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10

Synergisms between Compost and Biochar for Sustainable Soil Amelioration

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1. Introduction

Driven by climate change and population growth, increasing human pressure on land forces conversion of natural landscapes to agricultural fields and pastures while simultaneously depleting land currently under agricultural use (Lal, 2009). Consequently, a vicious circle develops; further aggravating climate change, soil degradation, erosion, loss of soil organic matter (SOM) and leaching of nutrients. Therefore, sustainable concepts for increased food production are urgently needed to lower pressure on soils, in order to reduce or prevent the negative environmental impacts of intensive agriculture. A key for such strategies is the maintenance or increase of SOM level inducing positive ecosystem services such as increased productivity, nutrient and water storage, intact filter capacity, rooting, aeration and habitat for soil organism etc. (Fig. 1). In summary, SOM improves soil fertility and C storage (C Sequestration).

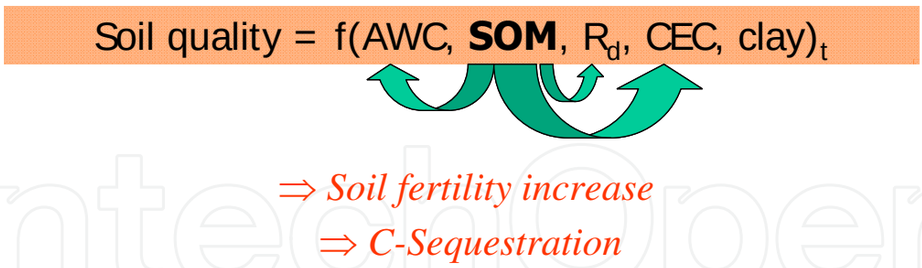


Fig. 1 Soil quality is a function (f) of available water holding capacity (AWC), soil organic matter level (SOM), root density (R_d), cation exchange capacity (CEC), clay content (clay) and time (t). The most important factor is SOM as it improves other variables such as AWC, R_d and CEC.

One efficient way to increase SOM level is compost application, produced especially from biomass wastes. During the last decades, attention was paid at the professionalization of composting due to several trends in today's society: On the one hand, growth of livestock breeding and intensification of crop production has occurred while an increasing shortage of

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resources, i.e. fossil fuels, fossil nutrients stocks and arable land, can be recognized. On the other hand, urbanization and growing population interconnected with an increased amount of waste output is responsible for environmental hazards and pollution. Therefore, composting became an efficient means of waste processing, soil amelioration and general environmental improvement.

However, up to now reported C sequestration potential due to compost management is limited in terms of C use efficiency and long-term C preservation even combined with organic farming and no till management. Therefore, new concepts for C sequestration combating against further raise of atmospheric CO_2 emissions are urgently needed. One promising option is using the "*terra preta* concept" combining biochar and composting technologies. This concept could enhance quality and material properties of compost products leading to a higher added value and to a much better C sequestration potential due to the long-term stability of biochar.

We hypothesize that composting of biochar together with other biogenous materials containing labile organic matter and nutrients can be an appropriate tool to produce a substrate with similar properties as *terra preta* such as enhanced soil fertility and C sequestration. Current available literature will be reviewed on these aspects.

2. Compost

Composting is the biological decompozition and stabilisation of organic matter derived from plants, animals or humans through the action of diverse microorganisms under aerobic conditions (Smith & Collins, 2007). The final product of this biological process is a humus-like, stable substrate, being free of pathogens and plant seeds which can be beneficially applied to land as an agent for soil amelioration or as an organic fertilizer. Although historical traditions such as those of Ancient Egyptians or Pre-Columbian Indians of Amazonia suggest that composting is an ancient method for soil amelioration, fundamental scientific studies of this biological process were published only in the past four decades. Process engineering and the knowledge about the dependence and interaction of numerous competing forces and factors within a composting matrix have been just recently established (Haug, 1993).

Multiple composting methods and systems have been developed, varying from small, home-made reactors used by individual households, over medium-sized, on-site reactors operated by farmers, to large, high-tech reactors used by professional compost producers. In spite of different process techniques, the fundamental biological, chemical and physical aspects of composting remain always the same. This concerns for example the suitability of different input materials and amendments as well as their appropriate composition, substrate degradability, moisture control, porosity, free air space, energy balance as well as decomposition and stabilization (Haug, 1993; Bidlingmaier et al., 2000).

2.1 What is compost and how is it produced?

All proper composting processes go through four stages: (1) mesophilic, (2) thermophilic, (3) cooling, finally ending with (4) compost maturation (Fig. 2). The duration of each stage depends on the initial composition of the mixture, its water content, aeration and quantity and composition of microbial populations (Neklyudov et al., 2006; Smith & Collins, 2007).

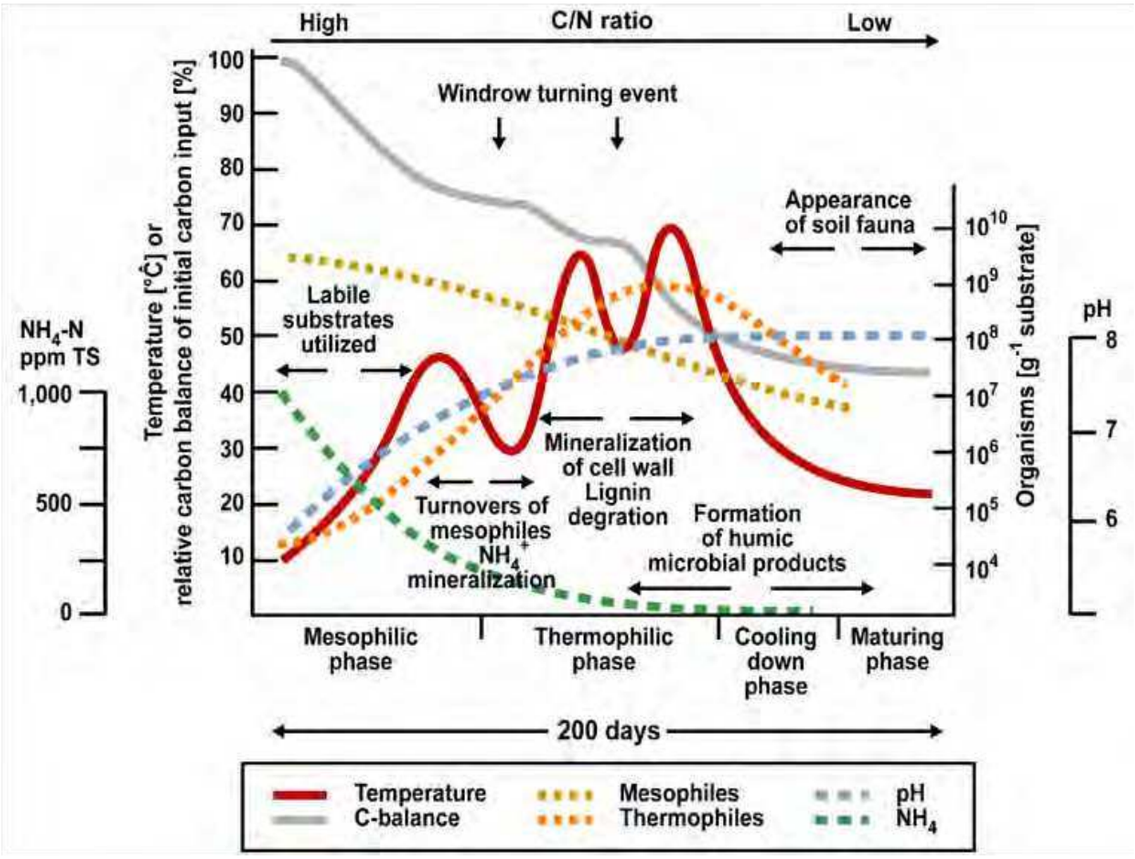


Fig. 2. Different stages during composting as function of time, appearance and succession of compost biota, temperature and further processes (based on Lechner et al., 2005 and Smith & Collins, 2007).

During the mesophilic phase, labile C-rich substrates are rapidly metabolized by a mixture of bacteria, actinomycetes and fungi preferring moderate temperature typically between 15 and 40 °C. Due to this aerobic metabolism, heat is generated. Turning the material leading to aeration temporarily decreases temperature, resulting in a rapid decomposition of further available material and thus, temperature increases again (Fig. 2). During the termophilic phase, temperature rises above 40 °C, favouring mainly actinomycetes and thermophilic bacteria such as *Bacillus*. When labile C compounds of the feed substrates decline, a gradual decrease in temperature occurs leading to the cooling phase (Fig. 2). Especially fungi have a preference for the remaining and more complex and thus degradation-resistant lignin and cellulose compounds. In addition, actinomycetes have a major importance when humic materials are formed from decomposition and condensation reactions Smith & Collins, 2007). The final maturing phase is characterized by even lower temperature below 25 °C and reduced oxygen uptake rates of aerobic microorganisms. During this stage, degradation of the more refractory organic compounds continues and soil meso and macro fauna enters. Organisms of this stage have beneficial influence on compost maturation as well as plant diseases suppression as they are able to metabolize phytotoxic compounds (Gottschall, 1984; Haug, 1993). Thus, compost quality increases especially during the last phase. Compared to the starting feed mixture, the final compost is attributed by a lower C/N ratio of 15 – 20 and

a higher pH value (Smith & Collins, 2007). It can contain considerable amount of plant-available NO_3^- while NO_{4+} content is generally decreasing (Fig. 2). Furthermore, odour potential from compost is significantly reduced (Haug, 1993). But of utmost importance seems the fact that the organic matter has been stabilized, thus containing fairly resistant C compounds (Smith & Collins, 2007). Its application to the land influences several biological, chemical and physical soil properties in a positive and sustainable way which is outlined in Fig. 1 and which will be discussed in the following in more detail.

