitrant C (Sohi et al., 2010; Farrell et al., 2013; Luo et al., 2018). This can possibly lead to relatively shorter residence times than projected. An inference that could be reached is that, though biochar is not indestructible, it certainly is not a preferred substrate of microorganisms, and this is advantageous for long-term soil utility.

Due to its inherent alkalinity and high buffering capacity, biochar is effective in alleviating soil acidity (Jeffery et al., 2017; Cornelissen et al., 2018; Yu et al., 2019). The effect of biochar on alkaline soils is limited and has only been sporadically investigated (Liu et al., 2012). Further increase in pH of alkaline soils from biochar amendment may increase nitrification which can inhibit plant growth (Marks, 2013; Song et al., 2014). However, low temperature biochar is found to induce positive plant growth parameters in alkaline soil (Mete et al., 2015). More long-term experiments, especially under field conditions, will be useful for understanding the mechanistic effects of biochar on alkaline soils.

The characteristically high SSA and sorption capacity of biochar with diverse functional groups (mostly negatively charged) makes it suitable for immobilising both organic and inorganic pollutants in soil (Peng et al., 2018; Nzediegwu et al., 2019). Interaction between biochar and HMs within soil particles, for example, alters the mobility of the metal species through adsorption, ion exchange, surface precipitation, complexation or stabilization, leading to the formation of stable organo-metallic complexes (Nejad et al., 2018) (Fig. 2). This subsequently limits the availability of HMs and their translocation into plants (Beesley et al., 2011; Jiang et al., 2012). Sorption mechanisms of organic pollutants in soil by biochar include multilayer adsorption, surface distribution and pore-filling mechanisms (Ogbonnaya and Semple, 2013; Tang et al., 2018). In the case of the latter, when an organic compound is sorbed to the surface of biochar, a network of micropores and mesopores found in- and outside of the biochar structure traps the compound and limits its transfer to soil (Ogbonnaya and Semple, 2013; Tong et al., 2019). Meanwhile, some organic pollutants including polycyclic aromatic hydrocarbons (PAHs), formaldehyde, cresols, xylenols and acrolein are commonly found as condensates on the surface of biochars (Joseph et al., 2010). Pyrolysis further increases the risk of producing biochars with high levels of aromatic ring-containing organic pollutants such as PAHs, polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) (Weidemann et al., 2017; Rey-Salgueiro et al., 2018). However, the levels of organic pollutants found in most biochar do not exceed thresholds set for agricultural and industrial uses (Rey-Salgueiro et al., 2016; Weidemann et al., 2017), and therefore do not pose additional threats to soil.

Aside from sorption, a number of environmental processes such as biodegradation and photodegradation influence the behaviour and fate of degradable organic pollutants (e.g. PAHs, antibiotics and some pesticides) in soil (Sadegh-Zadeh et al., 2017; Ren et al., 2019). The high OM content and dark colour of biochar suggest that it can play an important role in both degradative processes. Organic pollutants such as dioxins, furans and polychlorinated biphenyls (PCBs) are highly persistent in soil, and therefore require further investigation to determine the most suitable type of biochar for their remediation (Ogbonnaya and Semple, 2013). A summary of the effects of selected biochar types applied to a range of high and low fertility arable, marginal, polluted and degraded soils has been provided in Table 2.

The national regulations of most EU countries have not included biochar as an agricultural input. An exception, however, is Switzerland, which passed a directive to regulate the direct application of biochar to soil (Kammann and Schmidt, 2014). At present, there is no regulation yet at the European Community level, even though national threshold limits exist for several other organic materials (e.g. sewage sludge) (Conte et al., 2016). Biochar produced from agricultural wastes or biowaste may be classified as a thermally converted waste product, according to the Waste Act, but it does not explicitly list biochar in the waste catalogue. For regulatory acceptance, biochar as a by-product should meet a set of criteria including the guarantee that further use would not have negative consequences on the environmental and health (EC, 2008). To help policy makers establish precise recommendations for biochar application, we suggest rules and regulations be set about making biochar. There is a need to conduct long-term trials for a variety of reasons using the same biochar produced under precise conditions and feedstock to produce comparable results. This can be done by building a robust database from field trials using platforms such as the European Biochar Research Network.

Even though the production of biochar by pyrolysis is identified as one of the simplest and cheapest carbon capture and storage methods (Woolf et al., 2010), the production costs are still high and considered expensive for large-scale agricultural use (Vochozka et al., 2016). The average cost of biochar according to the US Biochar Initiative (2019) is 500 US$/ton. Attempts have been made to identify cheaper methods of biochar production. For example, slow pyrolysis is preferred to fast pyrolysis as it produces more biochar and has lower pre-treatment

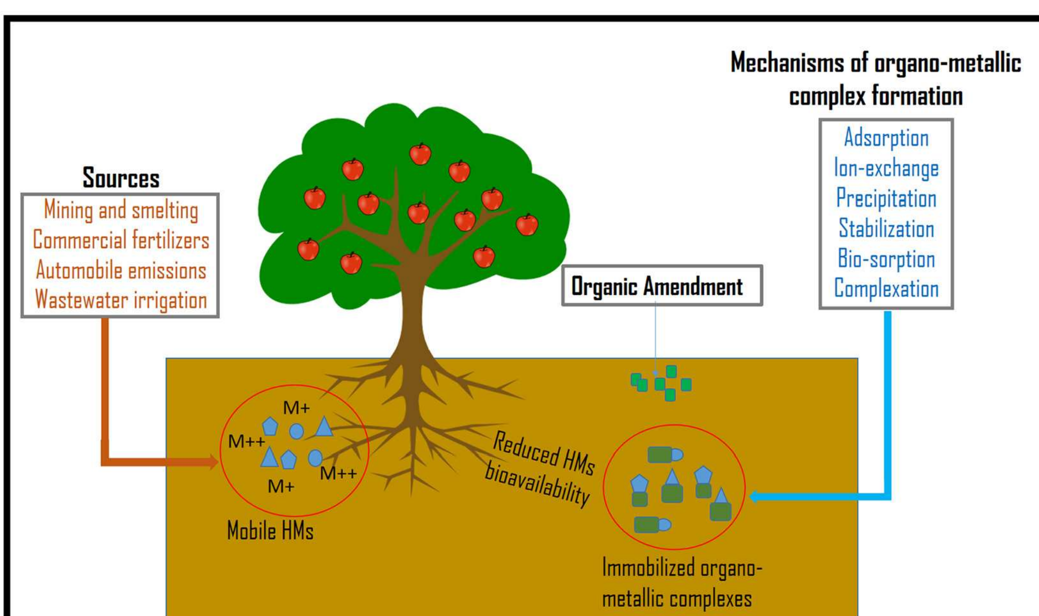

Fig. 2. The effects of emerging organic wastes on bioavailability of HMs in soil. Organic matter from amendments binds to and immobilizes HMs (from diverse sources) in soil via organo-metallic complexation reactions, thus reducing their availability to plants.

Table 2
Overview of selected short- to long-term effects of biochar application to soil.

