Terra Preta Sanitation 1

Background, Principles and Innovations

Deutsche Bundesstiftung Umwelt

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TUHH
Hamburg University of Technology

aww
Institute of Wastewater
Management and Water Protection

GFEU e. V.

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Deutsche Bundesstiftung Umwelt

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Foreword

»Water, water everywhere not any drop to drink.« is no longer just a stanza from the poem »The Rime of the Ancient Marinere by S. T. Coleridge«.

This indeed is the case with millions of people who lack safe drinking water due to poor sanitation. Poor sanitation is responsible for transmission of many diseases like cholera, typhoid, and infectious hepatitis. Scientific studies have also shown that many children are malnourished not due to lack of food but due to poor sanitation. As the standard of living of certain sections of the people in developing and under-developed countries is high enough to have and use mobile phones, poverty alone cannot be held responsible for the open defecation or poor sanitation problems. It is often the availability of solutions which are simple, reliable and culturally acceptable with some economic benefits. On one hand there is no clean water and on the other hand the soils are degrading through loss of nutrients. It is necessary to replenish the soil with nutrients so as to maintain soil fertility.

Terra Preta composting is one such age old technology from Amazon forests which leads to a special type of soil with high nutrient storage chapacity. Developing countries which have a huge gap in installed waste-water treatment capacity against required capacity can directly leapfrog onto technologies or systems that are resource recovery oriented.

This handbook on Terra Preta sanitation (TPS) will serve as a guide to practitioners and individuals interested in new sanitation approaches.The aim is to provide an overview of this emerging technology and briefly examine the nexus of food security, sanitation and poverty in a global context. The book is highly compelling as it presents a coherent narrative of Terra preta formation processes and an in-depth analysis of the scientific basis and the management practices of the TPS system. The whole TPS development process has been iterative where the methodologies and the designers knowledge gradually improve, and inputs over time become a matter of ongoing fine tuning as opposed to re-invention. The chapters have been carefully chosen and laid out in a logical framework to facilitate understanding, even to the non-practitioner.

The handbook begins with an introduction by Prof. Ralf Otterpohl who discusses about synergistic systems for sustainable living. Chapter I focuses on the history of Terra Preta which is very useful to beginners. Chapter II discusses charcoal production which is a key ingredient of Terra Preta sanitation. Chapter III and IV discuss the different ways of integrating Terra Preta sanitation in existing sanitation systems. Chapter V deals with hygienisation of the organic matter and Chapter VI presents an example from Asian where the TPS approach is successfully applied since many centuries.

On the whole this handbook provides a holistic view of a simple and reliable sanitation approach which also leads to increased soil fertility.

Srikanth Mutnuri

Associate Professor,
Applied Environmental Biotechnology Laboratory
Birla Institute of Technology and Science – Pilani, K K Birla Goa campus
Goa, India

Introduction: Synergistic Systems for living Soil, Water, Food and Energy

Ralf Otterpohl

The Sustainability debate has lead to the assumption that the ecosystem is of equal importance as the social and the economic aspects. However, in real life the social aspect is a sub-set of the ecosystem; and economy is clearly a subset of the social aspect. The aggressive marketing of dangerous agro-chemicals takes a lot of money out of the local added value while contributing to water pollution and degradation of our most important resource: humus. If we really want to create a good future for all life on earth we need to give directions for economic activities that serve people while enhancing the productivity, diversity and health of our planet, too. Many good and proven solutions for thriving rural areas are available; but every year millions of children die as a result of fecal matter flushed into water, millions more grow up with nutrition-related disabilities including permanent brain damage due to starvation. This is a sign for a widely failed world society and there is no excuse for inaction. Misuse of economic and political power has reached an incredible dimension. How can all those wonderful tools that benefit the locals but not anonymous shareholders be spread out? We do know that most large civilizations were breaking down after degrading their arable lands (Montgomery, 2007) and often along with the soils of the regions they appropriated by war. City life, too, depends on sufficient living soil for water, food and balanced climate. Rural regions are the key to abundance of nature (vegetation) and climate resilience. Over one-third of all arable land has been strongly degraded or destroyed globally (UN millennium ecosystem assessment, UNEP 2005) with the consequence of major changes of local climate, more drought and flooding and loss of food security. The destruction is on-going and is driven by powerful corporations most of which will a strong influence on nations' legislation. Rural populations usually lack support, but they can act with proper methods of improving local economy. Most of the powerful restoration solutions are not well known, some even contradict common beliefs. Restoring local economy will first and foremost require caring for or building of living soils.

01. Good soil makes Water

Humus rich soils can absorb enormous amounts of water. Long and intensive rain events that would lead to devastating flooding in a catchment with degraded soils can be soaked up by living soil. The same water will contribute to restoring aquifers and soil can remain moist for long periods, avoiding drought and reducing the need for irrigation. The key issue for water and food security is soil quality, mainly the humus content in the living top soil layer. The disregard for this most crucial issue contributes to further degradation. One of the biggest threats for water is agricultural activity that is built on readily soluble mineral fertilizers and toxic pesticides and herbicides. Commercial mineral fertilizers contain cadmium and uranium through the meanwhile very low quality raw phosphates. These problems can be avoided by means of full reuse of fertilizer through resources oriented sanitation and proper biowaste management. Major tools for improvement of topsoil quality and restoration of degraded land are:

- Implementation of organic agriculture with proper humus management. Capacity building for highly efficient organic methods for high yields. Support of highly efficient horticulture that is producing more food per hectare and offering more employment.
- Soil improvement through clean organic materials: Production of biochar-compost rather than installation of biogas systems. Biogas units convert organic matter to relatively little energy and can lead to a loss in humus feeding capacity. Restriction of biogas systems to regions with abundant biomass production (mainly tropical regions) and to waste and sludge treatment.
- Apply rainwater harvesting on a global scale. This method is based on a number of measures like contour trenching, swales and check-dams for retention and infiltration of rainwater runoff and has proven to be highly efficient. The most efficient measure that should be combined with all others is mostly forgotten though: building humus in the catchment area.
- Reforestation as part of improvement of water retention, flood and drought protection. Ideally and wherever suitable this should include food trees such as Moringa trees. The leaf and fruit are excellent food and fodder with fast growing wood that can be used for producing fuel for woodgas stoves. Theses stoves will produce in turn plenty of charcoal for Terra Preta compost while cooking efficiently.
- Holistic Planned Grazing: Keep larger numbers of grazing animals for fastest soil recovery in the way of high-animal-density-short-impact-time. Any industrial style mass »production« of animals, manure pollution and hormone poisoning can thus be phased out. In exchange we get animals which can express their life the natural way, soil improvement, healthy grass fed, meat and a base for restoring savannah regions on a large scale and in a very profitable way. This type of system has a factor four of productivity over the conventional grazing while restoring land and humus. See »Holistic Planned Grazing« by Allan Savory or Joel Salatin, Polyface Farm, USA.

02. Water efficiency and reuse

When it comes to water efficiency in scientific, political and public debates there is a strange repetition of issues that are already well known. Drip irrigation is still described as an innovation, even though sub-surface systems can work with much less water (not all systems work well though-requiring good soil). The very far reaching possibilities of rainwater harvesting on catchment level with contour swales, check dams, humus building and reforestation especially of uphill areas are mostly not mentioned. Even within the rainwater harvesting community the most efficient tool is mostly forgotten: improvement of the top soil quality in the whole catchment. Another crucial issue is to grow drought adapted plants where water is short instead of water intensive cash crops. However, lack of justice in a global market makes this difficult.

Water utilization in cities and towns should also become more efficient. Many water efficient devices for households are on the market. Unfortunately, in many dry regions like Berlin in Germany there is a lack of political will to have long term plans for water efficiency. For example, savings in hot-water utilization like wash basins and showers are not encouraged even where politicians make the impression to really care for the limitation of fossil energy utilization. There are very few shower heads that do fulfill hygiene regulations with 6 liters per minute (instead of the usual 18!) and allow pleasant showers. A small German company invented a unit with magnificent performance, whereby a vortex swirl inside the shower head producing a sort of bubble rain, with water drops filled with air. Another system is using intermittent feeding of the holes and is also pleasant and safe. However, the usual spray units that are on the market are unpleasant, produce dangerous aerosols where the presence of legionella becomes most dangerous.

Resources oriented systems like Terra Preta Sanitation are based on separate collection and treatment of blackwater. Reuse of nutrients requires low dilution or loop systems, saving a large proportion of the household water. The remaining wastewater, the greywater, can be treated for local or on site reuse easily. It will be necessary to manage rainwater run-off on site with infiltration to avoid the need for expensive central sewerage systems. Infiltration, too opens many ways for producing water locally.

03. Energy systems that restore soil

Supply of energy can be combined with soil restoration. Soil quality is far more important than the energy issue – food, water and a balanced local climate are crucial for all life. Most bio-energy systems are competing with food production and contribute to soil depletion through agro-chemical monoculture and extraction of materials that are essential for feeding the humus layer. Extensive studies have shown that most of bioenergy does not make a lot of sense if seen in a wider context. The main exception is woody materials. While conventional technical devices incinerate wood or woody waste, Terra Preta systems require large amounts of clean charcoal. Interestingly, woodgas stoves as well as woodgas-to-heat/cooling-and-electricity units use woody materials in a highly efficient way. In addition, they produce charcoal at the same time. This opens low-tech (stoves) and high tech pathways to regenerative energy that is actually helping to improve top soil.

The German NGO Climatefarming has developed efficient movable metal woodgas stoves in Senegal and Burkina Faso which can be operated with briquettes made from woody waste and invasive reeds. Users will get a discount on new briquettes by handing in the charcoal produced while cooking. It makes sense to give new fuel in the weight equivalent what will equal a price reduction of about 25 to 30 %. The company ProLehm (Mud-Brick-Producers in Germany) has developed a mud woodgas stove, the ADAM stove. It has a larger pyrolysis chamber to assure longer cooking times and is made for fixed installation.

A lot of development has been done to run engines and electricity generators with woodgas. Some good devices are on the market, but maintenance is still an issue. The NGO Climatefarming (Joerg Fingas) and the institute of this author are consultants to a huge wet rice farm in northern Senegal. The farm had a persistent problem of decreasing productivity after 20 years of agro chemical production. The soil had no more earthworms, which is something alarming. We started co-composting of organic materials from the region with charcoal from the woodgas-to-electricity unit that Climatefarming installed for the rice factory of the farm, running on the otherwise unusable waste material, rice husk. It turned out to be difficult to supply sufficient organic material in a depleted savannah region. Interestingly, the addition of charcoal into the wet rice system alone could raise productivity on average by around 30 % over 4 harvests in large scale trials; which was most probably due to the specific situation in a paddy field. In order to restore soil quality we have recommended introducing an organic system like intermediate planting of Sesbania Rostrata. Otherwise charcoal application should always be part of composting processes, which can also avoid wind or water erosion of the charcoal particles.

Woodgas devices that co-produce power, heat/cooling and charcoal are now available on the market in scales from around 20 KW up to several MW of electricity. However, some woodgas units burn the charcoal for more energy production.

04. Re-Localization, Reverse-Migration and New Town development

Globalization of economy has turned to a disaster for most rural regions of the world. Re-localization of production, taking care of soil and water resources are not trade barriers but a basic method of good housekeeping. It is easily understood that people and corporations use their power to become even more influential. It seems that politics have widely lost the means and/or the will to care for global justice. Therefore it is in the hands of rural communities to reverse their fortunes, reverse rural-to-urban migration and come up with integrated concepts. The methods described above are a great base for improving the local economy and become more resilient. The town of Hiware Bazar in India (see Miracle Water Village) has shown this in a stunning way, mainly with rainwater harvesting combined with reforestation, using water efficient crops and irrigation systems. The town is thriving in a region where other towns are losing population through migration due to water scarcity and drought. Hiware Bazar won a prestigious national prize but politics failed to implement this far reaching model into legislation. Land desertification, starvation that is often causing mentally retarded children and a lack of income is the harsh consequence of ignorance by policies, administration and people.

New Town is an initiative of the author to promote pathways to develop rural areas with a number of proven sustainable solutions. Unlimited urbanization has an enormous risk potential. Actual estimates for 70 % of urban population by 2030 should be seen as a horror scenario; considering that urban dwellers are mostly 100 % dependent of outside supplies. Supply with clean and sufficient water and food are a consequence of land use. It is crucial to establish new lifestyles e.g. with part time commercial gardening, only then there will be sufficient numbers of people working for and with living soils.

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Chapter I: Historical and scientific re-discovery of Terra Preta do Indio

Bruno Glaser and Friedemann Klimek

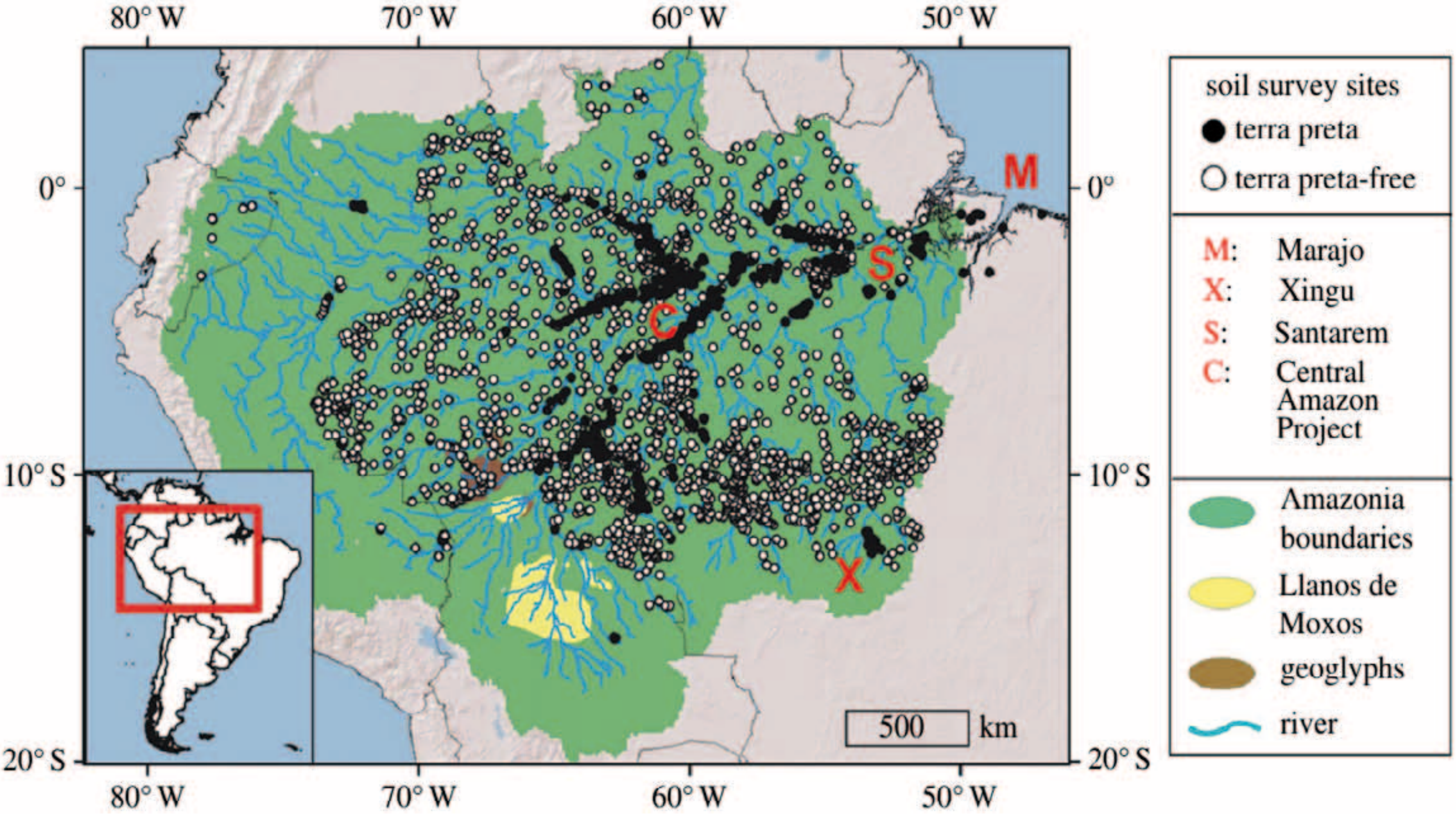

Figure 1.3: Potential Terra Preta occurrence within Amazonia based on known observations and modelling (McMichael et al. 2014).

1.1. History of Terra Preta re-discovery

In 1542, the Spanish conquistador Francisco de Orellana went on a great adventure trip. Together with a group of countrymen, he cruised the Amazon and its tributaries to look for the legendary El Dorado, which was unknown and unexplored at that time. He was accompanied by the Dominican friar Gaspar de Carvajal, who kept records of this journey in a diary (Carvajal ,1934). He reported in his chronicles about Amazons, armed female warriors who fought in the first row of the natives. After this episode, he named the river Amazon. De Orellana reported that they encountered millions of indigenous people, who settled on the river banks in huge, fortified towns, which were densely populated (Table 1.1). For a long period of time, these descriptions were dismissed as fantasy and propaganda because a few records of that adventure trip have been proven as truly fabrications, so the depiction of the indigenous settlements were condemned too. Close to the place, where the river Tapajós flows into the Amazon River, roughly where Santarém is located today, many people must have lived who forced the conquistadors to flee. Later expeditions could not find any of these described references but rainforest. This fate happened to many testimony of human activities and their cultural achievements in that region. In the meantime, the indigenous folks disappeared by pock, flu and other epidemics, which have been introduced by the conquerors from Europe.

Therefore, for a long period of time anthropologists thought that in the rainforests at the Amazon no higher developed civilization could have emerged in the past. Big cities were unthinkable as the acid and unfertile soils common in the tropical forests could not support the food supply of thousands of people. In spite of the above assumptions, one might have expected that the widespread and still partly cultivated dark earths had been studied in more detail. But this was not the case until the Canadian geologist Charles Hartt noticed Terra Preta in the late 1860s as one of the first western scientists (Table 1.1). It took roughly 400 years to get back to this imposing cultural heritage. Hartt was a member of the expedition in 1865/66 led by Louis Agassiz. Even more important to the re-discovery was the establishment of settlements in the Santarém area of former Confederate Civil War soldiers and their families starting in 1867 (Table 1.1). These Confederados learned about the black soils from local farmers and established highly productive crops of sugar cane and tobacco on them. The English-speaking travellers just mentioned naturally visited the English-speaking colonists and observed their soils and fields.

James Orton, an American geologist and explorer, mentioned dark earths in Amazonia for the first time in his book »The Andes and the Amazon« in 1870. In the following ten years, Hartt, his assistant Smith and the British geologists Brown and Lidstone published additional articles (Table 1.1). They all knew each other, interacted and primarily referred to the Santarém region of the lower Amazon.

Table 1.1: Milestones of Terra Preta discovery (Glaser, 2014).

Year	Discoverer	Discovery
1542	Francisco Orellana	Cities with millions of people along the Amazon River
1868	James Orton	»The soil is black and very fertile«
1870	Charles Hartt	Deep black fertile soils with pottery in Brazil
1876	Barrington Brown	Deep black fertile soils with pottery in Guyana
1878	Barrington Brown	First scientific report in which the name »Terra Preta« was used
1879	Herbert H. Smith	Terra Preta is a product of Indian kitchen middens accumulated »the refuse of a thousand kitchens for maybe thousand years«
1885	Charles Hartt	Terra Preta contains ceramic fragments, lithic artifacts, and charcoal
1895-1898	Friedrich Katzer	50,000 ha of Terra Preta south of Santarém First report on anthropogenic origin

25 years later, Friedrich Katzer, a German geologist, conducted first field studies on the chemical characteristics of Terra Preta. He identified the organic matter content giving the black colour and suggested a cultural origin, too (Table 1.1).

From 1920 to 1960, several scientists of different research fields and countries spent time debating whether Terra Preta is natural or anthropogenic (Table 1.2) rather did not work so much on soil analysis. The first more accurate description and investigation on Terra Preta do Indio occurred in the late 1940s and early 1950s. Among these scientists were e.g. Pierre Gourou who mentioned a number of places where this soil can be found. The ceramics therein have been identified by Hilbert as pottery of pre-Columbian Indian tribes. They described the area of Terra Preta patches as often not exceeding 1000 m^2. In the 1960s, scientists discovered relics of pre-Columbian human settlements at the confluence of Amazon, Rio Negro and Madeira rivers (Sombroek, 1966). Still doubting these facts, scientists later returned for more investigations on the pre-Columbian soils to find evidence for their capability to nourish huge civilizations.

Newer research results from the 1980s already describe coherent areas of Terra Preta at an average size of 20 ha (Zech et al., 1990). But very large Terra Preta sites up to 350 ha have also been reported (Glaser et al., 2001). Soil physical and chemical investigations were carried out by Sombroek in the 1960s and by Zech, Smith and Glaser in the 1990s

Table 1.2: Milestones in early Terra Preta »research« which was mainly based on field observations. Please note that most of these studies favoured a natural (geogenic) but only few human (anthropogenic) origin (Glaser, 2014).

Year	Scientist	Origin	Natural	Human
1941	Felisberto Camargo	Volcanic ash	X	
1944	Barbosa de Faria	Sedimented organic matter in dry lakes attracted people to settle	X	
1949	Pierre Gourou	Archaeological		X
1958	Zimmermann	Fluvial sedimentation	X	
1962	Cunha Franco	Sedimented organic matter in dry lakes attracted people to settle	X	
1962	G. Ranzani	Plaggen epipedon		X
1965	Ítalo Falesi	Sedimented organic matter in dry lakes attracted people to settle	X	
1966	Sombroek	Kitchen midden (Terra Preta) Long-term cultivation (Terra Mulata)		X
1968	Hilbert	Archaeological		X

(Glaser et al., 2001). At the same time, first hypothesis about the genesis of Terra Preta emerged. Further research of the Terra Preta do Indio by archaeologists and soil scientists discovered that the soils contain residues of charcoal, artefacts, bones, human excreta, ash and fish bones (Glaser et al., 2001; Glaser 2007; Glaser und Birk, 2012).

There were many different groups working on this topic, previously mostly independently, coalesced and interacted at three international conferences held in 2001–2002. The leadership of Glaser, Woods, Kern, Lehmann and Zech was keys to the successful integration of diverse people at these meetings and in the books that followed. The Lehmann, J.; Kern, D.; Glaser, B.; Woods, W. (2003) volume contains 23 chapters from 55 authors and the Glaser and Woods (2004) volume contains 15 chapters from 27 authors. Some chapters have as many as seven co-authors from four different countries and three different disciplines. This work represents an explosion of knowledge about Amazonian dark earths in less than ten years. However, there is still much more to be learned about these remarkable soils of human origin and their potential for nowadays world.

1.2. Characteristics of Terra Preta

Due to intense weathering, typical soils of the humid tropics are stained red or yellow by haematite or goethite, respectively (Figure 1.1), have acid pH and are very poor on plant nutrients (Zech et al., 1990). Water retention and nutrient retention capacities are very low, as well. Organic matter is decomposed quickly and the nutrients are washed out by heavy rainfalls so that these soils contain only small quantities of soil organic matter (SOM) and plant-available nutrients (Zech et al., 1990).

Figure 1.1: Typical soils of the Amazon region: Xanthic (left) and Rhodic Ferralsol. Pictures by Bruno Glaser.

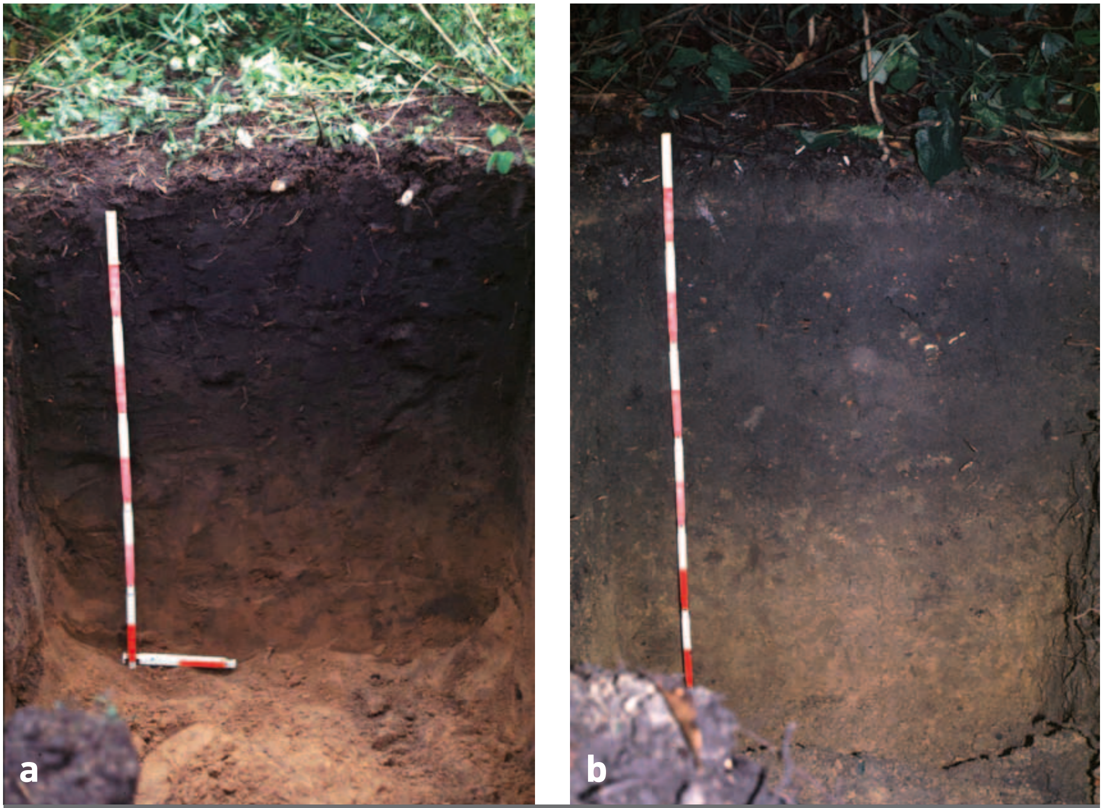

Figure 1.2: Impressive and famous images of Terra Preta soil profiles. Pictures by Bruno Glaser.

Therefore, it is surprising to find soils with opposite properties such as Terra Preta in the Amazonia (Figure 1.2). Herbert Smith (1879) delivered one of the most detailed descriptions about Terra Preta. He wrote that the Amazonian dark earth was »the best [soil] in the Amazons … a fine, dark loam, a foot, and often two feet, thick … [which] owes its richness to the refuse of a thousand kitchens for maybe a thousand years … [in one stretch] it forms almost a continuous line … thirty miles long … and strewn over it everywhere we find fragments of Indian pottery so abundant in some places they almost cover the ground … like shells on a surf-washed beach.« So Smith, and also Hartt, Brown and Lidstone, already clearly recognized the anthropogenic origin of these soils (Table 1.2).

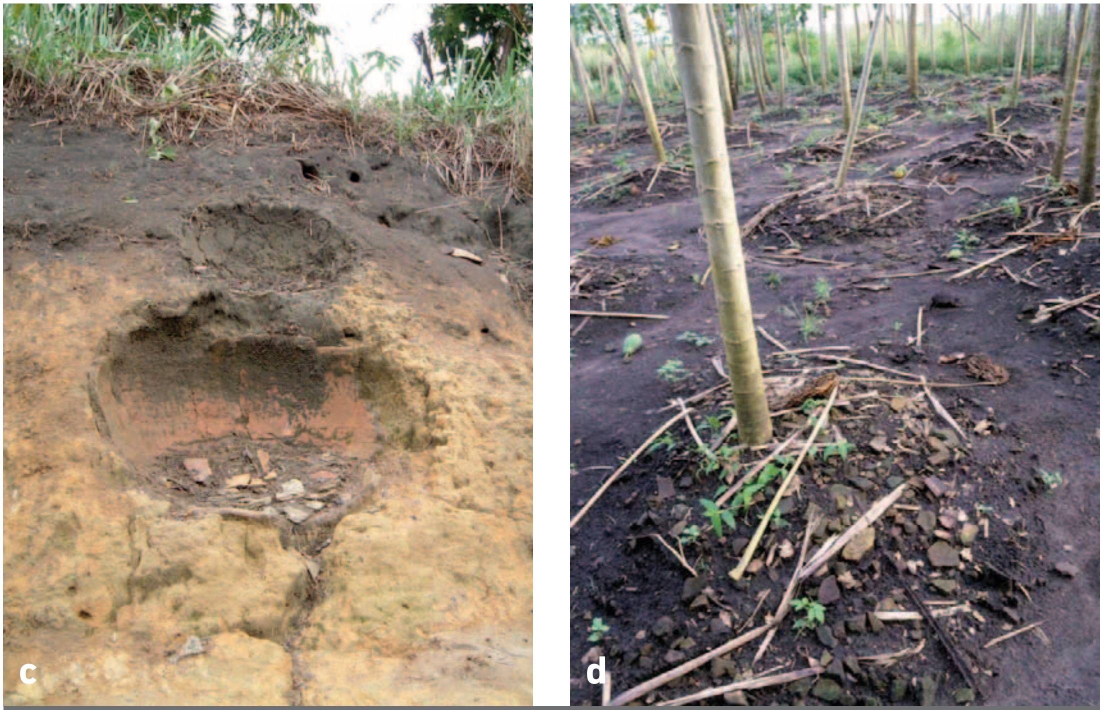

Figure 1.3: Impressive and famous images of Terra Preta soil profiles.
Pictures by Bruno Glaser.

The black earth was mostly found on raised and sheltered riverbanks close to the Amazon and its tributaries (Glaser et al., 2001). At the time of the first European penetration, the then populous Indian tribes used to dwell in well developed communities on dry terrains along the waterways, which were the best sites for fishing, hunting and warfare strategy. These spots are located from Columbia via Santarém and Manaus to the estuary of the stream (Figure 1.3). They are widespread and occur in a variety of climatic, geologic, and topographic situations. Recent investigations showed that Terra Preta occurs at about 154,063 km^2 equivalent to 3.5% of the Amazon rain forest (McMichael et al., 2014, Figure 1.3). They also predicted that Terra Preta formation was limited in most of western Amazonia (Figure 1.3, page 12). Model results suggested that the distribution of Terra Preta was highly predictable based on environmental parameters (McMichael et al., 2014).