2.2 How does compost influence soil properties and plant growth?

Numerous publications provide evidence on the multiple benefits of compost application to soil. Effects range from soil stabilization and amelioration to phyto-sanitary impacts of mature compost. Feedstock, compost maturity and compost quality can influence intensity and degree of effects on soil physical, chemical and biological properties. Application may trigger short-term improvements such as increasing microbial activity. Long-term effects on soil properties could be achieved by preservation and increase of the stable SOM pool (Amlinger et al., 2007).

2.2.1 Can soil organic matter be maintained or increased upon compost application?

Soil organic matter is of essential importance for maintaining soil quality by improving biological, physical and chemical soil conditions (Fig. 1). It consists of a variety of simple and complex carbon compounds. While the stable SOM pool is characterized by hardly decomposable organic compounds with several beneficial, long-term effects for soil amelioration and conservation, the labile pool of SOM provides easily accessible food for soil organisms and nutrients for plant growth (Termorshuizen et al., 2005). Soil fauna, notably earthworms (*Lumbricidae*), in turn, positively influence a wide variety of different physico-chemical properties. These positive effects are especially caused by their feeding behaviour, bioturbation and the production of droppings consisting of organo-mineral complexes. The latter is of main importance for the formation of stable SOM pools in soils.

Even though the importance of SOM for the ecological functionality, efficiency and performance of soils is obvious, its worldwide reduction due to intensive agriculture gives cause for concern (Lal, 2009). According to Termorshuizen et al. (2005), this reduction has multiple reasons, but increased SOM mineralization rates due to intensive soil tillage and use of mineral fertilizers, which has often resulted in decreased application of organic soil conditioners and fertilizers, are among the most important ones.

In order to sustain agricultural productivity in the long term, SOM needs to be maintained by continuous addition of organic residues and amendments. Soil organic matter reproduction rate increases in the order green manure, leaves 15%, slurry, straw, liquid digestate 20 – 30%, fresh compost, stable manure, solid digestate 35 – 45%, mature compost > 50% (Table 1). The main factors for SOM enrichment are quantity, type and humification degree of compost and soil properties such as soil type and clay content. Mature composts increase SOM much better than fresh and immature composts due to their higher level of stable C (Bundesgütegemeinschaft Kompost e. V. [BGK] & Bundesforschungsanstalt für Landwirtschaft [FAL], 2006). There are few trials which show no significant differences in SOM level by the application of diverse C sources (straw, manure, compost). But the

majority of studies of different authors have unambiguously proven a better humus reproduction for composted materials (Amlinger et al., 2007).

According to Amlinger et al. (2007), the average SOM demand of agriculturally used soils can be met by applying 7 – 10 Mg (dry matter) compost ha^{-1} a^{-1}. Therefore, for a long-term increase of SOM, however, more than 10 Mg dry matter compost ha^{-1} a^{-1} is required.

Organic fertilizer	Organic matter (dm)	Organic C (dm)	Humus reproduction	TOC increase [Mg ha^{-1}]
Green manure, leaves	90%	52%	15%	0,4
Slurry, straw, liquid manure	75%	44%	20-30%	0,5
Fresh compost, stable manure, solid digestate	50%	50%	35-45%	1,0
Mature compost	36%	50%	>50%	1,3

Table 1. Organic matter and SOM reproduction of different organic fertilizers when applied at 10 Mg ha^{-1} a^{-1} (Data from BGK & FAL, 2006).

2.2.2 How are physical soil properties influenced?

Reduction of Bulk Density: Compost application generally influences soil structure in a beneficial way by lowering soil density due to the admixture of low density OM into the mineral soil fraction. This positive effect has been detected in most cases and it is typically associated with an increase in porosity because of the interactions between organic and inorganic fractions (Amlinger et al., 2007).

Increase of aggregate stability: In general, soil structure is defined by size and spatial distributions of particles, aggregates and pores in soils. The volume of solid soil particles and the pore volume influences air balance and root penetration ability. As a general fact the more soil structure is compacted, the more unfavorable are the soil conditions for plant growth. By incorporation of compost into the soil, aggregate stability increases most effectively in clayey and sandy soils. Positive effects can be expected by well humified (promoting micro-aggregates), as well as fresh, low-molecular OM (promoting macro-aggregates). Macro-aggregates are mainly stabilized by fungal hyphen, fine roots, root hair and microorganisms with a high portion of easily degradable polysaccharides (Amlinger et al., 2007). Subsequently, the importance of stronger degraded organic compounds for the stabilization of smaller aggregates increases with time of transformation periods ranging from some few to several thousand years (Kong et al., 2005; Lützow et al., 2008; Marschner & Flessa, 2006). In this respect, the aromatic structure of inert organic compounds seems to play an important role in stabilizing micro-aggregates in the range of 2 – 20 µm as well as 20 – 250 µm by polyvalent cation bridges with clay minerals (Tisdall & Oades, 1982). Besides clay minerals and oxides, fine roots, hyphen networks as well as glue-like polysaccharides originated from root and microbial exudates significantly contribute to the formation of micro-aggregates.

Furthermore, aggregate and pore properties of soils are associated with specific "active" surface area influencing several storage and exchange processes in soil. The higher the specific surface area, the more intensive interactions can occur between soil fauna, microorganisms and root hairs under optimum conditions (e.g. sufficient humidity). As a result, a high specific surface area can create the prerequisite for an optimal soil formation (Amlinger et al., 2007).

Improvement of pore volume and hydraulic conductivity: Hydraulic conductivity is the percolation rate in soils per area and time unit depending on (i) actual soil moisture tension

and (ii) number, size and form of soil pores (pore size distribution). Organic matter applied by compost improves water conductivity of soils (Carter et al., 2004) by providing a food source for soil organisms which contribute to the formation of macro-pores, in turn. Additionally, it has a direct structure-stabilizing effect for soil. A resulting increase of hydraulic conductivity is of main importance, especially for clayey soils.

Increase of field capacity, secondary pore structures and improved water retention: Field capacity (FC) is defined as the amount of water which a water-saturated soil can retain against gravity after 2 – 3 days. It is mainly influenced by pore volume and pore size distribution because only pores below a pore diameter of 50 µm (corresponding to pF 1.8) can retain water against gravity due to higher capillary force. However, adhesive force of pores with a diameter below 0.2 µm is so high that this water is not available for plants (permanent wilting point or PWP corresponding to pF 4.2). Field capacity and available water holding capacity (AWC, pF 1.8 – 4.2) are generally influenced by the particle size, structure and content of OM. Several studies confirm a significant, positive impact of OM amendment to soils on FC (Evanylo et al., 2008; Tejada et al., 2006; Carter et al., 2004). Amongst others, this effect results from the improved formation of secondary pore structures which can be mainly ascribed to root and animal tubes. This is important for soils with low portions of primary meso-pores. In this respect, compost increases the portion of meso- and macro-pores because of an improved aggregation and stabilization of soil significantly initiated by various soil organisms (Liu et al., 2007). In addition, organic matter (OM) is able to take up 3 to 20 times more water compared to its own weight. Considering these effects, an increase of total organic carbon (TOC) content from 0.5% to 3% resulted in a duplication of AWC (Hudson, 1994).

Improved air balance: The portion of air in soils results from the difference between total pore volume and the pores filled with water (Amlinger et al., 2007). Air permeability and air exchange in soils predominantly depends on pores > 50 µm. While sandy soils are characterized by a high portion of primary macro pores resulting in a proper aeration, clayey or compacted soils have few macro pores which may cause lack of oxygen availability. For these latter soils, OM applied by compost has a significant ameliorating effect by improving porous soil structure and its stabilization, stimulating the formation of secondary macro pores especially by roots and animals tubes.

Reduction of soil erosion and run-off: Reduced erosion is mainly related to the improved soil structure by the addition of compost which, in turn, is pointed out by better infiltration rate, pore volume and enhanced stability through aggregation (Diacono & Montemurro, 2010). According to Amlinger et al. (2007), experimental trials showed a clear correlation between increases of SOM, reductions of soil density, soil loss and water run-off. The effect of compost on soil erosion has been quantified in detail by Strauss (2003). Five years long compost application resulted in 67% reduced soil erosion, 60% reduced run-off, 8% lower bulk density and 21% higher OM content compared to control plots. Similar results were observed by Hartmann (2003) in a wind tunnel experiment by testing the resilience of compost application against wind erosion for two different soil types: By the incorporation of compost, loss of soil particles from the topsoil was reduced to a maximum of 61 % for a podzol and 71 % for a luvisol.

Improved heat balance of soils: Soil temperature influences the reaction rate of chemical, metabolic and biological growth processes of organisms. While temperature fluctuations

mainly depend on climate, radiation absorption can be influenced by color. Composts are dark-colored resulting in higher light absorption and thus lower albedo (reflection rate of light from a light source). Thus, higher light absorption will warm up soils supplied with compost faster than light-colored soils (Stöppler-Zimmer et al., 1993). This will promote germination of seeds, especially during spring. However, as temperature increases in summer, uncovered dark soils can heat up extremely. As a result, soil can dry out due to a higher evaporation which, in turn, affects plant growth and soil biology negatively. In such case, compost mulching systems offer a good solution because they obtain reduced fluctuations of soil temperature which results from the shading effect of mulch loosely covering the soil surface.

2.2.3 How are chemical soil properties influenced?

Enhancement of nutrient level: Compost contains significant amounts of valuable plant nutrients including N, P, K, Ca, Mg and S as well as a variety of essential trace elements (Seiberth & Kick, 1969; Bischoff, 1988; Lenzen, 1989; Haug, 1993; Smith & Collins, 2007). Thus, compost can be defined as an organic multi nutrient fertilizer (Hartmann, 2003; Amlinger et al., 2007). Its nutrient content as well as other important chemical properties like C/N ratio, pH and electrical conductivity (EC) depend on the used organic feedstocks and compost processing conditions (Table 2). By an appropriate mixture of these organic input materials humus and nutrient-rich compost substrates can be produced (Table 3) serving as a substitute for commercial mineral fertilizers in agriculture. However, their diverse beneficial properties for amelioration outreach their nutrient content.