Experimental summary					Effects of amendment/inference	Reference
Soil type	Experimental type	Biochar feedstock/production conditions	Application rate	Yr		
Loamy sand	Pot	Miscanthus and winter wheat; furnace pyrolysis at 300 °C, 10 °C min^{-1} for 15 min.	0.5, 1, 2 and 4%	<0.5	• **Physical properties:** Increasing rates and decreasing particle size of biochar reduced soil BD (up to 26%); and increased TP (52%); smaller biochar particles reduced volume of micropores but increased volume of macropores; no difference between biochar types. • **Water Characteristics:** Increased soil AWC (130%, highest from Miscanthus) with increasing rates and decreasing particle size of biochar; and hydraulic conductivity (45%, highest from wither wheat) with increasing biochar size, but highest at 2% biochar application rate. Biochar from Miscanthus and winter wheat may be effective for improving the physical properties of coarse-textured soils to increase water retention especially at 4% application rate with fine grain biochar, particle size below 500 μm.	Głąb et al. (2016)
Cultivated Quaternary loess (brown soil)	Field	Corn straw	1500, 3000 and 6000 kg ha^{-1}	<0.5	• **Total soil nutrients**: No significant increases in total N, P and K at any biochar rate. • **Available soil nutrients:** Increased available N (up to 18% at 1500 kg ha^{-1}), P (17% at 6000 kg ha^{-1}), and K (36% at 3000 kg ha^{-1}). Corn straw biochar may not be a good source of soil nutrient but can improve conditions of brown soils (e.g. liming, improved soil structure and high CEC) which may enhance availability of soil macronutrients. .	Gao et al. (2018)
Cultivated acidic Entisols (pH 4.8)	Incubation in plastic cups	Corn stover (CS, pH 11.4) and switch-grass (SG, pH 10.5); microwave pyrolysis at 650 °C for 18 min.	52, 104 and 156 Mg ha^{-1}	<0.5	• **Soil properties:** CS and SG increased pH (up to 1.36, 0.91 units), EC (159, 57%) and CEC (142, 95%); reduced EA (99, 100%). Biochar from different feedstock produced under the same pyrolytic conditions may have varying effects on soil properties. CS improved soil conditions better than SG, and its high liming potential could be due to a high base cation content or proton consumption, and makes it more suitable for ameliorating acidic soils than SG.	Chintala et al. (2014)
Silt loam Chernozem (pH 7.4), clay loam Cambisol (pH 6.6) and sandy loam Planosol (5.4)	Glasshouse, pot	Woodchip (pyrolysis at 525 °C, pH 8.9 in $CaCl_2$), wheat straw (525 °C, pH 9.7) and vineyard prunings (525 °C, pH 8.8 and 400 °C, pH 8.3)	3 wt%	3	• **Soil BD:** Greatest reduction of BD from woodchip biochar in the Planosol (13%) • **Soil AgS**: Biggest increase from straw biochar in Planosol (98%); no effect in any soil from woodchip biochar. • **Soil AWC***:* Highest increase from straw biochar in Planosol (38%); least from woodchip biochar with no effect in any soil. Straw biochar is effective for improving physical properties of soil, especially coarse-textured types such as Planosols.	Burrell et al. (2016)
Acidic Ferralsols (pH 4.7, in $CaCl_2$)	Field (Pasture management)	Cattle feedlot manure (FM, 44% C) and municipal greenwaste (GW, 76% C); Pyrolysis at 550 °C, 5–10 °C min^{-1} for 30 min (continuous flow 300 kg/h pilot)	10 ha^{-1}	3	• **Soil properties:** Increased SOC accumulation (better with GW) and liming effect; no effect on pH and pH-dependent CEC. • **Soil nutrients:** Increased agronomic N use efficiency (23%) and available P (88%) from FM amendment; no significant effects from GW. . • **Pasture:** Increased pasture productivity with FM (11%); no effect from GW. Lower C content of FM suggests it may have higher content of labile material with high N and P which may have led to increased pasture productivity. Higher SOC accumulation from GW may be due to its high C content and may take longer to reflect in plant productivity.	Slavich et al. (2013)
Cultivated sandy loam	Randomzed field, Rice-wheat rotation	Rice/wheat straw; pyrolysis at 500–600 °C in a vertical coal furnace.	1 t ha^{-1}	6	• **Soil properties:** Increased SOC (64%); reduced alkaline pH (0.4 units), Nt (8%) and EC (20%). • **Soil aggregation:** Increased macroaggregates (34–51%), MWD (17–29%) and GMD (29–47%); decreased microaggregates (11%). • **Fungi:** Decreased fungal community richness, diversity and population of pathogenic fungi. Straw biochar can stimulate macroaggregate formation and stabilization (shown by indicators of agglomeration stability, MWD and GMD) in	Bai et al. (2019)

(continued on next page)

Table 2 (*continued*)

Experimental summary					Effects of amendment/inference	Reference
Soil type	Experimental type	Biochar feedstock/production conditions	Application rate	Yr		
					coarse-textured soils which may provide physical protection for OM to improve C sequestration. However, effects on soil fungi may be mixed.	
7 Acidic Red Clays (variable pH 3.8–5.3)	Pot (maize cultivation)	Rice straw (pH 8.5); pyrolysis at 400 °C for 4 h in a muffle furnace.	24 t ha^{-1}	<0.5	• **Soil properties:** Marginally increased pH (0.1–0.3 units) and decreased exchangeable Al^{3+} concentration (37–62%) in all soils; no effect on available N; increased available P in only two soils (31–142%, both pH < 4). • **Maize:** Direct nutritional effect from biochar on maize biomass in all soils was 12–67%; effect of biochar as a conditioner on biomass was 1–16% in poor soils but decreased biomass (4–15%) in relatively fertile soils. More pronounced soil conditioning benefits of biochar in highly degraded soils with high Al^{3+} concentrations than relatively fertile soils.	Zhu et al. (2014)
Silt loam Haplic Luvisols (pH 6.2)	Spring barley-spring wheat field rotation	Mixture of paper fibre sludge and grain husks; (pH 8.8 in $CaCl_2$); pyrolysis at 550 °C for 30 min in a Pyreg reactor.	10 and 20 t ha^{-1} (with 40 and 80 kg N ha^{-1})	2.5	• **Biochar only:** Increased soil pH (0.2–0.4 units, higher at 20 t ha^{-1}) • **Biochar + N:** Increased pH soil (0.1–0.5 units, higher at 10 t ha^{-1}/40 kg N ha^{-1}). Higher biochar dose without N fertilization increases pH of mildly acidic-neutral soils. When combined, lower doses of biochar and N may provide best pH increases.	Vladimir and Klimaj, (2017)
Sandy clay loam Eutric Cambisol	Field, randomized (maize cultivation)	Chipped trunks and branches of *Fraxinus excelsior L.*, *Fagus sylvatica* L. *and Quercus robur L.*; pyrolysis at 450 °C for 48 h.	25 and 50 t ha^{-1}	3	• **Year 1**: No significant effect on nutrient quality or growth performance of maize • **Year 2:** Increased foliar N (up to 32% at 50 t ha^{-1}), soil respiration, fungal and bacterial growth rates and turnover; no significant effect on grain quality or biomass • **Year 3:** Increases in crop height (up to 16% at 50 t ha^{-1}) and above-ground dry biomass (up to 79% at 50 t ha^{-1}). • **General:** Limited effect on DOC and N, NO_3^- or NH_4^+ pool sizes. In the short-term benefits from biochar amendment to highly productive soils (especially in temperate regions) may be limited. Long-term regular application of woody biochar at 50 t ha^{-1} may improve maize growth.	Jones et al. (2012)
31 Acidic (pH 3.4–5.6)	Field	Cacao (pH 10.5) and oil palm shells (pH 5.7) and rice husks (pH 7.3); pyrolysis at 300 °C for 1, 2 and 3.5 h, respectively	1, 0.3, 1, 3, 10 and 30 dry wt %	N/A	• **Soil properties:** Increased pH and CEC (up to 44%, at 30% biochar) in all 31 soils from all biochars (differed between biochar types, best outcome from cacao shell biochar). • **General:** Soil pH change most sensitive at 1% biochar, dependent more on soil CEC than the initial soil pH. Biochar has increasing effect on pH of acidic soil, and this depends on both soil and biochar properties.	Martinsen et al. (2015)
Sandy Podzol (pH 4.7)	Glasshouse, pot (corn cultivation)	Oil palm residue biochar (pH 9.7) (size <2 mm); slow pyrolysis at 300–350 °C.	10, 20 and 30 t ha^{-1}	<0.5	• **Soil properties:** Increasing biochar rate increased soil pH ($r^2 = 0.81$, P $\langle 10^{-3}$) and total C ($r^2 = 0.72$, $P < 10^{-3}$); decreased exchangeable Al ($r^2 = 0.75$, $P < 10^{-3}$). • **Tissue nutrients:** Increased corn tissue K ($r^2 = 0.45$, $P < 10^{-3}$); decreased N ($r^2 = 0.34$, $P < 0.05$), Ca ($r^2 = 0.57$, $P < 10^{-3}$) and Mg (at 20 and 30 t ha^{-1}) • **Corn yield:** Increased corn dry matter ($r^2 = 0.64$, P $\langle 10^{-2}$) and corn height ($r^2 = 0.36$, $P < 10^{-3}$; significant difference not found at lowest biochar rate). Biochar amendment in coarse-textured soils may require supplementing with mineral fertilization to maintain adequate tissue levels of N, Ca and Mg.	Syuhada et al. (2016)
Multi-metal (Cd, Cr, Cu, Fe, Pb and Zn)-irrigated, sandy soils (pH 5.5)	Outdoor PVC lysimeter (potato cultivation)	Plantain peel (pH 10.3); pyrolysis in a gasifier unit at 450–500 °C for 18–25 min.	1 wt%	<0.5	• **Soil properties:** Increased pH (0.3 units) and CEC (64%); SOM not affected • **HMs uptake:** Reduced potato uptake of Cd (50%), Cu (25%), Fe (40%) and Zn (75%); increased for Pb (200%); unchanged for Cr • **Tuber flesh HMs:** Reduced Cd (69%), Cu (47%), Zn (33%) and Fe (10%) in potato flesh; did not affect Cr and Pb.	Nzediegwu et al. (2019)

Table 2 (*continued*)