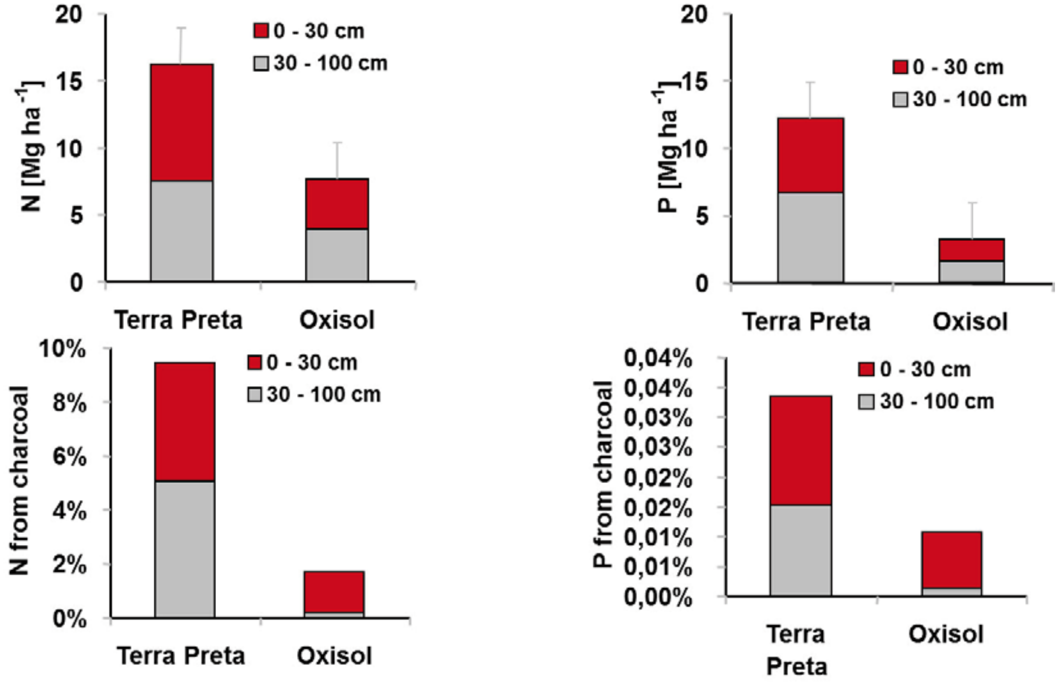

Figure 1.4: Stocks of total nitrogen and phosphorus (top) and potential contribution of biochar (bottom) to these nutrient stocks (Glaser et al., 2003).

Radiocarbon dating indicates that these soils were formed between 7000 and 500 cal yr BP (Neves et al., 2003) and it is most likely that Terra Preta was not made intentionally. Instead, it resulted as a by-product of human occupation (Glaser and Birk, 2012). In addition, Terra Preta is an old settlement place, although it has been under continuous agricultural use for centuries. Thus, the black topsoils are often half a meter thick, sometimes even 2 meters or more and some hundreds, partly even thousands of years old and still very fertile (Glaser et al., 2001).

The enhanced fertility of Terra Preta is expressed by higher levels of soil organic matter (SOM), nutrient-holding capacity, and nutrients such as nitrogen, phosphorus, calcium and potassium, higher pH values and higher moisture-holding capacity than in the surrounding soils (Sombroek, 1966; Zech et al., 1990; Glaser and Birk, 2012; Figure 1.4). According to local farmers, productivity on Terra Preta sites is much higher than on the surrounding poor soils.

The Terra Preta phenomenon is not only restricted to areas in Amazonia but it occurs world-wide on ancient settlement places. Recently, Slavic settlement sites near Gorleben at the river Elbe in Germany were described with similar properties as Terra Preta (Wiedner et al., 2014). Due to a similar genesis to Amazonian Dark Earths these soils were called Nordic Dark Earths (Figure 1.5).

Figure 1.5: Nordic (Slavic) Dark Earth as pendent to Amazonian Dark Earth (Terra Preta). Please note the similarity of both Anthrosols and their infertile adjacent soils (Pictures Bruno Glaser).

1.3. Ingredients of Terra Preta

As mentioned above, Terra Preta contains several ingredients which clearly points to an anthropogenic origin. But which ingredients makes Terra Preta so special? As outlined in Figure 1.6 and summarized by Glaser and Birk (2012), Terra Preta was formed over centuries by repeated input of nutrients in form of garbage and human excrements together with charred residues (biochar). Indigenous soil microorganisms (predominantly saprophytic fungi) recycled the organic materials and made them partly plant-available and partly stabilized them by forming soil organic matter or organo-mineral complexes. Biochar served as habitat for soil microorganisms and contributed to the stability of Terra Preta humus by its inherent chemical recalcitrance (poly-condensed aromatic compounds). The high surface area of biochar further contributed to sorption of labile organic molecules and nutrients. From Figure 1.6 it is clear that biochar plays a prominent role in Terra Preta genesis, as without biochar not stable soil organic matter can be formed under humid tropical conditions. On the other hand, it is also clear that with biochar alone no Terra Preta can be formed due to the lack of nutrients important for plant nutrition.

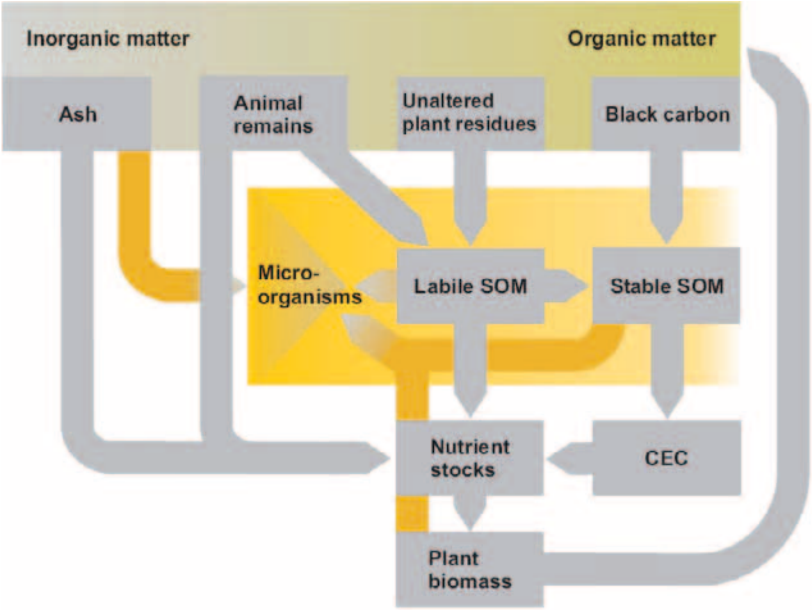

Figure 1.6: Principle of Terra Preta genesis (Glaser and Birk, 2012).

a.) Charcoal: The chemical structure of charcoal in Terra Preta is characterized by poly-condensed aromatic moieties which are responsible for both the prolonged stability against microbial degradation and, after partial oxidation, also for the higher nutrient retention (Glaser et al., 2001). Besides this remarkable chemical structure, the Terra Preta charcoal has a porous physical structure, also being responsible for higher retention of water and dissolved organic nutrients and even pollutants such as pesticides and polycyclic aromatic hydrocarbons. Studies indicate that Terra Preta contain on average 70 times more charcoal than surrounding soils (Glaser et al., 2001).

b.) Nutrients: Only carbon and nitrogen can be produced and accumulated *in situ* by photosynthesis and biological N Fixation. All other micro and macro nutrients have to be incorporated from the surrounding. The original tropical soils can largely be excluded as a nutrient source since these do not contain

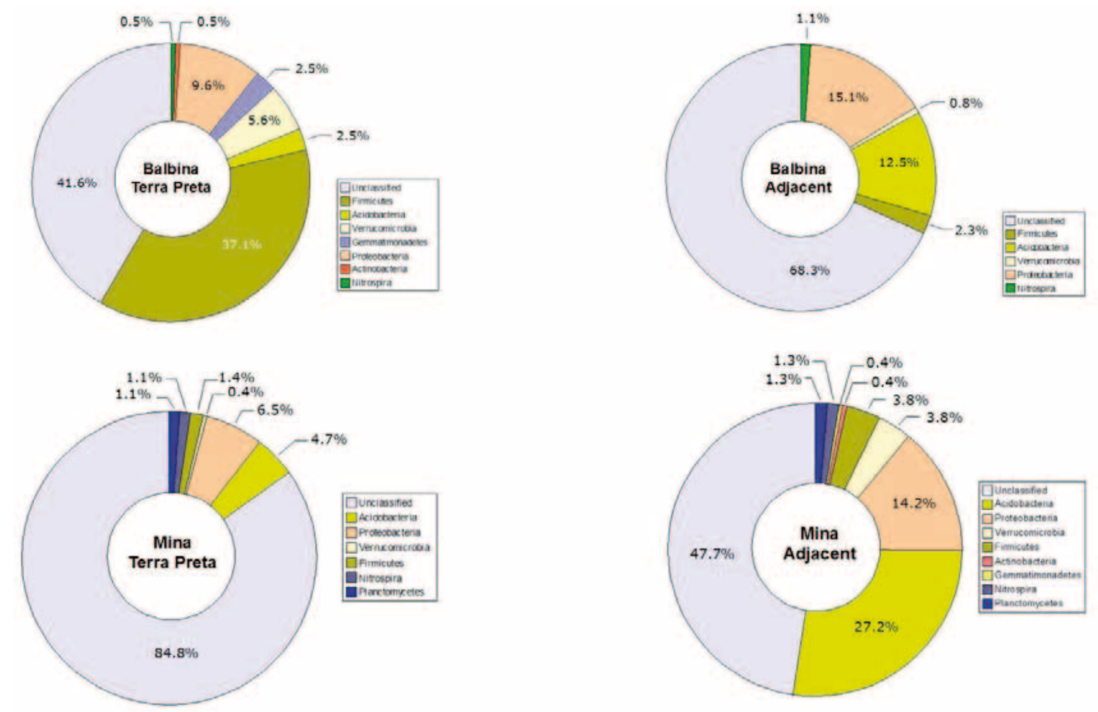

Figure 1.7: Soil microbial diversity of Terra Preta and adjacent soils (Tsai et al. 2009).

high concentrations of these elements. Therefore, for Terra Preta genesis, different nutrient sources are necessary. The excreta from humans and animals are rich in P and N, waste including bones deliver P and Ca. Ash and charcoal contain Ca, Mg, K and P. All this was supplemented by terrestrial plant biomass (Glaser and Birk, 2012).

c.) Micro-organisms: Soil micro-organisms are important for nutrients cycling and supply for plant growth. It has been shown that soil microbial diversity of Terra Preta is different from surrounding soils (Figure 1.7). Furthermore, different Terra Preta sites have different soil microbial diversity (Figure 1.7). In addition, most soil microorganisms could not be identified (Figure 1.7). Therefore, there could be no »Terra Preta code«, as often claimed. Instead, it has been shown that soil (saprophytic) fungi play a more prominent role in Terra Preta compared to surrounding soils (Glaser and Birk, 2012).

1.4. Processes

That the pre-colonial development of agriculture in South America was quite different from the one in Europe was due to two crucial differences. Firstly, the humus layer in the rainforest was too thin for long-lasting agriculture and secondly, besides the semi-wild Lamas and Alpacas, there were no bigger animals, which could have been domesticated by indigenous people. Thus, the Aztec, Maya or Inca could not form stock-breeding, nor employ them as working animals for farm labour. This was also the reason why neither wheel nor plough was spread widely.

To establish high and reliable yields of corn, vegetables and fruits, sophisticated systems of mixed crops and intelligent re-use of waste were essential. However, as Terra Preta only formed over a period of about 500 years (Birk et al. ,2008) due to disposal of organic wastes and biochar followed by microbial degradation in soil (Glaser and Birk, 2012), soil fertility gradually increased over time enabling long-lasting cultivation and high yields. As they barely had animal manure or dung, human excrements might have been utilized as organic fertilizer.

There are a range of technologies, which could have been used to enable or support Terra Preta formation. First of all, pre-Columbian people did not have candles or mineral nutrients for fertilization as the whole Amazon region is dominated by nutrient-poor highly weathered soils and almost no nutrient-rich stones occur. This is also the reason why one cannot find any construction of those people today in contrary to the monumental buildings of the Maya or Aztecs. Therefore, the only information on former land use can be extracted from (Terra Preta) soil, which acts as an archive for former land use (Glaser, 2002). Fire was used ubiquitously under many circumstances in the house and kitchen as well as on the fields and forests. Especially smoldering fires with incomplete combustion were used frequently especially when no energy was needed for cooking as no matches were available yet and it was very difficult under those humid conditions to light a fire (Glaser et al., 2001). Glaser et al. (2001) reported an average of 50 Mg ha^{-1} biochar residues in Terra Preta being 70 times more compared to surrounding soils, documenting intensive smoldering activities.

Composting certainly took place either in soil or on organic waste heaps / dumps. This could be scientifically proven by higher ^{15}N contents of amino acids which is typical for organic manure (Glaser and Birk, 2012). Many different kinds of organisms are involved in diverse aerobic degradation processes (Figure 1.7).

There is no scientific proof for the use of lactic acid fermentation because as already mentioned above, especially saprophytic fungi are enriched in Terra Preta compared to surrounding soils (Glaser et al., 2012). At least this information is not stored in soil and it is most unlikely that lactic acid fermentation plays a major role in Terra Preta formation. However, it cannot be excluded that lactic acid fermentation was used for food conservation. Anthropologists should find out, whether this technology was already known at that time in Amazonia.

The processes involved in Terra Preta formation can be summarized as follows: Over a long period of time (several hundred years), preferential sites on the Terra Firma at the edge of a river were more or less continuously inhabited (about 1000 people per 8 ha size, Birk et al., 2008). During this inhabitation, people were forced to take their resources for daily life (food, tools, energy) from the surrounding primary or secondary forest, Milpas, Woodgardens and from the river (especially protein-containing fish). Most probably, this preferential inhabitation site was used more or less continuously as settlement and the surrounding was used for shifting cultivation due to the infertile soils (Ferralsol). Over time, the settlement places were enriched with biochar, nutrients and organic matter so that by help of indigenous soil microorganisms soil fertility increased gradually (Figure 1.8). Maybe later on, people realized that the settlement soils was more fertile than the surrounding forest soil and it was used subsequently for agroforestry type of cultivation. However, it is clear that no technology was used to intentionally create Terra Preta. This seems logic from the simple fact that tremendous amounts of soil need to be carried manually (no bulldozers were available at that time). For instance, to create an average Terra Preta site covering 20 ha and 1 meter soil depth, 200,000 m^3 of soil need to be moved forth and back which seems most unlikely under these climatic conditions averaging 30 °C and 3,000 mm precipitation (Glaser and Birk, 2012). Finally, it should be mentioned that Terra Preta (Nova) can be produced today in big quantities using low or high technology. However, it should be seen more as a concept (Figure 1.6) than a recipe coming back to a kind of circular economy re-cycling our »wastes« instead of dumping or incinerating them. Excuses such as »oh, we have a contamination problem in doing so« are no longer valid because also primary rock phosphate is increasingly contaminated with cadmium and uranium. In addition, natural resources are limited. Successful examples such as the Ecoregion Kaindorf in Austria or Botanic Garden Berlin-Dahlem in Germany make it promising that re-use of such old concepts could help us to be independent from external resources and money in the future.

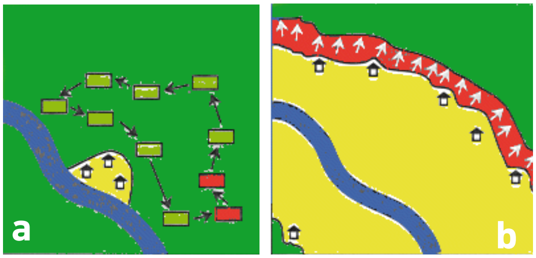

Figure 1.8: Model for Terra Preta formation (left) in comparison to modern land use (right) (Glaser 1999). Primary forest in dark green, secondary forest in light green, currently used sites in red and settlement sites in yellow.

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Chapter II: Biochar as soil amendment – Facts and myths

Bruno Glaser

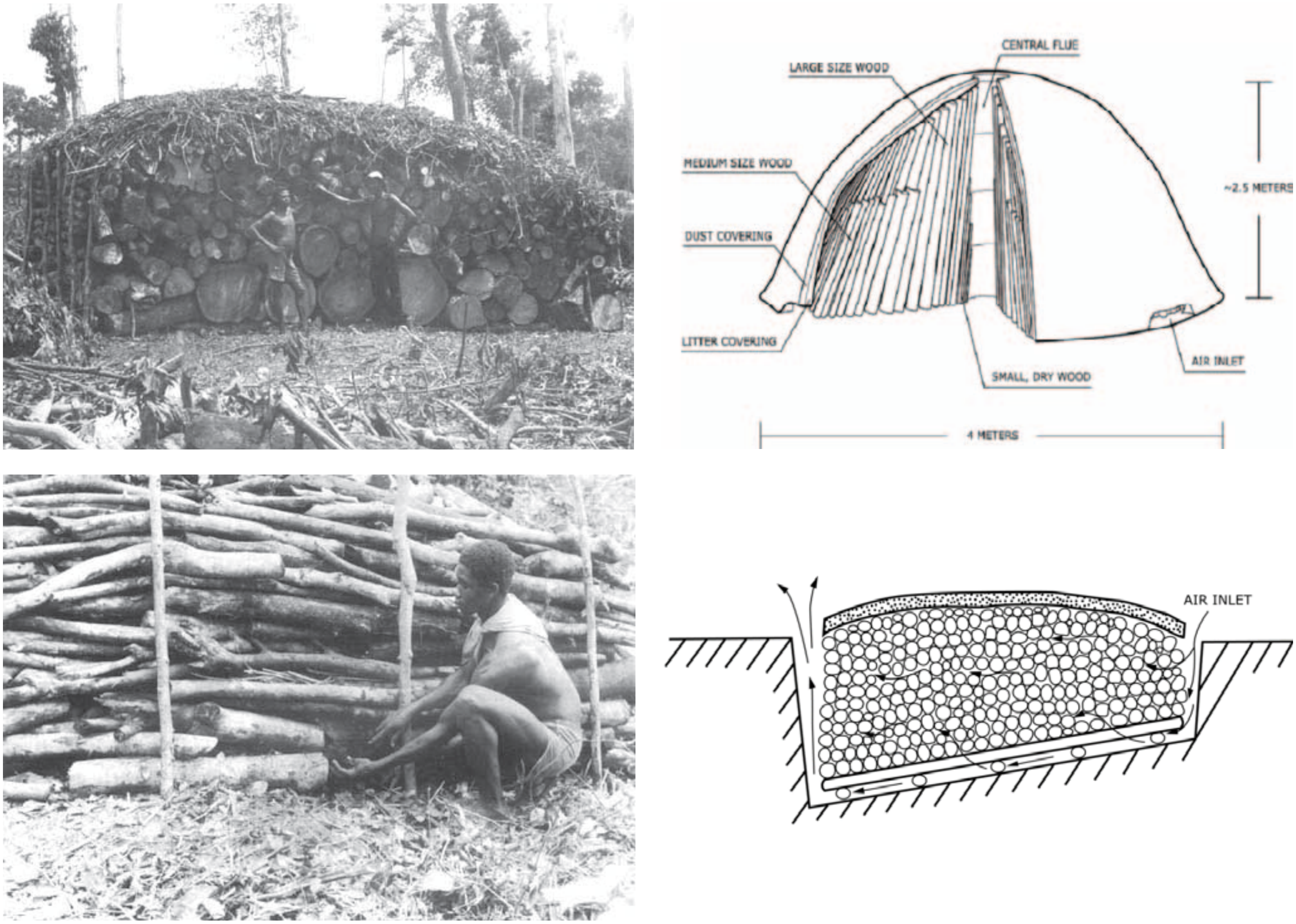

Figure 2.1: Simple techniques for charcoalmaking (FAO 1983).

2.1. Biochar systems – copying the Terra Preta concept

The existence of Terra Preta in Amazonia (Glaser et al., 2001) and of anthropogenic soils with similar properties and genesis Europe (Wiedner et al., 2014) today proves that it is principally possible to convert infertile soils into sustainably fertile soils. Therefore, Terra Preta is a general model for sustainable management of natural resources even under intensive agriculture improving soil fertility and ecosystem services while storing large amounts of C in soil for a long period of time (Glaser, 2007; Glaser and Birk, 2012; Glaser et al., 2001). Key factors for maintaining sustainable soil fertility are increased levels of soil organic matter (SOM) and nutrients stocks by using a circular economy with biogenic »wastes« as sources of natural resources as outlined (Glaser, 2007, Glaser and Birk, 2012). Biochar is a key factor of the Terra Preta concept together with input of tremendous amounts of nutrients and microorganisms turning over these resources, partly releasing nutrients during mineralization but also stabilizing organic matter as organo-mineral complexes. This concept can easily be translated to modern society re-using otherwise dumped resources such as sewage sludge and organic residues. From this concept it is clear that it makes no sense to work with pure biochar to mimic Terra Preta effects. It is like making a cake with flour only. Instead, nutrients and microorganisms have to be included into modern Terra Preta substrates and concepts together with biochar.

Biochar addition to agricultural soils can potentially enhance their fertility and is compatible with sustainable agriculture, in particular when the porous biochar matrix is soaked in, or co-applied with, nutrient-rich wastes such as slurries or digestate from biogas production. Furthermore, it is claimed that biochar reduces erosion, nutrient leaching and greenhouse gas (GHG) emissions, and binds toxic agents such as heavy metals or organic pollutants. Several ideas for C sequestration and GHG mitigation are in their infancy but developing rapidly. For instance, it is suggested to substitute peat substrates with biochar-composts for horticulture that takes the pressure off bogs, leaving this giant C pool untouched instead of being mineralized and emitted as CO_2. Further ideas are to use biochar in nutrient-loaded carbon-based slow-release fertilizers, or as animal food supplement for detoxification of food-chain pollutants in animal feeding which automatically creates C-based fertilizer slurry (biochar-enriched animal excrements).

2.2. Biochar production

2.2.1 Principle biochar production processes

Biochar is created by thermochemical conversion of organic materials especially for use as a soil amendment. Pyrolysis converts organic compounds into three fractions – one that comprises poly-condensed aromatic rings (char), which can be stored in the long-term in soil (biochar), another which can be used for energy generation: a liquid bio-oil and a third fraction; a gas (syngas), which can also be used for synthesis of organic molecules.

To produce carbonized organic matter, pyrolysis, gasification, hydrothermal carbonization, and flash carbonization technologies can be used (Meyer et al.,2011). Pyrolysis can be differentiated from gasification by the (nearly) complete absence of oxygen in the conversion process. Pyrolysis technologies can be further differentiated by the reaction temperature and time of the pyrolysis process (e. g., slow and fast pyrolysis processes), heating method (e. g., pyrolysis processes started by the burning of fuels, by electrical heating, or by microwaves; Meyer et al., 2011).

During gasification, biomass is partly oxidized in the gasification chamber at a temperature > 800 °C at atmospheric or elevated pressure (Meyer et al., 2011). The main product of gasification is gas as expected from its name and only small amounts of char and liquids are formed (< 10%). Hydrothermal carbonization of biomass is realized by applying elevated temperature (180–300 °C) in a closed vessel in the presence of a catalyst (mostly citric acid) under elevated pressure (10–60 bar) for several hours (Libra et al., 2011). It yields solid, liquid, and gaseous products. Libra et al. (2011) refer to hydrothermal carbonization as »wet pyrolysis«. Because no oxygen is supplied to the reactor with the biomass plus water suspension, this classification is justified. Hydrothermal carbonization under acid conditions degrades especially polysaccharides to 5-hyroxyfurfural (5-HMF), while lignin and lipids are only partly degraded. As 5-HMF is very reactive, a secondary polymerization takes place forming organic polymers similar to brown coal. Under alkaline conditions, also lignin and lipids can be degraded.

For flash carbonization of biomass, a flash fire is ignited at elevated pressure (at about 1–2 MPa) at the bottom of a packed bed of biomass. The fire moves upward through the carbonization bed against the downward flow of air added to the process. In total about 0.8–1.5 kg of air per kg of biomass are delivered to the process. The reaction time of the process is below 30 min, and the temperature in the reactor is in the range of 300–600 °C. The process results mainly in gaseous and solid products. In addition to that, a limited amount of condensate is formed. While the oxygen input into the carbonization process is a typical feature of gasification technologies, both process temperature and the product spectrum (distribution among solid, liquid, and gaseous outputs) of flash carbonization are uncommon for gasification processes.
It should be noted that typical solid product yields obtained by gasification and fast pyrolysis processes are significantly lower as compared to the solid product yields of slow pyrolysis, flash carbonization, hydrothermal carbonization and torrefaction (Table 2.1).

Table 2.1: Comparison of different biochar production technologies with respect to biochar yields, carbon concentration and yield (adapted from Meyer et al., 2011).

Process type	**Temperature**	**Residence time**	**Mass yield**	**Carbon**	**C yield**
Torrefaction	~ 290 °C	10–60 min	61–84%	50–55%	65–85%
Slow pyrolysis	400–800 °C	min to days	~ 30%	95%	~ 60%
fast pyrolysis	~ 500 °C	~ 1 s	12–26%	74%	20–30%
Gasification	500–1200 °C	10–20 s	10–30%	50–90%	~ 20–30%
Hydrothermal carbonization	180–300 °C	1–12 h	< 66%	< 70%	~ 90%
Flash carbonization	300–600 °C	< 30 min	~ 37%	~ 85%	~ 65%

Because biochar production for agricultural use in the EU is still under development, no legislative protocol or standard has been established. However, voluntary certificates are already available such as the European Biochar Certificate (EBC) or guidelines of the International Biochar Initiative (IBI). Certification and/or legislation of biochar is very important to satisfy consumer and policy concerns about potential adverse effects of biochar or products claimed to be biochar for human and environmental health. A simple definition of biochar can be obtained by elemental composition and ratios (Table 2.2). A threshold, O/C and H/C ratios of ≤ 0.4 and ≤ 0.6 was suggested by Schimmelpfennig and Glaser (2012). Further discussions between EBC and IBI revealed that H/C ratio is enough to unambiguously prove the nature of biochar and the current threshold was set at 0.7. Further criteria comprise absence of toxic compounds such as heavy metals mainly depending on feedstock material, and polycyclic aromatic hydrocarbons and dioxins, mainly depending on process parameters (Schimmlpfennig and Glaser, 2012). An overview comparing properties and thresholds of biochar certificates is given in Table 2.2.

Table 2.2: Properties and thresholds of currently available voluntary biochar certificates: European Biochar Certificate (EBC), International Biochar Initiative (IBI). Version of corresponding certificate is given in brackets.

EBC (4.7)	IBI (1.1)
1. Feedstock Positive list	1. Feedstock: Biomass No contamination
2. Material properities TOC > 50% (< 50% BCM) O/Corg < 0.4 **H/Corg < 0.7** **VOC, nutrients (report)** ***=> HTC and activated BC critical***	2. Material properities (A) TOC > 60/30/10% (C1, 2, 3) O/C - **H/C < 0.7** pH, EC, texture etc. report
3. Contaminants Heavy metal thresholds PAH < 12 (4) mg kg^{-1} (DIN EN 15527 A, B) PCB < 0.2 mg kg^{-1} PCDD and PCDF < 20 ng kg^{-1}	3. Contaminants (B) Heavy metal thresholds PAH < 20 mg kg^{-1} PCB < 0.5 mg kg^{-1} PCDD and PCDF < 9 ng kg^{-1} **Germination test: pass**
4. Standard and premium biochars	4. Soil enhancement analysis (C) Ntot, Nmin, Ptot, Pavail, BET

2.2.2. Industrial biochar production

Technologies for biochar production at industrial scale develop rapidly. In contrast to traditional charcoal production, modern technologies offer the opportunity to produce biochar under defined conditions (e.g., time and temperature) and from biomasses different from wood. In addition, environmental standards could be applied and controlled. Table 2.3 gives an overview of currently available biochar technologies at industrial scale.

Table 2.3: Currently available technologies for biochar production at industrial scale.

Process type	**Company**	**Country**	**Potential feedstock**	**Carbon yield**	**Running machines**	**Tons per year**	**Price [€]**
Pyrolysis	PYREG	Germany	Everything < 50% water content	~ 50%	~ 5	~ 400	~ 300k
Gasification	AGT	Italy	Wood(chips)	~ 20%	~ 1	~ 50	~ 1000k
Gasification	Carbon Terra	Germany	Wood(chips)	~ 50%	~ 3	~ 700	~ 250k
Gasification	Black Carbon	Denmark	Wood(chips)	~ 50%	~ 1	~ 200	unknown
HTC	Carbon Solutions	Germany	Everything	~ 80%	~ 1	~ 1000	~ 1000k
HTC	Artec	Germany	Everything	~ 80%	~ 3	~ 1000	~ 800k

The PYREG reactor is flexible with respect to biomass, which is automatically fed to the pyrolysis reactor (Figure 2.2). The only limiting variables are feedstock energy (> 10 MJ kg^{-1}), size (< 30 mm) and water content (< 50%). The feedstock is moved continuously through the pyrolysis reactor by a twin screw which is arranged in a fashion that it cleans itself (Figure 2.2). Residence time within the reactor is about 10 minutes. The temperature within the reactor is up to 850°C, depending on feedstock type and water content. Therefore, according to data given in Table 2.1, the PYREG process can be classified as slow pyrolysis. The gases produced during the PYREG process consisting of CO, CH_4, CO_2 and water, are subsequently oxidized by a flameless burner (FLOX®) at 1250 °C. As a result, exhaust emissions are reduced below the thresholds of the 17th German law for gas emissions (17. BImSchG). The energy produced is utilized for heating the PYREG reactor, for energy production or other heating purposes such as feedstock drying (Figure 2.2).