	TOC	TN	C/N ratio	pH_{H2O}	Total P	Total K	Total Ca	Total Mg	Reference
	--- g kg^{-1} DM ---				---------- g kg^{-1} DM ----------				
Household waste	368	21.7	17	4.9					Eklind et al. (1997).
Manure	330	22	15	9.4	3.9	23.2	9.1	4.8	Kimetu et al. 2008
Wood chips	394	14.3	28	7.4	3.5				Larney et al. 2008
Sawdust	490	1.1	446	5.2	0.1	0.4	1.5	0.1	Kimetu et al. 2008
Straw	358	1.0	138	8.3	4.0				Beck-Friis et al. (2001); Larney et al. 2008
Canola	457	1.9	24	6.3	1.1				Yuan et al. 2011
Rice	412	8.7	47	6.8	1.1				Yuan et al. 2011
Soybean	440	23.8	18	6.3	0.9				Yuan et al. 2011
Pea	436	35.0	12	6.3	4.6				Yuan et al. 2011

DM = dry matter
TOC = total organic carbon
TN = total nitrogen
EC = electrical conductivity

Table 2. Chemical properties of organic feedstock materials.

However, total nutrient content of compost is not plant-available to the full extent at once. This can be ascribed to the existence and different intensity of various binding forms within the organic matrix which result in a partial immobilization of nutrients (Becker et al., 1995). On the one hand, this condition makes it more difficult to calculate the fertilization effect and to estimate the nutrient balance in advance (Becker et al., 1995). On the other hand, the fertilization effect will last longer due to a slow and gradual release of plant nutrients (Smith & Collins, 2007). Therefore, with compost there is a much better protection from leaching compared to soluble mineral fertilizers. Especially the N fertilization effect of compost is limited due to

Table 3. Chemical properties of compost products.

	Water content	OM	TOC	TN	C/N ratio	pH_{H2O}	EC (1:5)	NH_4^+–N	NO_3^-–N	Total P	Total K	Total Ca	Total Fe	Refference
	%	% DM	--- g kg^{-1} DM ---				dS m^{-1}	--- mg kg^{-1} DM ---		--- % DM ---			g kg^{-1}	
Municipal solid waste	42.1	48.6	252	17	16.4	5.9	10.9	2100						Alluvione et al, 2010; Annabi et al, 2007; Vaz-Moreira et al. 2007
Bio-waste		36.2	181	19	9.5	8.5								Annabi et al, 2007
Domestic waste	36.2	38.3	192	15	12.8	6.8	0.5	<LD						Vaz-Moreira et al, 2007
Vermicompost	9.5	31.4	157	13	12.1	6.5	8	70						Vaz-Moreira et al, 2007
Green waste	37.9		291	0.8	38.3			41	135					Dalal et al, 2009
Green waste + Sludge		48.5	242	24	10.1	6.6								Annabi et al, 2007
Sewage Sludge	59.6	52.6	319	28	18.1	4.8	6.5	1030	51.5	1.3	1.9	0.1	12.8	Ahmad et al, 2008; Bar-Tal et al, 2004; Beraud et al, 2005; Vaz-Moreira et al. 2007
Manure														
Farmyard manure		36.2	210	11	19.1	8		40	120	0.5	0.5			Badr EL-Din et al. 2000
Feedlot manure	28.2		313	2.6	12			4.2	0					Dalal et al, 2009
Poultry	24.7	46.8	278.5	33.9	8.4	8.3	9.2	2900		0.6	4	6	0.1	Ahmad et al, 2008; Vaz-Moreira et al, 2007
Cattle		25.2	225	18	13.4	7.6	8	32.5	946.5	0.8	2.9	0.6	3.3	Ahmad et al, 2008; Bar-Tal et al, 2004; Beraud et al, 2005

DM = dry matter
OM = organic matter
TOC = total organic carbon
TN = total nitrogen
EC = electrical conductivity
LD = limit of detection (=0,04 mg kg-1)

low mineralization rates and microbial immobilization (Kehres, 1992, Vogtmann et al., 1991). In the first year after compost application, only 10 – 20% of the total N content will be mineralized according to Becker et al. (1995). Bidlingmaier et al. (2000) reported N mineralization rate of 10% in the first year and 40% in total in the long term. In contrast to the low N availability, a higher fertilization effect for P (50%), K (100%) and Mg could be observed (Bidlingmaier et al., 2000). With respect to micro nutrients, an increased plant uptake of Cu, Mn and Zn was reported (Amlinger et al., 2007).

Increase of cation exchange capacity (CEC): The CEC is one of the most important indicators for evaluating soil fertility (Fig. 1), more specifically for nutrient retention and thus it prevents cations from leaching into the groundwater. Kögel-Knabner et al. (1996), Kahle & Belau (1998) and Ouedraogo et al. (2001) proved that compost amendment resulted in an increase of CEC due to input of stabilized OM being rich in functional groups into soil. According to Amlinger et al. (2007), SOM contributes about 20 – 70% to the CEC of many soils. In absolute terms, CEC of OM varies from 300 to 1,400 $cmol_c\ kg^{-1}$ being much higher than CEC of any inorganic material.

Increase of pH value, liming effect and improved buffering capacity: Soil pH is is an indicator for soil acidity or soil alkalinity and is defined as the negative logarithm of hydrogen ions activity in a soil suspension. It is important for crop cultivation because many plants and soil organisms have a preference for slight alkaline or acidic conditions and thus it influences their vitality. In addition, pH affects availability of nutrients in the soil. Compost application has a liming effect due to its richness in alkaline cations such as Ca, Mg and K which were liberated from OM due to mineralization. Consequently, regularly applied compost material maintains or enhances soil pH (Kögel-Knabner et al., 1996; Diez & Krauss, 1997; Kahle & Belau, 1998; Stamatiadis et al., 1999; Ouedraogo et al., 2001). Only in some few cases a pH decrease was observed after compost application (Zinati et al., 2001).

Reduction and immobilization of pesticides and persistent organic pollutants (POPs): A contamination of soils or composts with pesticides and POPs can occur in consequence of environmental pollution, conventional farming practice by using chemicals and pesticides and by incorporation of contaminated materials into compost or soil. Therefore, unpolluted feedstocks should be generally preferred for composting in order to avoid critical concentrations of pollutants. However, pesticides and POPs can be degraded or immobilized during compost processing or by the properties of the final compost product. Based on temperature and oxidative microbial and biochemical processes, composting contributes to an effective reduction of organic pollutants. For instance, polychlorinated biphenyls (PCB) were degraded up to 45% during composting (Amlinger et al., 2007). Linear alkylbenzene sulphonates (LAS), Nonylphenols (NPE) and Di (2-ethylhexyl) phthalate (DEHP) which are mainly found in sewage sludge, are degraded almost completely under oxidative conditions (Amlinger et al., 2007). Furthermore, the degradation rate of halogenated organic compounds and pesticides is much higher than in soils, especially during the thermophilic stage (Amlinger et al., 2007). Mineralization rate of pollutants is reported to be more effective in compost soil mixtures if mature compost is applied. This concerns especially the degradation of polycyclic aromatic hydrocarbons (PAH) and other hydrocarbons (Amlinger et al., 2007). Due to the high level of humified OM, particularly mature composts contribute to sorption and immobilization of POPs resulting in a lower availability of POPs and reduced toxicity.

Immobilization of heavy metals: Similar to pesticides and POPs, there are several sources for heavy metal input. To a limited extent, heavy metals or trace elements serve as plant nutrients while their accumulation can cause toxicity. In this respect, OM applied by compost is able to adsorb heavy metals and reduce their solubility resulting in immobilization. Apart from some non-crystalline minerals with very high surface areas SOM has probably the greatest capacity to bond most heavy metals (Amlinger et al., 2007). The sorption strength of heavy metals to SOM generally decrease in the following order: Cr(III) > Pb(II) > Cu(II) > Ag (I) > Cd (II) = Co(II) = Li(II). On the other hand, significant correlations between the solubility of Cd, Cu, Zn, Pb and Ni and SOM content have been reported by Holmgren et al. (1993) for a range of soils from the USA. Organic matter applied by compost even effectively prevents mobilization of heavy metals for a long time after the cessation of compost addition (Leita et al., 2003). In order to guarantee the lowest possible pollutant input over time, raw materials for composting have to be separated and preferably unpolluted feedstocks should be used. However, the prevention of environmental pollution and thus the contamination with heavy metals is basically a general matter for the society and for politics. As long as there is an emission of pollutants by industry and society immission will occur including the pollution of valuable organic feedstocks.

2.2.4 How are biological soil properties influenced?

One of the most important effects of compost use is the promotion of soil biology. In this respect, the following three aspects seem essential: (i) Food supply for soil heterotrophic organisms by adding degradable carbon compounds with OM (Blume, 1989); (ii) optimization of habitat and niche properties in soil, e.g. water and air balances, increase of specific surfaces, retreat areas etc.; (iii) introducing compost biota into soil as an inoculant (Amlinger et al., 2007; Sahin, 1989; Werner et al., 1988). Compost has a stimulation effect on both the microbial community in the compost substrate as well as the soil-born microbiota of soils (Table 4). Two fractions of OM are responsible for the level of microbial activity in general: (i) Easily degradable organic compounds (labile OM pool) may increase microbial activity and biomass temporarily while (ii) a persisting increase of microbial biomass depends on a constant enhancement of stable OM which is particularly promoted by mature compost addition.

Material	Bacteria [10^6 g^{-1} dm]	Fungi [10^3 g^{-1} dm]
Pesticide containing soil	19	6
Reclaimed soil after surface mining	19-70	8-97
Fertile soil	6-46	9-46
Mature green waste compost	417	155

Table 4. Soil bacterial and fungal biomass in soils and compost (United States Environmental Protection Agency - Solid Waste and Emergency Response, 1998).