Experimental summary					Effects of amendment/inference	Reference
Soil type	Experimental type	Biochar feedstock/production conditions	Application rate	Yr		
					Biochar most effective for reducing Cd uptake by potato, though tuber concentration (0.9 mg kg^{-1}) still higher than CODEX permissible limit (0.1 mg kg^{-1}). Plantain peel biochar may not be effective for reducing translocation of Cr and Pb in sandy soil. Amendment could be more effective at higher biochar application rates.	
Acidic red clay Ferrasol (pH 5.6)	Field (maize culivation)	Waste willow wood (pH 8.3); pyrolysis at 500 °C for 5–7 h and ground to particle size <10 mm.	10 t ha^{-1}	<0.5	• **Soil properties:** Increased soil water content (9%), SOC (73%), NH_4^+-N (29%), NO_3-N (19%), available P (13%) and CEC (17%); no significant changes in pH, EC and BD. • **Foliar properties:** Increased leaf chlorophyll (4%) and foliar N (10%) and P (11%). • **Maize yield:** Increased biomass (18%) and grain yield (29%). Willow wood biochar application in acidic soils can increase crop yield and abate GHG emissions without pH increase. This can be attributed to the associated improvements in other soil conditions e.g. increased nutrient efficiency and water retention.	Getachew et al. (2016)
Disk-harrowed Ultisols (pH 5.6)	Field (corn cultivation)	Peanut hull (PHB, pH 10.1) and pine chips (PCB, pH 7.5); pyrolysis at 400 °C. Biochar ground by roller mill to prill fertilizer size.	11.2 and 22.4 Mg ha^{-1}	2	• **Soil properties:** Both biochars reduced pH (0.1–0.4 units); increasing PHB rate increased K (up to 114%), N (71%), S (124%), Mg (46%) and P (30%), but S increased non-linearly and Ca was not affected. Mixed response from PCB. • **Tissue nutrients:** No effect from either biochar. • **Corn yield, 1st year:** PCB reduced yield linearly (23, 30%); lower PHB rate reduced (35%), higher rate increased yield (29%). • **Corn yield, 2nd year:** Increased yield linearly with PCB (42, 55%) and PHB (1, 48%) . Higher corn yield from PCB in the second year than PHB may imply a high proportion of unavailable nutrient forms released by PHB into soil. Corn yield responses from both biochars whether positive or negative were too small compared to others.	Gaskin et al. (2010)
Sandy (pH 6.4)	Greenhouse (maize cultivation)	Cow manure (pH 9.2); muffle furnace pyrolysis at 500 °C. Biochar grounded to 0.18 mm particle sizes.	10, 15 and 20 t ha^{-1}	<0.5	• **Soil properties:** Increased soil pH (0.7–1.6 units), total C (356–526%), N (224–238%) and CEC (23–69%); water use efficiency increased at all rates (up to 150%, highest at 15 t ha^{-1}). • **Nutrients (N, P, K, Mg, Ca):** Increased grain nutrient content highest at 20 t ha^{-1}; but nutrient uptake highest at 15 t ha^{-1}). • **Yield:** Grain yield increased by 8, 150 and 98% (from 10, 15 and 20 t ha^{-1} biochar amendment, respectively). Cow manure biochar amendment of mildly acidic sandy soils at a rate 15 t ha^{-1} may provide excellent agronomic outcomes.	Uzoma et al. (2011)
Kiln Haplic Luvisols, Euric Cambisol and Colluvic Regosols	Field (Previously forested)	Hardwood biochar (charcoal residues from pre-industrial kiln charcoal production in Belgium)	N/A	>150	• **Soil C:** Higher OC (14–64 g kg^{-1}) than reference soil (10–26 g kg^{-1}), hence higher C/N (41%) and C/P (71%) values . • **Other soil Properties:** Slightly lower pH, though close to neutral (33% more than reference soil), total P (6%), available P (−3.4%), N-NO_3^- (22%), CEC (55%), exchangeable Ca, Mg, K and Na (58, 20, 1 and 42%, respectively). Long-term accumulation of SOC improves many soil conditions properties. The high N-NO_3^- may result from mineralisation and nitrification of large uncharred OM and when N remains unutilised, it may lead to reduction of soil pH.	Hardy et al. (2017)

Note: Percent expressions of amendment-induced changes are with respect to control treatments unless otherwise specified.
BD – bulk density, AWC – available water content, TP – total porosity, SOM – soil organic matter, EC – electrical conductivity, CEC – cation exchange capacity, EA – exchangeable acidity, AgS – aggregate stability, SOC – soil organic carbon, DOC – dissolved organic carbon, HM(s) – Heavy metal(s), OC – organic carbon, OM – organic matter, Nt – Total nitrogen, MWD – Mean weight diameter, GMD – Geometric mean diameter, GHG – greenhouse gas, N/A – unknown.

costs (Ahmed et al., 2016). In addition to the high economic costs there is limited availability of biochar at local scale. These factors have contributed to the current low biochar market and adoption among farmers (Jones et al., 2012). Excessive generation and increased non-regenerative disposal of agro-industrial bio-waste necessitates a reorientation to cheaper and mobile biochar technologies and would thus invariably raise farmers' awareness of biochar. Consequently, a pilot project for a mobile pyrolysis unit for on-site conversion of unutilised agricultural biomass into biochar was recently launched in Ireland, as a classical illustration of a true “circular economy” (Fig. 3) (EIP-AGRI, 2018). Elsewhere, the environmental and socioeconomic feasibility of mobile pyrolysis is being trialed using farm products (Ayer and Dias, 2018; Boateng et al., 2019). It is hoped that by increasing farmers' accessibility to technology and significantly cutting down or eliminating the cost of feedstock transportation, the real-world use case of biochar would increase.

2.2. BCW

Brown coal waste, also known as lignite, is a class of low-rank coal which is naturally abundant and deposited near the surface of the earth, enabling it to be mined more economically compared to other high-rank coals (Mahdy, 2011; Qi et al., 2011; Kashiwagi et al., 2015). There are different types of BCW which are characteristically distinct based on the origin and level of coalification of the parent material. In addition, BCW has a high moisture content which ranges from 30 to 70% (Krawczykowska and Marciniak-Kowalska, 2012). Much of this exists as free water which evaporates rapidly in dry conditions, leaving hygroscopic water that is bespoke to individual BCW (Krol-Domańska and Smolinska, 2012). Victorian BCW from Australia, for example, can have as high as 66% moisture content, which makes bulk transportation and storage difficult. Drying BCW prior to utilisation is an essential requirement to increase heat capacity, more especially as it was mainly used as fuel in power plants or raw material in the chemical industry until recently (Lu et al., 2019). There are high levels of organic compounds e.g. SOM, in BCW and this has drawn a lot of interest in its potential use as a soil amendment. The SOM in BCW has a high composition of humic (10–90% d.w.) and fulvic acids (Krol-Domańska and Smolinska, 2012; Saha et al., 2016; Anemana et al., 2019). These acids are relatively stable large organic complexes with diverse functional groups which have been reported to mediate many different soil processes e.g. complexation with metals, alleviation of acidity and GHG abatement (Spaccini et al., 2002; Turgay et al., 2011; Kwiatkowska-Malina, 2018a; Mikos-Szymańska et al., 2019). Consequently, the direct application of BCW-derived HSs to soil has become a common practice (Liu et al., 2011; Qin and Leskovar, 2018). The surface of BCW is dominated by oxygen-containing compounds including carboxylic, phenolic and carbonyl functional groups which when ionised in solution result in a characteristically low pH material (Domazetis et al., 2006; Qi et al., 2011). This suggests that when used alone, BCW may be more suited to neutral-to-alkaline soils and should be used with lime if the soil in question has a low pH.

Fractionation of incubated BCW samples reveals a high level of hydrophobicity which favours the accumulation and sequestration of ^{13}C. The high hydrophobic interactions among humic molecules and fresh organic compounds account for the bio-resistance and long-term sequestration of HSs (Spaccini et al., 2002). Multiple technique characterisation of the Zhaotong lignite from China revealed it consisted of 52.3% aliphatic and 42.2% aromatic carbons, with each aromatic unit containing two rings on average (Li et al., 2015). The high aromatic character implies a high level of recalcitrance which is possibly due to the inherently high HA content of BCW. This infers a high C sequestration and GHG abatement potential which must be given careful consideration for long-term soil management strategies.

Brown coal waste has also been found to have high adsorption capacity. Drying renders the surface of BCW hydrophobic, hence reducing its absorption capacity. Therefore, dried or processed BCW used for the purpose of sorbing compounds from soil must be wetted adequately before use. For example, Qi et al. (2011) found the adsorption capacities of two types of unprocessed Victorian lignite from Australia, Loy Yang (286 mg g^{-1}) and Yallourn (370 mg g^{-1}) for methylene blue higher than coconut shell-based activated carbon (167 mg g^{-1}), but lower than a coal-based activated carbon (435 mg g^{-1}). This also compares favourably with the sorption capacity of some biochars for methylene blue e.g. cattle manure-derived (242 mg g^{-1}) and sawdust-derived (333 mg g^{-1}) (Ghani et al., 2013; Zhu et al., 2018). These properties along with the reported high ion-exchange capacity makes BCW an excellent adsorbent for both environmental pollutants and plant nutrients, and justifies the current interest in exploring its propriety as a soil amendment (Debska et al., 2002; Saha et al., 2016; Robles et al., 2017; Anemana et al., 2019). It can be used to protect air and water quality through targeted adsorption of pollutants in soil. It has the ability to extract pollutants whilst enabling nutrients (e.g. NPK) and metals needed for plant growth to be unhampered for the maintenance of agronomic goals. Less N losses through N_2O emissions (up to 40%) and ammonium (NH_4^+) and NO_3^- leaching were found in soils (loamy sand) amended with a composite fertilizer made of BCW from Loy Yang, Australia and urea (Rose et al., 2016), for example. The NH_4^+ released from urea into soil is retained by BCW, thus enhancing N use efficiency. Consequently, a wide range of BCW-derived commercial products, mainly sold as humates, are available and promoted as plant growth stimulants. In a study to verify whether six of the products improve soil health indicators and early-stage growth of lucerne and rygrass in two contrasting soils, Little et al. (2014) found variable results after using the manufacturers' recommended application rates. Although significant growth effects were found for some products, the effects varied across the plant and soil types. It was suggested that the variable HA concentrations across the products (13.9–82.3%) may have contributed to the inconsistencies even though the performance of a product did not reflect the HA content, implying the need to further investigate mechanisms responsible for growth promotion in soils amended with BCW and its derivatives.