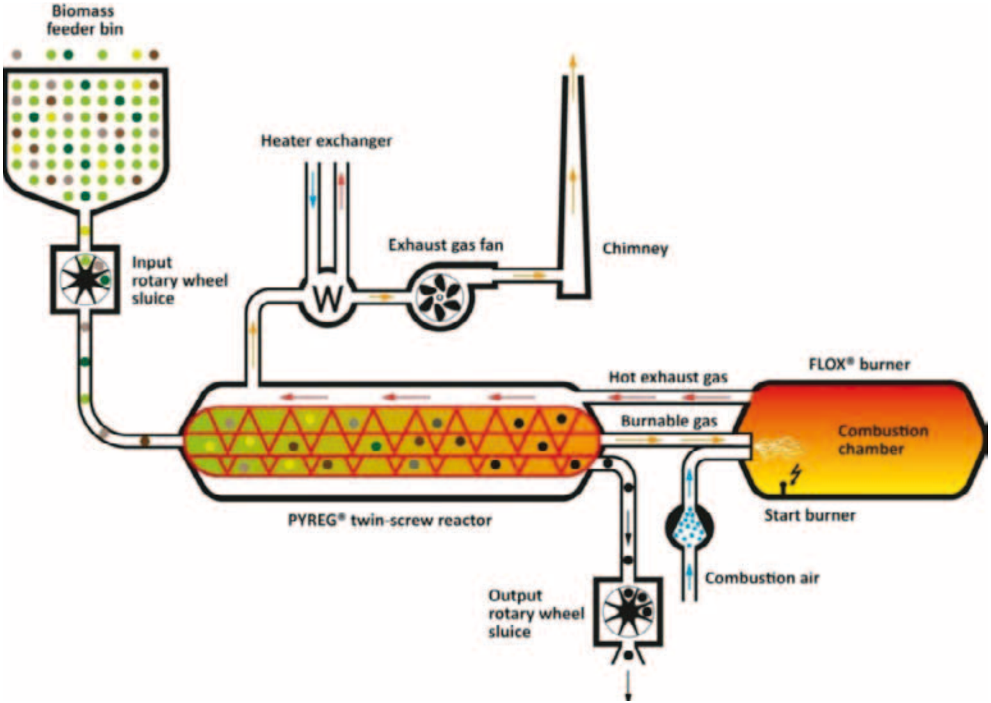

Figure 2.2: Principal components of the PYREG reactor (www.pyreg.de).

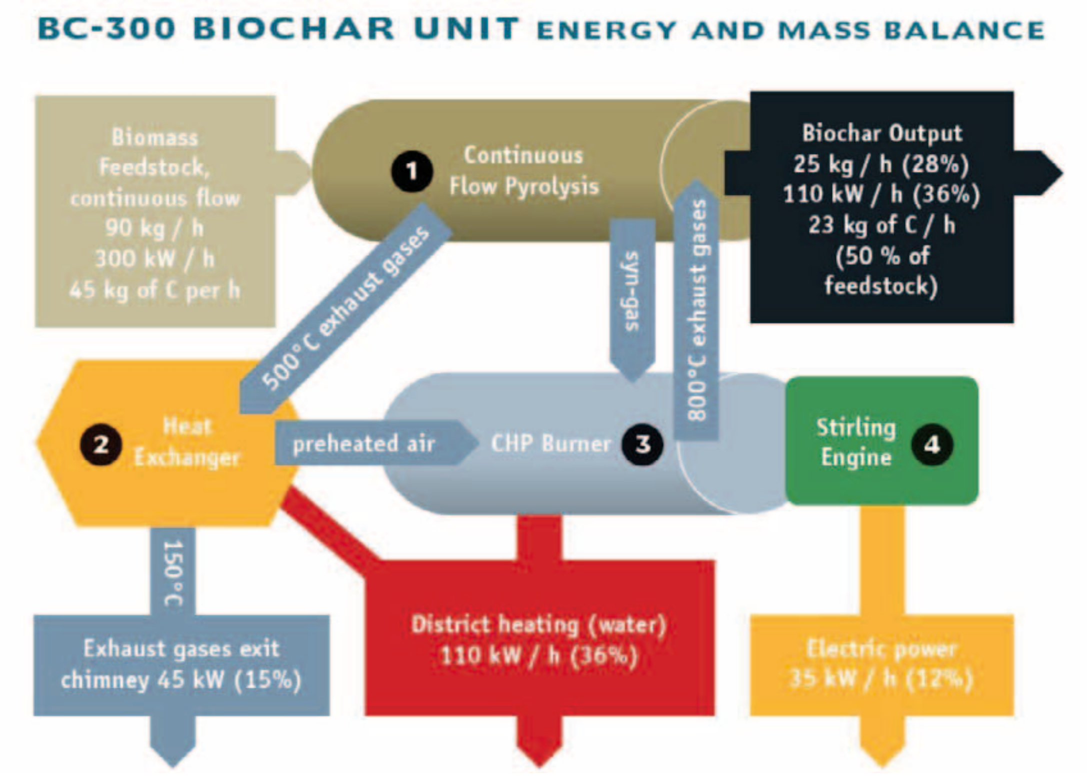

Figure 2.3: Energy and mass balance of the BlackCarbon unit BC-300 (www.blackcarbon.dk).

The BlackCarbon unit (BC300) is a pyrolysis-based combined heat and power unit with a Stirling engine. It converts fuel equivalent to 250 kW; of this, 35kW is electricity, 110 kW district heated water and 110 kW biochar. The wood chips are fed into the unit and are heated by pyrolysis. The gases produced from the pyrolysis process are combusted separately to create heat and electricity. The carbon-rich biochar is then extracted from the unit (www.blackdarbon.dk). A Stirling engine is a closed cycle external combustion engine that needs little maintenance, is noted for its high efficiency and quiet operation and the ease with which it can utilize almost any heat source. The fluctuating temperature causes the pistons to move up as the hot helium gas expands, then the pistons move down again as the cooled down gas contracts, allowing the pistons to run an external electric generator, which produces electricity. Energy and mass balance of the BC300 is given in Figure 2.3.

Advanced Gasification Technology (AGT) was developed for electrical energy production (350 kW nominal electric power). It is a fixed-bed, down-draft, open core, compact gasifier using agricultural products and by-products as feedstock. The gasification plant is composed of a reactor, in which gasification of feedstock takes place (Figure 2.4). Before electricity production, the syngas (containing CO, CH_4, CO_2 and H_2O) needs to be cleaned from dust and tar by electrostatic filtration and cooled down (Figure 2.4). At a temperature of 600–700 °C, syngas leaves the bottom of the reactor. Biochar is extracted from the gasifier and from the dust removal system by a screw conveyor system and is then transported to a storage tank (Figure 2.4).

The CarbonTerra gasification system can use more than 100 different feedstocks (< 40% water content) and is based on a vertical continuous flow system which is lit at the bottom and fed from top (Figure 2.5). Biochar is extracted at the bottom and diluted with 20% of water to avoid burning of biochar. Produced syngas is burned and heat is used for electricity production using a gas turbine. The system can be up-scaled due to its modular nature. One CarbonTerra gasifier module can produce up to 2 tons of biochar from 6 tons of dry biomass per day which is equivalent to a continuous thermal energy production of 700 kW plus 300 kW gas. Therefore, the annual biochar production can be around 730 tons (www.carbon-terra.eu).

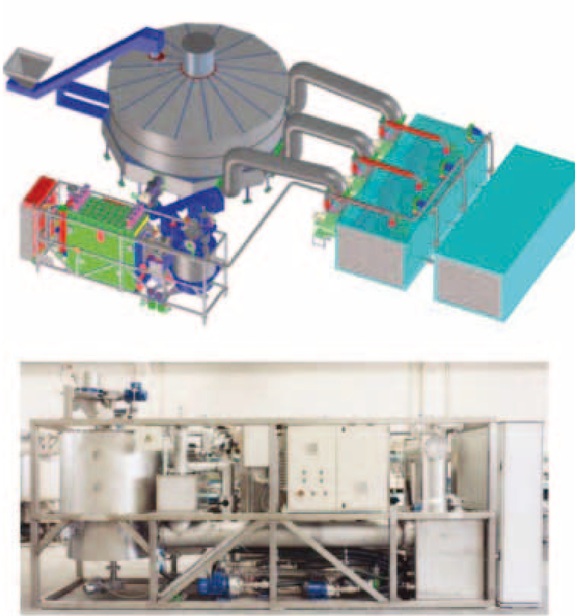

Figure 2.4: Principal components of Advanced Gasification Technology (AGT, www.agtgasification.com).

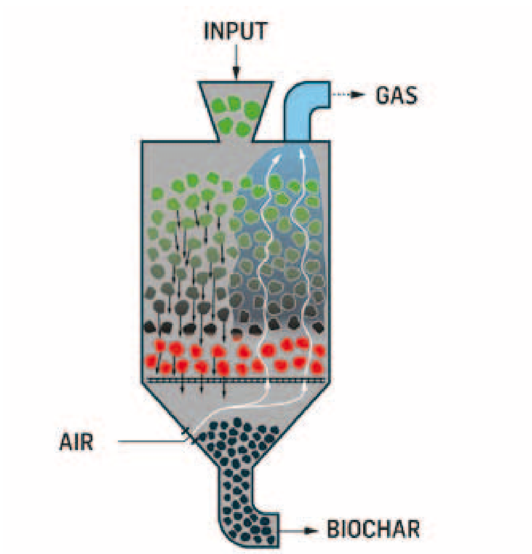

Figure 2.5: Principle of the Carbon Terra gasification system (www.carbon-terra.eu).

During hydrothermal carbonization, biomass is usually subjected to temperatures between 160–250 °C in acid aqueous conditions (Libra et al., 2011). In order to prevent the water from evaporation this conversion takes place in a closed vessel under elevated pressure between 10 and 60 bar. Under these conditions, water is released from carbohydrates of the biomass and new structures are formed from the carbon fragments. In the Carbon Solutions reactor, this conversion takes only 90 minutes. Carbon Solutions technology is an automated continuous process (Figure 2.6). The prototype CS-HT90TM was launched in October 2010. It is fully approved as waste treatment facility according to the German legislation (BImSchG).

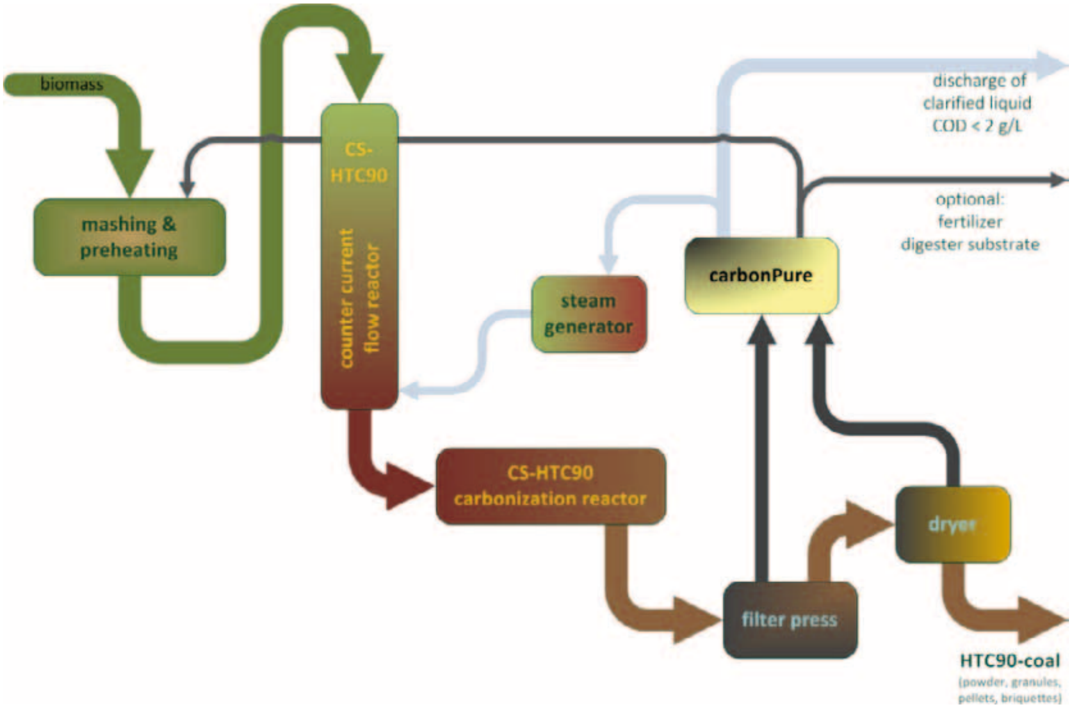

Figure 2.6: Principal components of the Carbon Solutions Hydrothermal Carbonization plant (www.cs-carbonsolutions.de).

Artec (www.artec-biotechnologie.com) is a spin-off of the Bavarian farmers association in order to develop continuous large-scale HTC reactors which can convert agricultural residues otherwise unused. There are different reactors available depending on purpose and amount of biomass to process. A research reactor (Art.coal 2.0) has 1.8 L reaction volume and programmable reaction parameters (max 230 °C and 35 bar), which are recorded every 10 s. It has a heating capacity of 2.24 kW and is equipped with a software for graphic representation of process data, inquiry of energy balances (e.g. German Biomass Research Center DBFZ, Leipzig). Art.coal 20 k is a quasi-continuous HTC reactor with 20 L capacity (max 230 °C and 30 bar), e.g. in use at the HAWK university Göttingen, Germany. The HTC pilot plant »mole I« consists of a 180 L reactor producing about 150 tons hydrochar per year. It was developed without public subsidies and could be operated > 4000 hours by end of 2008 running 300 different experiments with different feedstock. Liquid or solid biomass is introduced into a pressure room and after conversion the products (hydrochar plus liquid) is put out without loss of pressure (Figure 2.7). The module includes use of exothermic energy as well as proper safety units. Art.coal 3000k (max 220 °C and 25 bar pressure) is the biggest development. It is also a quasi-continuous machine which was produced 2013 for the Stadtwerke Halle/Saale, Germany in order to process 3 m3 equivalent to an annual biomass throughput of 1000 tons dry mass at about 5 hours dwell time in the reactor.

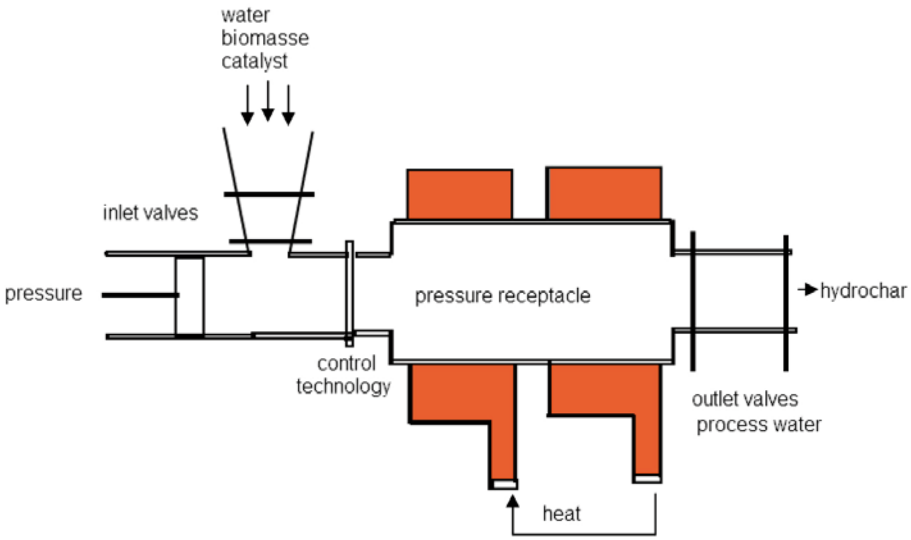

Figure 2.7: Principal components of the Artec Hydrothermal Carbonization plant.

2.2.3. Small-scale biochar production

In developing world scenarios, biochar will most likely be made in small amounts using simple techniques like (mound) kilns or pits (Figure 2.8). Numerous traditional kilns and pits, differing in structure and size, have been developed for charcoal production and the technology is rather simple. Mass yield and quality of charcoal strongly depends on the technique used and is influenced by several factors such as temperature, time, moisture, wood size, wood species and weather conditions. For instance, a mound kiln (Figure 2.8) yields between 20–30% charcoal on dry basis with 70% C concentration. In accordance with today's environmental requirements, traditional carbonization techniques are no longer appropriate, e.g., because of the large greenhouse gas and pollutant emissions. The alternative to digging a pit is to stack the wood above the ground and cover the stack with earth. This method is also very old and is widely used in many countries. Much effort has been spent to optimize the design. The process is the same as the mound – the wood to be carbonized is enclosed behind an air-tight wall made from earth, a universally available material wherever wood is grown. The earth mound is preferred over the pit where the soil is rocky, hard or shallow, or the water table is close to the surface. In contrast, the pit is ideal where the soil is well drained, deep and loamy. The mound is also more practical in agricultural zones where fuel wood sources may be scattered and it is desirable to make the charcoal near a village or other permanent site. A mound site can be used over and over again, whereas pits tend to be used a few times and then new ones dug to follow the timber resource. Also where the water table is close to the surface or drainage is poor, pits are not practical. The repeated digging of pits also disrupts cultivation for crops or pasture. The wood to be carbonized in a mound can also be accumulated slowly over a period of months, stacked in position and allowed to dry out well before covering and burning. This fits in well with the life style of a small farmer who may gather scrap wood, branches and logs and stack them carefully to form the mound. After some months, depending on the season, charcoal prices and so on, he covers the mound with earth and produces charcoal. A small cash income is produced this way which requires no initial cash investment.

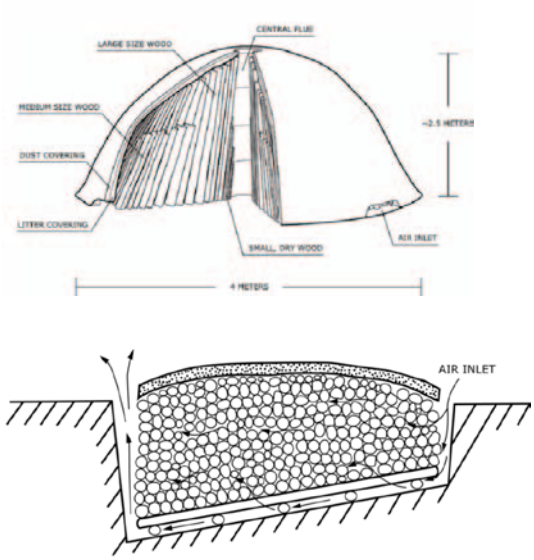

Figure 2.8: Examples for traditional charcoal production: mound kiln (on the top) and pit (Food and Agriculture Organization 1983).

A hybrid system containing elements of the earth mound and the pit is used in some parts of Africa. A rectangular pile of evenly cross cut logs is stacked on a grid of crossed logs, to allow gas circulation. The volume of the pile is usually about 5-8 m^3. The completed pile is then sealed behind earth walls made by ramming earth between the piled wood covered with leaves and a supporting wall of saplings or boards held by stakes. The top of the pile is covered with leaves and earth as in pit burning systems. An opening in the side wall is left for starting the burn and, when this fire is well established, the wall is closed with earth and boards in the same way. Inlets for air are opened at the base of the pile and are used to control the rate of burning (Figure 2.9).

The different stages of carbonization are (i) heating up from ambient temperature to 0 °C, (ii) dehydration between 100 and 120 °C, (iii) exothermic stage which begins at 270 °C, reaching 500 to 700 °C when carbonization is complete and (iv) cooling during which the chimney is removed and the mound is her-metically sealed.

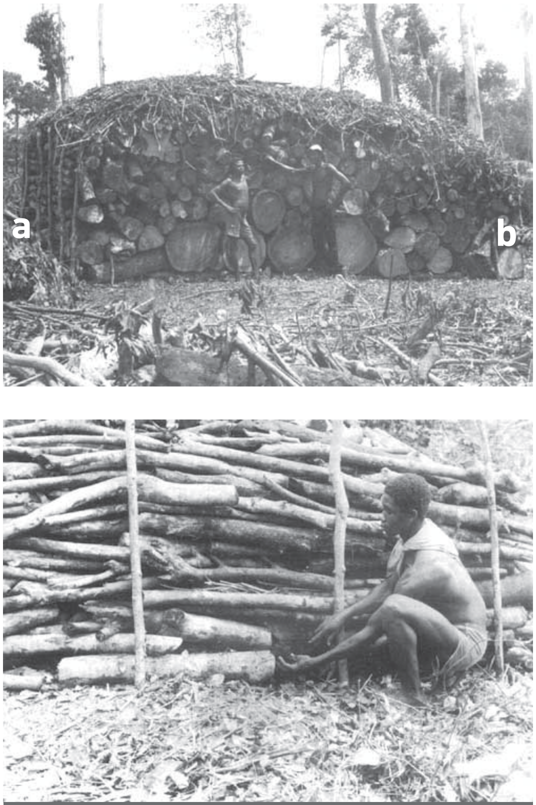

Figure 2.9: Combination of mound and pit kiln (Food and Agriculture Organization 1983).

With the recent increased focus on negative health impacts associated with emissions from solid biomass cooking fuels, better results on emissions reductions are needed if biomass is to remain a viable acceptable fuel for billions of people relying on it to satisfy their daily cooking energy needs. Micro gasifiers or wood gas stoves (Figure 2.10) approach the concept of generating heat from wood and biomass in a completely different way. Gasifiers separate the generation of combustible gases from their subsequent combustion to create cooking heat. These are »gas burning stoves« that make their own supply of gas when needed from dry biomass that can be safely stored and transported. Gasification advantages have been known for nearly two hundred years, but only recently could they be reliably accomplished at sufficiently small (micro) scales appropriate for household stoves.

Micro-gasification refers to gasifiers small enough in size to fit under a cooking pot at a convenient height (Figure 2.10). It was conceptualized as a top-lit up-draft (TLUD) process in 1985 and developed to laboratory prototype stages by Thomas B. Reed in the USA. Independently in the 1990s, the Norwegian Paal Wendelbo developed stoves based on the same TLUD principle in refugee camps in Uganda. Top-lit up-draft devices have always been intended as biomass-burning cook-stoves and there were some early Do-It-Yourself back packer efforts, but it was only in 2003 that the first micro gasifier was commercially made available by Thomas B. Reed when he presented the Woodgas Campstove to the outdoor camping niche market in the USA. Because gasifiers require high temperatures and heat transfer into cold biomass, making them small is difficult. As such, it has been a challenge to make biomass gasification suit-able for domestic cooking. Commercially viable gasifiers have long been understood and used in large industry and even in transportation: over one million vehicles were fueled by biomass (mainly charcoal) gasification during World War 2, when liquid fuel was hard to come by. But there was nothing similar for small applications such as a household stove. Commercially available models are still scarce, though there is growing interest.

Wood gas stoves have certain advantages over other improved cook-stoves:

- Cleaner burning of biomass (much less soot and indoor/outdoor air pollution)
- More efficient due to complete combustion (less total biomass consumption)
- Uses a wide variety of small-size biomass residues (no need for stick-wood or charcoal)
- Biomass fuels are often within the immediate area of the users (affordable access at own convenience), easy to transport and easy to store after gathering
- Creation of gas from dry biomass can be achieved with very simple and inexpensive technology directly in the burner unit (portable, no piping or special burner head needed)
- Performance similar to biogas (but not dependent on water and bio-digester) and approaching the convenience of fossil gases
- Gas available on demand (unlike electricity or LPG that are dependent on local providers and imports, and unlike solar energy that is dependent on clear weather and daylight hours)
- Pyrolytic micro gasifiers can create charcoal which may be used for energy purposes or to improve soil productivity as biochar
- Easy lighting permits cooking to start within minutes contrasted with charcoal slowness

Figure 2.10: Top-lit up-draft (TLUD) micro gasifier stove practical course by Paul Anderson during the 1st international biochar Summer School in 2012 (Potsdam, Germany).

2.2.4. Potential of biochar production

For biochar production, photosynthetically fixed CO_2 from the atmosphere is used by pyrolysis of plant biomass or its residue. Therefore, biochar production is not only a »carbon-negative« technology, but it is only limited by the amount of organic matter which is dedicated to biochar production. A conservative estimate for the scalability of biochar production is the conversion of organic wastes. Given the availability of appropriate biochar production technologies which is the case e.g. by PYREG or Carbon Terra machines, of about 500 Mio tons of organic waste across Europe, about 140 Mio tons of biochar could be produced with a conservative conversion rate of about 30%. This means that an additional C offset of about 10% could be achieved right now. If additional biomass would be »sacrificed« (e.g. via a »biomass tax«) for biochar production, these numbers would be even higher.

2.3. (Co)-application of Biochar to soil

2.3.1. Pure Biochar

Biochar has probably been used traditionally somehow in the management of soils globally, with charcoal being a ubiquitous product associated with any community that uses fire. It appears likely that all human society adopting stable agriculture for the first time, in the absence of artificial fertilizer or livestock, experimented with the use of some form of biochar. Indeed, the use of biochar in crop production was described in nineteenth century handbooks for agricultural management in both the UK and the USA. Its role in traditional soil management practices is ongoing in several African countries (Whitman und Lehmann, 2009) as well as Japan (Ogawa und Okimori, 2010).

Use of biochar in the form of charcoal has a long tradition in the production of potting media for horticulture. Although the origins of this practice and its objectives are not clear, it is generally perceived that charcoal mitigates odor that can emanate in the decomposition of other organic materials in horticultural media. Application of pure biochar to soil should be avoided although positive effects on soil properties and plant growth were reported (Glaser et al., 2002). Jeffery et al. (2011) calculated a mean agronomic yield increase of about 10% when pure biochar is applied to soil. Surprisingly, this yield increase did not further be improved when biochar was applied together with mineral or organic fer-tilizers. To date, no standardized best practice guidelines for biochar application to soil exist. Challenges include handling of dry biochar. Especially losses due to wind erosion and transport are critical as black particles in the atmosphere decrease the albedo effect with a considerable greenhouse potential (Woodward et al., 2009). However, dust development can easily be avoided by biochar wetting or by mixing it with organic wastes such as slurry or compost. Strategies of mixing or composting biochar with a nutrient carrier substance such as green waste (composting), slurry or manure will have the positive side effect of >loading< biochar with nutrients (Fischer and Glaser, 2012).

2.3.2. Biochar in added-value products

Terra Preta was created by mixing of charring residues (biochar) with biogenic wastes from human settlements (food leftovers including bones, ashes, plant residues and excrements), which were microbially converted to a biochar-compost-like substrate (Glaser et al., 2001; Glaser, 2007; Glaser and Birk, 2012). Thus, co-composting of biochar and organic material has a number of benefits compared to application of pure biochar or if biochar is simply mixed with compost. Examples are enhanced nutrient use efficiency, biological activation of biochar. Palm-shell charcoal mixed into poultry manure is used in Japan for 30 years (Ogawa and Okimori, 2010). Perception that these mixtures can function as >biological fungicide< has led to the commercialization of a product targeting crop health rather than soil conditioning or soil fertility. More recent experiments examining the combination of compost and biochar emerged from the understanding that biochar function in the absence of other inputs or soil fractions is limited, and functions best as a catalyst to other soil processes (Glaser et al. ,2001; Glaser, 2007; Glaser and Birk, 2012). Such mixtures were an element of early experiments in order to re-create the function of ancient Terra Preta (Glaser et al., 2002; Lehmann et al., 2003; Steiner et al., 2004; 2007; 2008).

From a compost point of view, there is evidence that biochar as 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 mixture of lactic acid and photosynthetic bacteria, yeasts, actinomycetes, and other beneficial microorganisms (Higa und Wididana, 1991). However, there is no scientific proof for the reported benefits and there are at least three arguments against this Terra Preta fermentation hypothesis. Firstly, 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 need to be moved by hand twice (forth and back) for Terra Preta generation which is most unlikely. Secondly, soil contains billions of microorganisms and addition of small numbers of additional non-indigenous microorganisms hardly will have any dramatic impact. Thirdly, fermentation is an anaerobic process but in un-compacted soil, aerobic processes dominate. Therefore, it is most unlikely that fermentative organisms have comfortable growing and living conditions in soil.

To test the Terra Preta fermentation hypothesis, a biochar composting versus fermentation experiment was conducted together with Gerald Dunst (www.sonnenerde.at). For this purpose, about 100 m^3 consisting of 50% grass, 40% wood residues and 10% loamy sand were mixed thoroughly. Thereafter, six piles were separated of which three were composted and three were fermented after addition of EM. After four weeks, the EM piles were also composted. Results showed no significant differences between composting and fermentation apart from the fact that fermentation conserved more organic matter (carbon) as long as anaerobic conditions prevail. Also practically oriented gardening experiments conducted by ten different end-users showed no significant differences among the two different products (www.sonnenerde.at).

Meanwhile, the eco region Kaindorf (Austria) has successfully implemented biochar-compost or Terra Preta substrate systems by combining nutritional elements from waste materials such as green wastes, slurries, or sewage sludge. Benefits arise from saving money for buying mineral fertilizers such as NPK and by reducing resources allocation for water purification e.g. when nitrate is leached into groundwater after improper slurry application to agricultural fields. The latter is supposed to increase in the near future due to rapid growth in biogas production followed by the disposal of huge amounts of biogas slurry.

2.4. Biochar effects in agroecosystems

2.4.1. Carbon sequestration

Biochar is more stable in the environment than other organic compounds due to its biological and chemical recalcitrance caused by the poly-aromatic backbone (Goldberg, 1985; Schmidt und Noack, 2000; Kuzyakov et al., 2009; Kuzyakov et al., 2014). The existence of Terra Preta even today proves that biochar is stable over millennia in extreme environments such as the humid tropics. Kuzyakov et al. (2009; 2014) calculated a mean residence time for biochar of about 2,000 years, using mineralization of ^{14}C-labelled biochar over eight years. However, the mean residence time and thus the C sequestration potential of different biochars depend on biochar formation conditions such as temperature, pressure, presence of oxygen and the process itself. C sequestration potential can be calculated as the amount of biochar carbon that is expected to remain stable after 100 years (BC+100). As this is very difficult to determine experimentally for individual biochars, more simple methods to estimate biochar stability (BC+100) are necessary. By means of the molar H/Corg ratio of a given biochar, the amount of stable biochar C can be determined which can be used for C offset payments. As shown in Figure 2.11, the stability of biochar significantly increases linearly with decreasing molar ratio of H/Corg.