Microorganisms perform several ecological and environmental functions. With regard to compost, the following microbial effects seem of main importance:

- Degradation and humification: A gradual breakdown of organic compounds is performed by a succession of different soil organisms over time. While at the beginning

easily degradable organic substances are decomposed, further decomposition and transformation of the remaining by-products occur, finally resulting in a stable humus-like compost product which is subjected to only slow decomposition rates.

- Mineralization, biological immobilization and nutrient cycling: On the one hand, microorganisms convert complex organic substances to low-molecular, inorganic substance. By this mineralization process, nutrients are released for plant growth so that the plant nutrients can cycle within the ecosystem. On the other hand, soil organisms immobilize nutrients into their own biomass. By this way, e. g. N is protected from leaching.
- Aggregation: Microorganisms contribute to the formation and stabilization of aggregates by the synthesis of biofilms and exudates as well as by their living or dead biomass.
- Degradation or reduction of pesticides, POPs and phytotoxic compounds: By microbial metabolism, several chemical compounds which are harmful for plants, can be decomposed, transformed or immobilized.
- Suppression of pathogens and diseases: The diversity of microorganisms in mature composts exhibit suppressive effects on several pathogens and diseases which could harm plant life or human health (Amlinger et al., 2007).

2.2.5 How are plant growth, plant health and crop quality influenced?

In general, compost creates a favourable environment for plant and root growth especially by

1. promoting a porous soil structure for optimized root penetration;
2. decreasing soil erodibility due to the formation of stable aggregates. Consequently, plant roots are less exposed to direct damage caused by eroded topsoil and water can better infiltrate into soil. Furthermore, air exchange is less interfered by the compaction of subsurface soil or by the formation of a soil crust, which tends to "seal" the surface (Buchmann, 1972; Richter, 1979; Krieter, 1980; Fox, 1986; Löbbert & Reloe, 1991);
3. intensifying essential interactions between root hairs, soil fauna and microorganisms due to an enhancement of specific surface area (Amlinger et al., 2007);
4. improving percolation. On the one hand, this prevents waterlogging which can result in a decay of plant roots due to anaerobic soil conditions. On the other hand, loss of nutrients is reduced by decreased run-off;
5. enhancing water storage capacity and improving water retention which helps plants better overcome critical climate conditions like droughts (Hartmann, 2003);
6. providing valuable macro- and micro-nutrients in the long term (Gottschall, 1984) due to slow mineralization rates, better nutrient adsorption as well as enhanced storage capacity which prevents from leaching;
7. improving buffering capacity which helps to maintain uniform reactions and conditions for better plant growth;
8. promoting the degradation, reduction or immobilization of harmful substances like pesticides, POPs, heavy metals and phyto-toxic compounds which can interfere plant life and health;
9. providing microbial symbionts and beneficial soil organisms a habitat which, in turn, has a positive influence on vitality and growth of plants;
10. protecting plants from pathogens and diseases due to antiphytopathogenic potential of compost (Hoitink, 1980; Nelson & Hoitink, 1983; Hoitink & Fahy, 1986; Blume, 1989; Hadar et al., 1992; Bidlingmaier et al., 2000);

Due to its multiple positive effects on the physical, chemical and biological soil properties, compost contributes to the stabilization and increase of crop productivity and crop quality (Amlinger et al., 2007). Long-term field trials proved that compost has an equalising effect of annual/seasonal fluctuations regarding water, air and heat balance of soils, the availability of plant nutrients and thus the final crop yields (Stöppler et al., 1993; Amlinger et al., 2007). For that reason, a higher yield safety can be expected compared to pure mineral fertilization. Better crop results were often obtained if during the first years higher amounts of compost were applied every 2nd to 3rd year than by applying compost in lower quantities of < 10 Mg (DM) ha^{-1} every year (Amlinger et al., 2007). However, crop yields after pure compost application were mostly lower when compared to mineral fertilization (Amlinger et al., 2007), at least during the first years. This can be explained by the slow release of nutrients (especially nitrogen) during mineralization of compost.

Compost use does not only improve the growth and productivity of crops in terms of quantity but it could be also proved that quality of agricultural products is influenced in a positive way (Söchtig, 1964; Flaig, 1968; Harms, 1983). By examination of several crops in situ, an increase of beneficial and healthy ingredients and a decrease of harmful substances in the final crop product after compost use compared to a treatment with mineral fertilizer application were observed (Vogtmann et al., 1991). In addition, Fricke et al. (1990) reported significantly higher dry matter content of beet root as well as a lower nitrate level after compost amendment compared to mineral fertilized sets. In a second trial with potatoes, the same authors detected a higher content of starch, vitamin C and dry matter for the compost-treated plants compared to the mineral fertilization variant. Furthermore, the portion of marketable potato tubers with respect to the total yield was enhanced in the compost treatment.

In spite of the potential and observed beneficial effects of compost application to agricultural soils, this technique is not widespread across Europe and especially in Germany, low quality composts are produced due to inefficient waste management regulations. In addition, long-term C sequestration potential of compost remains insufficient with respect to mitigation of global atmospheric CO_2 increase. Furthermore, as presented by data in Table 5, CO_2 emission during the rotting process of compost production generally

	Fresh compost from bio-waste			Mature compost from bio-waste			Mature compost from yard + parc waste		
	Processing	CO2 emission	Screening	Processing	CO2 emission	Screening	Processing	CO2 emission	Screening
Feedstocks	100			100			100		
loss during rotting process		35			55			55	
compost, not sieved	65			45			45		
compost, sieved	43			25			16		
Screening remains			22			20			29

Table 5. Relative carbon balance in percent of initial carbon input based on data from Reinhold (2009) concerning composting facilities in Germany.

cause high total carbon losses of 35 – 55 % compared to the initial carbon input by organic feedstocks. This fact indicates that current composting practice may be optimized with respect to a more efficient carbon conservation. Therefore, additional concepts such as *terra preta* / biochar are required which will be discussed in the following.

3. Biochar

3.1 How can biochar improve soils?

In central Amazonia, up to 350 ha wide patches of a pre-Columbian black earth-like anthropogenic soil exist, very well known as *terra preta (de Indio*) characterized by a sustainable enhanced fertility due to high levels of SOM and nutrients such as N, P and Ca (Glaser et al., 2001; Glaser, 2007; Glaser & Birk, 2011). However, the key for *terra preta* formation is the tremendous input of charred organic materials, known as biochar comprising up to 35% of SOM and on average 50 Mg ha^{-1} (Glaser et al., 2001). Biochar acts as a stable C compound being degraded only slowly with a mean residence time in the millennial time scale. Biochar has a high specific surface area (400 – 800 m^2 g^{-1}), it provides a habitat for soil microorganisms which can degrade more labile SOM. In addition, higher microbial activity accelerates soil stabilization as outlined in the previous section. Furthermore, higher mineralization of labile SOM and biochar itself provided important nutrients for plant growth. The general recipe of *terra preta* generation and the principal function of biochar are shown in Fig. 3.

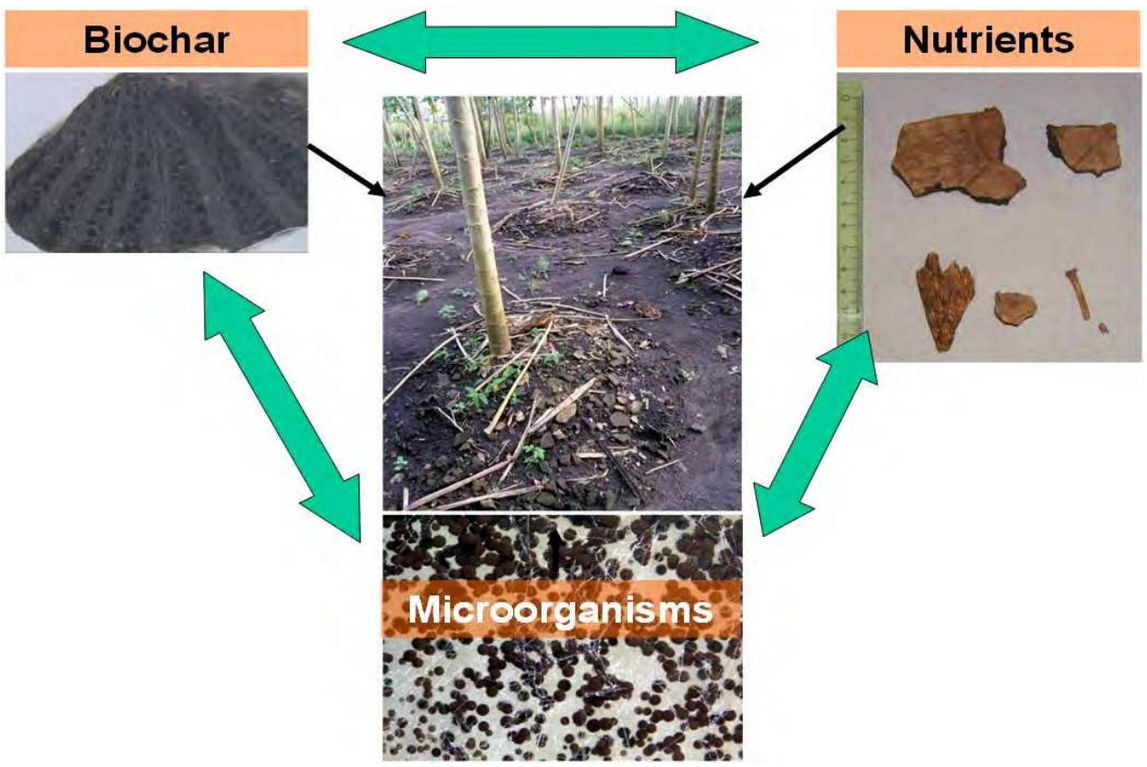


Fig. 3. Principles of terra preta formation and soil biochar interaction.