The complex heterogeneous structure of BCW made of amorphous polymers constituting double- or triple-substituted aromatic rings makes it suitable for immobilising metals (especially in di- and trivalent forms) in soil (Robles et al., 2017; Anemana et al., 2019). Thus, BCW has been used effectively for immobilising HMs in soil and reducing their availability to plants (Skłodowski et al., 2006; Kwiatkowska et al., 2008; Simmler et al., 2013; Kwiatkowska-Malina, 2018b). It has also been suggested that sorption of polar organic pollutants is controlled by the degree of aromaticity of BCW and the partition between the solid and aqueous phases involved in the interaction (Kopinke et al., 1995). A classic example of this was shown by Tong et al. (2014) who demonstrated the effectiveness of lignite-activated coke for removing polar organic pollutants by successfully extracting large molecular weight compounds (e.g. tetratetracontane, 7-oxabicyclo [4.1.0] heptane, 1,5-dimethyl-, phthalic acid, hex-2-yn-4-yl isohexyl ester) from soil. Vítková et al. (2011) found that BCW improved degradation of the pesticide, pentachlorophenol (PCP), under bioaugmented soil conditions, where further degradation by microorganisms proceeded sorption of pollutant by BCW. It is important to note that the sorption of PCP by HAs in BCW is reversible thus becomes bioavailable for microbial degradation, suggesting the need for improved understanding of the removal of other organic pollutants from soil.

There is limited understanding of the impact of BCW and derivatives on other soil processes aside from pollutant remediation. Other studies which have examined additional soil benefits from BCW use have found increased electrical conductivity in acidic soils (Imbufe et al., 2004), improved water retention capacity (Piccolo et al., 1997) and enhanced P uptake from fertilizers (Schefe et al., 2008). Tran et al. (2015), however, found a minimal and temporary effect of BCW on soil microbial community structure and activity, while it failed to alter microbial biomass. The impacts of selected BCW types in different soil types and a soilless medium have been summarised in Table 3.

Brown coal waste is a cheap resource but has inherent issues that can be addressed to improve their agronomic value. Coal conversion gives rise to products contaminated with diverse organic and inorganic pollutants (Kopinke et al., 1995). Subsequently, fragments of BCW in addition to their high aromatic contents, have high levels of organically-bound chlorides and inorganic species (e.g. Na, Mg, Al, Si, K, Ca, Ti, Cr, Fe, Mn, Ni, Cu and Ga) (Domazetis et al., 2006; Binner et al., 2011), implying an increased risk of pollution by PAHs, PCDDs, PCDDs and HMs. Different non-evaporative water removal techniques, e.g. mechanical press dewatering, have been trialed in the past. Though, most of them successfully removed up to 80% of water from BCW, the approaches were impractical due to the high mechanical pressures (~50 MPa) and long pressing times involved (Hulston et al., 2005). Thermal processes including hydrothermal dewatering involve extremely high temperatures (>250 °C) and could lead to loss of organic material (Li et al., 2019). The combined use of relatively lower pressure (<12 MPa) and temperature (<200 °C) coined by Strauß and co-workers in the mid 1990's as the Mechanical Thermal Expression (MTE) is widely accepted as pre-treatment for BCW (Hulston et al., 2005; Gui et al., 2017; Lu et al., 2019). The MTE process effectively removes moisture and enhances energy density. This has very little effect on the organic composition of the resultant BCW with the exception of volatile components which may comprise a range of inorganic pollutants. Thus, even though the MTE process was originally designed for energy production, it could become useful for concentrating OM and removing organic pollutants in BCW for agricultural use. The HMs are not removed at this stage, but they can be lost from wet coal at 800 °C or more due to metals migrating out of the coal matrix during rapid drying processes (Binner et al., 2011). Such high temperatures may be untenable for the present purpose partly because it could lead to the formation of PAHs, PCDDs and PCDDs and the loss of SOM. The Electro kinetic (EK) method involving the migration of metals to the anode of an electric field has shown promising results and has been successfully used in removing up to 91% of HMs from dry BCW (Manoharan et al., 2013). The cost of EK remediation of some HMs has been estimated to be 310–330 US$/ton sediment (Liu et al., 2018; Mao et al., 2019). Even though this represents additional costs to farmers, it is still cheap considering the untapped potential in an otherwise underexploited natural resource. Global reserves of BCW are estimated to be 200×10^9 t (Kashiwagi et al., 2015) and it is mined all over the world, especially in Europe. The use of coal derivatives for energy generation has declined considerably following a general preference for natural gas and renewables. This coincides with a growing interest in BCW for agricultural uses. A step forward would be the continued investment in research and technology for further understanding and refinement of BCW to enhance its use as a soil amendment.

3. Evaluating the effects of biochar and BCW on SQ

Soil, much like water and air, is a fundamental component of environmental quality assessment. Due to the presence of the non-hierarchic network of embedded ecosystems and multi-functional constitution of soil (Ponge, 2015; Schulte et al., 2015), it is sometimes considered an ecosystem on its own rather than a component of an ecosystem (Laishram et al., 2012). However, in different geographical areas including Europe, there are no soil-specific directives, therefore no legislative standards for the assessment of SQ. A SQ assessment therefore involves an evaluation of soil conditions, fertility and productivity, while integrating multiple ecosystem functions (Bunemann et al., 2018). Considering the general difficulty in directly estimating most soil functions, a set of QIs involving a broad spectrum of easily measured dynamic soil properties can be used (Doran and Parkin, 1996; Vasu et al., 2016; Vogel et al., 2019;). These QIs are categorised as physical, chemical or biological, to reflect the three dimensions of SQ assessments and to highlight the influence of each indicator on soil processes and functions (Table 4). A single soil property can affect multiple soil functions, therefore QIs are not strictly confined and may overlap (Doran and Parkin, 1996). These QIs can be especially useful to farm managers and regulators for both short- and long-term soil monitoring, and also for examining the effectiveness of management interventions.

3.1. Physical QIs

Physical QIs are good indices of water storage and infiltration, gaseous exchange, depth of root penetration, erosion and other important soil processes (Blanco-Canqui, 2017; Pandey et al., 2018). While some physical soil properties such as texture are inherent and therefore difficult to modify, others including BD, aggregate stability and porosity can

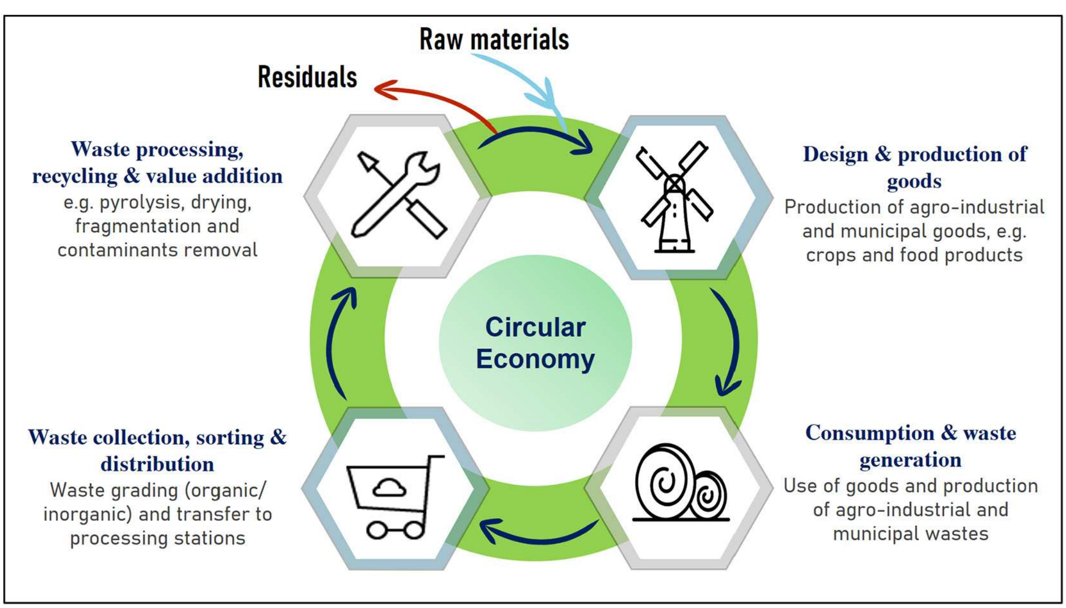

Fig. 3. Illustration of circular economy concept using emerging organic wastes as soil ameliorants. Emerging organic wastes collected from agro-industrial and municipal goods are processed, recycled and re-used as soil ameliorants for the production of goods. Residuals from waste processing are removed for further treatments and later rechannelled into the cycle, or safely disposed of.

be effectively altered by management practices including organic amendments (Oliver et al., 2013; Blanco-Canqui, 2017). Soil particle size and textural modifications are extremely slow processes that may take several years to occur regardless of the land management type (Are et al., 2017), but take very little time to reverse. Mitigation options such as subsoiling are very counterproductive and may increase the problem. Amendments could potentially lead to longer term benefits, but most farmers prefer machines and do not trust organic amendments very much.