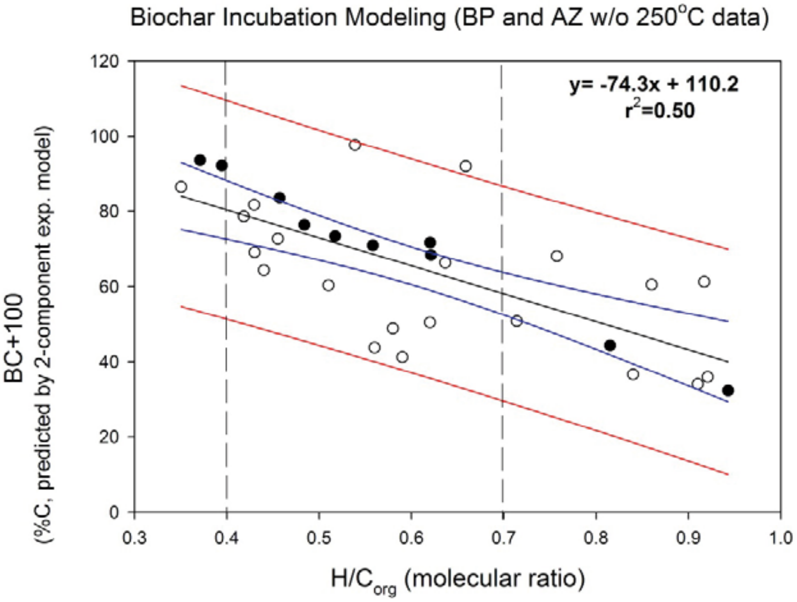

Figure 2.11: Prediction of the C sequestration potential (BC+100) of biochar based on the molecular H/Corg ratio indicating the degree of aromatic condensation (Budai et al., 2013).

Biochar stability depends on material properties, especially the degree of aromatization. Hydrochar (char from hydrothermal carbonization) has a less aromatic structure and higher percentage of labile carbon species (Schimmelpfennig and Glaser, 2012). Therefore, it decomposes similar to soil organic matter within decades (Steinbeiss et al., 2009).

In addition to the assessment of the true carbon sequestration potential, several indirect effects of biochar application have to be taken into account, such as fertilizer use, N_2O and CH_4 emissions, change in SOC and increased productivity. Libra et al. (2011) reviewed the effects of biochar additions to different agro ecosystems on greenhouse gas emissions. They found a reduction in N_2O release after biochar addition in seven out of nine reported studies. In addition, they reported an exponential decrease of N_2O emission from soil with increasing biochar addition (ng N_2O-N kg^{-1} h^{-1} = 206.19e$^{-0.122 \text{ g biochar/100 g soil}}$, $R^2 = 0.9705$).

Little is known about the effect of biochar on CH_4 emission. Zhang et al. (2010) reported 34–41% increased CH_4-C emissions when paddy soils were amended with biochar at 40 Mg ha^{-1}, while N_2O-N emissions were reduced by 40–51% and by 21–28% in biochar-amended soils with and without N fertilization, respectively. Using biochar, the N_2O emission could be reduced from 4.2 g kg^{-1} N to 1.3 g kg^{-1} N.

In summary, biochar is a potent tool for C sequestration if enough biomass (waste) is available or will be sacrificed (e.g. via CO_2 taxes or (voluntary) CO2 certificate trading) for biochar production.

2.4.2. Soil physical processes

Biochar has a porous physical structure which can absorb and retain water although its chemical structure being dominated by condensed aromatic moieties suggests hydrophobicity. Water retention of Terra Preta was 18% higher compared to adjacent soils (Glaser et al., 2002). 20 Mg ha^{-1} biochar addition to a sandy soil in NE Germany increased plant-available water storage capacity by 100% (Liu et al., 2012). Major et al. (2010) suggested that due to the physical characteristics of biochar there will be changes in soil pore-size distribution and this could alter percolation patterns, residence time and flow paths of the soil solution. In a field trial in NE Germany, 5 – 20 Mg ha^{-1} biochar application together with 30 Mg ha^{-1} compost significantly increased plant-available water both not only during wet but also during dry conditions when compared to the pure compost treatment or the control site which did not receive any organic amendment (Figure 2.12). This result was quite surprising as it was anticipated that the fine pores of biochar would retain water which was not plant-available which obviously was not the case.

Biochar can be lost from ecosystems by wind or water erosion or transport to the subsoil, either as small particles with the rain water, or through dissolution as (highly aromatic) dissolved organic carbon (DOC). Further mechanisms of biochar movement from the surface to deeper layers include bioturbation, kryoturbation or anthropogenic management (Major et al., 2010). The losses due to erosion or relocation to deeper soil

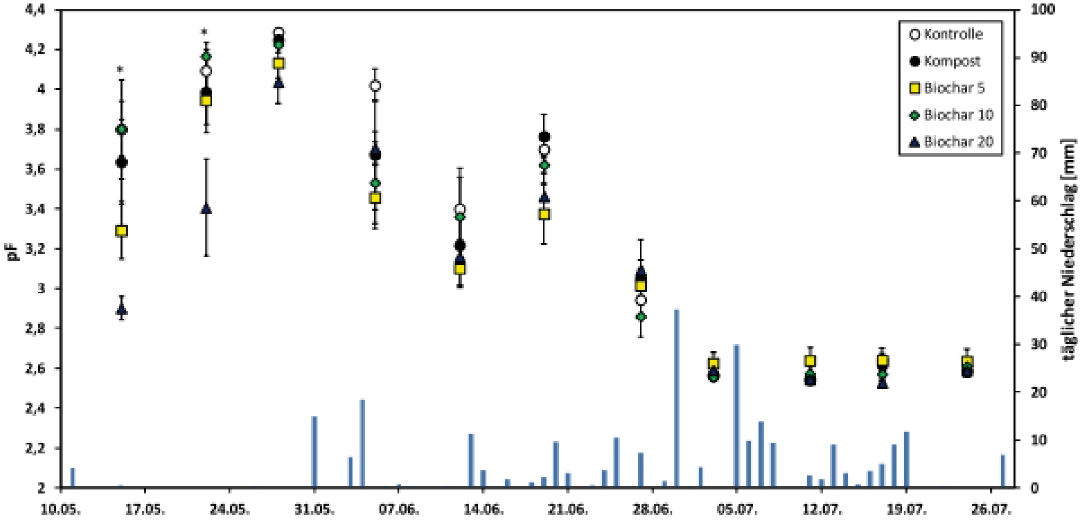

Figure 2.12: Water potential (pF) in a loamy sand at Petershagen (NE Germany) during the growing season 2012. During the dry period in May 2012, water potential in control soil reached the permanent wilting point (pF 4.2), whereas biochar-amended plots suffered from less water stress. These results clearly indicate the positive effect of biochar for plant water supply even under dry conditions despite of the porous structure of biochar being dominated by fine pores (Bromm, 2012).

can be considerable and quick. Major et al. (2010) reported a migration rate of 379 kg C ha^{-1} a^{-1} corresponding to 0.3% after biochar application of 116 Mg ha^{-1} to the top 10 cm of a grassland soil down to 15–30 cm depth during a 2-years study in Columbia. In the same experiment, respiratory biochar losses or losses via DOC leaching were 2.2 and 1%, respectively. In a temperate agroecosystem, no significant biochar losses were observed after 5, 10 and 20 Mg ha^{-1} biochar application to the top 10 cm during a 2-years study in Brandenburg, Germany (Schulz and Glaser, 2012).

There is a discrepancy or convergence between material properties expected from the chemical structure of biochar (recalcitrance, hydrophobicity) and the mechanistic understanding of claimed positive effects for ecosystem services such as enhanced water storage capacity and soil stabilization. The same is true for the reported high surface area of biochars related especially to the dominance of Nano pores which cannot store plant-available water. Therefore, soil hydraulic properties of various biochars under laboratory and field conditions need to be investigated in combination with 3D imaging of the porous architecture of biochars. In addition, increased storage time of biochar in soil may result in steric changes of aromatic regions, release of char-specific metabolites and oxidation in hot-spots of biochar particles. Another important issue is the theoretical recalcitrance due to the poly-aromatic backbone and thus non-reactivity of biochar in relation to a potential organo-mineral stabilization and thus reactivity. This aspect is also related to water infiltration, surface runoff and wind erosion. A further important physical aspect is interaction with solar radiation (albedo effect) which could contribute to soil and soil-near atmosphere warming, which may result either in soil organic matter degradation or in accelerated stabilization due to enhanced soil biological activity.

2.4.3. Soil chemical processes

Surfaces of fresh biochars are generally hydrophobic and have relatively low surface charges (Lehmann et al., 2005). However, over time, biochar oxidation in the soil environment may result in accumulation of carboxylic functionalities at the surfaces of biochar particles (Glaser et al., 2000; Figure 2.13), promoting further interactions between biochar and other soil components including soil minerals, organic matter and contaminants (Beesley and Marmiroli, 2010).

Biochar interaction with soil minerals is reported for Terra Preta (Glaser et al., 2000) and for cultivated soils in western Kenya to which biochar was amended 30 years ago (Nguyen et al., 2009). Therefore, in the long term it can be assumed that physical and chemical stabilization minimize biochar decomposition and soil erosion, while in the short term, biochar should be less reactive due to its assumed recalcitrance. However, enhanced cation exchange capacity (CEC) of soils a few months after biochar addition was also reported (Cheng et al., 2006).

As biochar generally has a low nutrient content, its nutrient retention capacity is of higher interest. The principal nutrient retention mechanisms such as pores, surface adsorption, cationic and anionic interaction are determined by the physical and chemical structure of biochar. Although fresh biochar has only a low number of functional groups such as carboxylic acid, higher cation retention was observed when mixing soil with biochar (Glaser et al. ,2002). The underlying mechanisms for this observation is still un-

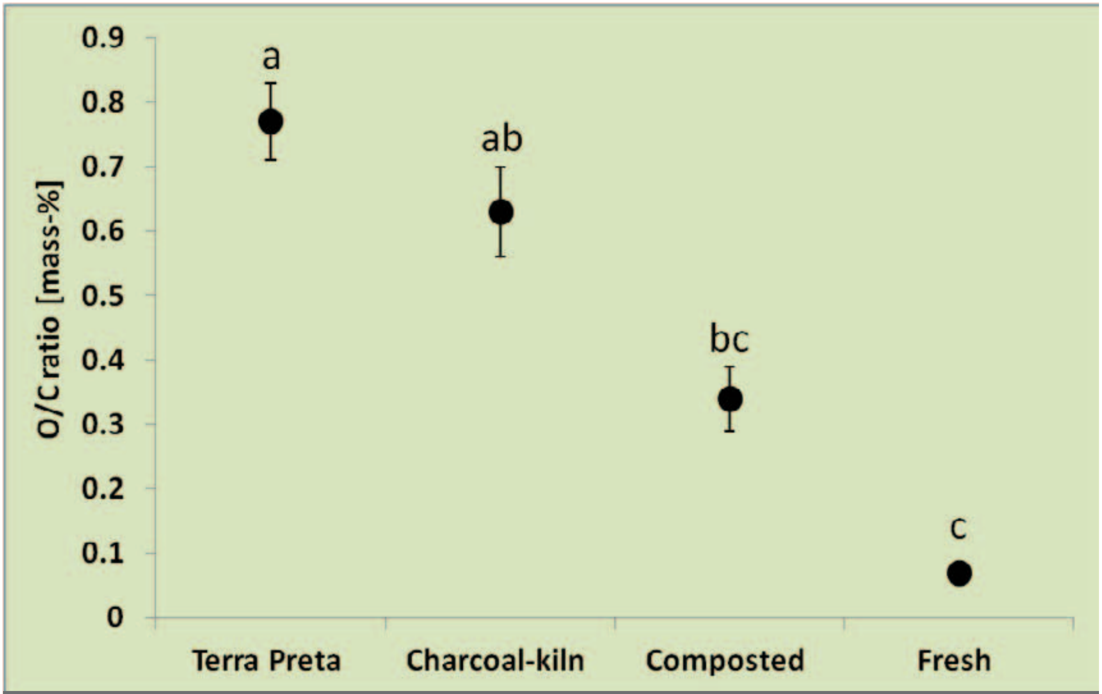

Figure 2.13: Surface oxidation of differently aged/modified biochars (Wiedner et al., 2012).

clear. Nevertheless, cation exchange capacity (CEC) of biochars can be increased by chemical (e.g. spraying with oxidizing acids during biochar production) or biological aging (e.g. composting of biochar, Figure 2.13). Biochar in Terra Preta was exposed on average 2,000 years of biological aging, significantly increasing its reactivity. The higher cation exchange capacity of Terra Preta is both a »simple« pH effect as it is known that variable (pH-dependent) cation exchange sites increase with increasing pH and Terra Preta has a higher pH compared to surrounding soils. However, also the pH-independent CEC (permanent exchange sites) is increased in Terra Preta corroborating the fact that CEC of SOM can be increased when biochar is present. This effect is only of minor importance, despite the fact that about 50% of biochar is organo-minerally complexed in the upper 50 cm of Terra Preta.

The nutrient retention of biochar systems can be further increased by higher crop production. Steiner et al. (2008) found a 60–80% higher total N retention in the ecosystem (plant and soil) when organic amendments (biochar and compost) were used compared to pure mineral fertilizer. One important process in this retention was found to be recycling of N taken up by the crop. In another study, biochar addition did not reduce ammonium, nitrate and phosphate leaching compared to mineral and organic fertilizers but it reduced nitrification (Schulz und Glaser, 2012). A new experiment with ^{15}N-labeled nitrate clearly demonstrated a reduced nitrate leaching of biochar-amended plots upon heavy rainfall when mineral (NPK) and organic (biogas digestate) fertilizers were used (Ebert and Glaser, unpublished).

A sound understanding of biochar interaction with soil minerals relies on knowing the extent and implications of the changes biochar surfaces undergo in soil over time. However, such knowledge remains sparse, and most experimental evidence has been gathered for other forms of black carbon using energy-dispersive X-ray spectrometry (Glaser et al., 2000). Therefore, advanced innovative analytical tools should be used to obtain a deeper understanding of biochar-mineral and biochar-SOM interactions and biochar-surface ageing in soils.

2.4.4. Soil biological processes

Biochar addition to soils can have various beneficial effects on soil microorganisms, such as stimulation of growth, activity and metabolic efficiency of soil microbial biomass (Thies und Rillig, 2009), including significant effects on plant symbionts such as arbuscular mycorrhizal fungi (Warnock et al., 2007). Especially saprophytic fungi profit from addition of recalcitrant complex carbon, compared to bacteria (Figure 2.14). Saprophytes such as basidiomycetes (e.g. wood-rotting *Schizophyllum commune*) are presumed to play a major role in biochar biodegradation, because they are the main actors in degrading similar polyaromatic macromolecules such as lignin. Also in Terra Preta, saprophytic fungi play a more dominant role than bacteria compared to surrounding soils (Glaser and Birk, 2012; Figure 2.14). The mechanisms and pathways of biochar degradation in soils are however not well studied. Recent studies suggest that biochar degradation is a co-metabolic process; the addition of an easily degradable C source was found to increase the degradation of biochar (Kuzyakov et al., 2009).

The process of biochar degradation by saprophytic fungi deserve further attention in order to predict the potential of long-term C storage with biochar in different environments. A large knowledge gap exists with respect to the responses of communities of soil and root-inhabiting fungi to biochar additions. So far, effects have only been documented for overall abundances. Stable isotope probing of soils amended with highly labelled biochars may offer a window into soil microbial and

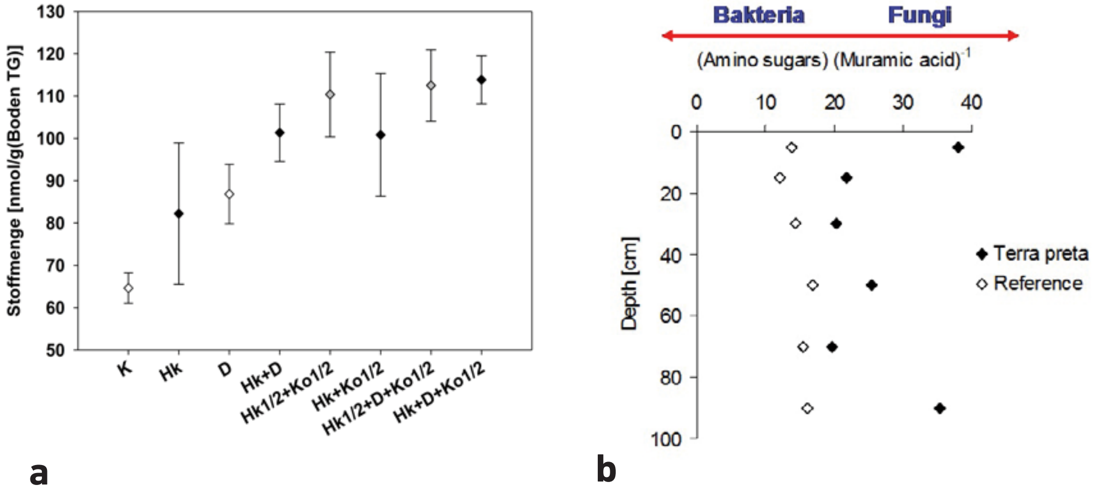

Figure 2.14: Soil microbial biomass (Stoffmenge, left, Birk et al., 2009) and saprophytic fungi (right, Glaser and Birk, 2012) are higher in biochar-containing soils. K = control, Hk = biochar, D = mineral fertilizer, Ko = compost.

faunal food webs and abundance shifts. Another important aspect concerns the influence of biochar on soil microbial diversity and on the interaction between soil microorganisms and plants as well as plant resilience and/or stress. Hardly any information is available on the ecological effects that biochar may have when incorporated into soils at the community level, i. e. ranging from plant eco-physiological performance (e.g. plant strategies to cope with stressors such as water stress, salinity, heavy metal toxicity or herbivores) to the plant/faunal community composition and diversity, up to ecosystem functioning.

Additional factors limiting meaningful interpretation of many datasets are sorption properties that interfere with standard extraction procedures for soil microbial biomass or enzyme assays, and the confounding effects of varying amounts of minerals. In a few studies, microbial biomass has been found to increase as a result of biochar additions, with significant changes in microbial community composition and enzyme activities that may explain biogeochemical effects of biochar on element cycles, plant pathogens, and crop growth (Rillig, pers. comm.). However, little is known about the mechanisms through which biochar affects microbial abundance and community composition. The effects of biochar on soil fauna are even less understood than its effects on microorganisms, apart from several notable studies on earthworms (Augustenborg et al., 2011; Busch et al., 2011).

Observations on microbial dynamics and soil CO_2 emissions lead to the conclusion of a possible improved resource use efficiency due to co-location of various resources in and around biochars. Sorption and thereby inactivation of growth-inhibiting substances likely plays a role for increased abundance of soil biota. No evidence exists so far for direct negative effects of biochars on plant roots. Occasionally observed decreases in abundance of mycorrhizal fungi are likely caused by concomitant increases in nutrient availability, reducing the need for symbionts. In the short term, the release of a variety of organic molecules from fresh biochar may in some cases be responsible for increases or decreases in abundance and activity of soil biota (Spokas, 2010). However, it must be stressed that all above-mentioned aspects are at the »concept and working hypotheses« stage and lack clear experimental proof by elaborate basic research.

Complications are expected due to the fact that decomposition rates of biochar cannot be simply calculated according to the concept of biologically active time, which was elaborated for decomposition of plant litter, being microbially better available compared to biochar. Additionally, other factors such as strong variation of environmental conditions and the presence of soil animals may contribute to faster mineralization rates of biochar-C under field conditions as compared to controlled laboratory incubation conditions. Furthermore, biochar may consist of various >pools< with different stability. Therefore, for more realistic determination of biochar stability, long-term field studies are required including modern sophisticated analytical tools such as (stable) isotope labelling combined with compound-specific stable isotope analysis which to date is a challenge under field conditions requiring again an interdisciplinary team of scientists.

Biochar C-N interactions and modification of soil gross N turnover processes are important for understanding and predicting long-term effects of biochar on soil fertility, GHG fluxes and plant performance. However, in particular soil N transformation processes appear to be a >black box< to date (Clough und Condron, 2010). Even the proportion of physico-chemical and biological contributions to observed changes is not understood. Thus, the application of state-of-the-art ^{15}N labelling techniques based on the pool dilution approach and developed into a complex sophisticated mathematical tool (Müller et al., 2007) could shed light on the unknown but essential fate of N in the presence of biochar. The interdisciplinary use of ^{15}N-labelled field plots as well as ^{15}N-chars could enable to go one step further, and allow the identification of organisms involved in the soil-biochar N turnover from the molecular/cellular level to soil food webs and plant N export.

2.4.5. Agronomic potential

Biochar application to soil can increase crop yields (Glaser et al., 2002; Jeffrey et al., 2011). Yield increase was observed especially in degraded or low fertility soils rather than in already fertile soils (Glaser et al., 2002). Crop yield increase was higher when additional nutrients were added, especially in organic form such as compost (Figure 2.15). Based on a literature survey on a high number of biochar studies, mostly conducted in tropical or subtropical regions, Jeffrey et al. (2011) calculated a mean of 10% crop yield increase upon biochar addition to soil with a trend of increasing crop productivity with increasing biochar addition if biochar is added only once. However, crop productivity was not linearly correlated to biochar addition. Instead, biochar response to crop yield ranged from –40 to +100% (Jeffrey et al., 2011). Furthermore, a large variation of crop response to similar amounts of biochar additions was observed, especially at low biochar addition (5.5 to 11 Mg ha^{-1}) but also for large biochar additions (above 100 Mg ha^{-1}). From these data it can be concluded that medium biochar application rates (10–100 Mg ha^{-1}) might be most appropriate for crop production increase. The reason for the large observed variation is likely due to the different biochar feedstock used, the different crops assessed and differences in soil type and soil properties to which the biochar was added. It is important to note that no single biochar application rate exhibited a statistically significant negative effect on the crops from the range of soils, feedstock and application rates compared. However, data used for meta-analysis did not cover a wide range of latitudes and they were mainly from tropical and subtropical regions (Jeffrey et al., 2011). This means that care should be taken when extrapolating these results to European latitudes, crops and soil types.

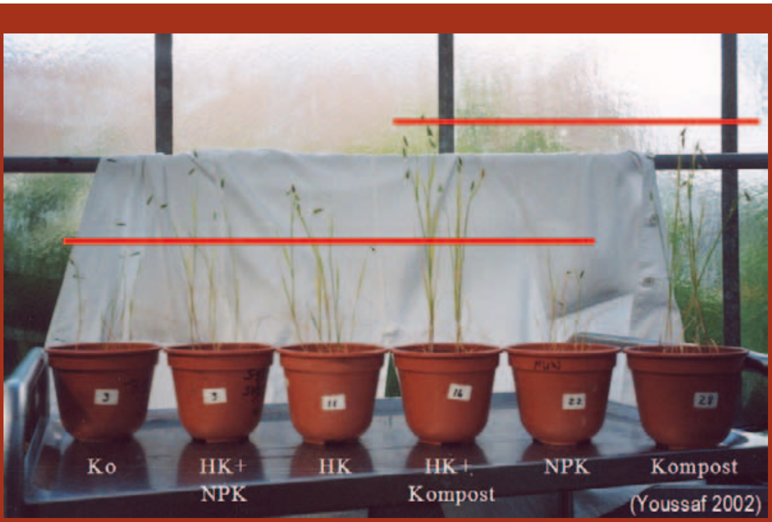

Figure 2.15: Growth of oats (Avena sativa) in sand upon mineral fertilizer (NPK), compost (Kompost) and biochar (HK) additions compared to no amendment (Ko) (Schulz and Glaser, 2012).

Hydrochars often exhibit higher labile carbon fractions such as carbohydrates and carboxylates compared to biochars (pyrochars), but have higher nitrogen contents. Therefore, hydrochars alone might be better for plant growth from a nutrients point of view. However, growth reduction was often reported when hydrochar was applied to soil. This could be explained by low molecular weight substances such as phenolic compounds being toxic for plant germination and/or growth (Rillig et al., 2010).

Soil quality may not necessarily be improved by adding biochar to soil. Soil quality can be considered to be relatively high for supporting plant production and provision of ecosystem services if it already contains sufficient amount of soil organic matter (at least 4% corresponding to about 2% organic carbon). If biochar is added to soil, the relative portion of easily mineralizable (active) SOM pool will be reduced. Therefore, simply adding pure biochar to a soil does not increase SOM quality or soil fertility. Instead, biochar should be mixed with nutrients and easily available SOM (Figure 2.15). This can be best achieved by composting biochar together with green waste and/or slurry from biogas where the amount of biochar being 10–50% of organ-ic carbon present in the final biochar value added product.

2.4.6. Plant nutrition

Besides improved crop production, it is anticipated that biochar reduces nutrient leaching and thus, improves fertilizer use efficiency (Glaser et al., 2002). However, a meta-analysis of biochar systems across the tropics and subtropics showed no additional fertilizer effect on crop productivity independent from the type of fertilizer used (Jeffrey et al., 2011). On the other hand, Schulz and Glaser (2012) showed that crop production could be significantly increased when biochar was combined with organic fertilizer (compost) compared to pure biochar, pure mineral fertilizer and biochar combined with mineral fertilizer (Figure 2.15). Also Steiner et al. (2008) showed improved N retention in the soil plant system when biochar was used with organic fertilizer compared to mineral fertilizer. Economic benefits strongly depend on mineral fertilizer and crop prizes.

Lehmann et al. (2003) demonstrated that plant nutrition was significantly influenced by biochar in tropical soils (Ferralsol, Terra Preta). Some nutrient concentrations in plants such as calcium and phosphorus were elevated but others such as nitrogen and magnesium were lower compared to non-biochar containing controls (Figure 2.16). These results are surprising as a similar behavior of nutrients with similar physico-chemical properties (e.g. positively or negatively charged) can be expected. Therefore, it is strange that Ca concentrations are higher but Mg concentrations are lower when biochar is present in soil. If we look at the Mg concentration in plant of around 125 mg kg^{-1} it is

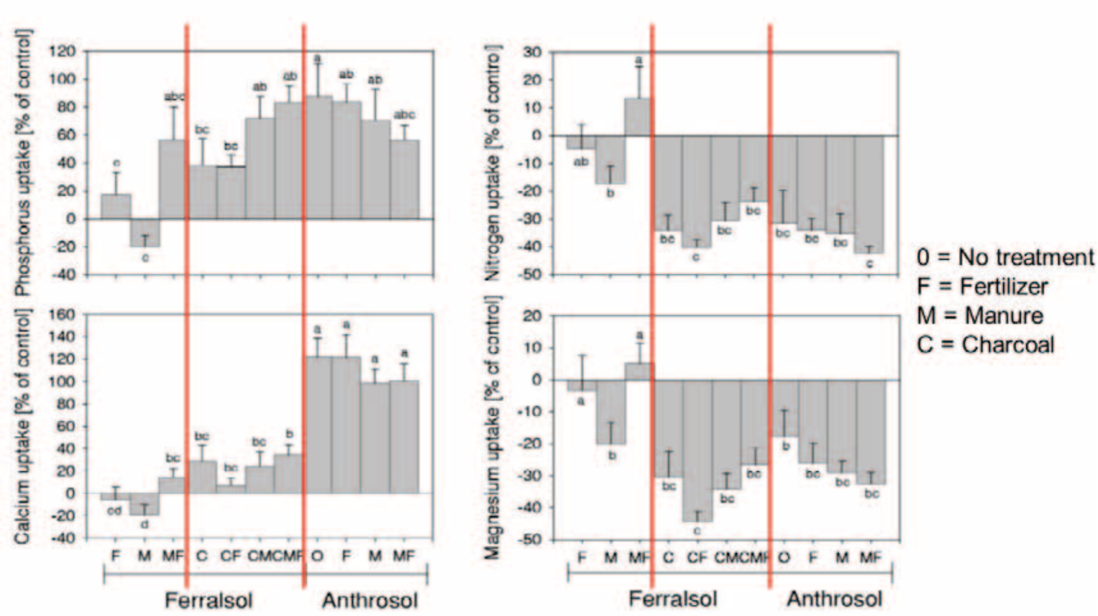

Figure 2.16: Nutrients uptake into cowpea of biochar-containing soils relative compared to non-biochar-containing controls (adapted from Lehmann et al., 2003).

evident, that biochar-containing soils exhibit no Mg deficit. A possible explanation for the lower Mg concentration might be antagonism with K as plants on biochar-containing soils showed K concentration of around 10,000 mg kg^{-1} (Lehmann et al. ,2003).

2.5. Further research needs

From a scientific point of view, it is imperative to address the mechanisms of biochar action in the environment as soon as possible and in coordinated and inter- and transdisciplinary projects before biochar technologies can be disseminated to a great extent which is already ongoing (biochar producers and pending Terra Preta patent). This coordinated biochar research should cover the following criteria.

- **Upscaling from the molecular (detail) to the ecosystem level (complexity)** using standardized, common state-of-the art as well as newly developed experimental tools with the same set of different well characterized biochars.

- **Process identification and quantification** (e.g. by isotope labelling such as ^{14}C, ^{13}C and ^{15}N) combined with compound-specific and/or position-specific isotope analysis with low detection limits as biochar turnover might be low. For this purpose, new innovative methods need to be integrated such as liquid chromatography (LC) linked via an oxidation device (O) to an isotope ratio mass spectrometer (LC-O-IRMS), integration of non-destructive and non-invasive methods directly in the field such as Fourier-Transformation Infrared Spectroscopy (FTIR) and Cavity Ring Down Spectroscopy (CRDS), X-ray (µ-XRT) and nuclear magnetic resonance tomography (MRT), atomic force microscopy (AFM), (Nano) secondary ion mass spectrometry (SIMS).

- **Exploring long-term mechanistic effects under real (field) conditions.** For this purpose, a range of long-term field trials are necessary and the advantage of already existing biochar field experiments covering a range of biochar application amounts, different biochar/fertilizer combinations and climatic gradients should be used.