3.2 What is biochar exactly?

Biochar is produced by thermal treatment at oxygen deficiency e. g. by pyrolysis or gasification, resulting in three products: char, gas and tarry oils. The relative amounts and characteristics of each are controlled by the process conditions such as temperature, residence time, pressure, and feedstock type. Biochar production can be chemically described by water elimination followed by increasing aromatic condensation, which can be expressed as decreasing atomic ratios of O/C and H/C along the combustion continuum (Fig. 4). However, biochar is no clearly defined chemical compound. Instead, it is a class of compounds along the combustion continuum and we need to define thresholds for materials which are claimed to be biochar (Fig. 4). Recently, on the basis of about 100 biochar samples differing in feedstock and production process, the following elemental ratio thresholds were suggested for biochar, O/C < 0.4 and H/C < 0.6 (Schimmelpfennig & Glaser, 2012).

As a consequence, the content of condensed aromatic moieties, known as black carbon, increases being responsible for its stability in the environment. The second important ecological property of biochar is presence of functional groups on the edges of the polyaromatic backbone (Fig. 4) which are formed by partial oxidation (Glaser, 2007). Therefore, biochar is an option for long-term C sequestration while maintaining or increasing soil fertility which was successfully proven by the *terra preta* phenomenon for at least 2,000 years (Glaser, 2007). Due to this fact, *terra preta* could be a model for sustainable resource management in the future not only in the humid tropics but also in temperate and arid regions around the world providing a solution for land degradation due to intensive land use and growing world population. In the following, we will review reported biochar effects on ecosystem services.

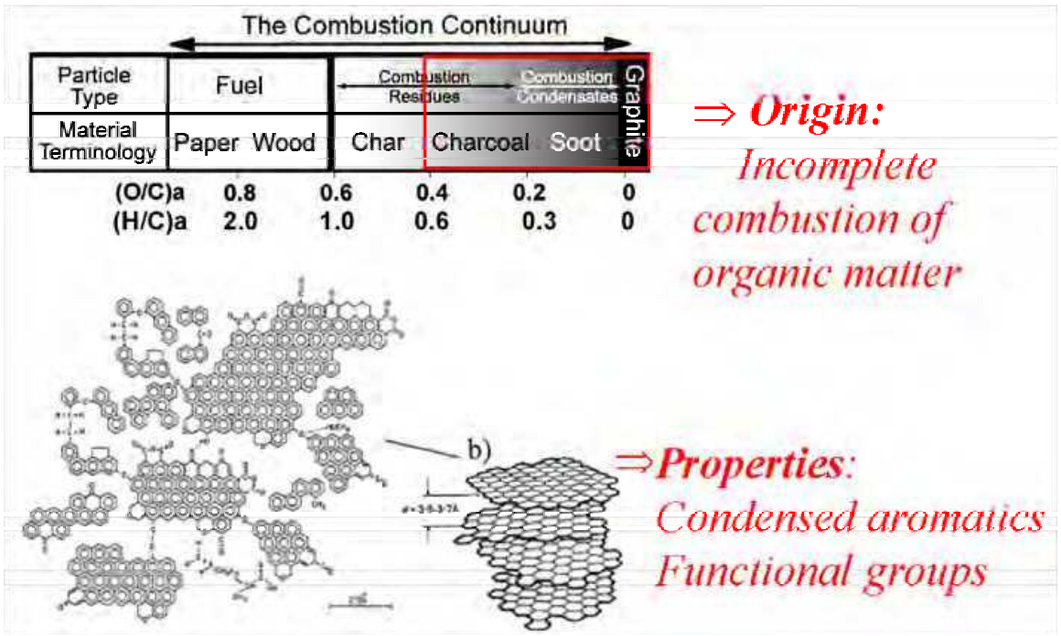


Fig. 4. Combustion continuum and biochar window (red rectangle) and model for biochar structure being important for ecological properties.

3.3 How long will biochar survive in soil?

Due to its recalcitrance against microbial degradation, biochar is very stable in soil compared to other OM additions, making its application to soils a suitable approach for the build-up of SOM and thus, for C sequestration. The prevailing scientific understanding of biochar degradation in soil is that some portions of it are quite readily decomposable (labile), while the core structure of the material is highly resistant to degradation (Fig. 4). Biochar in *terra preta* has been dated to 1,000 to 1,500 years (Glaser et al., 2000) and naturally occurring biochar in Australian soils to 1,300 – 2,600 years (Lehmann et al., 2008). As SOM decomposition rates in temperate regions are slower, mean residence time for biochar can be assumed to be higher in European soils. Controlled biochar decomposition experiments revealed a mean residence time in soils between 1,300 to 4,000 years (Cheng et al., 2008; Liang et al., 2008; Kuzyakov et al., 2009). Management practices such as tillage and addition of labile C (e.g. slurry) to soil significantly increased biochar mineralization by a factor of 0.5 to 2, however, only in the short-term (Kuzyakov et al., 2009) so that biochar application can be combined with such agricultural technologies without the disadvantage of additional SOM and biochar degradation.

In a range of other biochar incubation experiments, the interactive effects of biochar addition to soil on CO_2 evolution (priming) were evaluated by comparing the additive CO_2 release expected from separate incubations of soil and biochar with corresponding biochar and soil mixtures. Positive (C mineralization stimulation) or negative (C mineralization suppression) priming effects and magnitude varied with soil and biochar type. In general, C mineralization was higher than expected (positive priming) for soils combined with biochars produced at low temperatures (250 – 400 °C) and from grasses, particularly during the early incubation stage (first 90 d) and in soils of lower organic C content (Zimmerman et al., 2011). In contrast, C mineralization was generally less than expected (negative priming) for soils combined with biochars produced at high temperatures (525 – 650 °C) and from hard woods, particularly during the later incubation stage (250 – 500 d). Obtained data strongly suggests that biochar soil interaction will enhance C sequestration via SOM sorption and organo-mineral interaction in the long term.

3.4 How much biochar can be stored in soils?

C sequestration with biochar addition to soils could be quite significant since the technology could potentially be applied in many areas including croplands, grasslands and also a fraction of forestlands. The maximum capacity of carbon sequestration through biochar soil amendment in croplands alone was estimated to be about 428 Gt C for the world (Table 6). This capacity is estimated according to (i) the maximal biochar amount that could be cumulatively placed into soil while still beneficial to soil properties and plant growth; and (ii) the arable land area that the technology could potentially be applied through biochar agricultural practice. If using also grassland soils and 30% of forest soils, a worldwide biochar sequestration potential of 1,126 Gt C would be possible (Table 6).

3.5 Can we solve our climate problem with biochar alone?

Photosynthesis captures more CO_2 from the atmosphere than any other process on Earth. Each year, terrestrial plants photosynthetically fix about 440 Gt CO_2 being equivalent to 120

Applicable world lands	Land area /million hectares	Estimated capacity (GtC) of biochar carbon storage in soil
Croplands	1411	428
Temperate grasslands	1250	380
30% Forest lands	1181	358
Total	3842	1166

Table 6. Potential C sequestration with biochar in soils of the world. Estimated storage capacity is based on a maximum of 10 weight% biochar addition to the upper 30 cm and a soil bulk density of 1.3 Mg m^{-3} and 70% stable carbon in biochar (Lee et al., 2010).

Gt C per year from the atmosphere into biomass (Smith & Collins, 2007). This corresponds to about one-seventh of the CO_2 stock in the atmosphere (820 Gt C). However, biomass is not a stable form of carbon material with nearly all returning to the atmosphere in a relatively short time as CO_2 because of respiration and biomass decomposition. As a result, using biomass for carbon sequestration is no good option. Any technology that could significantly prolong the lifetime of biomass materials would be helpful to global carbon sequestration. A conversion of only about 7% of the annual terrestrial gross photosynthetic products into a stable biomass carbon material such as biochar would be sufficient to offset the entire amount (nearly 9.7 Gt C a^{-1}) of CO_2 emitted into the atmosphere annually from the use of fossil fuels (www.iwr.de). More realistic estimates are that annual net CO_2, CH_4 and N_2O emissions could be reduced by a maximum of 1.8 Pg C a^{-1} without endangering world food security and soil fertility (Woolf et al., 2010) corresponding to 16% of current anthropogenic CO_2 emissions. Therefore, biochar can significantly contribute to climate change mitigation but additional technologies are required to quantitatively offset fossil fuel-derived CO_2 emissions. The substitution of fossil fuels by developing and extending renewable energies is another essential key factor for greenhouse gas emission reduction or avoidance while still meeting the basic requirements of electrical or thermic energy consumption demands of society. An impressive example for such a concept is the integrative combination of innovative technologies: a PYREG pyrolysis reactor unit (Gerber 2010), for instance, locally produces biochars from organic wastes in an environmentally friendly way, while also generating heat and electricity from renewable, carbon neutral resources.

Thus, a decentralized application of this technology represents a promising and sustainable strategy for the future.

3.6 Can biochar increase soil fertility and thus crop performance?

Biochar application to soil influences various soil physico-chemical properties. Due to the high specific surface area of biochar and because of direct nutrient additions via ash or organic fertilizer amendments, nutrient retention and nutrient availability were reported being enhanced after biochar application (Glaser et al., 2002; Pietikäinen et al., 2000). Higher nutrient retention ability, in turn, improves fertilizer use efficiency and reduces leaching (Steiner et al., 2008; Roberts et al., 2010). Most benefits for soil fertility were obtained in highly weathered tropical soils but also higher crop yields of about 30% were obtained upon biochar addition in temperate soils (Verheijen, 2009). Furthermore, enhanced water-holding

capacity can also cause a higher nutrient retention because of a reduced percolation of water and the herein dissolved nutrients (Glaser et al., 2002).

However, since biochar has only low nutrients contents in general, plant nutrients must be supplied externally (Woods & Mann, 2000; Glaser & Birk, 2011). With respect to potential nutrient sources, only C and N can be produced in situ via photosynthetic organisms and biological N fixation, respectively. All other elements, such as P, K, Ca and Mg must be added for nutrient accumulation (Glaser, 2007) which can be best achieved by adding organic fertilizers such as manure or compost (Schulz & Glaser, 2011).