Soil BD is correlated with soil physical indicators such as texture, density and porosity (Blanco-Canqui, 2017). It is affected by other properties including soil water content, texture and depth, as well as cropping system. Yet, the most critical influence on BD is SOM content, as increased OM content leads to a reduction in BD of soil (Pritchett et al., 2011). This holds true for many soil applications of biochar and is one of the most studied soil properties following organic amendment (Omondi et al., 2016; Xiao et al., 2016). Blanco-Canqui (2017) found that biochar application reduced BD by 3–31% and on average by 12% in 19 of 22 studied soils, which is not far from the 7.6% reported from the meta-analysis by Omondi et al. (2016). While BD was found to be less responsive to biochar application rates below 10 Mg ha^{-1} (Xiao et al., 2016), there was also no response to application rates above 10 Mg ha^{-1} (Rogovska et al., 2016). Amendment of a Salidic Caliustolls degraded by salinisation with 5 kg m^{-2} BCW (from Guajira, Colombia) showed no changes in BD (1.62 g cm^{-3}) after six months (Cubillos-Hinojosa et al., 2017). This could have been due to the extensive degradation of the amended soil; therefore, beneficial changes in BD should be considered in the long-term.

It has been suggested that a decrease in soil BD from biochar application may increase total porosity while reducing pore size of soil in a linear manner (Blanco-Canqui, 2017). For example, Pranagal et al. (2017) observed that increasing rice husk biochar application rates increased the total porosity of a clayey Vertisol. This is not always the case as biochar could also have variable effects on soil. Devereux et al. (2012) found the porosity of 1.5% w/w wood biochar amended soils lower than the unamended soil, while the first and second scans in 2.5% biochar amended soils showed a respective decrease and increase in porosity, though there were consistent increases with the 5% biochar. However, the average pore sizes of most soils decrease linearly with biochar addition and improve water retention through reduced drainage as a result of water being stored in smaller pores. The limited water retention capacity of soils with lower clay content, e.g. sand, may be due to their small surface areas and lower proportion of micro- and mesopores relative to macropores. In soils of contrasting textures, for example, a single application (104 Mg ha^{-1}) of corn stover and switchgrass biochars (each produced by fast and slow pyrolysis) resulted in up to 25% increase in water retention in both soils (Mollinedo et al., 2015). All treatments significantly increased plant-available water capacity (PAWC) (tension range 0.01–1.5 MPa) in the sandy loam soil while there was a 40% greater PAWC (0.03–1.5 MPa) in the clay loam for all treatments except in the switchgrass slow pyrolysis biochar treatment, which was not significantly different from the control. This suggests that differences in the ability of biochar to enhance water retention were dependent on feedstock and pyrolysis and less on soil type. The increase in water retention by biochar amended soils can also be attributed to a decrease in soil hydrophobicity or water repellency (Devereux et al., 2012). Thus, biochar can play an even more important role in global warming by neutralising increased soil hydrophobicity that may arise from increased soil temperature. Piccolo et al. (1997) observed that two soils with severe structural problems, Orthic Xerofluvent and Udic Ustochrept, amended with HSs from oxidised BCW (at 100 and 200 kg ha^{-1}, respectively) had a similar reduction in soil loss (36%). The reduced runoff erosion was attributed more to increased water retention from the amendment than improved aggregate stability. The amendment ostensibly delayed the onset of runoff and favoured water entry into soil through the stable pore spaces within the soil beds. Even at low application rates BCW-derived HSs could be useful for enhancing the physical properties of degraded soils to offset runoff erosion.

Organic amendments could benefit heavy soils by increasing macroporosity, which improves hydraulic conductivity for enhanced infiltration in soil (Li et al., 2012). Herath et al. (2013) found that an increase in hydraulic conductivity of two silt loam soils of different drainage capacities following amendment with two corn stover biochar produced at 350 °C and 550 °C (11.3 and 10.0 t ha^{-1} respectively), was linear with the overall porosity of the soil. The effect of the high temperature biochar was more prominent in the poorly drained soil, while the opposite was the case for the low temperature type. Biochar with higher C contents (in the case of the high temperature type) may be more suited to improving macroporosity of fine-textured soils. Conversely, under field-grown conditions in a cultivated loam soil, biochar (fir woodchips, pyrolysed at 1200 °C) applied at a low rate (1% w/w) can reduce water drainage and solute leaching (Libutti et al., 2019).

Increased accumulation of SOM may lead to increased soil aggregate stability, with biochar known to significantly enhance formation and stability of macroaggregates (Ouyang and Zhang, 2013). Omondi et al. (2016) found mean increases in aggregate stability from biochar amendment across multiple studies to be 8.2%. Biochar-induced aggregation, however, may be more pronounced in fine-textured soils than in coarse-textured types (Obia et al., 2016). In four soils of different textural classes it was found that biochar (sawdust from Chinese pine and locust, in an 11-month study) did not increase aggregate stability in soils that had sand content >17.4% (Liu et al., 2012). The increases in aggregate stability were generally greater at higher biochar application rates (8 and 16 g kg^{-1}). Change in soil aggregation is a long and slow process which is best interpreted through long-term studies and may be greatly influenced by soil type and amendment rate.

3.2. Chemical QIs

Soil colloids, clay and OM are the main determinants of the chemical properties of soil (Singh et al., 2017). These properties, including CEC, pH and nutrient availability, may be affected by soil management interventions. The CEC is strongly linked to mineral composition and OM content of soil. While it is almost impractical to alter the former, the latter can be modified through organic amendments (Costantini et al., 2016). Generally, biochar can induce changes in pH, CEC and exchangeable cations of soil with the efficiency of change closely linked to the magnitude of the difference between the biochar and the soil's initial properties, especially exchangeable Ca^{2+}. For example, increments in exchangeable Ca^{2+} and CEC from biochar application were found only in soils with lower starting exchangeable Ca^{2+}, whereas decreases were observed in soils with higher initial exchangeable Ca^{2+} (Hailegnaw et al., 2019). This suggests that under uniform experimental conditions it may be possible to predict the efficiency of biochar amendment to modify soil pH, CEC and exchangeable Ca^{2+} provided the value of the latter is known for both the starting soil and biochar.

Soil pH is greatly influenced by properties of the parent material but can also be modified by organic amendments over time, even if slowly. Strongly acidic or alkaline soils are often characterised by nutrient deficiencies and/or elemental toxicities. This is because pH affects the solubility, concentration and mobility of ionic species in aqueous environments, and consequently their uptake by plants (Malik et al., 2018). Soil acidity is naturally much more widespread due to long-term pedogenesis, leaching of salts and anthropogenic processes such as mining (Costantini et al., 2016). The high concentrations of carbonates and oxides of Ca, Na, K and Mg formed on the surface of biochar during pyrolysis induce a liming effect which is more efficient in soils having pH < 5 (Wang et al., 2014; Yu et al., 2019). Increased soil pH from biochar amendment can increase macronutrient (e.g. Ca and Na) availability and reduce the solubility of metals including Al, Pb and Mn (Ahmad et al., 2017; Malik et al., 2018). The pH of two acidic tropical

Table 3
Summary of different applications of brown coal waste and its derivatives.