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Chapter III: Terra Preta Sanitation systems and technologies

Torsten Bettendorf, Claudia Wendland and Thorsten Schuetze

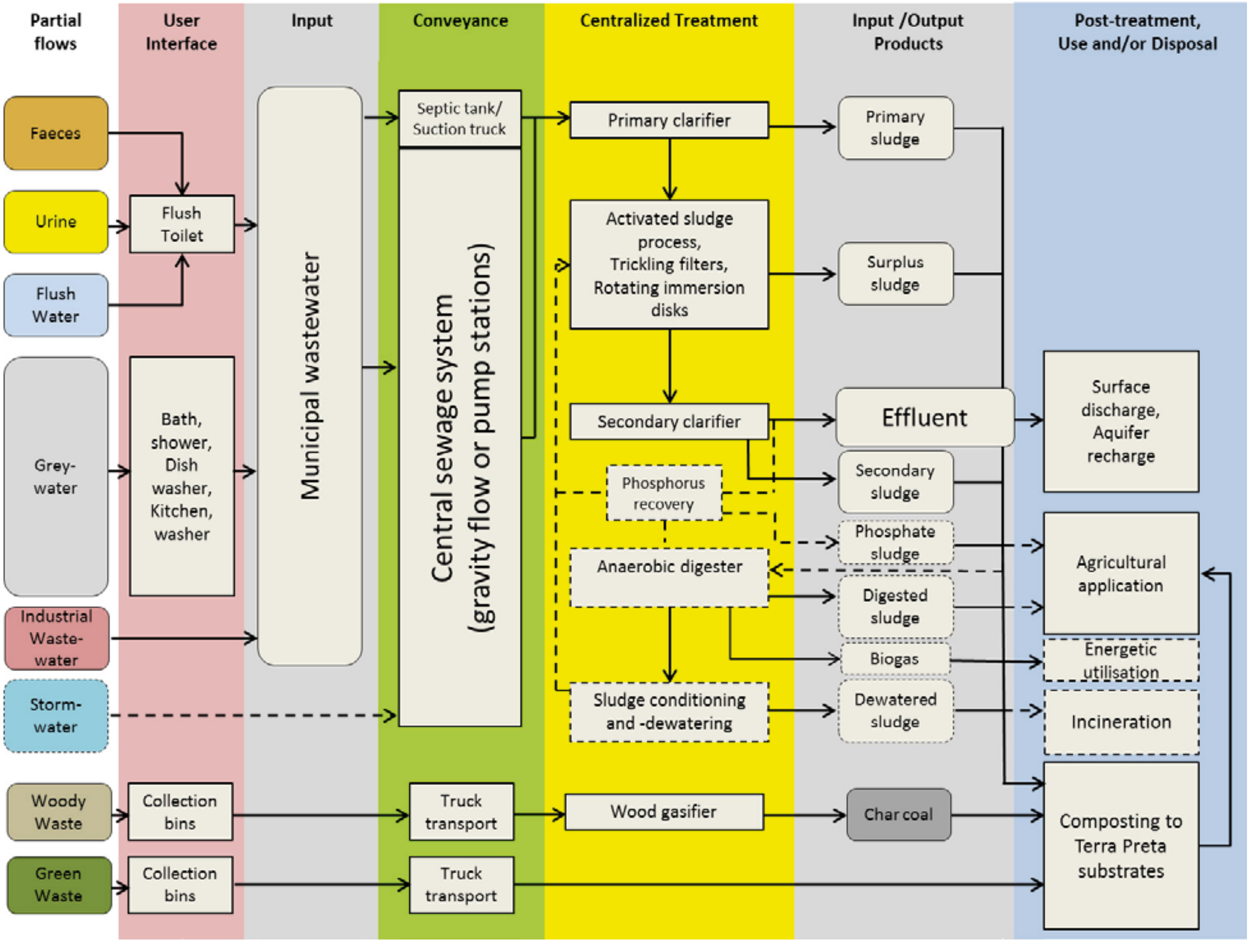

Figure 3.1: Integration of TPS in conventional sanitation systems.

3.1. Introduction

During the last two decades various new sanitation systems (NSS) have been developed to improve sanitary conditions, making them more sustainable in terms of water consumption and resource efficiency and thus providing an alternative to conventional sanitation systems (CSS) (Schuetze et al., 2008; Larsen et al., 2013).

Alternative terminologies for NSS can be found in publications of various research and demonstration projects, such as »resource oriented sanitation« (ROSA, 2008), »ecological sanitation« (Winblad, 2004), »sustainable sanitation Alliance« (SuSanA), »decentralized sanitation and reuse« (Lens et al., 2001). The development of NSS marks a paradigm shift from end of pipe wastewater management systems to resource-oriented sanitation systems (Luethi et al., 2008). Separate collection, treatment and utilization of separated domestic wastewater flows aim to save and reuse water and to recover valuable constituents (plant nutrients). In many developed countries NSS are considered as growing alternative to conventional sanitation systems (CSS), but they are difficult to implement due to already existing CSS. In contrast, in developing countries, NSS are often the only choice due to absence of CSS. Furthermore, new installations of CSS are not regarded as appropriate, for instance due to high investment costs, the high water demand, electricity requirement and chemical auxiliaries required for their operation. Skilled labour for operation and maintenance is also an important limiting factor (Luethi and Panesar, 2013).

Nevertheless, both NSS and CSS have possible interfaces to Terra Preta sanitation (TPS) and can contribute to Terra Preta (TP) production.

In the following sections; partial flows within CSS and NSS are discussed with respect to TPS (3.2), collection and transportation systems are described (3.3), the principles of TPS are explained (3.4) and examples of different sanitation systems and their possible interfaces to TP are presented (3.5).

3.2. Domestic separated flows versus municipal wastewater

With the development of NSS, new terminologies for source separated flows have been defined. An overview of terminology definitions is presented in Table 3.1 (Tilley et al., 2008). Regarding TPS, toilet wastewater is of high concern as it contains the largest fraction of nutrients and organic carbon compared with other domestic wastewater flows. At the same time the specific amounts and volumes of urine and feces compared with the remaining wastewater flows are low. Both feces and urine flows are suitable for the production of TP due to high plant nutrients and organic content. Greywater represents the largest fraction of domestic wastewater. It is generated when blackwater is collected separately or subtracted from domestic wastewater. Due to comparative low contaminations of greywater with nutrients, organic compounds and pathogens, treatment can be carried out with less complexity or higher treatment targets, e.g. production of service water, or even drinking water (Schuetze et al., 2008).

The characteristics of mixed wastewater can vary significantly depending on local conditions as water availability, state of nutrition, individual habits, technical installations, etc.

Table 3.1: Source separated, (waste) water streams – and organic resources.

Term	Definition	Capturing	Comments
Feces	Solid human excreta	Dry toilets (no flush water)	Concentrated feces without urine. Main source of pathogens in wastewater, Low C/N ratio for composting.
Brownwater	Feces mixed with (flush-)water[1]	Urine separating flush toilet	Diluted feces without urine, contains pathogens.
Urine	Liquid human excreta via urinary tract	Urine diverting dry toilet, Waterless urinals	Concentrated Urine without feces. Main source of nutrients, very low pathogen content.
Yellowwater	Urine mixed with (flush-)water	Urine separating flush toilet, Urinals with water flush	Diluted urine without feces. Main source of nutrients.
Excrement, Excreta, Fecal sludge*	Urine and Feces	Dry toilets * flush toilets	Feces mixed with Urine. Often collected with addition of bulking material. * Contain flush water and toilet paper.
Blackwater	Excrement with flush water	Flush toilets	Feces mixed with Urine and diluted with water. Main source of pathogens, nutrients and micro pollutants.
Greywater	Domestic wastewater without E	Kitchen sink, bath, shower, washbasin, dishwasher, laundry, etc.	GW can be further distinguished between GW with low pollution (e.g. bath and shower) and high pollution (e.g. kitchen sink, laundry, dishwasher).
Rain water, *storm water	Water from precipitation, *rainwater runoff	Sealed areas, such as roofs or *traffic areas)	Pollutant level is primary dependent on properties of collecting surfaces. Decentralized management facilitates direct or indirect use.

Beige Water	Water from wet anal cleansing	Bidet	Wet anal cleansing as an alternative for dry anal cleansing with toilet paper; prevalent in some societies. Contains pathogens from feces
Biowaste Solid organic waste	Separately collected kitchen and garden waste	Kitchen and garden	Seasonal variation in emergence and composition might occur.
Municipal wastewater	Domestic and industrial wastewater, partly mixed with RW and infiltrating groundwater	Households and industry	Wide variation of type and concentration of containing pollutants, depending on domestic water use, and type and volume of connect industry.
Sewage sludge	Primary and secondary sludge from wastewater treatment	Wastewater treatment plants, septic tanks	Also potential source of contaminants such as heavy metals and organic pollutants, depending on pollutants from industries, and stormwater runoff.
Primary sludge	Sludge obtained in primary treatment of wastewater	Wastewater treatment plants (WWTP)	Contains all solids, which can be separated from wastewater entering a WWTP.
Surplus sludge, activated sludge (Secondary Sludge)	Sludge produced by aerobic wastewater treatment	Secondary clarifier (WWTP)	Consists mainly of microbial biomass, enrichment with Phosphorus possible (bio.-P).
Digested sludge	Sludge resulting from anaerobic digestion of sewage sludge.	Anaerobic digester for primary and secondary sludge	Increased dewater ability and release of Phosphate and Ammonia in liquid phase.

[1] toilet paper can be included

Generally, all sanitation systems can be linked to the production of TP, but dry sanitation systems tend to be more suitable, since urine and feces are obtained in undiluted fractions. The specific volumes of urine and feces flows are comparatively low and have accordingly high nutrient concentrations and comparably low water content.

The high water content and low nutrient concentration makes CSS at first glance not suitable for TPS. However, CSS can be linked to the production of TP, for example, by utilization of sewage sludge. In activated sludge systems both surplus sludge and primary sludge contain high amounts of organic carbon and plant nutrients.

Regarding partial flow characteristics, limited data is available from NSS compared to CSS. Present literature on specific volumes of partial flows and the specific wastewater parameters was evaluated by DWA (2008). Greywater represents the largest volume in domestic wastewater and has generally a good potential for nutrient utilization. However, nutrient recovery is less efficient compared to urine or feces due to low nutrient concentration in greywater. Values given in Table 3.2 further show wider ranges compared with urine and feces.

Table 3.2: Domestic wastewater separated flows and specific loads.

Parameter	**Greywater**	**Blackwater***	
		Urine	**Feces**
Q [l/(P*d)]	108 (65–50)[2]	28 (6–37)[2]	
		1.37 (0.5–2.5)[2]	0.14 (0.07–0.4)[2]
TSS [g/(P*d)]	19[3]	41.8[3]	
		12[3]	23[3]
COD [g/(P*d)]	47 (7–102)[2]	10 (5–24)[2]	60 (37–63)[2]
N [g/(P*d)]	1 (0.1–1.7)[2]	10.4 (3.6–16)[2]	1.5 (0.25–4.2)[2]
P [g/(P*d)]	0.5 (0.1–2.2)[2]	1 (0.4–2.5)[2]	0.5 (0.3–1.7)[2]
K [g/(P*d)]	1 (0.2–4.1)[2]	2.5 (1.0–4.9)[2]	0.7 (0.24–1.3)[2]

* Blackwater inclusive toilet paper

[2] According to DWA (2008); values given in brackets represent the range of evaluated data

[3] According to Friedler et al. (2013): wastewater composition

Since greywater is obtained from various sources, such as washing basins, showers, laundry or dishwashers, its characteristics can vary accordingly. Thus, it is recommended to distinguish greywater further, with respect to greywater with higher and lower contamination. Greywater is produced in relatively large quantities and its contamination with pathogens and nutrients is comparably low. Therefore, it should be the preferred partial flow to be used for reclamation and water reuse (Schuetze & Santiago-Fandiño, 2013). The US-EPA or WHO guidelines (US-EPA, 2008; WHO, 2006) describe a wide spectrum of possibilities for reuse, different requirements and options for treatment, and also examples of worldwide applications.

Undiluted urine contains the highest concentrations of Nitrogen and Phosphorus compared with other domestic wastewater partial flows. Due to its nutrient composition urine itself is considered a liquid fertilizer. According to WHO guidelines, it may be directly applied on agricultural land; in moderate climate after storing urine for six months, in private households also without storage (WHO, 2006). Nitrogen in fresh urine is mostly contained in the form of urea, which is hydrolyzed in short terms into ammonia. After hydrolysis, nitrogen is present as ammonia up 95% and pH raised from approximately 6 to 9. Within collection and storage systems a certain percentage of phosphate and nitrogen is reduced due to precipitation induced by hydrolysis and rise in pH (Udert et al., 2003). Within the last decade several nutrient recovery processes were developed for utilization of urine. Due to the high concentration of phosphate and ammonia, as well as the pH of hydrolyzed urine, magnesium-ammonia-Phosphate precipitation gained highest interest in this context. Moreover, processes were developed based on a biological (partial) nitrification in order to allow production of nitrate based fertilizers and achieve stabilization of urine. Next to high nutrient content, human urine may contain residues and derivatives from pharmaceuticals (Kümmerer, 2008; Winker, 2009). Contamination with such micro pollutants should be taken into account if it is used directly for fertilization of edible crops. It can be assumed that treatment of urine within a TPS approach will lead to reduced health risks from consumption of possible pharmaceutical residues. Contamination risks can be reduced by bindings of pollutants to humus matrix and charcoal and through decomposition by various biological processes. Regarding potential pathogen contamination of urine, it is considered that relatively small quantity of disease-causing pathogens is excreted by humans via urine (Hoeglund, 2001; EcoSanRes, 2008). Nevertheless, cross-contaminations with fecal pathogens can occur within collection systems. If urine is collected together with flush water in the form of yellowwater, the specific hardness of the flush water influences the level of precipi-tation, which leads eventually to significant nutrient reduction in case of higher water hardness.

Undiluted feces have the smallest volume compared with other domestic wastewater partial flows, followed by undiluted urine. In the form of blackwater the volume of diluted feces is comparably low compared to greywater. Due to the pathogen content of feces that contains various coliform bacteria, viruses and parasites, treatment of fecal matter requires special attention, particularly since most water borne diseases origin from fecal contamination (WHO, 2006). With respect to health protection the chain of collecting, treating and utilizing fecal matter has to be strictly controlled. However, adequate treatment, for instance by involvement in TP production, facilitates the reuse of feces as resource for plant nutrients and organic carbon.

3.3. Collection and transport systems

In CSS, municipal wastewater from industrial and domestic sources, together with rainwater and infiltrating groundwater, need to be transported, to be treated in centralized treatment facilities. The collection and transportation of municipal wastewater is realized by sewage systems. CSS require large volumes of water to facilitate the transportation of solids in a sewer system. NSS require much lower water demand for operation. The development of NSS is accompanied by the development of toilets without, or with reduced water consumption, compared to conventional flush toilets. Table 3.3 gives a general overview of various toilet types, their implementations and specific requirements. Simplified sewage systems were developed for transport of both wastewater without solids and rainwater. Such sewage systems require less investment costs and maintenance compared to sewer in CSS. Simplified sewage systems generally have a solid-liquid separation at the source and are used for the transport of liquid wastewater with insignificant solid concentrations. Due to low volumes of solids, which can be transported with simplified sewage systems, source separated solids like feces or dewatered sludge have to be treated and processed locally. Alternatively, collected solids can be transported to semi-central or central treatment facilities.

Table 3.3: Toilets types, specific requirements and sanitary system implementation.

Name	**Water and auxiliary means demand**	**Implementation**	**Transport**
Flush toilet, Water closet (WC)	1.5–12 l/flush[I)]	Connection to sewage system or septic tank.	Gravity flow in piping (DN80/100) and sewage system (BW); Transport by suction truck (septic tank).
No-Mix flush toilet[II)]	0.7–1.1 l/flush (YW) 3.5–7.0 l/flush (BrW)	Various options[III)] for BrW. YW has to be collected and stored separately.	Gravity flow in piping, separate for YW and BrW.
Dry/ Composting toilet	No water demand, Bulking material for drying and covering.	Independent from sewer, »stand alone« solution.	Manually for on-site treatment and utilization or truck transport to central or semi-central treatment facilities.
Urine diverting dry toilets (UDDT)	No water demand, Bulking material for drying and covering.	Independent from sewer, »stand alone« solution, U has to be collected and stored separately.	Manually for on-site treatment and utilization or truck transport to central or semi-central treatment facilities. Transport of U in simplified sewer possible.
TPS dry toilet (under development, not yet available on the market)	No water demand, addition of lactic acid fermentative microbial mixture for conservation and pretreatment[IV].	Independent from sewer, »stand alone« solution, also suitable for multi-story buildings.	Transport via suction trucks to central or semi-central treatment facilities, pumps and pipes to on-site treatment.

Vacuum toilets	0.7–1.1 l/flush	Semi-centralized vacuum sewer systems with anaerobic digestion and bio gas production facility.	Vacuum pipes to storage tank and biogas facility, subsequently digested BW is transported by suction trucks or further treated and utilized on-site.
Vacuum separation toilet[V)]	F/BrW: 0.2–2 l/flush U/YW: 0–0.2	Vacuum systsem for BrW (see vacuum toilet); U/YW: separate management.	BrW: see vacuum toilets U/YW: Gravity flow in piping system (DN50).
Urinals[VI]	0–1L/flush	Mostly installed in public toilets	Gravity flow in piping system (DN50).

[I] Demand of 1.5 litres per flush is valid for WC with low flush or water saving option, only for transport of urine. Lowest water demand of WC for transport of feces is to find with 3.5 litre per flush

[II] First no-mix toilets were produced in Sweden and later also in Germany, but there the production and further development stopped due to limited acceptance and low number on demands

[III] Implementation is possible in systems with 2 or 3 partial flows; e.g. YW separately for use as liquid fertilizer on-site and BrW treatment in co-composting processes; YW and GW for treatment onsite by constructed wetlands.

[IV] Microbial mixtures can be purchased (e.g. Effective Microorganisms®) or cultivated (e.g. Bokashi or »Sauerkraut«)

[V] Most urinals are designed for men only. Models for women or unisex are very limited and implementation of these models scarce realized.

[VI] Urinals are nearly exclusively designed for men. Implementation of waterless urinals can reduce the BW volume by 40%.

3.4. Principles of TPS and TP production

The idea of TPS started with the rediscovery of the ancient TP soil in the Amazon in the second half of the 20th century (Factura et al., 2010) (see also chapter on »History of Terra Preta re-discovery«).

TP is an anthropogenic soil, which is assumed to be formed from a combination of organic-wastes, viz; fecal matter from humans, animals, and charcoal. The relatively high nutrient content of TP soils derives from certain nutrient sources such as fish residues as well as human and animal excreta. Hence TP soils represent a sink for organic carbon and plant nutrients deriving from various waste streams.

Inspired by the discovery of TP, toilet wastewater could be used for the production of soil amendments as a source for plant nutrients and organic carbon, due to its high nutrient. One of the main concerns is the large volume of toilet wastewater. Therefore, flows, which are rich in nutrients and organic matter have to be separated from the biggest portion of the water, to be included in a TP production process. Such separation has to be either realized at the source (user interface) or within the collection and/or treatment processes. The production of TP soil amendments requires addition of various organic waste products, and the mixture has to fulfill certain demands in terms of carbon to nitrogen ratio and water content. Source separated fecal sludge, urine, and sludge obtained within conventional treatment of municipal wastewater are characterized by high water content and/or a narrow carbon to nitrogen ratio. Hence, further ingredients have to be chosen to balance these parameters, and in order to achieve a mixture which is suitable for composting and/or vermicomposting (see chapter on »Bioresources and conversion technologies in TPS«). The high water and nitrogen contents of (source) separated wastewater streams can be compensated in the mixture by the addition of woody materials. Woody materials are characterized by low water and nitrogen contents. The amount of woody material for composting of urine can be estimated based on the C to N ratio to 200–300 kg per person and year. Involving charcoal in the composting process gives, besides improved nutrient content due to increased ion exchange capacity and structure that promotes microbial colonization, additional positive effects such as compensation of high water content (Bettendorf et al., 2014). By increasing microbial biomass the contents of organically bound nitrogen and phosphorus in the products is also increased leading to long term nutrient depots and reduced nutrient leakage.

The idea of integrated treatment and utilization of (source) separated wastewater streams and solid organic waste is not new. It is also part of the EcoSan principles. But, TPS widens the scope by including charcoal into the treatment and utilization chain with proven long-term positive effects, which already start at the capturing and collection and end up in long lasting soil improvement.

3.5. Integration of TP production in different sanitation systems

TP production can be integrated in various parts of sanitation systems and the sanitation chain. It is most effective to integrate TP production already in the design and planning of sanitation systems. However, it is also possible to integrate TP production in existing sanitation systems. In the framework of refurbishment and remodeling of existing sanitation systems, certain technologies, notably sub-systems of sanitation systems could be replaced by technologies which facilitate the separation and collection of nutrients and organic matter for TP production. Water saving sanitation technologies in combination with filter units for separation of solids from sewage streams are, for example, suitable technologies to increase the efficiency for TP production. By replacement of conventional interface such as flush urinals and toilets by waterless urinals or low flush toilets, treatment volumes can be decreased; nutrient concentration of blackwater can be significantly increased and solids can be separated to reduce the water content of solid organic matter (Larsen et al., 2007). Separation of solids close to the source is further an appropriate strategy to reduce solid deposits within sewers of CSS.

In the framework of research and development projects, retrofitting of existing sanitation systems to more resource efficient TPS systems has been successfully carried out. Various systems developed for TPS retrofitting can be operated in real life conditions. These systems have conventional user interfaces, for example water saving toilets and waterless urinals. The undiluted urine is collected and stored until it is transported to TP production site together with organic solids, which are separated from blackwater originating from water saving flush toilets. A wedge wire filter facilitates the separation of feces and toilet paper which are collected in containers together with certain amounts of microbial supplement[1] and biochar (coal produced from organic solid waste) in order to introduce lactic acid fermentation processes during the collection and storage phase. The result is a concentrated mix of toilet paper and feces that emits no malodorous gases. After a given period the containers are collected together with containers for urine to TP production sites for further processing, including composting for the production of soil amendments.

In Germany, for example, such systems are operated in a public toilet facility at the central train station in Hamburg and another system is operated in toilet facilities for visitors and employees of the botanical garden in Berlin. The retrofitted TPS systems are currently monitored and evaluated. The following sections will discuss different system approaches for the integration of TPS and TP production in different CSS. However, the discussion of specific case studies is beyond the scope of this chapter. Detailed information about the TPS sanitation case studies in Hamburg and Berlin are available in Schuetze & Thomas (2013).

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[1] Microbial supplements can be self-cultivated (Park et al., 2008), but also commercial product are available at the market (e. g. Effective Microorganisms®).

The TP production unit can be attached to treatment facilities for both wastewater and solid organic waste. The choice of the specific TP production site is dependent on the overall system approach, logistic requirements, and the available space for TP production. In order to minimize transport effort, the TP production facilities should be located close to the source.

By integration of TP production in existing sanitation systems an increased value chain could be created. In contrast to products from CSS (e. g. sewage sludge), the TP product could be sold on private and agricultural markets. The production of TP from sewage sludge is an attractive alternative to conventional sludge management. TP products are valuable alternatives to compost and fertilizer. In fact, TP products can be regarded as a combination of both. Furthermore, it is possible to adapt TP products with respect to specific customer demands regarding soil and cultivation requirements. Product adaptation and adjustments of nutrient values has potential to reduce efforts in soil cultivation and improve nutrient availability over the vegetation period and reduces nutrient losses (Voss, 2012).

The illustration of selected sanitation systems discussed in the next sub-sections follows the systematic approach presented by EAWAG (2008). In order to avoid repetitions of content presented in the compendium, the descriptions and illustrations presented below mainly focus on technologies and interface for solid waste utilization and the production of TP.

3.5.1. Integration of TPS in conventional sanitation systems

Within the 20th century CSS were developed and implemented in most parts of the industrial world. These systems include collection, drainage and centralized treatment of municipal wastewater and are intended to end with the environmental friendly disposal of (treated) sewage and sludge. By agricultural sewage sludge application a certain percentage of wastewater organic carbon and plant nutrients can be utilized. But, negative effects from sewage sludge application lead to declining acceptance among farmers resulting in alternative utilization or disposal methods. Negative effects derive from pollutants contained in sewage sludge, such as heavy metals and certain organic compounds, as well as from the way of application. The application of sewage sludge is associated with the risk of nutrient losses and thus limited to vegetation periods to ensure nutrient uptake by plants and reduce nutrient emissions via the gas and water phase. It is assumed that conversion of sewage sludge into TP mitigates the risk of nutrients leaching since the nutrients get incorporated in microbial biomass and also held by adsorption. In case of high heavy metal levels alternative sludge treatment and utilization is recommended. In such a case, treatment should aim for extraction of valuable compounds (e. g. phosphorus recovery), volume reduction (by drying and/or burning) and environmental friendly disposal of contaminated sludge or its ashes.

Due to elevated levels of heavy metals in sewage sludge, recent research and development projects aim for the separation of pollutants and the recovery of valuable content, particularly phosphorus, to increase the resource efficiency of CSS. Phosphorus recovery processes are applicable to different streams and products of the wastewater treatment process, e. g. treated sludge, effluent from sludge dewatering processes, and ash from sludge incineration processes (Ludwig, 2009; Pinnekamp, 2011). The highest potential for phosphorous recovery is with sewage sludge since phosphorus gets accumulated in it. Products from recovery processes show wide heterogeneity in terms of particle size, impurities and chemical bindings of Phosphate. A post treatment of phosphate sludge or phosphorus particles is mostly necessary in order to obtain a homogeneous product quality with good applicability in agriculture and providing good phosphorus availability for plants. Magnesium ammonium phosphate (MAP) is the prevalent product obtained from various available recovery processes. Phosphorus recovery products can be post-processed either to mineral fertilizers or to organic-mineral fertilizers. The latter can be obtained, for example by involving MAP in the conversion of organic waste into TP. Various positive effects can be assumed, such as increased nutrient content of the product and improved plant availability due to different bio-chemical processes within the conversion to TP.

A much promising approach for the integration of nature oriented systems in the management of sewage sludge, and the creation of synergies with TP production, is the utilization of artificially constructed wetlands (either vertical or horizontal flow) for sewage sludge.

The process of sewage sludge humification is an established treatment technology, but limited to smaller treatment facilities with population equivalents (PE) below 100,000 people. Within the sewage sludge humification process, untreated sludge is for example drained in reed beds for a period of up to one year. For the period of another year the reed bed is kept untouched. During this period, the humification process is finalized. Two years after the start of the reed bed operation, the humified sludge is excavated. The reed beds are equipped with a drainage system allowing collection of leachate and its recirculation into the prior treatment processes. Specific space requirements are roughly 1 m^2/PE, whereas the typical operation period of one reed bed is between 6 and 10 years. After this period, the wetlands have to be refurbished by cleaning of gravel beds and renewal of vegetation. Afterwards, the renewed wetlands can be utilized for sludge treatment for another operation cycle.

The following flow chart (Figure 3.1) illustrates an exemplary integration of TPS in a CSS, with centralized treatment of municipal wastewater. In this example, TP is produced from primary and (secondary) surplus sludge originating from the centralized sewage treatment process, in combination with charcoal and green waste.

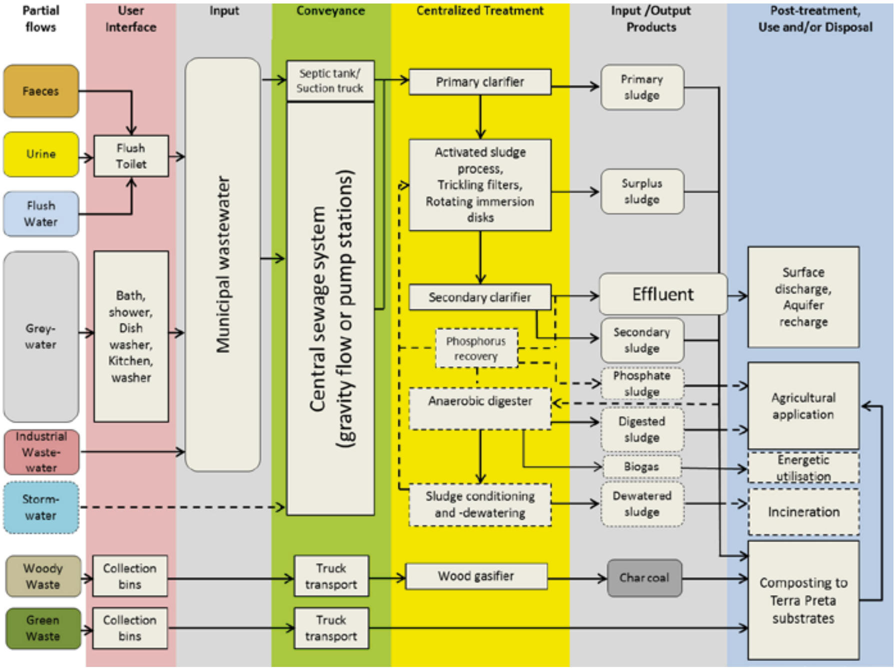

Figure 3.1: Integration of TPS in conventional sanitation systems.

3.5.2. Integration of TPS in new sanitation systems

In recent years several approaches for NSS have been developed for implementation in rural and urban environments. Compared to CSS, person equivalents of such NSS are lower. Generally, NSS systems are based on the separate management of greywater and blackwater; eventually further separation of urine and feces (e. g. in form of brownwater and yellowwater). This section discusses three selected TPS systems, namely the »Blackwater Vacuum System« (BVS), »Dry Toilet Systems« (DTS) and the »Loo-Loop System« (LLS), the technologies involved, interfaces and aspects relevant for TP production. The selection was done with respect to present developments and suitability for implementation in rural and urban contexts. Within the following presentation of selected sanitation systems, bins are used for the collection and transportation of organic waste. Bins are most commonly used but principally also kitchen waste grinders (e. g. installed in kitchens) could be used for the milling of organic waste. The resulting product would be transported with water in gravity- or vacuum pipe systems.

3.5.2.1 Blackwater Vacuum Systems

NSS with vacuum toilets as interface for blackwater collection are very effective tools to reduce the water consumption required for toilet flushing and to facilitate appropriate treatment and utilization. Operational experiences with BVS show a significantly reduced water demand for collection of blackwater in comparison with both conventional and water saving flush toilets (Oldenburg et al., 2008). According to experiences gained in Lübeck Flintenbreite, Germany, water demand of installed vacuum toilets is on average 6 l/P/day leading to blackwater with approximately 4–6 g/l total solids and nutrient concentration notable for recovery. Hence, resulting blackwater also offers opportunities for energetic utilization by biogas production along with efficient nutrient recovery (Wendland, 2009; Zeemann and Kujawa-Roeleveld, 2011).
In the case of the BVS in Lübeck-Flintenbreite, a nature-oriented system, an artificially constructed wetland (vertical flow) is used for greywater treatment, before the purified water is discharged to local surface water bodies. However, the greywater treatment in NSS can, generally, also be realized with more technical treatment facilities, such as sequencing batch- or biological membrane reactors. The advantages of technical systems are their smaller space demand compared with nature-oriented systems. However, in contrast to technical systems, the advantages of artificially constructed wetlands are less technical effort required for construction and operation, higher robustness and additional biomass production in form of phragmites (reed in the case of Flintenbreite) which grow in the wetlands. Residues from wetland

plants can be utilized in the TP production process as well. An outstanding example for a BVS is currently under construction for a settlement with 2000 PE in Hamburg-Jenfeld, Germany. The BVS is designed for anaerobic digestion of blackwater and co-substrates such as kitchen waste, lawn cuttings or sludge from grease separators. Artificially constructed wetlands will be integrated in the settlement to serve also as landscape-shaping element with positive effect on the micro-climate.