3.7 The role of soil organisms

According to Ogawa (1994), biochar is generally characterized by a proliferation effect for several symbiosis microorganisms due to its porous structure providing an appropriate habitat for soil microbes. Steiner et al. (2004) observed a significant increase of microbial activity and growth rates by applying biochar to a Ferralsol. Furthermore, an increase of soil microbial biomass and a changed composition of soil microbial community were also observed after biochar amendments (Birk et al., 2009).

While microbial reproduction rates after glucose addition in soils amended with biochar increased, soil respiration rates were not higher (Steiner et al., 2004). This difference between low soil respiration and high microbial population growth potential is one of the characteristics of *terra preta*. These results indicate that a low biodegradable SOM together with a sufficient soil nutrient content are able to support microbial population growth. According to Birk et al. (2009), these effects can be ascribed to different habitat properties in the porous structure of biochar. The following factors might be the reason in decreasing order of currently available evidence supporting them:

- high surface area and porous structure of biochar suitable for several kinds of microbes as habitat and retreats;
- enhanced ability to retain water and nutrients resulting in a stimulation of microbes;
- formation of 'active' surfaces covered by water film, dissolved nutrients and substances providing an optimal habitat for microorganisms; these specific surfaces serve as interaction matrix for storage and exchange processes of water and substances between soil fauna, microorganisms and root hairs (Amlinger et al., 2007);
- weak alkalinity (Ogawa, 1994);
- preserving character against decay probably resulting in the (partial) inhibition of certain 'destructive' and pathogenous organisms while simultaneously supporting beneficial microbes.

Based on these possible stimulating factors, biochar promotes the propagation of useful microorganisms such as free-living nitrogen fixing bacteria (Tryon, 1948; Ogawa, 1994; Nishio, 1996; Rondon et al., 2007). Further reports from Japanese scientists prove increased yields by the stimulation of indigenous arbuscular mycorrhizal fungi (AMF) via the application of biochar (Ogawa, 1994; Nishio, 1996; Saito & Marumoto, 2002): e. g. improved yields for soybeans because of enhanced nodule formation by means of biochar addition (Ogawa et al., 1983). Results from Nishio (1996) obtained with alfalfa (*Medicago sativa*) in pot experiments indicate that biochar was ineffective in stimulating alfalfa growth when added

to sterilized soil. However, alfalfa shoot weight was increased by a factor of 1.7 and nodule weight by 2.3 times in a treatment receiving biochar, fertilizer and rhizobia compared to a set only treated with fertilizer and rhizobia. According to Nishio (1996), this clearly indicates that the stimulatory effect of adding biochar may appear only when a certain level of indigenous AMF is present. Biochar amendment generally seem to stimulate soil fungi which seems logic as biochar is a complex matrix being degradable only by soil fauna and soil fungi (Birk et al., 2009).

4. Combined compost and biochar

4.1 Effect of process (mixing, composting, fermentation)

Terra preta was most likely formed by mixing of charring residues (biochar) with biogenic wastes from human settlements (excrements and food wastes including bones and ashes) which were microbially converted to a biochar-compost-like substrate (Glaser et al., 2001; Glaser, 2007; Glaser and Birk, 2011). Thus, co-composting of biochar and fresh organic material is likely to have a number of benefits compared to the mere mixing of biochar or compost with soil. Examples are enhanced nutrient use efficiency, biological activation of biochar and better material flow management and a higher and long-term C sequestration potential compared to individual compost and biochar applications (negative priming effect).

Compared to compost and biochar mixing, an increased decomposition of biochar can be expected during composting although biochar is much more stable than other organic materials. As observed by Kuzyakov et al. (2009), biochar decomposition rates increase as long as easily degradable C-rich substrate is available. Additionally, Nguyen et al. (2010) reported that higher temperature increased biochar oxidation and thus decomposition. However, these effects are much lower for biochar than for compost feedstock. On the other hand, surface oxidation will enhance the capacity of biochar to chemisorb nutrients, minerals and dissolved OM. The overall reactivity of biochar surfaces therefore probably increases with composting (Thies & Rillig, 2009).

From the compost point of view, there is evidence that biochar as a bulking agent improves oxygen availability and hence stimulates microbial growth and respiration rates (Steiner et al., 2011). Pyrolysis condensates adsorbed to biochar initially provoked increased respiration rates in soils which most likely occur also during composting (Smith et al., 2010). Biochar in compost provides habitats for microbes, thereby enhancing microbial activity. Steiner et al. (2011) reported increased moisture absorption of biochar-amended composts with beneficial effects on the composting process.

It was often stated in non-scientific literature, that *terra preta* was formed by anaerobic fermentation of biochar with organic wastes using "effective microorganisms ®" (EM ®) which consist mainly of a mix of lactic acid and photosynthetic bacteria, yeasts, actinomycetes as well as other genera and species of beneficial microorganisms (Higa & Wididana, 1991). However, there is no scientific proof for this and from a practical point of view it is most unlikely that pre-Columbian Indians manually moved tremendous amounts of soil and organic wastes for fermentation in closed containers. For the average dimension of *terra preta* being 20 ha wide and one meter deep, 200,000 m^3 or 260,000 tons of soil would have being moved by hand twice (forth and back) for terra preta generation which is most unlikely.

Nevertheless, fermentation theoretically provides microorganisms to soil which could be beneficial for soil health and ecosystem services. In a composting / fermentation experiment with and without biochar, the overall C loss during fermentation was about 30% lower when compared to composting (Fig. 5). However, when composting the fermented material, overall OC loss was even higher compared to the composted only material (Fig. 5). This indicates that fermented OM is only stable as long as it was kept anaerobic. As soon as piles were turned (after fermentation) and oxygen became available, the intermediate fermentation products were mineralized to an even higher extent than the non-fermented counterparts (Fig. 5). Biochar addition appeared to amplify fermentation-induced stabilization, since compost piles with 50 (DEM50) and 100 (DEM100) kg biochar per ton of organic feedstock material showed reduced OC loss compared to the fermentation control without biochar (DEM0, Fig. 5).

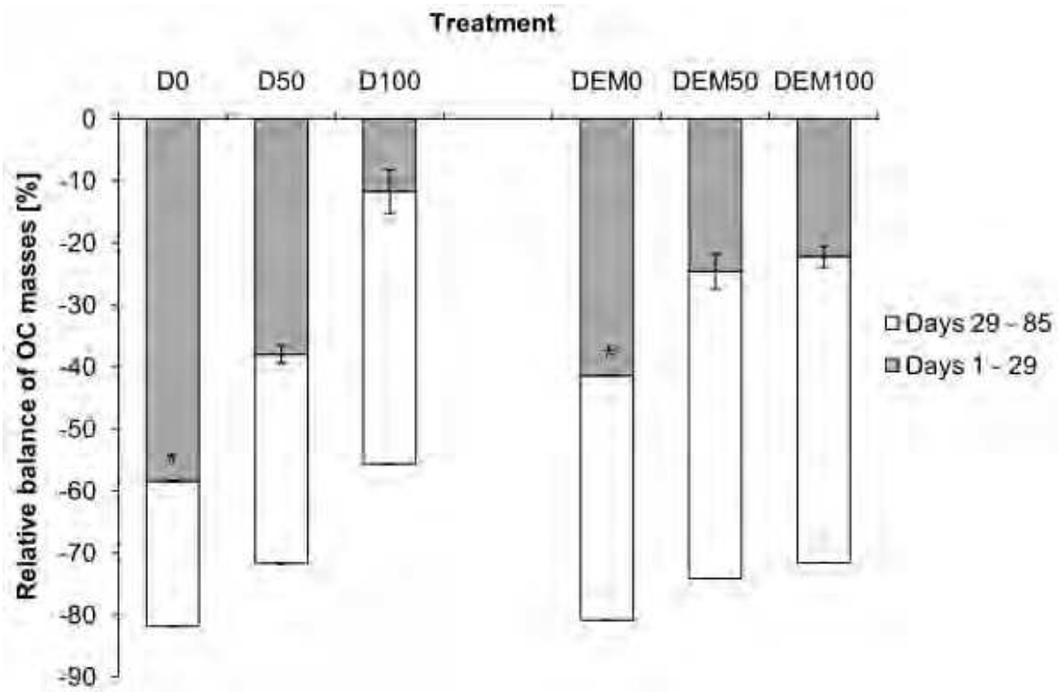


Fig. 5. Relative mass balance of organic carbon (OC) during fermentation (Days 1 – 29) and composting (Days 9 – 85; means ± standard error; significant differences between 'Days1-29' OC losses of D0 and DEM0 (see asterisks), $p < 0.05$, n=3, tested with a Student's t-test). D0, D50 and D100 are composted materials at 0, 50 and 100 kg biochar addition per ton of composted materials, respectively, For DEM 0, 50 and 100 it was the same approach but during the first 29 days of the experiment, these piles were incubated with effective microorganisms under anaerobic conditions (Erben, 2011).

Fermentation-induced negative priming of fresh OM could indeed be observed, but only as a temporary effect which was reversed during subsequent composting. Thus, fermentation did not result in an enhanced stabilization of compost. A distinct effect of the EM preparation could not be identified (Erben, 2011). Nevertheless, benefits of fermentation in OM treatment and for soil application remain to be assessed.

4.2 C sequestration and priming as function of biochar amount

Biochar could cause a positive priming effect due to its high surface area providing habitat for microorganisms and due to input of partly labile C substrate (condensates). On the other hand, biochar is a stable compound which could stabilize labile compost OM thus providing a negative priming effect.