Experimental summary					Effects of amendment/inference	Reference
Soil/medium	Experimental type	BCW type/origin	Application rate	Yr		
Loamy sand Haplic Luvisols	Greenhouse, pot (HAs extraction from soils)	Rekulter/ Poland	50 g kg^{-1} with liming	2	• **Soil properties:** Increased TOC (~300%) and pH (0.7 units); reduced N (45%), no effect on oxygen. • **HAs:** higher aromaticity (38.6%) compared to control (35.4%). Increased SOC with higher aromatic properties implies higher recalcitrance and C sequestration potential. Reduced N after 2 years suggests the need for combined Rekulter-N application.	Debska et al. (2002)
Dermosol (pH 5.4) and Tenesol (pH 7.2)	Pot (silver beets cultivation)	BCW-urea blend, Australia	100 N kg ha^{-1} and 50 N kg ha^{-1} with mineral P and K.	<0.5	• **Soil properties:** Increased N and OC in both soils. • **N_2O emission:** Supressed in Dermosol (13%) and Tenesol (29%). • **Silver beet**: Increased biomass in Dermosol (23%) and Tenesol (29%) compared to urea (only) amendment. Increased SOC enhanced soil physical properties, e.g. AgS, which may have increased N retention by abating N_2O emissions and N leaching (possibly), leading to increased nutrient availability. BCW-urea amendment was more effective in the Tenesol than the acidic Dermosol.	Saha et al. (2016)
Alluvial soils (pH 4.8–6.8)	Greenhouse, pot (*Lolium perenne* cultivation in Cd-polluted soil)	BCW (pH 4.5) and BCW-biosolids blend/ New Zealand	1.0 and 3.4 wt% 1.0, 3,4 and 7.1 wt% with 10% biosolids	<0.5	• **Soil pH:** All treatments reduced pH (by 0.1–0.6 units). • **1 wt% BCW:** Most effective for reducing Cd uptake (30%,); no adverse effect on pasture biomass or nutrient uptake. • **Other BCW rates:** 7.1 wt% BCW decreased pasture biomass; no effect on biomass from 3.4% wt BCW. Highest biomass reduction in BCW-biosolid treatments. Reduced soil pH from BCW can adversely affect soil nutrient and pollutant dynamics, implying that without adequate liming higher BCW rates may lead to increased toxicity to plants. Reduced biomass may also be due to the nutrients released from biosolids being locked on the highly reactive surfaces of BCW leading to reduced nutrient availability.	Simmler et al. (2013)
Loamy sand Haplic Luvisols	Field, pot (Winter rye cultivation)	Rekulter/ Poland	5, 10 and 20C t ha^{-1} (Soil spiked with Cd, Zn, PB)	1	• **Soil properties:** Linear increases in pH (up to 1.25 units) and OC (122%) with Rekulter application. • **HMs:** Dose-dependent reduction in concentrations of Cd, Pb and Zn (up to 56, 33 and 28%, respectively) leading to reduced translocation to rye roots, stalk and ear. • **Rye:** Increased fresh rye biomass with increasing Rekulter amendment (up to 103%). Rekulter amendment improves soil conditions and ameliorates possible HMs toxicity to promote biomass increase in rye.	Skłodowski et al. (2006)
			5C Mg ha^{-1} (i. Soil only; ii. Soil spiked with Cd, Zn, PB)	<0.5	• **Soil properties:** Increased soil pH (0.4 units), TOC (105%) and Nt (35%). • **Tissue nutrients:** Increased K concentration in roots and improved fodder quality (high Ca and Mg), but no effect on Na in aboveground parts of rye. • **Rye***:* Increased fresh biomass (66%) of rye (48% for HM polluted soil). Improved soil conditions from Rekulter amendment enhances bioavailability and plant uptake of nutrients leading to improved biomass growth. Though soil properties were not affected by HM pollution, the resulting toxicity on plants led to a slightly smaller biomass increase than in unpolluted soil and could indicate a resultant reduction in nutrient retention due to saturation of the reactive surface of BCW by HMs.	Leszczyńska and Kwiatkowska-Malina (2011)
Sandy loam Calcic Kastanozems (pH 8.4)	Field (Reforestation)	Oxidised BCW humic acid/ Mongolia	2000 mg L^{-1}, 10,000 mg L^{-1} and 20,000 mg L^{-1}	3	• **Soil properties:** Increased EC and OM in all treatments, highest at 10000 mg L^{-1} (50 and 46%, respectively); no change in pH; general increase in assimilable P_2O_5 (highest at 20000 mg L^{-1}) and K_2O (highest at 10000 mg L^{-1}); pH and Mg not significantly affected. • **Emissions:** All treatments significantly reduced CO_2 (highest at 10000 mg L^{-1}, 50%) and NO_3 (similar rate for all treatments) emissions. • **Tree:** Inconsistent increases in relative height growth rate of three tree species. BCW-derived HA fertilizer applied at 10000 mg L^{-1} was most effective for improving soil properties and mitigating GHG emission (may lead to increased nutrient retention) but did not reflect in tree height	Tsetsegmaa et al. (2018)

(continued on next page)

Table 3 (*continued*)

Experimental summary					Effects of amendment/inference	Reference
Soil/medium	Experimental type	BCW type/origin	Application rate	Yr		
					growth. BCW-derived HAs are highly recalcitrant, and may require a longer observation period to see the effects of improved soil conditions in tree growth.	
Zn smelter-polluted soil (ZS) and Unpolluted mine soil (UM)	Phytotron chamber, pot (Giant Miscanthus and Scots Pine cultivation)	Lake chalk slurry from brown coal mine (pH 7.3)/ Poland	2 wt%	1.5	• **SOC:** Increased in ZS (15–20%) and UM (90–100%). • **HMs:** Decreased bioavailability of Cd and Zn, but increased Pb (100–300 μg L^{-1}) in both soils. • **Plants:** Increased respective root biomass of Giant Miscanthus and Scots Pine in ZS (40 and 150%) and UM (150 and 90%). Lake chalk slurry from BCW might be a potential source of Pb, thus, it must be treated to remove Pb or any other HMs prior to use even though Pb did not appear to affect plant growth in either soil. Amendment more effective in unpolluted soil, therefore, BCW may be more suited to moderately polluted soils compared to ones with high HM concentrations.	Placek et al. (2017)
*Cultivation mats	Greenhouse, soilless (Growdena tomato)	Poland	Particle diameters: 20 mm, 10 mm, 2.5 mm and earthy fraction	2	• **Growing medium:** Crashing of BCW decreased pH of the growing medium while increasing hydrological properties and BD (by at least 500%; the greatest BD from the earthy fraction). • **Nutrients:** No effect of lignite crashing on available N, P, K, Mg and Ca contents. • **Tomato:** Improved yield of Growdena tomato, with highest yields on mats with BCW particles 2.5 mm in diameter and lowest from earthy fractions. BCW particles which are 2.5 mm sized may be best suited for crop cultivation in soilless media while the earthy-sized fraction may lead to unfavourable growing conditions.	Dyśko et al. (2015)

Note: Percent expressions of amendment-induced changes are with respect to control treatments unless otherwise specified. *Lignite application in non-soil medium.
Rekulter preparation – composed of 85% brown coal, 10% peat, 4% brown coal ash and 1% mineral fertilizers. BD – bulk density, AgS – aggregate stability, EC – electrical conductivity, HMs – heavy metals, TOC – total organic carbon, SOC – soil organic carbon, OC – organic carbon, EDTA – ethylenediamine tetraacetic acid, OM –organic matter, Nt – total nitrogen, GHG – greenhouse gas, BCW – brown coal waste, HA(s) – humic acid(s).

soils, Alfisol and Haplic Ferralsol, increased from 4.8 to 6.1 and 4.6 to 5.8, respectively, in response to 2% w/w corncob biochar by reducing exchangeable acidity and increasing effective CEC which increased N and available P (Mensah and Frimpong, 2018). On the other hand, BCW and derivatives do not have any liming effect on soil, but the carboxylic and phenolic groups in BCW-derived HSs can provide reactive sites for cation exchange which can increase pH buffering and electrical conductivity (Imbufe et al., 2004; Turgay et al., 2011).

Different types of biochars have been shown to be important sources of plant macronutrients (e.g. P, K and Ca) which are directly released into soil and used by plants (Conz et al., 2017). Manure-based biochars have a higher potential to release more P and K to soil than the hardwood alternatives (Novak et al., 2018). Aside from this, biochar can also have a strong influence on nutrient retention and availability in soil. However, the effect of biochar on nutrient leaching can vary for individual biochar and nutrient types. A high temperature (600 °C) biochar made from Brazilian pepperwood effectively reduced leaching of NO_3^-, NH_4^+ and phosphate (34, 35 and 21%, respectively) while peanut hull biochar, produced at the same temperature, also reduced leaching of NO_3^- (34%) and NH_4^+ (14%), but could not sorb phosphate under the same experimental conditions (Yao et al., 2012). Phosphates, for example, are tightly bound in highly weathered tropical soils that are rich in Fe and Al oxides (Hale et al., 2013), and thus solubility may improve with a stronger adsorbent or liming effect. Therefore, the sorption capacity of the different types of biochar must be studied for specific nutrients prior to their use. Alternatively, HSs from BCW may have high nutrient contents and therefore, can be used to increase plant nutrient supply in soil the same way as mineral fertilizers (Sangeetha and Singaram, 2007; Liu et al., 2011). Turgay et al. (2011) found significant increases in SOM, available P and bread wheat yield in the first cropping season after adding a humic-fulvic concentrate (1 Mg ha^{-1}) from gyttja BCW (Turkey) to an alkaline soil. Except for SOM, the nutrient status and other soil parameters were not affected in the second year, whereas the combined HSs-mineral fertilizer application showed significantly better results. This may indicate a low nutrient supply from the BCW extract, which was immediately utilized by plants, therefore requiring supplementing with mineral fertilizers. It may also be possible to improve the nutritional performance by increasing the application rates of BCW derivatives.

Increasing SOC stock and stability through soil application of biochar and BCW yields both agronomic and ecological dividends and presents a win-win solution to the growing food security and climate change concerns. Bista et al. (2019) found that biochar produced from Douglas fir (*Pseudotsuga menziesii*) at 900 °C and applied to a silt loam at 22.4 Mg ha^{-1} increased soil pH, OC, P, K and S contents, which led to increases in the shoot and root biomass of wheat. A one-time addition of Rekulter (85% BCW, 10% peat, 4% BCW ash and 1% mineral fertilizers) to a light clay resulted in significantly higher increases in total OC and N contents of soil compared to conventional organic wastes such as peat and farmyard manure (Kwiatkowska-Malina, 2015). Although the total OC and N contents dropped slightly over a seven-year period, they remained at a high level for a standard light soil. The capacity of BCW to increase SOC content and sequestration has also been investigated by amending soils with BCW-derived HSs. Spaccini et al. (2002) found a higher retention of ^{13}C in soils amended with BCW-derived HAs (58%) compared to HAs from compost (40%). Thus, it is possible to develop a successful long-term amendment scheme with BCW and derivatives where re-application may only be necessary every five years. The derivatives of BCW have high hydrophobic properties (Spaccini et al., 2002), which is a predisposition for increased sequestration of OC in soil. Thus, BCW can also contribute to the mitigation of CO_2 emissions from arable soils.