Primary sludge occurring in the framework of greywater treatment processes could be added to composting, for instance in combination with other organic matter. However, experiences from the case study in Lübeck-Flintenbreite show that the volumes are very small compared to the blackwater sludge from the vacuum toilets (Oldenburg et al., 2008). Accordingly, the contribution of the sludge from blackwater production to TP production is relatively small.

The flow chart in Figure 3.2 describes the utilization of digested blackwater residues of a BVS for TP production. The illustrated treatment of greywater in constructed wetlands can be replaced generally by alternative treatment processes, such as sequencing batch reactors, (membrane) bio reactors, fixed bed reactors or rotating submerged disk reactors.

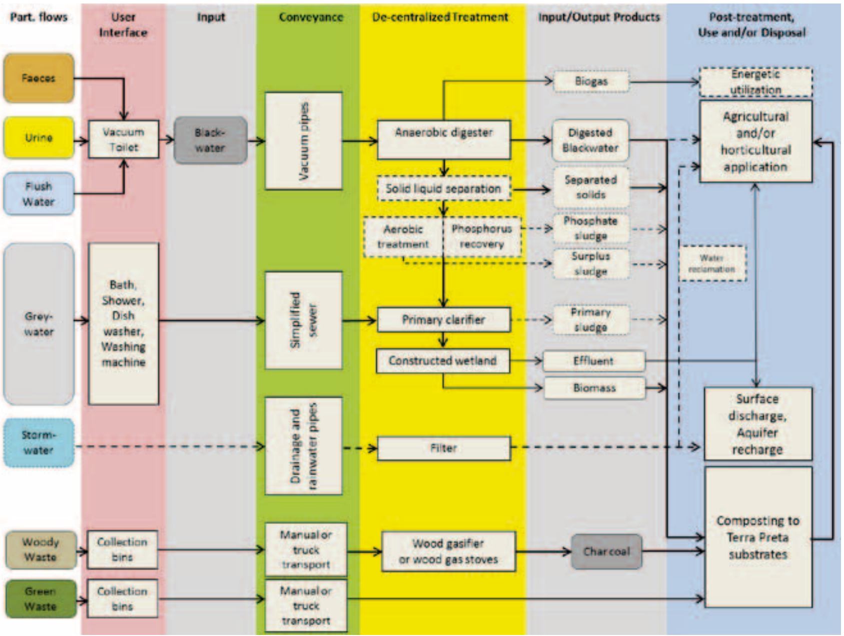

Figure 3.2: Extended Blackwater Vacuum System.

3.5.2.2 Dry Toilet Systems

DTS can provide suitable solutions for low cost and resource efficient sanitation in environments where non-flush toilet based sanitation systems are acceptable. A number of different DTS have been installed in areas of non-existing or unreliable water supply, especially in rural, peri-urban, and in remote settings (Morgan, 2006; NWL, 2006; Jenkins, 2012). Depending on the type of specific DTS, feces and urine are collected either separately or combined, and either with toilet paper and certain additives, or with beige water. Certain additives, such as ashes, lime or soil are used for different purposes, for example to cover fecal matter, to prevent odor formation, to regulate humidity, to store the fecal matter or to initiate and optimize composting processes. Charcoal is also a suitable additive in dry toilet systems because it has high adsorption capacity for water, nutrients and gases. However, in conventional dry toilet systems charcoal is generally not applied. The reason is that charcoal is, generally, not available in significant quantities in environments where dry toilets are installed. For the transformation of common dry toilet sanitation systems to TPS systems, the utilization of charcoal is indispensable. For a widespread application of charcoal in dry toilet systems and the development of TPS systems, the production and utilization of charcoal needs to be included in the layout of sanitation systems.

In DTS the stabilization and conversion of fecal sludge and other organic matter to compost can either be done in-situ, inside the toilet and next to the user interface (e. g. double vault composting toilets) or ex-situ, after transport of the raw or stabilized fecal sludge to a central composting site, and serving for the processing of fecal and organic matter from multiple dry toilet systems.

Urine diverting dry toilets (UDDT) have benefits, such as a reduced demand for the addition of dry material to control odor. UDDT have been successfully implemented in a number of countries all over the world (Wendland et al., 2011). Furthermore, separately collected urine could be either applied as liquid mineral fertilizer or be used for the production of dry fertilizer (Schuetze et al., 2013, Schuetze & Van Loosdrecht, 2010). Composting processes are beneficial for the biological decomposition of pharmaceutical residues in urine since sorption and biodegradation processes lead to retardation and elimination of potentially harmful substances. Retardation of pharmaceutical residues correlates with soil organic matter content, while biological degradation correlates with soil microbial activity (Chefetz, 2008; Xu, 2009).

A new approach for stabilization of fecal matter by lactic acid fermentation has been adopted from research findings on traditional TP production (Yemaneh, 2012; Factura, 2010, 2011). Here, collection under anaerobic conditions in air-tight containers is possible and collected fecal matter can also be pumped and transported with state of the art suction trucks. This type of collection and transport seems to be well suitable for implementation in urban- or peri-urban areas. Due to the new system approach and lack of additional practical case studies, further research and development needs to be carried out. The applicability of the described sanitation system, particularly the extraction and transportation, has to be proven under real life conditions. This approach is also applied successfully to DTS in a pilot project, where lactic acid fermentation of fecal matter has been induced by addition of a liquid microbial supplement (Andreev et al., 2012).

The flow chart in Figure 3.3 describes the collection, transportation and utilization in dry toilet systems and the extension to TP production. Details for the treatment and utilization of greywater is referred to blackwater vacuum system (see Figure 3.2).

3.5.2.3 »Loo-loop-Systems«

Another type of DTS is represented by the »Loo-loop-systems« (Lindner, 2008, Antholz et al., 2009). This systems uses biologically treated urine for flushing toilets in a closed loop. The system was developed at Hamburg University of Technology and the first technical plant has been installed at a public toilet at the Hamburg (Germany) central train sta-tion. It is currently operated on a pilot basis.

Within the »Loo Loop«-system, separation of solids (feces and toilet paper) and flushed

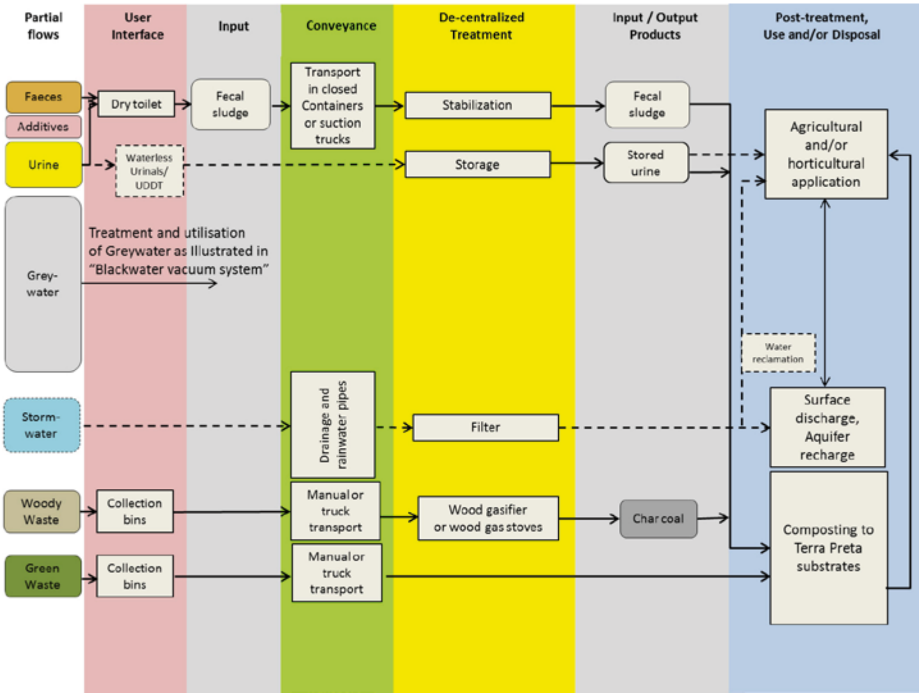

Figure 3.3: Dry toilet system.

water originating from flush toilets is realized in a first treatment step. The liquid – solid separation is based on mechanical sieves and/or filter bag units. Afterwards, the blackwater liquid phase is treated in aerobic reactors and by membrane filtration, in order to obtain an effluent fulfilling the requirements for toilet flush water (service water with bathing water quality). Urine is also collected with waterless urinals directly added to the blackwater liquid phase prior to aerobic biological treatment. At the end of the treatment, effluent is used for flushing and the surplus volume (entered urine) either used as liquid mineral fertilizer or is further processed to a solid fertilizer by evaporation of water and drying of separated solids.

Next to fecal sludge, surplus sludge is produced by the aerobe treatment step. Both types of sludge can be collected together in closed containers and stabilized by lactic acid fermentation for a few weeks, or months, until being converted to TP soil enhancers by composting (Bettendorf, 2014). A detailed description of the TPS system at the central train station Hamburg is available in the TPS conference paper of Schuetze & Thomas (2013).

The flow chart in Figure 3.4 describes the collection, transport and utilization within the »Loo-loop«-System. For the treatment and utilization of greywater it is referred to blackwater vacuum system (see Figure 3.2).

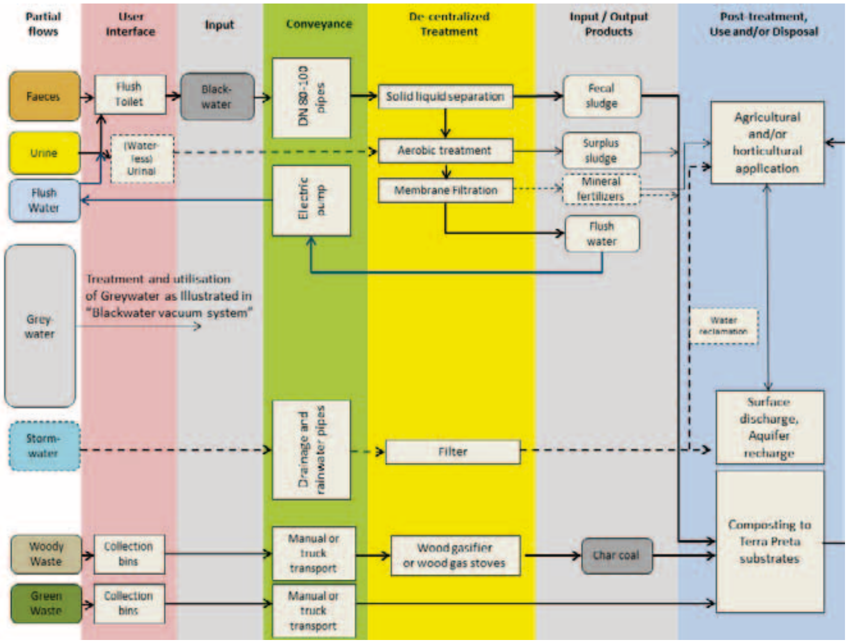

Figure 3.4: »Loo-loop«-system.

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Chapter IV: Composting of bioresources for Terra preta-inspired products

Christopher Buzie and Ina Körner

This chapter examines bioresources usable for production of composts and terra preta-inspired products (TP) employing common (thermophilic) composting and vermicomposting as conversion processes.

Figure 4: Integration of TPS in conventional sanitation systems.

4.1. Introduction

A major difference between common compost and terra preta-inspired products (TP) lie in their input materials.TP production requires as pre-requisites human faeces and charcoal, in addition to common compost substrates such as kitchen waste and green waste. The objective of TP production is to generate a nutrient-rich and carbon-storing product. Charcoal is expected to support nutrient storage as well as carbon sequestration. High nutrient contents (Nitrogen and Phosphorous) are conferred to the material by the excreta (faeces and urine). However, Theuretzbacher et al. (2014) have reported that not all products marketed as TP contain excreta. They also conclude that it is still unclear, which ingredients make a product TP-like. Furthermore, common compost also stores Carbon and contains nutrients.

4.1.1. Bioresources suitable for Terra preta inspired products

Common composts may be produced from a wide variety of biogenic substances, ranging from wood materials to kitchen waste (Table 4.1). Lignocellulosic woody materials generally give structure and porosity to a composting mixture, allowing good aeration, water and nutrient absorption. Kitchen waste has a high content of readily degradable organic substances and contains more nutrients compared to woody feedstocks. Preparing the right mix is a pre-condition for composting, both for common composting (see chapter 4.2.2) and vermicomposting (see chapter 4.2.3).

Table 4.1: Feedstocks typical for composting (adapted from Krogmann and Körner, 2000).

Mixed municipal solid **Waste** (MSW, biogenic waste fractions mixed with other residues from e.g. plastics, glass, metal) **Residual waste** (residuals after source separation of biowaste and dry recyclables) **Yard waste and other green wastes** Grass clippings Brush and tree trimmings Leaves Cemetery wastes Christmas trees Seaweed and other aquatic plants **Agricultural wastes** Excess straw Spoiled hay and silage Beet leaf residuals Dead animals (not allowed in some countries) Solid and liquid manure	**Biowaste** (source separated food and yard waste) **Sewage sludge** (biosolids; residual sludge from waste water treatment facilities) **Paper products** (partly with limitations regarding the accepted amount; e.g. in Germany) **Market wastes** (e.g. spoilt and unsold fruits and vegetables) **Processing residuals** Residuals from the food processing and beverage industry Residuals from vegetable oil production Fish processing wastes Paunch contents from slaughterhouses Barks Sawdust and shavings **Forestry wastes** Residuals from wind breaks Loggingresiduals

The feedstocks used for common composting and vermicomposting were discussed frequently in the literature. The following box summarizes the aspects that are relevant to understanding composting, regardless of whether it is common composting or composting for TP.

Properties of composting substrates

Körner, 2009 summarized information regarding common composting substrates based on, for example, Glathe and Farkasadi, 1966; Golueke, 1977; Bidlingmaier, 1985, 2000; Schuchardt, 1988; Kutzner und Jäger, 1994; Flemming und Faulstich, 1995. Based on the summary, the input substrates for common composting can be sub-divided into easily degradable (sugar, starch, hemicelluloses, cellulose: e. g. paper), medium degradable (cellulose: e.g. wood, fats, waxes) and persistent components (lignin and other high-molecular, phenolic compounds). The substrates also contain inorganic components. The biodegradability of the organic compounds can vary between 0 and 90%, whereas the inorganic components are, for the most part, inert. The degradabilityof organic compounds depends on the chemical structure of the respective organic substrate. For the degradation process, microorganisms require mostly carbon (C) and nitrogen (N), in addition to other nutrients. In general, sufficient amounts of phosphorus (P), potassium (K), sulphur (S), magnesium (Mg) and calcium (Ca) are contained in input mixes. The nutrients are also essential for vermicomposting, which is mainly a microorganism-driven process. Earthworms are mere facilitators, whereby they increase the substrate's surface area and modify other physical characteristics such as particle size and porosity thereby enhancing microbial degradation (See section: 4.2.3.1). A risk of undersupply sometimes exists with regard to N.

In the following paragraphs, the additional composting substrates which contribute to TP are briefly described with respect to their suitability for composting:

Charcoal: It is commonly a powder-like substance if produced from plant or animal residues (or whole primary plants, but not recommended due to the fact that it lacks resource efficiency) in industrial scale and hence lacks the structure necessary for aeration. It may be generated in gasification, pyrolysis or hydrothermal carbonization processes. The charcoal is air dry, which means the water content is most probably below 10%.The nutrient contents are irrelevant.

Faeces and urine (Excreta): They are comparable with animal manure with regards to nutrients, but often tend to be more diluted. For instance, nutrient concentrations in blackwater may be as follows: N – 25% DM; P – 2% DM. The dilution of nutrients with water depends on the toilet system used. With vacuum toilets the water content is for example, 99.4%, with common flushing toilets it is even higher (Körner and Hertel, 2014). The water content in raw, undiluted faeces is between 50 and 80% (Shalabi, 2006; Buzie, 2010) and in urine 95% (Academic, 2009). In latrine systems the water content of the mix ranges between 60–85%. In any case, the consistency is liquid or sludgy.

Faecal solids from TPS-toilet-systems: The so called »Terra-Preta-sanitation« toilet systems (TPS) are so named since it is desired to collect the excreta undiluted as possible and mix it with charcoal for further treatment and transformation to generate TP carbon-rich substrates, and microorganisms are added into the toilet during faecal matter collection, thus differentiating TPS systems from ordinary latrine systems. The purpose of adding microbes and especially easily available carbon sources is to initiate lactic fermentation (LAF) in order to lower pH and with it odor emissions. Factural et al. (2010) report that a considerable quantity of the simple sugars is degraded by the LAF process. However, most of the polysaccharides remains undegraded, since the bacteria (e.g. *Lactobacillus lactis, Lactobacillus acidophilus*) responsible for the LAF process lack the capacity to degrade long-chain carbon compounds. However, the authors assume that the simple sugars would also be degraded without adding specific bacteria.

4.2. Conversion of bioresources into Terra Preta-inspired products

4.2.1. Basic requirements

The main objectives of the follow-up treatment of the bioresources discussed in section 4.1 *are to stabilise organic matter, eliminate potential health hazards, and allow the recovery of materials for re-integration into the materials cycle.* In order to generate a product with fertilizing and soil improving properties from wastes for soil improvement purposes, some basic conditions regarding the production process have to be considered. Often requirements are stated in national legislations. For example, in Germany, the Biowaste Ordinance (BioAbfVO, 1998) stipu-lates the requirements for compost production for land application.

Here, we examine two important conversion processes: common composting and vermicomposting. Common composting (also-called thermal composting or simply composting) is an existing and well-established method for organic matter conversion. Various technological approaches such as windrow composting, container composting or tunnel composting are successfully implemented in technical scale since a long time in many countries. Vermicomposting, on the other hand, is often practiced on small scale at household level. But also examples for technical scale application exist. Which system is chosen actually depends on the situation (see section 4.2.4.). However, in vermicomposting earthworms are involved in the organic matter degradation process in addition to microorganisms. For this reason, it can only work under certain conditions, with temperature (between 15 and 30 °C) and moisture (60 and 75%) contents being the main factors. Owing to this low temperature range, the technology does not guarantee pathogen elimination. However, studies by Factura et al. (2010) and Buzie (2010) suggest that pathogens are neutralized during the vermicomposting process probably due to predation (earthworms feed on microorganisms) and competition. In a well managed common composting process, hygienization is feasible due to elevated temperatures (see section 4.2.2, Figure 4.2).

For the special ingredients required for the production of TP, the following points are important to be considered when looking at composting processes with regards to hygiene and stability issues.

Charcoal: It can be considered as stabilized and free of pathogenic organisms as its production (by pyrolysis, gasification or hydrothermal carbonisation) involves thermal degradation under oxygen deficient conditions with process specific temperatures between 100 and 1000 °C (See section 4.3). In any case, temperatures are high enough for pathogen elimination. During charcoal production, the stability increases with temperature due to removal of predominantly oxygen and hydrogen which gives charcoal similar properties as fossil coal.

Faeces and urine: The occurrence of disease causing organisms in human excreta is a result of infection of individuals. A wide range of pathogens are documented in Schönning and Stenström (2004). For instance*, Leptospirainterrogans, Salmonella typhi, Salmonella paratyphi and Schistosomahaemotobium* are traditionally known pathogens occurring in urine. More than 120 types of viruses may be excreted in faeces. Among bacteria, *Salmonella* spp., *Campylobacter* spp. and enterohaemorrhagic *E. coli* (EHEC) are of general importance. Furthermore, parasitic protozoa and helmith eggs may be of concern. For this reason, hygienization (sanitization) is necessary. If this is achieved, the product will be a sanitized TP.

Stability according to the U.S. Environmental Protection Agency (US-EPA)

Stability is defined as the point at which readily degradable substrate is diminished so that its decomposition rate does not control the overall rate of decomposition. Decomposition rate expresses the effectiveness of the conversion process and is an important parameter to assess the process. Because only the volatile solids can be decomposed during the conversion process, the decomposition or conversion rate is usually expressed as a reduction in volatile solids (Qiao and Ho, 1997). As stability is related to vector attraction, the US-EPA recommends a 38% reduction of volatile solids as one alternative for vector attraction reduction. Organic material that remains degrades so slowly that vectors are not attracted to it (US-EPA, 1999).

Pathogen limits accordingto the U.S. Environmental Protection Agency (US-EPA)

For protecting public health, several international standards for meeting pathogen limit in biosolids have been established. The US-EPA for example, designates treated (converted) faecal solids as »Class A biosolids« or »Class B biosolids« in regards to the density (numbers/unit mass) of pathogens in the material. This classification uses faecal coliform and *Salmonella* spp. as indicator or reference pathogens. For »Class A biosolids«, either: the density of faecal coliform must be less than 1000 MPN per gram total solids (dry-weight basis), or the density of *Salmonella* spp. must be less than 3 MPN per 4 gram of total solids (dry-weight basis). For »Class B biosolids« either the density of faecal coliform must be less than 2 million MPN per gram total solids or less than 2 million coliform forming units(CFUs) per gram of total solids at the time of use (US-EPA, 1999).

It is important to note that the conversion of faecal matter as well as charcoal within composting processes is strongly influenced by their physical and biochemical characteristics and the characteristics of the other substrates within the mixture. Also important are the composting conditions. The key aspects of composting are explained in section 4.2.2. for common composting and in section 4.2.3 for vermicomposting.

4.2.2. Common Composting

4.2.2.1 General overview

Many researchers have described the common composting process in detail (among others are Bidlingmeier, 1985; Krogmann and Körner, 1999, Körner, 2009; Krogmann et al., 2010; Boldrin et al., 2010). It is a natural process in which a consortium of microorganisms, notably bacteria and fungi, decomposes organic material to carbon dioxide and water as main products whereas heat is generated under aerobic conditions. With limited supply of oxygen, anaerobic microorganisms may produce compounds such as methane (CH_4), hydrogen sulphide (H_2S), and organic acids. These processes are unwanted. They can be reduced using suitable input mixtures and controlled (aerated) composting conditions. Favourable C to N ratios lies between 20 and 40, depending on the substrate. The pore volume at the start of composting should be between 20 and 50% to allow good aeration (Körner, 2009).

In the following sections key aspects of common composting in general and under special consideration of faecal matter as a composting substrate are discussed. Examples for situations in different countries and for different technologies are included.

Feedstock

Substrates with a high proportion of organic material are, generally speaking, compostable.

In the EU, the majority of substrates treated in composting plants originate from the separate collection of organic household waste. The composition of bioresources or waste is influenced by its origin, as well as by climatic, social or cultural circumstances. Other feedstock sources are landscaping, agriculture, and commercial and industrial businesses (see Table 4.1). In addition, compost is also produced out of mixed municipal solid waste (MSW) in several countries. This is not allowed, for example, in Germany MSW composts often show high contaminant contents (Körner, 2009). The feedstocks suitable for producing composts for agricultural applications are listed in the biowaste ordinance (BioAbfVO, 1998). Sewage sludge (biosolids) as ingredient has to fulfil special requirements regarding contaminant content if used in composting. It has to be controlled to fulfil demands of the sewage sludge regulation (AbfKlärV, 1992). Human excreta and charcoal are so far not considered as suitable ingredients in the German legislation.

Methods of composting

The methods employed for common composting can significantly differ from each other with regard to pre-processing and post-processing techniques, rotting systems, process control and emission treatment. Pre-Processing and post-processing can comprise procedures such as screening, shredding, sorting, homogenising and mixing. Pre-Processing serves, among others, to remove foreign particles and to adjust suitable rotting conditions. Post-processing aims mainly to adjust the product properties to the application area. In a composting plant, however, not all process steps must always be carried out. The treatment of emissions is often omitted, for example when the emissions are either insignificant or when no legal provisions regarding the treatment exist (Körner, 2009).

Rotting is the central process step in a composting plant. The rotting systems can be subdivided into variants which are open towards the environment or closed. According to the form of the substrate filling or of the reactor, it can be further differentiated into windrow, tunnel, hall, box, container, tower and drum systems. Examples for different types of composting systems are shown in Figure 4.1a and 4.1b. The adjustment of suitable rotting conditions during composting is implemented primarily through the controlled aeration and humidification.

The process control has a significant influence on the composting time. This period can range, for example, from less than a month to more than a year and is additionally determined by the waste type and the anticipated product quality (Körner, 2009).

The throughput capacity can also be highly variable. Big European composting plants can be found e.g. in the Netherlands, where approximately 470,000 Mg of organic waste are processed per year. Facility sizes between 5,000 and 20,000 Mg/year are more often implemented in Europe. Decentralized small open agricultural plants with less than <1000 Mg/year can additionally be found e.g. in Austria. In Asia, most of the existing composting facilities are of capacity 10,000–180,000 Mg/year (Körner and Visvanthan, 2013).

Figure 4.1a: Open aerated windrow composting (Photo by Brent Auvermann, courtesy Extension.org).

Figure 4.1b: Container composting with controlled aeration (Photo by Ina Körner, courtesy Hamburg University of Technology).

Milieu conditions during composting

The course of composting depends strongly on the milieu conditions and the process control methods applied to influence them. The methods applied in composting plants vary greatly and are normally targeted at water content, temperature and/or oxygen content. Thus, the control elements are aeration, turning and moistening which are employed individually or in different combinations. The following summarizes the main operational parameters and options for modifications (Körner, 2009):

- ***Aeration:*** It aims mainly to provide oxygen (O_2). As a side effect, it may lead to a cooling and drying of the substrate, and to the development of gradients. Active aeration can be characterised by the amount of air directed into the substrate. Variations are possible with regard to aeration intervals (number, duration, and order of magnitude), direction (suction and pressure aeration), type (fresh air, exhaust air) and air conditions (temperature, humidity). In several plants, aeration is ad justed to constant operation at the beginning of composting. However, in most cases, the aeration follows the demands of the specific processes. An example for passive aeration is shown in Figure 4.1a. Furthermore, natural aeration may be applied, whereas the efficiency mainly is determined by substrate structure and size of the pile.
- ***Turning:*** It aims to balance gradients (water content, temperature, O_2, substrate distribution). In addition, it may improve aeration. The quality of turning depends on the aggregate (e.g. wheel

loaders, special turning machines) and their operation method including the number of turning processes within the different phases of composting. In many cases, the turning rhythm is defined within the scope of an initial setting. In some cases, however, the decision on whether or not turning is required is made during the process, taking into account odour development or measurements regarding O_2, CO_2 or temperature. In addition, the turning rhythm can be influenced by certain given variables in the composting plant, such as the availability of employees and turning devices or the weather.

- ***Water content regulation:*** The optimum water contents at begin of composting is substrate dependent and ranges between 45 and 70%. During composting the optimum water content changes; in tendency it becomes lesser due to a change in substrate composition. High water losses may occur especially during the thermophilic phase of composting (Figure 4.2) due to evaporation or due to aeration under high temperature conditions. On the other hand, substrate degradation leads to a relative increase of the water content and during microbial degradation water is also formed. In any case, the water content has to be controlled and if necessary readjusted. If the substrate is to dry, water may be added, which is commonly done during turning. If the mixture is too moist, water adsorbing materials should be added. A possibility would be wood chips or eventually charcoal.

These general control parameters are true for both common substrate mixtures and mixtures containing the special ingredients (charcoal, faecal matter) for TP products.

Hygienization

Common composting is divided into different phases which are characterised by their temperature development. The phases result from the aerobic decomposition of organic substances connected with energy production, which is partially released as heat. The decomposition process may result in the temperature profile schematically represented in Figure 4.2. However, the concrete temperature course depends on the energy balance of the entire system. Influencing factors are, for example, the type and amount of substrate, substrate aeration and turning, insulation of the system and ambient conditions.

The development of high temperatures during composting is very important for hygienization or sanitation of the substrate – meaning the elimination or inactivation of pathogenic micro-organisms. German legislation requirements for sanitized compost are regulated in the BioAbfVO (1998), for instance. It considers specific temperatures for a specific time as shown in Figure 4.2. Composting facilities are obliged to control the temperature evolution in order to prove that they produce a safe product.

The phases of common composting

In each phase of composting, specific substrate components are degraded and a varying product quality is achieved. During the first phase, mesophilic organisms prevail (e. g. acid-forming bacteria and sugar-utilising fungi). With the transition to the thermophilic phase, a species change takes place to a less broad range of thermophilic bacteria and actinobacteria and only a couple of thermophilic fungi. At 65 °C, fungi have usually completely withdrawn. At higher temperatures, the actinobacteria also withdraw. At temperatures in the self-limitation range (at approximately 75 °C), the richness in species is very limited and *Bacillus* spp. prevail. With the decreasing temperatures during the cooling phase, microorganisms surviving through spores and formation of conidia, or which were introduced from outside, re-colonize the substrate. During the second mesophilic phase, fungi in particular prevail; as they are adapted to the substrate components which are less degradable and to the substrate humidity that tends to be lower (summarized from various literature in Körner, 2009).