Composting of biochar could be successfully conducted over a wide biochar / organic material ratio covering up to 50% biochar by weight. During composting, a relative enrichment of biochar was observed which is obvious as biochar is much more stable than organic waste materials (Erben, 2011). However, biochar caused a significant positive priming effect on non-biochar composting materials at low (up to 1 weight%) biochar concentrations (Erben 2011) while at high (up to 50 weight%) biochar concentrations a significantly negative priming effect could be observed (Erben, 2011; Fig. 5). Therefore, a synergistic benefit for overall C sequestration could be observed when biochar was composted together with organic waste material (Erben, 2011). Further co-benefits might arise for soil microbial biomass and community structure composition and for biochar surface oxidation which still has to be proven scientifically.

Combining biochar addition and fermentation resulted in negative priming (Fig. 5), but the effect was weaker here than that of non-fermented treatments and hence ascribed rather to biochar alone than to its reinforcement of fermentation-induced negative priming.

4.3 Synergisms for soil fertility and plant growth

Combination of biochar with inorganic and organic fertilizers is clearly advantageous over the sole biochar or fertilizer amendments (Fig. 6). Plant growth significantly increased after biochar addition. Although pure compost application showed highest absolute yield during two growth periods, biochar compost mixture revealed highest relative performance. It should be mentioned here that biochar compost mixture received only 50% of pure biochar and 50% of pure compost treatments, thus providing evidence for biochar compost synergism (Fig. 6). In addition, it can be expected that in the long-term, compost will be mineralized more quickly than biochar or compost biochar mixtures. Mineral fertilizer retention was significantly more efficient when biochar was present although biochar did not increase cation exchange capacity at least after the first harvest (Schulz & Glaser, 2011). In comparison to mere mineral fertilizer there were clear advantages of plant growth and soil quality of the biochar-amended soils, especially when combining fertilizer (both inorganic and organic) with biochar. Therefore, optimization of biochar compost systems will be discussed in the following.

In a greenhouse experiment on a sandy soil under temperate climate conditions, plant growth (and thus soil fertility) generally increased with increasing amendment of biochar-compost (Fig. 7). This effect is more pronounced in a (nutrient-poor) sandy soil compared to a loamy soil (Fig. 7). It is interesting to note however, that at individual application rates, a synergistic effect of higher biochar application is obvious in the sandy soil (Fig. 7). This is even more interesting as biochar application rates were generally low with a maximum of 10 kg biochar per ton of compost material.

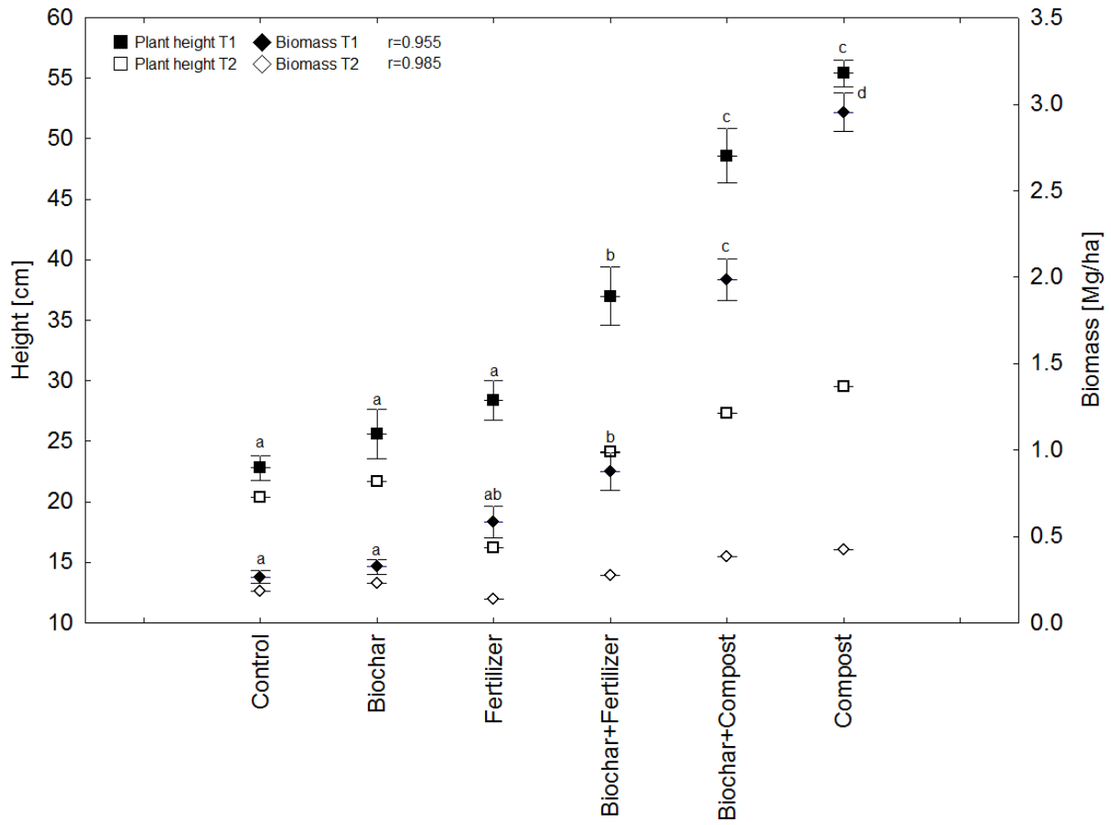


Fig. 6. Crop (oats, *Avena sativa*) response of two consecutive harvests on a sandy soil amended with different materials. Treatments comprised control (only water), mineral fertilizer (111.5 kg N ha^{-1}, 111.5 kg P ha^{-1} and 82.9 kg K ha^{-1}), compost (5% by weight), biochar (5% by weight) and combinations of biochar (5% by weight) plus mineral fertilizer (111.5 kg N ha^{-1}, 111.5 kg P ha^{-1} and 82.9 kg K ha^{-1}) and biochar (2.5% by weight) plus compost (2.5% by weight) (Schulz & Glaser, 2011).

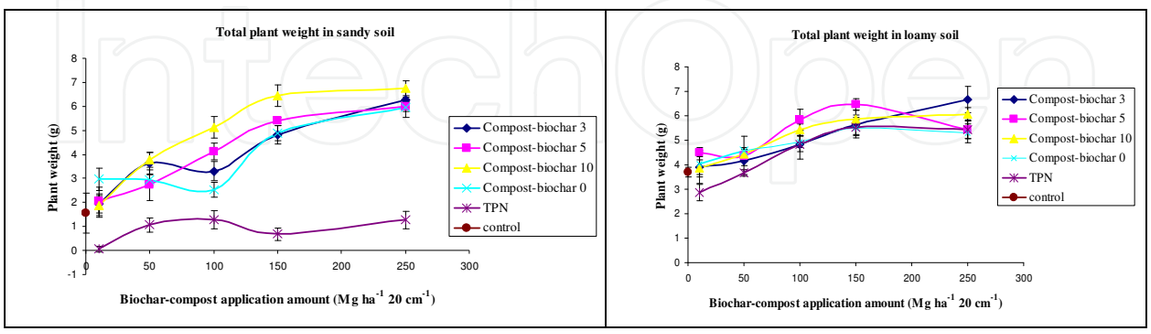


Fig. 7. Crop (oats, *Avena sativa*) response on a sandy (left) and loamy (right) soil with increasing biochar-compost amendments (x axis) at low biochar additions (3, 5 and 10 kg per ton of compost, different symbols) compared to control soil (without amendments) and a commercial biochar-containing product (TPN) (Schulz and Glaser, unpublished).

When looking at high biochar amounts, crop (oats, *Avena sativa*) yield significantly increased with increasing amounts of biochar and compost amendments, both for sandy (Fig. 8 left) and loamy soils (Fig. 8 right). However, in both cases, plant growth response was higher for biochar than for compost (sand: plant weight = 2.490 + 0.00676 compost + 0.0400 biochar, loam: plant weight = 4.088 + 0.0144 compost + 0.0349 biochar).

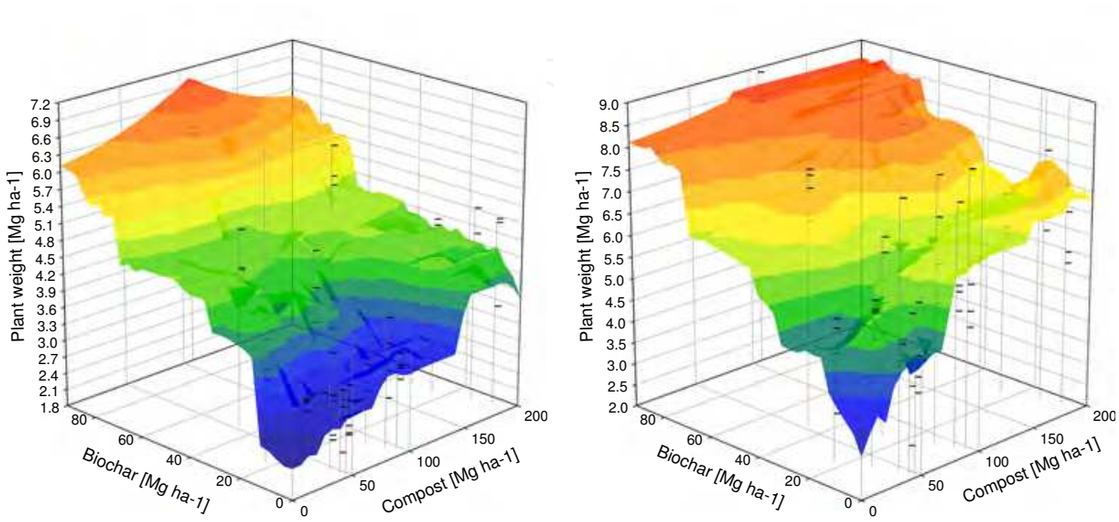


Fig. 8. Crop (oats, *Avena sativa*) response on a sandy (left) and loamy (right) soil with increasing biochar-compost amendments at high biochar additions (Schulz & Glaser, unpbulished).