Biochars produced at higher temperatures have higher C but lower N contents compared to types produced at lower temperatures. This is often due to the condensation of C in aromatic clusters while N and other nutrients are lost with increasing pyrolytic temperatures.

However, using three different feedstock types, Kloss et al. (2012) observed that biochars produced at 525 °C had both higher C and N contents than at 400 °C. Depending on the production method, low temperature biochars (e.g. produced by slow pyrolysis) can have lower N contents than high temperature types (e.g. by charring) (Santín et al., 2017). The use of biochar for GHG abatement has been broadly discussed for CO_2 and N_2O emissions, but not NH_3. Mandal et al. (2016) found that poultry litter and macadamia nut shell biochars (5% w/w) could reduce NH_3 volatilisation by up to 71% in calcareous soil while at the same time increasing N uptake by plants by up to 76%. It was explained that the volatilisation mitigation mechanisms comprised NH_3 adsorption/immobilisation and nitrification. They reported that higher NH_3 volatilisation was found at soil pH exceeding 8. This is corroborated by Schomberg et al. (2012), who found that NH_3 losses increased when soil pH increased through biochar amendment. The mechanisms for biochar-based mitigation of NH_3 emissions could be managed by selecting relatively low pH biochars (pH ≤ 8) which can efficiently promote the formation of NH_4^+ salts for N retention.

The presence or absence of toxic elements in soil can also be used as an important QI. The routes of arable soil (including paddy and arid) exposure to environmental pollutants are diverse and convoluted, ranging from atmospheric deposition, wastewater irrigation, sewage processing and long-term application of pesticides, fertilizers and plastic films (Igalavithana et al., 2015; Sun et al., 2018). These pollutants, including polyaromatic hydrocarbons, polycyclic biphenyls, organochlorine pesticides and HMs, are characterised by their high bioaccumulation, field-scale heterogeneity, persistence and toxicity (Ogbonnaya and Semple, 2013; Williams et al., 2014; Fang et al., 2018; Sun et al., 2018). Several studies have shown that biochar, especially when produced under high pyrolytic temperatures, can enhance the immobilisation and sequestration of soil pollutants (Ogbonnaya and Semple, 2013). It has been shown that biochars produced from pine needle (100–700 °C) were more effective for sorption of PAHs (naphthalene, phenanthrene and pyrene) in paddy soil when produced at higher temperatures (300–700 °C), even though nonlinear sorption increased when biochar content was increased (Chen and Yuan, 2011). The sorption pattern is similar for the biochar-based removal of inorganic pollutants from soil and has been reported for different HMs. Shen et al. (2019) found rice straw biochars produced at higher temperatures (500 and 700 °C) to be more effective for the removal of Pb from soil solution than biochars produced at 300 °C. It has been suggested that increased pH and electrostatic interaction between biochar surfaces and HMs are responsible for metal removal in biochar-amended soil. These mechanistic changes are higher with high temperature biochars, hence resulting in faster uptake kinetics and increased metal immobilisation (Palansooriya et al., 2019). The outcome of HM remediation from soil by biochar will depend on the type of soil or metal, therefore, considerable caution must be exercised when applying biochar to soil contaminated with multiple metals. High temperature biochars (700 °C), for example, were found to decrease Pb and Zn mobility by 100% in an acidic arable soil, whereas their low temperature counterparts (300 °C) were more efficient in reducing Pb and Cu mobility (>93%) in alkaline shooting range soil (Ahmad et al., 2017). The mobility of As and SB were increased in both soils by both biochar types, in the same study, possibly as a result of low metal sorption due to electrostatic repulsion. The stabilising effect of BCW on HMs in soil has been demonstrated using a 5% w/w Visonta BCW (from Hungary) which significantly reduced the solubility of HMs including Pb (up to 72%), Zn (18%) and Cr (88%), in different acidic solutions (Uzinger et al., 2014). This is supported by Anemana et al. (2019) who found that particle sizes of BCW in the ranges 0.5–1.0 and 1.0–2.0 mm can remove 50% of the phytoavailable concentration of Cr (III) in an acidic soil.

Table 4
Soil quality indicators – physical, chemical and biological – and the soil functions they influence.

Category	Soil indicators	Strongly-related soil functions
Physical properties	Hydraulic conductivity	B D E
	Infiltration rate	A B C D
	Soil texture	A B D E
	Aggregate strength and stability	A B C D E
	Water retention	B C D G
	Soil compaction and resistance to penetration	A D E
	Porosity	A D E
	Bulk density	A B D E
	Stoniness	A D
	Topsoil depth	C F G
	Soil heat capacity and temperature regime	A B D F
	Aeration	A E G
Chemical properties	Cation exchange capacity	B C D E
	Reaction (pH)	B C D E F
	Salinity	B D E
	Plant available nutrients	C E G
	Toxic elements	B E G
	Carbon content	C E F G
	C/N	C E F G
	Colour	A B F
	Electrical conductivity	B C D
	Organic matter content	B C E F G
Biological properties	Enzyme activity	C F G
	Activity and diversity of soil fauna and flora	A C F G
	Fractions of organic matter	B C F G
	Microbial biomass	C E F G
	Respiration rate	C F G
	Bioavailability of contaminants	B E G
	Mycorrhizal associations	C E G
	Fatty acid profile	C E G
	Absence of pest and/or pathogens	E G

For conceptualisation, the main functions of the soil have been grouped as follows: Provision of physical stability and support (A), Filtration, buffering, degradation of organic and inorganic materials (B), Storage and cycling of nutrients (C), Regulation of water and solute flow (D), Production of biomass (E), Turnover and sequestration of soil organic carbon (F), Source of biodiversity (G). Scheme presents the most relevant soil functions (at least 2 and at most 5) for each indicator.

3.3. Biological QIs

Biological activity is a crucial index of productive soils and most prominent in the topsoil. Yet, biological components, mainly soil microorganisms, occupy only a minuscule portion (< 0.5%) of the total volume of soil (Biswas and Naher, 2019). Soil microorganisms (fungi and bacteria) and other fauna (earthworm, insects, arthropods etc.) play a very important role in SOM decomposition, nutrient cycling and soil aggregation. The size, composition and activity of soil microbial communities are sensitive to organic amendments, and hence they are important biological indicators for SQ monitoring (Elbl et al., 2019; Bonilla et al., 2012). The sensitivity of these indicators provides ancillary advantages in their applicability for assessing short-term impacts of soil amendments (Costantini et al., 2016). Resource availability has been shown as an important regulatory factor of the diversity of key functional soil microbial communities (Hahn et al., 2018; She et al., 2018). The addition of exogenous OM to soil can stimulate microbial activity and enhance substrate-induced respiration which can greatly increase microbial biomass (Elbl et al., 2019; Onagwu, 2019).

The high stability of biochar and BCW could mean that in the short term, their effects on soil microbial indices may be minimal. This may be due to their limited contents of potentially mineralizable OM (compared to manure and compost) even though priming of native SOC is known to occur with exogenous C inputs, including biochar and BCW. The effects of BCW on microbial community structure and activity are not well understood. Only negligible changes in microbial biomass after amending a clay loam with Victorian BCW were found, whereas temporary shifts in microbial activity and community composition were observed during a 60-day trial by Tran et al. (2015). Longer experiments may be needed to determine the potential impacts of BCW modification on microbial community structure. Bekele et al. (2015) also found that even though separate applications of wood biochar and oxidised BCW increased SOC contents of three soil types (clay, loam and sand), they had no significant effects on microbial biomass and average geometric mean diameters of dry soil aggregates. They were therefore considered ineffective for reconstructing functioning agronomic topsoil of disturbed agricultural lands. The opposite outcome was found using a labile organic mix (sawdust, wheat straw and alfalfa; LOM), implying the simultaneous application of LOM with biochar or BCW could provide both short- and long-term benefits to SQ.

Organic inputs, including biochar and BCW, can promote the relative abundance of arbuscular mycorrhizal fungi (AMF) which form symbiotic root associations with about 80% of vascular plants (Wang et al., 2019). They produce glomalin and stimulate root exudation which can modify residual soil C and enhance microbial activity. Fungal filaments and their metabolic products are also binding agents at the soil meso- and macroaggregate levels (Carneiro et al., 2015; Thies et al., 2015). Thus, AMF improve agglomeration, forming more stable macroaggregates which can enhance the hydrological properties of soil. Additionally, AMF are essential in the establishment and maintenance of arable crops as they increase the recovery of water from subsoil and improve the cycling of macronutrients (e.g. N and P) using their hyphae (Mickan et al., 2016; Vasconcellos et al., 2016). Addition of biochar made from pine woodchips to a P-deficient Andosol stimulated AMF abundance and hyphal function which led to increased P accessibility and uptake from high-P soil patches, thereby enhancing plant growth (Shen et al., 2016). Biochar and BCW particles may also serve as suitable habitats for AMF. The extent of fungal colonization will depend on the amount and nature of labile organic molecules and C present in the amendment materials (Thies et al., 2015).