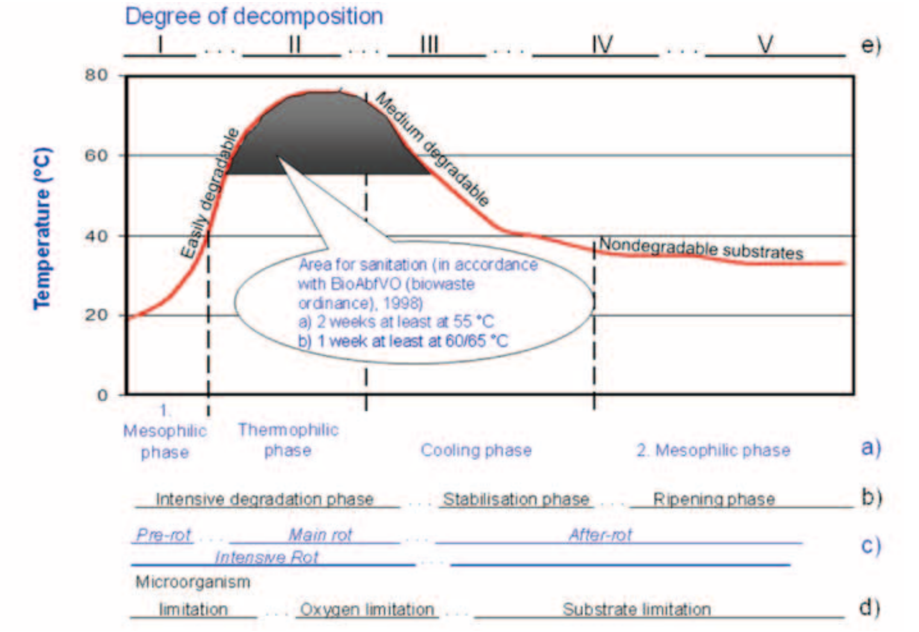

Figure 4.2: Phases of composting with terminologies regarding a) temperature b) degradation and build up phases c) process units in composting facility d) Limitation e) product qualities (Körner, 2009).

To generate TP hygienization aspects have to be considered the same way as in common composts and the self-heating properties used to do so. It is more challenging to reach the desired high temperatures in mixtures with charcoal and faecal matter since they are not easily degradable. For example, if the proportion of the inert charcoal is too high not enough easily degradable substances may be available for good degradation and with it suitable temperature development. In such cases, mixing ratios have to be modified till a suitable temperature evolution is reached.

4.2.2.2 Faecal matter as ingredient

Composting technology has been widely used for the processing of source-separated human faeces (WHO, 2006). The main objective of composting faecal solids is to neutralise pathogens (section 4.2.1). Vinneras et al. (2003) reported that the time needed to reach the temperature levels needed for sanitization in composting of separated faeces is approximately 10–15 days. It is also in this thermophilic range that the maximum decomposition of organic material occurs followed by maturation. Since few literatures exist regarding faecal matter composting some information were added for sewage sludges. Burge et al. (1987) and Millner et al. (1987) reported that composting of sewage sludges effectively reduces pathogen concentrations to very low levels. However, Russ and Yanko (1981) and Sidhu et al. (2001) have pointed out that absolute removal of pathogens is difficult to achieve.

4.2.2.3 Charcoal as ingredient

Since charcoal is supposed to be inert, it does not contribute to the composting performance by own degradation. However, it may have indirect effects which could be positive or negative. A positive effect may be the property to store compounds. This effect could be beneficial to trap ammonia, at least partly, which otherwise may be emitted in significant quantities since faecal matter is nitrogen rich. Mumme (2014) investigated the ammonia catching effect in anaerobic digestions systems, confirmed this property but also states that it is lower than using zeolithe, a compound which is also often mentioned in composting literature for emission reduction. Furthermore, charcoal could influence the microbial flora supporting degradation or also stopping it due to toxic effects. Bettendorf (2014) recommended a charcoal proportion not higher than 30% in the mix. However, data in this direction is limited.

4.2.2.4 Practical considerations

Input adjustment: In order to reach thermophilic temperatures as requirement for sanitation of the substrate mixture e.g. faecal matter from TPS toilets, charcoal and biowaste within a common composting system, the physical characteristics of the substrate mix must be adjusted. This is achieved by blending the faecal solids with bulking agents to give it a structure that permits free circulation of air to allow smooth aerobic decomposition to proceed. The bulking agent, in addition to providing structure, facilitates expulsion of gases through the air flow in the material mix and adsorbs nutrients. Various organic materials can be used as bulking agents suitable for faecal matter are e.g. wood chips, wood shavings, hay or straw. The bulkier the material the better the air circulation, which in turn accelerates the conversion process. Wood chips can be considered as most appropriate with respect to bulking properties. However, the origin has to be considered. Wood chips produced from quality wood from primary production should be excluded, since it would be contra-productive in terms of resource-efficiency. Residual wood, e.g. from landscaping or gardening (branches, twigs) or low quality thinning materials from forests is suitable. It has to be hackled to the appropriate particle sizes. The ratio to which the faecal solids and the bulking material are mixed depends on the moisture content of the faecal material and the bulking agent. But a two or three parts bulking agent to one part faecal solids seems to be appropriate in most cases. In case thermophilic temperatures may not be reached due to a limitation of easily degradable ingredients, wastes with such ingredients can be added. A very suitable option is kitchen waste. Special equipment is required to mix the faecal solids with bulking material and if necessary, other ingredients or additives. A special consideration has to be taken regarding security in terms of hygiene to avoid transmission of pathogen to the person handling the materials.

Open aerated windrow composting: In aerated windrow system could be an option for faecal matter if mixed bulking material. The mix can be spread, for instance, in rows which may be e.g. 0.5–2 m high and 0.75–4 m wide and are set-up outdoors. Periodic mechanically turning is necessary to homogenize the entire material and to avoid formation of gradients. Such gradients may lead to unfavourable zones (e.g. to dry or to moist) which may inhibit microbial degradation and with it may lead to low rates of sanitization within these zones. Depending on the specific system and local conditions, the piles may be covered to control odours, conserve heat, protect from rain and fend off pests. Aeration can be carried out by forcing air through the material (vacuum-induced or pressure-forced) by means of perforated pipes lying underneath the material Also passively aerated or natu-rally ventilated systems are possible.

Controlled in-vessel composting: This could be also an option for treating faecal matter. However no practical applications are known so far to the authors. The mixture of faecal matter and bulking material is processed in a reactor, e.g. in the form of a container or a box. Turning is also necessary, which may be carried out via installations within the reactor or via shifting the material from one reactor to the next e.g. with a front-end truck. In vessel systems are designed to minimise odours and accelerate the processing rate by controlling the microbial degradation progress for example, via temperature measurements and analysing the composition of the exhaust gas. Depending on the measurement results, airflow and/or turning rates may be adjusted.

Mass and volume reduction during composting: Also in composting with faecal matter losses of mass and volume occur. Various researchers (Van Lier et al., 1994; Larney et al., 2000; Brodie et al., 2000; Veeken et al., 2002) have demonstrated that significant reduction in material volume and mass occurs during composing of common substrates. On average, volume reductions of 19-58% have been recorded during thermophilic composting of most organic wastes. Mass loss is typically in the range 12 to 27% dry matter. The mass is mostly lost via Carbon dioxide. Compared to other substrates, faecal dry matter losses may be more in the lower range, since easily degradable compounds are missing. Easily available food compounds were already consumed in human metabolism.

Environmental considerations: Concerns related to thermophilic composting of faecal matter are related to pathogens spreading, emissions, odours and high energy demands. However, whether such problems occur, highly depends on the management of the composting facility and also the facility type. If the odours of faecal matter are a problem, an in-vessel system or a covered system should be used. If the substrate is well mixed and aerated, and the above mentioned operational requirements properly managed, malodorous gases and methane emissions as result of anaerobic processes are likely to be avoided. An insufficient air supply can cause anaerobic conditions within zones leading to processes connected with formation of odorous compounds such as diamines, ethyl mercaptan, hydrogen sulphide, ethyl amine, and methyl mercaptan or the greenhouse gases methane and N_2O. Ammonia (NH_3) emissions may mostly occur in well aerated systems during the thermophilic phase. They may be especially high with faecal matter as ingredient due to high nitrogen content in the faecal matter. However, emissions may be reduced by additions of adsorbing ingredients (e.g. wood chips, charcoal, zeolites) and if emissions occur, the installation of a biofilter is an easy and effective method to handle them. Thermophilic composting with active aeration is an energy-intensive process. The main uses of energy during composting relate to aeration. Further, less important energy consumers are the initial mixing of the faecal solids with bulking materials and turning during composting. Naturally or passively aerated systems may also be applied. The advantage is that they are not energy-intensive, but, on the other side the mixture may not easily reach high temperatures and the composting process commonly takes longer and is more area-intensive. Leachate generation should be avoided and if it occurs, it may not be released into the environment and may not be mixed the materials which are already through the thermophilic phase.

4.2.3. Vermicomposting

4.2.3.1 General overview

Vermicomposting is alternatively called earthworm stabilisation, or worm composting. It is an old approach in the field of soil sciences. In solid waste management it is partly practiced in very small scales in household levels; large commercially working facilities exist, but only a few countries are following this approach, including the United States (Aalok et al., 2008). It is less common in Europe. The process involves complex mechanical, chemical and biological transformations. Microorganisms are the main agents responsible for conversion of organic compounds, whereas earthworms accelerate the process by modifying the substrate. Substrate modification is accomplished by increasing surface area for microbial activity through reduction of particle size, and conditioning through mixing and secretion of digestive enzymes by earthworms.

The employment of earthworms for the conversion of sludge and biosolids into compost was first attempted by Mitchell (1997). Later, this investigator studied the potential role of the earthworm *Eisenia foetida* on the stabilisation of sewage sludge in drying beds, with promising results. Since then, several researchers (Benitez et al., 1999; Bansal and Kapoor, 2000; Suthar and Singh, 2008; Khwairakpam and Bhargava, 2009; Warman and AngLopez, 2010) have amassed scientific data supporting the viability of vermicomposting as a source of fertility (Eastman et al., 2001; Edwards, 1998; Ndegwa and Thompson 2001; Shalabi, 2006; and Buzie, 2010) as means of disease suppression (Szczech et al., 1993), and a means of bio-remediation (Ma et al., 2002). A comprehensive review of the literature on the evolution of the vermicomposting technology, with emphasis on substrate types, stabilization efficiency, pathogen inactivation and ultimate disposal and utilization is provided by Wang et al. (2009).

Species selection for Vermicomposting

While several researchers repeatedly point at *Eisenia foetida* as a suitable species for vermicomposting, there is indeed a wide range of other species that may be also effective as decomposers. For practical applications, the choice of species depends largely on temperature. Ashok Kumar (1994), showed that *E. foetida, E. eugeniae, P. exca*vatus *and P. sansibaricus* are well suited to Southern regions of India where summer temperatures are lower than in the north. In tropical regions, *E. eugeniae,* the African night crawler, is commonplace as a composting worm (Ashok, 1994; Kale, 1998). Aston (1988) report lethal temperatures from 25 to 33 °C for earthworms common to temperate regions and 34 to 38 °C for tropical and sub-tropical species, yet this range is higher than those reported by Edwards (1988): 30 °C for *P. excavatus* and *E. eugeniae*.

In literature the pathogen reducing property of vermicomposting is often mentioned. However, this effect cannot be considered as reliable. For that reason composting legislation, e.g. in Germany the BioAbfVO, demands thermophilic temperatures (Figure 4.2) and vermicomposting would only led to a save product in combination with a first thermophilic step. Viljoen and Reinecke (1992) have observed that earthworm mortalities occur at temperatures above 30 °C. Therefore, faecal mixture should be allowed to cool after the thermophilic step before inoculation with earthworms.

Vermicomposting techniques

Different variations of windrows exist; static pile windrows (batch) and top-fed windrows (continuous flow). The size of the windrows can range e.g. from 1 to 2.5 m wide and can be as long as 0.5 km. The faecal mixture should be placed, in successive layers, on top of the windrow at a thickness of 3 to 10 cm. Haimi and Huhta (1986) report that worms can work a maximum thickness of 5 cm of sewage sludge. Mitchell (1997) reported two-fold greater reductions of organic matter in windrows 20 cm deep than in windrows 30 cm deep.

- Static pile windrows are beds that are inoculated with worms on top and allowed to stand until the processing is complete (Figure 4.3).
- In semi-continuous flow top-fed windrows the earthworm media is placed first, then inoculated with worms, and then covered successively with thin (less than 10 cm) layers of feedstock. The worms tend to be active at the interfaces between the old and the new layer, but they drop their casting near the bottom of the windrow. By this, a layered windrow is created over time, with the finished product on the bottom partially consumed material in the middle and the fresh feedstock on top. The advantage is higher degradation efficiency with a greater worm production mainly due to improved control of parameters like feeding rate and moisture levels.
- Single-batch reactor sizes range from small boxes or bins to large, walled beds, or troughs. While being the most feasible for experimentation and small-scale vermicomposting, batch systems are labour-intensive for effective production since vermicompost must be removed before

Figure 4.3: Static pile windrows (Courtesy: J. Walker).

new material can be added. However, the total removal of material following vermicomposting allows for cleaning and is a means of avoiding mite infestation (Beetz, 1999).

Substrate loading rate

Determining the substrate loading rate is also very important for vermicomposting systems. An optimal vermicomposting process depends primarily on the appropriate delivery faecal solids to the treatment system and the compliance of optimum physical-chemical conditions for microbial aerobic biodegradation and activities carried out by the worms. An inadequate mass and frequency of loading may lead to inefficient utilization of substrate connected with the accumulation of intermediate products. Furthermore, excessive levels of substrate may lead to heat build-up with adverse effects on worms. It is recommended to apply the material frequently in thin layers, a few centimetres thick.

A major criterion in setting up a composting system is to stack waste in sufficiently large quantities to ensure that the waste piles. This condition stimulates the proliferation of thermophilic microbes, which then carry-out the decomposition activity. The common approach is to apply waste frequently in thin layers, a few centimetres thick, to beds or boxes containing earthworms in order to prevent overheating and help keep the waste aerobic (Fredrickson and Ross-Smith, 2004). Shalabi (2006) suggests that earthworms accelerate waste decomposition rather than being the direct agent. Loehr et al. (1988) reported that the rapid degradation of organic matter may be due to the increased aeration and other factors brought about by earthworms. Fredrickson and Ross-Smith (2004) however, point out that the processing rates will crucially depend on many factors such as the system being used, the processing temperature, and nature of the waste and the ratio of the earthworms to waste.

4.2.3.2 Faecal matter as ingredient

Human faeces are toxic to earthworms, and unless worms are acclimatized or the physical characteristics of the material are modified, faecal matter; even when pre-treated cannot be effectively processed by vermicomposting (Buzie, 2010). This problem is linked to the high electrical conductivity of faecal matter (approx. 2.8 mS/cm), the production of ammonia (>1 mg/g) during decomposition and the tendency for anaerobic conditions to prevail in faecal material. Therefore, modification of the substrate's physical characteristics is a necessary precondition for treatment of faecal matter by vermicomposting. Modification is carried out by mixing with wood chips or similar organic materials. Faecal solids from TPS systems require minor modification due to additives. The lactic acid fermentation (LAF) which takes place within the TPS system leads to considerable reduction of microorganism, including pathogens (Factural et al., 2010). However, it cannot be guaranteed that the substrate would be pathogen free. For safe soil application of the treated material, hygienization is necessary.

4.2.3.3 Charcoal as ingredient

There is no literature to the best of knowledge of the authors on the behaviour of earthworms in excreta-charcoal mixture.

4.2.3.4 Practical considerations

The substrate resulting from the LAF process is mostly anaerobic and a vast majority of its aerobic microbial community would have been eliminated under the low pH conditions. However, pathogens may survive. But assuming the substrate mixture from TPS systems is sanitized due to low pH conditions during the LAF process, it will additionally need a further treatment for maturation and stabilization. The substrate needs to be adapted to enable treatment by vermicomposting in two steps:

- *Step I: Aeration:* Air should be forced through the material or the material should be spread in a well-ventilated environment during a minimum of 72 hours. This allows expulsion of unwanted gases and re-anima-tion of aerobic organisms in the substrate.
- *Step II:* Earthworm inoculation: The substrate needs to be inoculated with a suitable density of earthworms for proper earthworm growth, reproduction and performance. Even when environmental conditions such as temperature and moisture are optimum, worm mortality and inefficient substrate decomposition can develop due to overcrowding Garg et al. (2008). A worm density of 2.3 kg worms/m^2 or 1.2 kg-feed/kg-worms & day is recommended (Buzie, 2010). Frederickson et al. (1997) and Dominguez and Edwards (1977) have reported significant reduction in growth rate and reproduction of earthworms as population densities increased. Worms should be applied with a fairly large quantity of their original media (the bedding material or soil containing the earthworms). A 1:2 ratio (worm: original medium) is recommended.

This approach provides solution to the following problems: Vermicomposting without pre-aeration would be very slow due to a low concentration or complete absence of aerobic microorganisms. If sanitation is not reached during the LAF process, aeration has to be prolonged, so that a self-heating profile similar to Figure 4.2 is reached.

Operational parameters

The main operational parameters for the vermicomposting process are generally moisture and temperature of the material. As already mentioned, ammonia concentration as well as the carbon to nitrogen ratio of the material are also critical parameters.

- *Moisture:* 65–75% moisture is suitable for vermicomposting of faecal matter mixed with the co-substrate. 70% moisture is optimal (Buzie, 2010). Diligent monitoring of water content is crucial for the success of the vermicomposting process.
- *Temperature:* Shalabi, 2006 states that temperature should lie in the range 20 to 25° C for optimal functioning of the process and to produce a stable product from the faecal matter mix in a relatively short period of time. The optimum temperature he reported to be 25 °C.

- *Carbon to nitrogen ration:* No specific study of note has been conducted to determine the C/N requirement of earthworms in vermicomposting with faecal solids as substrate. However, Shalabi (2006) and Buzie (2010) have suggested efficient vermicomposting C/N ratio of 20–25 for common vermicomposting substrates.
- *Ammonia:* Worms are very sensitive to ammonia and have sharp cut-off points between toxic and non-toxic concentrations. Worm mortality will occur at concentrations <1 mg/g of ammonia (Dominguez and Edwards, 2004). With high contents of faecal matter the danger increases, since it is very rich in N.

Existing vermicomposting systems with traditional vermicomposting substrates are reported to present a number of **practical problems**. Firstly, applying waste to beds and periodic earthworm harvesting by hand are considered labour intensive and costly. Most existing practical vermicomposting facilities are based on the model of open-air bed systems containing a bedding material and an inoculum of earthworms. Waste is applied to the surface of the beds and this is subsequently decomposed by the worms. The design and construction of typical beds often leads to several technical problems, including difficulties in applying waste to beds and inadequate drainage. Such systems are require much labour and are often marred by operational challenges. Alternative systems that minimise labour, operational problems and increase waste processing rates need to be investigated. The technical aspects of such systems such as basic design criteria (e.g. starter stocking density, feed application rates, system temperature and moisture specifications) and performance levels such as waste processing rates and worm productivity need to be established for systems working with faecal matter and charcoal as ingredients.

Hygienization

Environmental issues linked to faecal solids processing by vermicomposting concern mainly **public health**. This means the fate of pathogens during the vermicomposting process is important, especially where the material is intended for re-integration into the material cycle. In US, Pathogens elimination must meet the standards established by the US-EPA (see section 4.2.1 above: »Stability according to the U.S. Environmental Protection Agency«). In contrast, in Germany vermicomposting would not lead to a hygienized product regarding the standards provided by BioAbfVO (1998), since the temperatures enabling the growth of worms is far below the thermophilic range accepted for hygienization (Figure 4.2). In this case, vermicomposting would demand a pre-treatment – the thermophilic phase of common composting.

4.2.4. Common composting versus vermicomposting for faeces and urine containing substrates

While composting and vermicomposting both involve the decomposition of organic matter by microorganisms, there are key differences in the biochemical and physical factors controlling the processes. **Common composting** is a decomposition process that passes through a thermophilic stage where microorganisms liberate heat, carbon dioxide and water. Heterogeneous organic waste is transformed into a hygienic and homogeneous humus-containing product. Aeration (natural ventilation, passive or active aeration) and turning are important operational parameters. High demands are set regarding the substrate structure. **Vermicomposting** is a decomposition process of organic material that involves the combined action of earthworms and microorganisms. It does not involve a thermophilic stage. The earthworms are the agents of turning and fewer demands are posed regarding substrate structure. Since the process is carried out in flat beds no additional aeration is necessary. For vermicomposting, a key factor is to maintain temperatures below 35 °C throughout the process, otherwise earthworms will die. Therefore, a critical design criterion for vermicomposting systems is the feeding rate and also the system design. It has to enable that heat is retained so far to keep optimum worm temperatures, but also set free exhaust heat in order to prevent self-heating of the pile. Vermicomposting demands much more area compared to common composting.

Based on an analysis of the work published by various authors, it can be concluded that common composting and vermicomposting are different regarding process conditions and control, biological processes, operation techniques, space and energy demand as well as and compost quality. If faeces is involved as composting substrate the sanitation properties of the system are most important as well as the existing regional conditions. Generally, vermicomposting may reduce pathogen level, but cannot fully inhibit them. Common composting can efficiently inactivate or kill faecal pathogens if elevated temperature levels are kept long enough, however in practice also in well done common composting processes some pathogens may survive, since composting is connected with inhomogeneity's and also in well mixtures zones with too low temperatures may occur.

To decide on the system the local conditions regarding actual state of faecal matter whereabouts, legislative conditions and demanded scale of the system as well as availability on area, working power and energy provision has to be considered. Some scenarios are explained in the boxes to illustrate the connections.

Developing country scenarios:

Regions where faecal matter is actually directly released into the environment: Each type of composting system may be an advantage compared to a release of untreated faecal matter into the environment. Small scale home solutions could be a good option for improvements, if no public faecal matter collection systems exist. A private collection could be carried out in common latrines or eventually with LAF-systems. The latter has higher demands on collection, but has advantages regarding hygiene and odours. However, in each case safety measures in terms of hygiene have to be considered if handling the material (e. g. washing hands, keep away from food and drinking water). If common composting is carried out in small private scale, it cannot be expected, that the process runs through the required thermophilic stage. For that reason vermicomposting would be the preferred option, since at least partly a hygienization is reached and less handling effort is necessary. As co-substrates kitchen waste are suitable. Charcoal could be added, but only if available as a residue, e.g. from cooking with wood residues.

Regions where faecal matter is collected in latrine systems: If the latrines could by emptied by a public or professional service, it would be an advantage in terms of hygiene, since the personal would be better equipped and better educated in terms of hygiene compared to private persons. Also the follow up treatment would be more effective compared to private solutions no matter if a common composting or vermicomposting system is used. In each case co-substrates are needed. If there are enough woody residues and kitchen wastes available, common composting should be chosen. If the co-substrates allow a good structure and self-heating capacity with common composting a higher hygienization standard may be expected compared to vermicomposting. However, also vermicomposting is acceptable compared to no treatment. The additional demands here are the availability of kitchen waste and acquisition of sufficient quantities of worms for inoculation. Charcoal may be added, but only if it is available as a residue from a commercial process in the surrounding.

Developed country scenarios:

Urban regions where faecal matter from water-flushed toilets is collected via pipelines and centralized treated: The diluted excreta are commonly transported via pipelines to waste-water treatment facilities. The systems commonly work well in terms of hygiene. But the systems are not resource efficient since they consume a lot of water and additional energy to remove nitrogen, which is an important fertilizing element. However, the established situation cannot be changed within a short timeframe. As mentioned above, public solutions are better than small scale private solutions for faecal matter utilization, since the later has the risk of pathogen contamination of the private persons concerned, as well as pollution of the environment. A suitable option so far without changing toilet systems seems to be the so called »Blackwater-cycle« (Antholz et al., 2009), where the solid faecal matter including toilet paper is partially removed from the mix. It would be a suitable substrate for further utilization. The question regarding follow up treatment would be not so much common composting or vermicomposting; a better option seems to be anaerobic digestion followed by digestate treatment eventually including a composting process for separated solid fractions. The choice in the type of com-posting step primarily depends on the country and the existing standards and legislation there.

Urban regions which are to be newly developed: Here new toilet systems may be installed in order to avoid water wastage. These may range from vacuum toilets over advanced latrine-like systems to LAF-like systems and connected with new centralized faecal matter collection methods in order to avoid actual waste-water treatment practices which are very energy intensive and result in the losses of nutrients. Also here, the question of common composting or vermicomposting is less important compared to the decisions on the overall faecal matter utilization chain. An example for a new type of waste water collection and treatment is the Jenfelder Au demonstration project. In Jenfelder Au, a combination of renewable energy and innovative wastewater systems is being introduced. The blackwater collected from vacuum toilets will be supplied to an anaerobic fermentation plant. The anaer-obic treatment of blackwater is energetically advantageous compared to standard wastewater treatment Strategies for the utilization of digestates are being investigated. In-vessel composting of a fraction is included in some scenarios (Körner et al., 2013).

4.3. Comparing common composts and terra preta-inspired products

Nitrogen contents in common composting substrates and composts
The nutrient contents in common composts depend strongly on the input substrates. Total nitrogen (N) for instance can lie below 0.4 or over 4% dry matter (DM) depending on the input substrate (Körner, 2009). In tendency, woody input material are N poor; kitchen wastes and especially animal processing waste or animal manures are rich in N. Additionally, N contents in composts depend on the composting process. For instance, frequently observed losses of ammonia range between 5 and 45% of the initial N and are mainly depending on ammonia/ammonium contents in the substrate as well as temperature and pH. The higher these parameters, the higher are the losses. Resulting organic N contents in common composts may range between 0.4 and 4.1% DM with additional content of ammonia/ammonium between 0 and 1.8% DM and nitrate between 0.0 and 0.7% DM (Körner, 2009).

In this chapter specific TP ingredients and their behavior during composting are briefly evaluated regarding their nutrient provision, with nitrogen as example, and regarding carbon storage properties and the resulting TP products were compared with common composts. It has to be noted that the comparison is based on theoretical considerations. Results from practice are so far not known to the authors. The intention of TP products is to provide specific properties, which may be expected since human faecal matter is rich in nutrients, and charcoal is expected to store carbon. For that reason, these two aspects are examined in the following:

The box above gives information of N contents from common composts. If especially N rich feedstocks are used in common composting, N contents in composts increase in tendency (Körner, 2009). Table 4.2 evaluates some feedstock with respect to N. It shows that, related to dry matter, blackwater is by far the N richest medium, followed from pig slurry. To compare their influence on composting feedstock mixes, six scenarios were evaluated, as shown in Table 4.3. The suggested ratios were assumed to be practicable considering the discussions in the previous chapters. They take into consideration the assumed upper limit of charcoal. All six mixtures result in water contents suitable for composting. Scenario IV-VI are also in tendency more on the upper limit of a composting mixture regarding the initial water content, with it also on the upper limit of blackwater or pig slurry addition. In scenarios I-III there would be room to increase the human or pig faecal matter a little further. It can be seen that the water content of the faecal matter has a big influence on the resulting N in the mixture. With blackwater from latrines highest N contents in feedstock mixture could be reached. Comparing pig slurry and faecal matter from vacuum toilets the outcome regarding Nitrogen was similar. Substituting charcoal with fresh wood chips did not result in large differences.

Table 4.2: Total nitrogen content related to dry matter (TN) for various feedstocks with numbers of analysed samples ic requirements and sanitary system implementation.

Feedstock	TN content (% DM)			No.	Source
	Mean	Min	Max		
Blackwater	30.7	20.3	41.4	18	Hertel, 2014
Blackwater	23.0	-	-	123	Wendland, 2008
Sewage sludge (biosolid)	3.8	-	-	418	Smith, 2012
Poultry litter	5.0	-	-	40	Sharp & Smith, 2005
Poultry layer manure	5.4	-	-	95	Sharp & Smith, 2005
Pig litter	9.5	-	-	418	Smith, 2012
Pig manure	3.1	-	-	418	Smith, 2012
Cattle litter	4.0	-	-	418	Smith, 2012
Cattle manure	2.6	-	-	418	Smith, 2012

Table 4.3: Scenarios for various feedstock mixes (I–VI) regarding resulting dry matter content (DM) and total nitrogen content (TN) in the initial composting mix.

	Feedstock properties		**Scenarios with charcoal**			**Scenarios with charcoal**		
Feedstock	**DM**	**TN**	**I**	**II**	**III**	**IV**	**V**	**VI**
	%	**%DM**	**%FM**			**%FM**		
Blackwater (vacuum)	0.5[1]	30.7[1]	10	-	-	10	-	-
Blackwater (latrine)	30.0[2]	30.7[3]	-	10	-	-	10	-
Pig litter	3.4[4]	9.5[4]	-	-	10	-	-	10
Charcoal	98.0[5]	2.0[5]	30	30	30	-	-	-
Fresh wood chips	45.0[6]	0.5[7]	30	30	30	60	60	60
Kitchen waste	40.0[8]	0.5[8]	30	30	30	30	30	30
Resulting DM	**-**	**-**	**55**	**58**	**55**	**39**	**42**	**39**
Resulting TN (% DM)	**-**	**-**	**18**	**33**	**18**	**12**	**33**	**12**

[1] Hertel, 2014
[2] assumed based on chapter 1.1
[3] assumed based on blackwater from vacuum toilets investigated by Hertel, 2014
[4] Smith, 2012
[5] Voss & Bettendorf, 2014
[6] Baumgärtner, 2011
[7] Körner et al. 1999
[8] KTBL, 2014

The whereabouts of N during composting depend on a lot of factors, which are discussed in detail in Körner 2009. However, assuming a 30% degradation rate of organic matter during composting and 20% N losses, *the resulting N in compost in the six scenarios would be between 14 and 37% DM, which is significantly higher than in common composts, which is not higher than 6% DM considering the values in the box.*

Production of stabilized C and degradability of charcoal and of humic substances from composts

Charcoal is generated under high temperature conditions, whereas different processes are possible. Temperature of pyrolysis is above 450 °C, gasification occur at 650–950 °C (Üveges et al., 2014). A further approach is the hydrothermal carbonisation which works at temperatures in the range of 180–250 °C (Kopinke et al., 2014). For charcoal it is assumed, that it is inert. However field results are still lacking. Üveges et al. (2014) suggest that residence time in soil may be 1300–4 000 years for charcoal from pyrolysis. Humic substances are the end product of composting and they result from biotic and abiotic degradation processes. According to Miehlich (2007) humic substances can be divided roughly into the following three groups with respect to their degradability; 1) labil: easily degradable plant residues, degradation within months till a few years; 2) intermediate: hardly degradable plant residues and physically stabilized humic substances; 3) inert: organomineralic compounds (black carbon), principally undegradable. The longer composting continues, the less labile and the more intermediate/inert fractions produced. Degree of degradation II–III in Figure 4.2 would have a higher content in labile fractions compared to degree of degradation IV–V. Also charcoal can be considered as a humic substance (Miehlich, 2007), the material belongs probably mostly to the inert group.