4.4 Can combined biochar compost processing contribute to optimized material flow management?

By taking into account that *terra preta* formation was originally induced by human activity relying on the combined incorporation and biological transformation of charred stable OM on the one hand and nutrient-rich, organic feedstocks on the other hand (Fig. 3), it seems obvious that *terra preta* genesis can be understood as a sustainable and optimized management of natural resources. However, *terra preta* soils do not normally occur under conditions in which just compost or mulching material have been applied. Therefore, the addition of biochar can be recognized as a key factor for the reproduction of Terra preta similar substrates (chapter 3.1). However, the sole addition of charred biomass does also not result into the formation of *terra preta* soils. Thus, nutrient incorporation and microbial activity can be specified as further key factors.

In this respect, it seems to be a promising approach to combine the existing scientific knowledge about ancient *terra preta* genesis with modern composting technology to promote positive, synergestic effects for an efficient and optimized management of natural resources including 'organic wastes' to create humus and nutrient-rich substrates with beneficial effects for soil amelioration, carbon sequestration and sustainable land use systems. Fig. 9 gives a synthesis of the information about composting and biochar application and their beneficial effects hitherto presented in this review to show options for a sustainable material flow management.

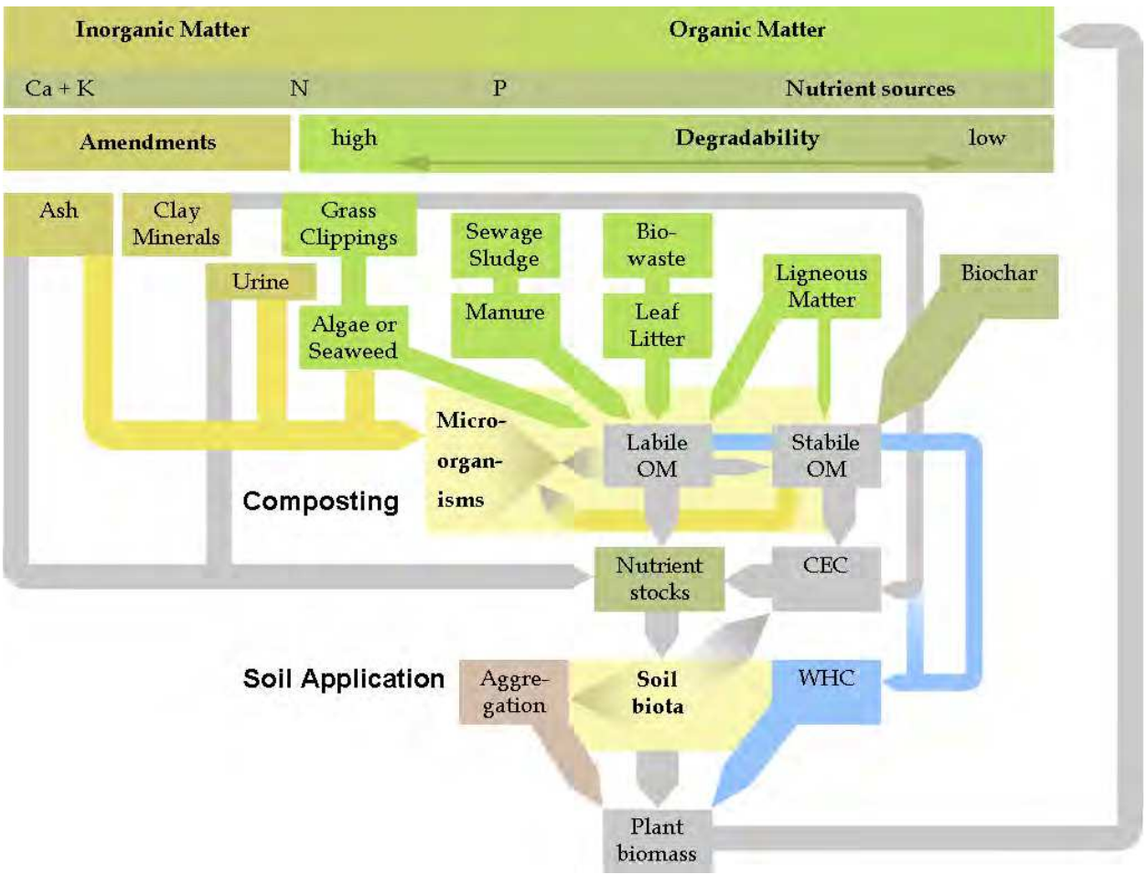


Fig. 9. Sustainable management of natural resources by combining biochar with organic and inorganic wastes in compost processing (based on Glaser & Birk, 2011).

Based on the model of *terra preta* genesis (Glaser & Birk, 2011) various organic and inorganic feedstocks are mixed for composting providing different nutrients resources. Ideally, their physico-chemical properties should complete each other promoting an appreciable C/N ratio, water content, aeration, nutrient composition etc. of the initial compost pile. Besides their nutrient level, the used organic input materials can be characterized by their biological degradability and their contribution to different carbon pools. N-rich feedstocks such as grass clippings are easily decomposable particularly contributing to the labile OM pool which is used as an easy available food source of microorganisms and thus providing optimum conditions for a rapid rotting process. In contrast, ligneous materials are characterized by a lower degradability due to their higher lignin content partially contributing to the stable OM pool which has beneficial long-term effects for soil amelioration, carbon sequestration (Fig. 1) as well as humus reproduction (Table 1). The most recalcitrant material towards biological degradation is represented by biochar contributing at most to the stable OM pool of substrate mixtures. During subsequent aerobic decomposition OM getting stabilized resulting in an increase of stable C content. According to Yoshizawa et al. (2005) biochar promotes this rotting process due to its functions as a matrix for the involved aerobic microorganisms probably increasing decomposition speed. An co-composting experiment with poultry litter and biochar applied by Steiner et al. (2010)

seems to confirm the accuracy of this assumption since changes in pH and moisture content with greater peak temperatures and greater CO_2 respiration suggest that composting process was more rapid if poultry litter was amended with biochar. In the same study the authors detected a reduction of ammonia emissions by up to 64 % and a decrease of total N losses by up to 52% if poultry litter was mixed with biochar. These observations support the hypothesis of higher nutrient retention ability induced by biochar amendment previously mentioned in this review.

Furthermore by the proliferation of microorganisms on the biochar backbone as well as between its pores, Yoshizawa et al. (2005) suggest that biochar properties are influenced by biological processes. Especially slow oxidation of biochar over time has been suggested to produce carboxylic groups on the edges of the aromatic backbone, increasing the CEC (Glaser et al., 2000). Due to higher temperature during compost processing, especially during thermophilic stage, biological activity as well as chemical reaction rate is increased, probably accelerating the partial oxidation and formation of functional groups of the amended biochar material but also interaction with labile OM and with minerals is favoured.

Besides the importance of biochar incorporation, additional amendments like clay minerals can add further value to the final compost product, e.g. by promoting an enhanced CEC or WHC due to their high adsorption or swelling capacity. Furthermore, their incorporation into organic substrates promotes the formation of organo-mineral complexes initiated by the biological activity of soil fauna after subsequent soil application. This aspect seems important since SOM in *terra preta* is stabilized by interaction with soil minerals (Glaser et al., 2003).

Other amendments like ash, excrements or urine contribute to the nutrients stock of the final composting product and can enhance microbial activity by their nutrient supply (Glaser & Birk 2011). According to Arroyo-Kalin et al. (2009) and Woods (2003), ash may have been a significant input material into *terra preta*, too. Furthermore for providing adequate moisture conditions during composting urine can be added instead of water for preventing the dehydration of composting piles while adding nutrients at the same time.

After compost maturation, the final compost substrate can be beneficially applied to soils. In this respect, the soil biota contribute to a further transformation of the applied material and provide essential ecological services, for instance by promoting aggregation and further OM stabilization. By enhancing the specific biological, physical and chemical properties of soils amended with the biochar composting substrates, plant growth is generally promoted.

5. Conclusions

Our review clearly demonstrated beneficial effects of compost for ecosystem services. In addition, it is a promising tool for sustainable management of natural resources (soils, organic 'waste'. Especially two of the major problems of modern society (anthropogenic greenhouse effect and desertification) could be coped with proper compost technologies. However, as compost has only a moderate SOM reproduction potential, strategies for further optimization are required. These could be applying the *terra preta* concept, especially

the integration of biochar into management of natural resources. Recent studies provide optimism for synergistic effects of compost and biochar technologies for ecosystem services and for sustainable management of natural resources including 'organic wastes'.

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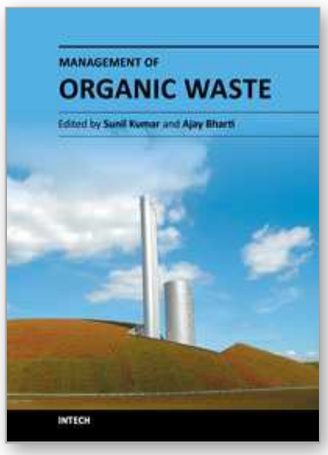
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Management of Organic Waste
Edited by Dr. Sunil Kumar

ISBN 978-953-307-925-7
Hard cover, 198 pages
Publisher InTech
Published online 01, February, 2012
Published in print edition February, 2012

This book reports research on the utilization of organic waste through composting and vermicomposting, biogas production, recovery of waste materials, and the chemistry involved in the processing of organic waste under various processing aspects. A few chapters on collection systems and disposal of wastes have also been included.

How to reference
In order to correctly reference this scholarly work, feel free to copy and paste the following:

Daniel Fischer and Bruno Glaser (2012). Synergisms between Compost and Biochar for Sustainable Soil Amelioration, Management of Organic Waste, Dr. Sunil Kumar (Ed.), ISBN: 978-953-307-925-7, InTech, Available from: http://www.intechopen.com/books/management-of-organic-waste/synergism-between-biochar-and-compost-for-sustainable-soil-amelioration

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