Depending on the nature of enzyme-soild phase interactions, the impact of organic inputs on enzyme activities in soil can vary (Paz-Ferreiro et al., 2012). For example, decreased activities of β-glucosidase (BG) and phosphatase (40%) were observed in soil following addition of pinewood and grass biochars (Foster et al., 2016), whereas arylsulphatase activity was found to be unresponsive to sewage sludge biochar (applied at 4 and 8% w/w) amendment (Paz-Ferreiro et al., 2012). On the other hand, Oladele (2019) found increased activities of invertase, alkaline phosphatase, urease and catalase following soil incorporation of rice husk biochar (12 t ha^{-1}) which also led to a reduction in soil concentrations of pH-lowering rhizospheric carboxylate secretions. Rice yield at the high biochar rate (12 t ha^{-1}) was lower compared to lower application rates (3–6 t ha^{-1}), therefore reiterating the need for selecting biochars tailored to specific purposes.

Soil mesofauna, especially earthworms, are crucial for their role in OM distribution, litter fragmentation, and macroaggregates formation and therefore considered important biological indicators of SQ. Earthworms can ingest soil particles including organic materials, hence contributing to their dispersion and reduced BD (Elmer et al., 2015). Soil management practices, including biochar and BCW amendment, must therefore have no detrimental consequences on soil mesofauna. Biochar produced from spent coffee grounds applied to soil at 5% w/w or above can induce oxidative stress in earthworms (*Lumbricus terrestris*) which could lead to a reduction in their body mass (Sanchez-Hernandez et al., 2019). Under different conditions, Li et al. (2011) showed that earthworms (*Eisenia foetida*) exhibited no signs of oxidative stress in response to apple wood sawdust-derived biochar applied to soil at 20% w/w. Zhang et al. (2019) found increased earthworm (*Eisenia foetida*) weight and decreased toxicity in a pesticide (mesotrione)-polluted soil following amendment with plant-derived biochars at 1 and 3% w/w, whereas 10% w/w biochar caused DNA damage even in the absence of mesotrione. This shows that the effect of biochar amendment on earthworms may be contingent on the earthworm species and type of biochar and soil.

While there is ample understanding of the effects of biochar on soil properties and crop productivity, plant physiological responses are not yet well covered. The impact of BCW-derived HSs on bell pepper morphology and physiology when exposed to different levels of water stress was investigated in sandy and clay soils by Qin and Leskovar (2018). When subjected to four irrigation levels (20, 40, 60 and 80%) based on water-holding capacities of the individual soils, BCW-derived HSs mediated the reduction of stomatal pore conductance and transpiration in bell pepper under the water-stressed conditions (20 and 40% irrigation levels). In soils with moderate or no water stress, plant root development and soil bacteria population were increased. This demonstrates the dual functionality of BCW in soil to mitigate adverse or promote favourable conditions where needed to support plant productivity. The addition of biochar and BCW can offset soil constraints that limit the proper functioning of plants. Biochar significantly improved the yield of lettuce and also increased leaf area (130%), rosette diameter (61%) and root length (100%) of *Arabidopsis* in a study by Viger et al. (2015). It was found that the growth stimulation, however, was accompanied by down-regulation of a large array of plant defence genes comprising the jasmonic acid biosynthetic pathway, defensins and most categories of secondary metabolites. Similarly, while the immobilisation and degradative effects of biochar and BCW on organic pollutants, including pesticides and herbicides have been cited as a benefit against soil toxicity (Vítková et al., 2011; Sadegh-Zadeh et al., 2017), they can also reduce crop resistance against soil pathogens (Nag et al., 2011). It is hoped that this area will be researched more thoroughly in the future to provide clearer insights on how this antithetic aspect of biochar use can still benefit agriculture. This will undoubtedly improve crop productivity which is so often a misused benchmark for measuring the efficacy of organic amendment, especially without considering the intricate details of SQ benefits.

Several studies have investigated the effects of biochar on the productivity of a range of arable crops (Zhang et al., 2012; Devereux et al., 2012; Mete et al., 2015; Jeffery et al., 2017). Malik et al. (2018) found that the application of sludge and straw biochars (at 2 and 4% w/w each) with lime substantially increased dry wheat biomass (60–80%) and grain weight (40–75%) in a strongly acidic Ultisol. Sewage sludge biochar was more effective in reducing soil acidity, whereas straw biochar provided a better combined effect on wheat growth, with 2% w/w application considered more economically feasible for large-scale applications. Elsewhere, Arjumend et al. (2015) reported significant increases in nutrient uptake and growth parameters of wheat following amendment of two soils (loam and silt loam) with BCW-derived HAs added at five different rates (0, 50, 100, 150 and 200 mg kg^{-1}). The 100 mg kg^{-1} selected for assessment of amendment efficacy led to significant increases in (i) soil nutrient status: organic matter, total N, available P and available K (9, 30, 166 and 52%); (ii) plant nutrient uptake: NPK (57, 96 and 62%); (iii) growth parameters: shoot length, root length, shoot dry weight, root dry weight and chlorophyll content (18, 29, 76, 100, 96%); and (iv) yield parameters: grain weight, biological yield, dry matter yield and grain yield (8–16, 18–36, 15–25 and 19–58%), respectively. It was observed that the response to amendment was greater for higher application rate, but responses above 150 mg kg^{-1} were not significantly different. This is supported by Schillem et al. (2019), who found a nearly two-fold average increase in weight of wheat grain cultivated in Quaternary sands amended with N-modified BCW granulates (82% HSs and 5% N) at 5 rates (5, 7.5, 11, 15, 28 t ha^{-1}). The highest amendment rate produced wheat weight more than threefold heavier compared to the control. The role of emerging carbonised organic amendments in crop productivity is promising. However, at current trading and production prices, these materials, especially biochar would not be considered cost effective unless consistent crop productivity is demonstrated from their use.

4. Conclusions and future research directions

Soil applications of carbonised waste organic materials, such as biochar and BCW hold substantial promise for the restoration of SQ. Different types of biochar exist due to differences in feedstock and production conditions, while BCW properties differ with respect to the level of coalification. Therefore, characterisation is important and matching a purpose with a specific type of amendment may be necessary to achieve positive outcomes. The prevailing conditions such as soil type and region (i.e. tropical or temperate zone) should also be considered when selecting a biochar or BCW type. Even though biochar and BCW generally do not have immediate significant impacts, they provide a stable long-term source of SOM which positively influences a broad range of soil properties. Through knowledge transfer (backed up by evidence-based science) and education, farmers must be encouraged to adopt measures that are beneficial in terms of SQ. The options that may be most successful may need long-term commitments. Again, matching a specific amendment type to the problem at hand will be important.

Generally, the addition of high C sources of OM to soils does not necessarily correlate with increased soil fertility, but the associated increased C sequestration is linked to improvement in other soil conditions (e.g. enhanced soil pH and microbial activity) which increases the availability of nutrients. Optimum SOC stock also provides several other soil benefits including improved structure, which minimises risk of erosion, increased water retention for plant use and diverse sources of energy to soil.

Biochar can be used as an amendment in polluted soils and to promote plant available nutrients. Therefore, it has a dual function and provides a win-win scenario in terms of environment and agronomic goals. The high liming potential of biochar means there is an inadvertent tilt in experimental trials towards neutral and acidic soils, with alkaline soils remaining largely untested. An extension of the scope of biochar research to alkaline soils will undoubtedly provide plenary perspectives on a range of biochar applications. Unlike biochar, BCW is weakly acidic and ostensibly unsuitable for soil amendment, given that most degraded soils are often acidic rather than alkaline. However, even in the absence of direct marked liming effects from BCW, it improves SQ and productivity by mediating several other beneficial changes in soil (e.g. increasing the buffering capacity of soil) and has also been used effectively with liming. Consequently, BCW has only been widely used as amendment in HM-polluted soils. It also has potential use in organic pollutants (e.g. pesticides) remediation due to its high aromaticity and sorption capacity for large polar organic molecules. Additionally, the high HA content of BCW (which can be up to 90% d.w.) suggests that it can be of more use in arable agriculture than is currently established. The focus of research on biochar and BCW use should also shift to long-term experiments, as most of the outlined applications of biochar and BCW have been derived from short- to medium-term experiments.

Finally, before the development of policy considerations, there is a need, through coordinated research, to increase confidence in the performance parameters of the different types of biochar and BCW. The costs of producing biochar and for processing the relatively cheaper BCW, pose legitimate questions about the economic feasibility of these materials for large-scale applications. The on-farm mobile pyrolysis unit is currently being trailed and could provide a way to get more farmers to use biochar. A way forward would be the continued investment in low-cost technologies to reduce the production costs of biochar. It has also been shown that simple processing techniques such as the Mechanical Thermal Expression and the Electro kinetic method can rectify problems relating to the high moisture and pollutant contents of BCW at a cheap cost.

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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