In the previous box some aspects regarding stability of charcoal and humic substances from composts are mentioned. Therefore, charcoal can be considered as inert. The humic substances from composts consist from on labile, an intermediate and an inert fraction. The actual composition of the humic substances in composts depend e.g. on used substances and composting time. As a rule of thumb it can be said, as longer the composting time and as more lignocellulosic substances are used, as less labile and as more intermediate/inert compounds can be found.

Table 4.4: Comparion of two scenarios (II, V; see Table 4.3) regarding labile, intermediate and inert compounds in common composts and TP products.

	Input			**TP**			**Compost**		
Feedstock	**DR**	**II**	**V**	**II**			**V**		
	%DM[1]	**kg FM**	**kg FM**	**Kg DM**[2]			**kg FM**		
				labile	**intermediate**	**inert**	**labile**	**intermediate**	**inert**
Blackwater	30	10	10	0.5	1.1	0.5	0.5	1.1	0.5
Charcoal	0	30	0	0.0	0.0	29.3	0.0	0.0	0.0
Woodchips	30	30	60	2.4	4.7	2.4	4.7	9.5	4.7
Kitchenwaste	70	30	30	1.0	2.0	1.0	1.0	2.0	1.0
Sum		**-**	**-**	**3.9**	**7.8**	**33.2**	**6.3**	**12.5**	**6.3**
Ratio		**-**	**-**	**1**	**2**	**9**	**2**	**3**	**2**

[1] Feedstock degradation rates (DR) are estimated

[2] Content in the different humic fractions was calculated based on following estimations: Charcoal – 100% inert; Compost – 25% labile; 50% intermediate, 25% inert

To get rough estimates on the share of the different fractions in composts and TP products, the scenarios II and V form Table 4.3 were compared additionally regarding theoretic contents of different humic fractions (Table 4). However, calculations were done with assumptions, which are not proven. Table 4.4 shows that more product matter remains for TP compared to common compost, since the average degradation rate was lower. The calculated values, based on the estimations in Table 4.4, were a degradation rate of 24% DM for TP and of 42% for the common compost. The inert fractions were the majority in the TP product, whereas the labile, indermediate and inert fractions were nicely distributed in the compost.

Regarding Miehlich (2007) the average share of labile compounds in agricultural soils is around 1–5% of the organic substance und from intermediate around 50 % of the organic substance; however with strong variations depending on the frame conditions. Following advantageous properties have humic substances on soils: Nutrient for soil organism and plants, storage media for plant nutrients, stabile bonding of pollutants, texture formation and stabilization, increase of soil temperatures due to dark color, storage of carbon. The first is not true for charcoal, but eventually all the others.

4.4. Summary and conclusion

Composting feedstocks, common composting and vermicomposting techniques as well as common composts and TP products were evaluated with respect to the specific TP ingredients faecal matter and charcoal.

Feedstocks: The substrate characteristics in section 4.1 shows that charcoal can be considered as inert, and much of the organic material in faecal matter is not easily degradable. Therefore, easily degradable residual bioresources such as kitchen waste need to be added to the composting mixture to facilitate microbial or worm activity. Faecal matter and charcoal, both are lacking in structure, therefore for common composting, they should be blended with bulky materials such as wood chips that facilitate aeration. For vermicomposting, blending is also necessary as high ammonia contents from faecal matter may be harmful to worms.

Composting: Common composting and vermicomposting were compared in section 4.2. Both can deliver TP-products, however, whether composting or vermicomposting is the better option depends from the prevailing conditions. Eventually, other technologies, such as anaerobic digestion among others, may be additional options. Concerns are with respect to hygienic issues, since faecal matter may contain far more and a higher variety of pathogens compared to common composting substrates. Vermicomposting has hygienizing properties, but even with common substrates secure hygienization cannot be guaranteed. Elevated temperature reached via self-heating brings hygienization with common composting feedstock, which can be considered as secure. However, when faecal matter is involved this is yet to be fully proven. Standards allowing secure procedures are needed if faecal matter is an ingredient. For example, by prolonging hygienization and/or storage times after composting.

Compost: Finally, the theoretical considerations in section 4.3 show that common composts and TP-products indeed should have different properties regarding nutrients and organic inert fractions. However, the question on which product is better for application cannot be answered. It depends on the application purpose. It can be stated, that the nutrients in the faecal matter are a valuable resource worth recycling and many soils need to be upgraded whereas humic substance additions maybe helpful.

For consideration of the application of faecal matter and charcoal the whole chains from the generation of the bioresource over their conversion till product application have to be carefully evaluated and alternative routes compared. Some concerns regarding the discussed ingredients, but also their potentials are summarized in the following in form of theses':

Potential and concerns using excreta:

- Excreta should be used in one form or another, since it contains valuable nutrients in high amounts.
- Compost may not be the best utilization option. Excreta contain nutrients in easily plant available mineral form. During

composting nutrients are bound to humic substances and therefore become less plant available.

- Faecal matter contains pathogens which have to be inactivated or killed before any faecal matter based product is applied. If composting is included as processing step, a part-hygienization may be reached, but it is not certain that complete sanitation would be reached. Procedures ensuring a higher security should be implemented.
- If faecal matter is used in composting, lowquality bioresources with respect to pathogens are mixed with higher value bioresources such as green and kitchen waste, which are less contaminated with pathogens. After mixing with faecal matter their value is lowered too.
- Faecal matter composts from common composting or vermicomposting procedures should not be used for food production. A better option seems to be the use for the growth of material and energy crops.
- A demand on faecal matter compost in forestry is not seen, since often trees are already over-fertilized by ubiquitous available nitrogen compounds.
- Charcoal is not needed to produce nutrient rich composts with faecal matter.

Potential and concerns using charcoal:

- Charcoal has a high carbon storage property.
- Charcoal producing processes need energy and result in emissions which are partly difficult to handle and even may contain toxic substances.
- The use of primary bioresources (e.g. trees) for charcoal production is counter-productive. The best carbon storage is received, if the tree remains on place and/ or if the tree is used for production of substantial products.
- The use of primary wood for charcoal production bears the danger to increase the »Wood demand lack«. The deficit results from the competition of wood-use for material (e.g. pulp and paper, wood products, biochemical) or for energy generation. It would worsen if charcoal production for soil improvement would become an additional competitor.
- Charcoal should only be produced from plant or animal residues. The charcoal quality including the production processes most be controlled/ certified.
- Charcoal may have counter-productive effects on soil biology if used in high quantities. It may even immobilize soil nutrients.

To maintain soil quality humic substance delivery with common composts is recommended. To re-animate desertified soils, charcoal may be an option.

»Desertification, land degradation and drought affect over 1.5 billion people in more than 110 countries, 90% of whom live in low income areas. Up to 50,000 km^2 are lost annually through land degradation, mainly due to soil erosion. Each year, the planet loses 24 billion tonnes of topsoil.« (COM/2012/046).

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Chapter V: Stabilization and hygienization of organic matter

Asrat Yemaneh and Gina Itchon

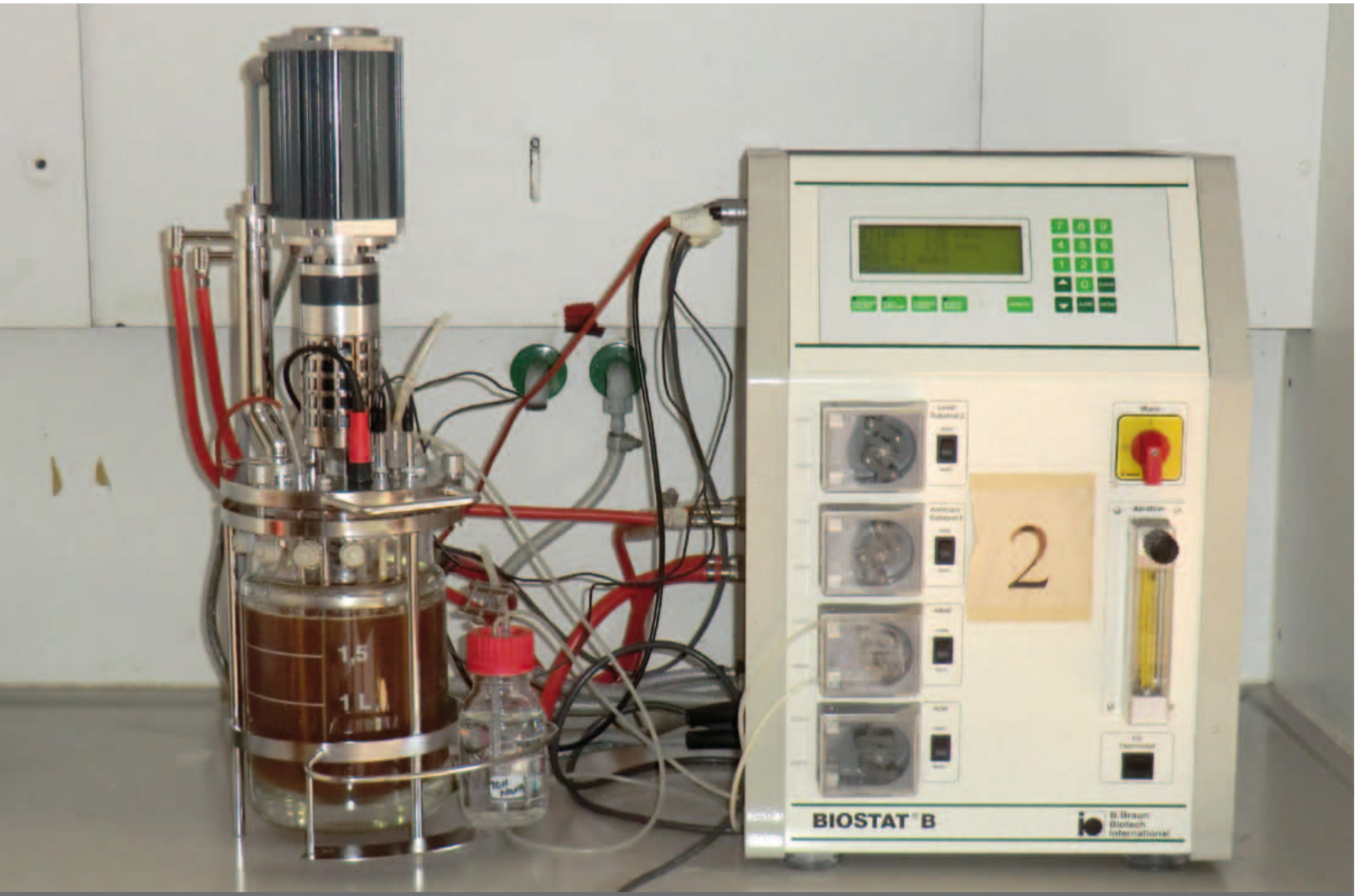

Figure 5.1: Lactic acid fermentation in laboratory trials (Yemaneh).

5.1. Introduction

Basic sanitation, safe drinking water and good hygiene are fundamental to health, survival, growth and development. In the last two decades mankind has received constant and often devastating reminders that water is not an infinite resource. Repeated occurrences of the El Niño and the La Nina phenomena, floods, droughts, and famine in many areas of the world attest to this. It is therefore imperative that water is conserved to ensure that this basic natural resource does not run out and become inaccessible to more people.

Sanitation facilities and safe drinking water are inextricably linked to each other. However, the common water-borne sanitation system in current use in most countries of the world, and which has been accepted as a standard for sanitation, is also a system that depletes water. Chronic shortage of water, the expensive capital cost of putting up such a sanitation system, and its high cost of maintenance, make water-borne sanitation systems an unrealistic option for many developing countries (WHO & UNICEF, 2006). In less developed areas of the world, waterless toilets have emerged as a more practical option for basic sanitation because of the following reasons: 1) it does not require water for flushing but for hand washing only, 2) it is relatively less expensive to install and maintain, and 3) both urine and excreta can be collected and treated for use as fertilizer in agriculture and aquaculture (Scott, 2002).

In recent years the re-use in agriculture of biowaste collected from waterless toilets has emerged to as an attractive option in developing countries, especially because chemical fertilizers have progressively become expensive. Although human urine and excreta have been used extensively in many parts of the world for agriculture, there is a dearth of studies on its public health implications. Bacterial and parasitic infections are significant causes of mortality and morbidity in developing countries and major health risks should be considered in the formulation of any recommendation for biowaste derived from toilets for re-use as soil amendment.

The main objective of sanitation system provision is the containment of human excreta and preventing the spread of faecal pathogens to the environment. If no proper treatment methods are established for waste from waterless sanitation systems, they can be source of severe pollution through spread of faecal pathogens to water or land and finally ending up in the food chain, causing infections to humans. Any sanitation measure that aims at recycling the resources in waste must ensure proper management so that pathogens are eliminated before the treated waste is return to the environment. This chapter examines the mechanisms employed in TPS system to hygienize organic waste materials for ensuring a safe recycling of nutrients contained in the waste through agricultural use. The issues covered in particular are: pathogenic microorganisms in excreta, hygienic requirements and regulations pertaining to the recycling of human excreta, and the role of lactic acid fermentation process for stabilization and hygienization of organic matter.

5.2. Pathogenic microorganisms in human excreta

Pathogenic microorganisms that are associated with human excreta and which can be transmitted from the environment to humans to cause infections can be classified into four main groups: bacteria, protozoa, viruses and helminths (Feachem et al., 1983). Almost all of the pathogenic microorganisms related to human excreta come from human faeces. Bacteria are generally considered as the most common source of gastrointestinal related infection and they constitute the majority of faecal pathogens existing in human faeces. Urine of a healthy person is considered to be free of pathogenic microorganisms. Feachem et al. (1983) indicated the occasional excretion of pathogens associated with urinary tract infections and venereal diseases, however there is no evidence on their survival outside human body to be spread into the environment to pose health hazard.

The three common groups of sanitation indicator bacteria are *faecal coliforms,* the *fecal streptococci* and the anaerobic bacterium; *Clostridium perfringens* (Feachem et al., 1983). A detailed list of various pathogenic microorganisms that can be found in human excreta is given in (EC, 2001). Although not all the pathogenic microorganisms are present in human excreta, the hygienic safety of the final recycled product should be ensured by applying appropriate treatment methods and technologies. Among the pathogenic microorganisms, Helminths eggs are the most resistant pathogens to existing treatment methods. In the following section some of the available treatment methods and requirements for recycling of human excreta are discussed.

5.3. Secondary treatment methods and hygienic requirements for recycling human excreta

Human excreta contain plant nutrients and have the potential to be used as a fertilizer in agriculture. According to (WHO, 2006) the use of treated excreta in agriculture can have a positive impact in providing households and communities ability to produce sufficient quantity of nutritious food that can be self-sustaining, however measures should be taken to ensure that the practice doesn't pose a risk to the community by exposing them to faecal related infections.

The principal primary method of excreta treatment recommended by the World Health Organization (WHO) is storage in a dry place for a period of at least a year at ambient temperatures. This is recommended to achieve the guideline for helminthic quality of < 1 viable intestinal nematode egg per 100 g of excreta (WHO, 2006). This storage period may be reduced by treatment at a higher temperature, for instance in aerobic composting. Also, chemical treatment to increase the pH of the substrate to above 9, is considered suitable to achieve the recommended reduction in sanitation indicator microorganisms. Detailed assessment of the health risks associated with human excreta use in agriculture is given in the WHO guideline (WHO, 2006). The following table gives the recommended treatment for storage treatment of human excreta and faecal sludge for achieving hygienic quality for its use at the household and municipal levels.

Table 5.1: Recommendations for storage treatment of dry excreta and faecal sludge before use at the household and municipal levelsa (WHO, 2006).

Treatment	Criteria	Comment
Storage; ambient temperature 2–20 °C	1.5–2 years	Will eliminate bacterial pathogens; regrowth of E. coli and Salmonella may need to be considered if rewetted; will reduce viruses and parasitic protozoa below risk levels. Some soil-borne ova may persist in low numbers.
Storage; ambient temperature >20–35 °C	>1 year	Substantial to total inactivation of viruses, bacteria and protozoa; inactivation of schistosome eggs (<1 month); inactivation of nematode (roundworm) eggs, e.g. hookworm (Ancylostoma/Necator) and whipworm (Trichuris); survival of a certain percentage (10–30%) of Ascaris eggs (≥4 months), whereas a more or less complete inactivation of Ascaris eggs will occur within 1 year.
Alkaline treatment	pH >9, during >6 months	If temperature >35 °C and moisture <25%, lower pH and/or wetter material will prolong the time for absolute elimination

[a] No addition of new material.
Source: (WHO, 2006)

At present two methods of secondary treatment for excreta at high temperature are recommended by the WHO, these are: 1) batch thermophilic digestion at 50oC for 13 days which will ensure the inactivation of all pathogens; and 2) forced aerobic composting for 1 month (WHO, 2006). However, both of these methods require technical knowledge and skill to ensure that all pathogens and helminth ova are inactivated. The required technical knowledge and skills to treat excreta are often difficult to obtain in deve-l-oping countries and where capacity building efforts for farmers are often very difficult to conduct. Often, it is necessary to recommend other methods for the secondary treatment of excreta which will be technically less challenging while assuring that hygiene standards for the re-use of excreta in agriculture are also adequately met.

The European Union (EU) has also proposed treatment requirements for the recycling of biosolids from human excreta which is shown in Table 5.1 below. In the EU requirements, the treatment methods suggested are thermal or alkaline treatments for a specific period of time (EC, 2000).

Table 5.2: EU's advanced and conventional treatments for biosolids and pathogen density limits. Source (EC, 2000).

Conventional	**Advanced**
General requirements	
>2 log10 reduction of E. coli	>6 log10 reduction of *E. coli* to less than 500 CFU/g WS Initial validation of process through 6 log10 reduction of test organism such as Salmonella *Senftenberg W775*
Treatment options	
Thermophilic aerobic stabilization at ≥55°C at a mean retention period of 20 days Thermophilic anaerobic digestion at ≥53°C at a mean retention period of 20 days Conditioning with lime to pH ≥12 for at least 24 hours Mesophilic anaerobic digestion at 35 °C with a mean retention period of 15 days Extended aeration at ambient temperature as a batch (time dependent on prevailing climatic conditions) Simultaneous aerobic stabilization at ambient temperature (time dependent on prevailing climatic conditions) Storage in liquid form at ambient temperature as a batch (time dependent on prevailing climatic conditions)	Thermal drying at ≥80°C to water content ≤ 10% while maintaining a water activity of ≥0.90 during the first hour Thermophilic aerobic stabilization at ≥ 55°Cfor 20 hours as batch Thermophilic anaerobic digestion at ≥5°C for 20 hours as batch Thermal treatment of liquid sludge at 70°C for ≥30 minutes, followed by mesophilic digestion at 35°C at a mean retention period of 12 days Conditioning with lime to pH ≥12 while maintaining ≥5°C for 2 hours Conditioning with lime to pH ≥12 for >3 months

5.4. Terra preta sanitation approach for treatment of human excreta

Terra preta sanitation (TPS) employs two biological treatment processes: treatment by lactic acid fermentation (LAF) during collection of human excreta by application of LAF and treatment by vermicomposting of the LAF-process end-product off-site, which is planned as a decentralized further treatment method. TPS is inspired by the discovery of the ancient anthropogenic Amazonian black soil called >Terra Preta<, which owed is formation from the accumulation and subsequent degradation of various organic residues including human faeces, biowaste, and charcoal. TPS aims to improve soil carbon and nutrients content thereby increasing soil productivity through efficient management of human waste (Otterpohl, 2012).

Both lactic acid fermentation and vermicomposting processes are reported to have good hygienizing effect on organic wastes. The antimicrobial effect of LAF is widely reported as it plays an important role in food processing and preservation, silage preservation and in management of different organic wastes (Briens et al., 2008). Vermicomposting alone is demonstrated to be very efficient for treating faecal matter (Shalabi, 2006; Buzie-Fru, 2010). Therefore, the combination of the two processes in TPS is considered to be very efficient in the elimination of faecal pathogens.

5.5. Application of lactic acid fermentation process in TPS

Lactic acid fermentation (LAF) is the treatment method employed in the collection phase of human excreta in TPS system. LAF process is an anaerobic process in which lactic acid fermenting microorganisms in the presence of easily fermentable sugars and a nitrogen source produce lactic acid, antimicrobial compounds and low pH environment in a fermentation system. These have a combined effect of killing other pathogenic and non-desirable microorganisms and help in the conserving the nutrients and organic matter. Simple sugar molecules are metabolized by lactic acid bacteria (LAB) and are converted to pyruvate, releasing 2 ATP molecules and pyruvate is further transformed mainly to lactic acid and few other metabolic by-products depending on the type of LAB involved (Benninga, 1990; Rajvaidya and Markandey, 2006). Detailed experimental investigation for application and optimization of LAF process for human excreta management are given in Yemaneh et al. (2012) and Yemaneh et al. (2013).

LAF process has been used for millennia in food preservation ranging in scale from small household application to industrial processes (EUFIC, 1999). The other commonly known applications of LAF are production of fermented food products like sauerkraut process, production of silage in agriculture, and stabilization and disinfection of various organic wastes. The basis of LAF application for hygienization and preservation of resources in human waste for efficient recycling depends on the ability of lactic acid bacteria to produce antagonistic environment towards other pathogenic microorganisms. The following sections examine the scientific basis of LAF application in TPS.

5.5.1. Lactic acid fermenting microorganisms

For a good LAF process, the presence of appropriate lactic acid fermentation microorganisms is very important. If enough native lactic acid fermenting microorganisms exist in the material to be fermented the LAF process can start spontaneously. However, in most cases lactic acid fermenting microorganism has to be inoculated. This is available as commercial product or obtained from previous fermentation batches. LAB include different groups of bacteria with common metabolic property of producing lactic acid from fermentation of carbohydrates (Carr et al., 2002). Depending on their carbohydrate metabolism pathways LAB are classified as homofermentative and hetrofermentative. Homofermentative bacteria convert C6-sugars solely into lactic acid, with two mole of lactate formed from one mole of glucose. Hetrofermentative LAB, on the other hand, produce carbon dioxide and ethanol or acetate in equimolar quantities in addition to lactic acid. Well-known species of the homofermentative bacteria are *Lactobacillus plantarum, Pediococcus acidilactici, P. pentosaceus, Enterococcus faecium, Lactobacillus delbrueckii, Lactobacillus casei* and *Lactobacillus rhamnosus* (Woolford and Pahlow, 1997).

From TPS research at Hamburg University of Technology (TUHH), a mixed culture LAB inoculum consisting of the three strains: *Lactobacillus plantarum, Lactobacillus casei* and *Pediococcus acidilactici* is identified as effective microbial mix to be used for lactic acid fermentation process in Terra Preta Sanitation system (Yemaneh et al., 2012). Effective microorganism (EM), the commercially available microbial mix, can also be used as inoculum, however the three LAB mix identified is found to be more effective than EM for LAF of human excreta with supplementation of easily degradable sugar sources (Yemaneh et al., 2012). Another easy way to obtain LAB inoculum is using juices from sauerkraut (Factura et al., 2010) or similar fermented local food, such as Korean Kimchi, Nigerian Gari, Kenyan Uji, or Egyptian Kishk (Steinkraus, 1992).

5.5.2. LAF application for hygienization of organic materials

Production of lactic acid and lowering of pH in the fermentation system is considered as one of the major factors associated with elimination of pathogenic microorganisms during LAF of organic material. Effective lactic acid fermentation process aimed at preservation should achieve a final pH between 3.5 and 4.2. Within this range, most bacteria and other microbes cannot survive. The lactic acid compound itself has a sterilizing effect and it plays a role in killing pathogenic microbes. Moreover, in addition to the lactic acid other antimicrobial compounds, like bacteriocins, diacetyl and hydrogen peroxide are produced by lactic acid bacteria during the process which have additional hygienization effect in the fermentation system. Due to this combined effects, lactic acid fermentation is considered as an effective natural process to eliminate pathogenic microorganisms in organic wastes.

According to (Al-Zoreky et al., 1991; Caplice and Fitzgerald, 1999; De-Vuyst and Vandamme, 1994; Lyon et al., 1993; De-Vuyst and Vandamme, 1994) the antimicrobial mechanisms of lactic acid bacteria employed in the biopreservation of foods include the production of organic acids, hydrogen peroxide, diacetyl and broad-spectrum of antimicrobials such as reuterin and the production of bacteriocins. It is reported that, in particular bacteriocins show a wide range of antibacterial effects on gram-positive putrefactive bacteria, such as *Listeria monocytogenes, Clostridium botulinum* and *S. aureus* (Wang et al., 2001; Matsusaki et al., 1997). Lade et al. (2006) reported that lactobacillus plantarum species produces bacteriocins which inhibits the growth of E. coli. Kim et al. (2012) demonstrated that the use of Kimchi extract, traditional Korean food from lactic acid fermented vegetables, inhibited larval development of Ascaris scum eggs. Amézquita and Brashears (2002) and Lade et al. (2006) reported that LAB strains of *Pediococcus acidilactici* and *Lactobacillus casei* are very effective inhibitors of *Listeria monocytogenes* in meat products. Faid et al. (1994) reported LAF as a biological process which can be effectively applied to preserve fish waste and also to remove odour.

Ramírez et al. (2005) demonstrated that ensiling of 80% solid fraction of residues from swine farms consisting of mainly swine excreta mixed with 12% sorghum and 8% molasses resulted in complete elimination of *Salmonella spp*. El-Jalil et al. (2008) reported that with LAF of poultry waste with the addition of 10% molasses as sugar supplement different hazardous microorganisms, including *enterobacteria, enterococci, Clostridium, Salmonella*, are reduced significantly after 7 to 10 days of fermentation. The elimination of pathogenic bacteria such as *coliforms*, *enterococci* and spores such as those of *Clostridium botulinum* by ensiling of fish waste with the addition of lactic acid bacteria and fermentable sugar is reported by (Ledward et al., 1983). The complete elimination of *Salmonella spp.* and a significant decrease in other Gram-negative bacteria and Clostridium spp. was reported by Kherrati et al. (1998) in LAF study of slaughterhouse wastes, including animal and poultry wastes, mixed with 15% molasses and inoculated with a starter culture of Lactobacillus plantarum. Kamra and Srivastava (1991) reported the killing of *Clostridium perfringens* by application of LAF process in a mixture of straw and cow dung supplemented with molasses as sugar source.

5.5.3. LAF as a process for stabilization and preservation of organic materials

LAF process has been applied in preservation and recovery of resources from various kinds of wastes. Its application in silage preservation (ensiling) is well documented. The main features of lactic acid fermentation employed in silage process is its ability to preserve the silage by destroying spoilage microorganisms and preventing losses of dry matter and nutrients (Danner et al., 2003; Ohshima and

McDonald, 1978; Prakash et al., 2012). During ensiling the moist crops are preserved by application of lactic acid fermentation process under anaerobic conditions, whereby LAB converts water-soluble carbohydrates mainly to lactic acid. As a result, the pH decreases, the growth of spoilage and other undesirable microorganisms are suppressed and the forage is preserved (Stefanie et al., 1999; Seglar 2003). In most occasions inoculants containing LAB are used as silage additives in order to improve preservation efficiency. Samberg and Meroz, (1995) reported that poultry carcasses were successfully preserved by lactic acid fermentation when the carcass material is combined with fermentable carbohydrate source, such as sugar, whey, molasses or ground corn. In a study of LAF application to preserve shrimp waste for chitin recovery (Cira et al., 2002) reported that fermentation of the waste with the addition of 10% (wet weight basis) sucrose as sugar supplement was able to lower the pH to less than 5 allowing for the preservation of the waste for about 3 months. The fermentation process also helped chitin recovery process by facilitating deproteinization and demineralization of the waste. Wang et al., (2002) studied the application of LAF process for preservation and deodorization of kitchen garbage and demonstrated that spontaneous fermentation of kitchen garbage at ambient temperature can reduce the generation of odorous compounds by suppressing the growth of putrefactive bacteria such as *coliforms* and *Clostridium spp*. which are considered to be responsible for the production of offensive odour compounds. El Akhdari et al. (2005) reported the successful stabiliza-tion of effluent from gut-dressing work by the application of LAF process with supplementation of the effluent with 20% molasses and inoculation with starter culture consisting of Lactobacillus delbrueckii.

5.5.4. Hygienization of human excreta through lactic acid fermentation

From the previous sections, it has been established that LAF process has important antimicrobial effects and can play a role in the hygienization of human excreta. Acidification is the first factor for hygienization as many pathogenic micro-organisms do not survive in a media with low pH. Actions of antagonistic constituents produced by LAB also increase the antimicrobial effect. Limited research has been conducted on the application of LAF process for elimination of pathogens in human excreta. Experimental studies on LAF of human faecal matter at the Institute of Wastewater Management and Water Protection, TUHH, with addition of 5% (by weight) molasses as sugar supplement and inoculum consisting of mixed culture homofermentative lactic acid bacteria showed effective hygienization with complete removal of *faecal coliforms* and *E-coli* monitored as sanitation indicator bacteria (Yemaneh et al., 2012).

Itchon et al. (2010), based on detailed study of LAF conducted on faecal matter collected from urine diverting dehydration toilets, reported that LAF could effectively kill off parasite eggs. Based on laboratory and field experiments (Scheinemann and Krüger, 2010) also reported that LAF facilitates the die-off of most pathogens in faecal waste from veterinary hospitals. Pathogenic bacteria like

Listeria monocytogenes, Salmonella Anatum, Salmonella Senftenberg, E. coli 0157 strain and Straphylococcus aureus were inactivated through fermentation within 3 days. The study also reported inactivation of viruses and roundworm eggs within a maximum of eight weeks. However, to fully assess the hygienic safety of a sanitation system it is suggested that a risk assessment based on multi-barrier approach (WHO, 2006) should be conducted and a combination of different health protection measures should be taken to reduce health risk (Windberg et al., 2013).

5.5.5. Practical application of TPS concept in the Philippines

The global carbon cycle has been brought to wide attention due to its importance for the global climate. The Intergovernmental Panel on Global Change (IPCC, 2001) recently confirmed that the anthropogenic greenhouse effect is a reality, which we have to deal with in the future. The atmospheric CO_2 has increased from 280 ppm in 1750 to 367 ppm in 1999 and today's CO_2 concentrations have not been exceeded during the past 420,000 years (IPCC, 2001). The release or sequestration of carbon in soils is therefore of prime importance. Soil organic carbon is an important pool of carbon in the global biogeochemical cycle. Implementation of TPS system apart from providing sanitation service plays important role in retention of soil organic carbon.

The potential of terra preta soil as a means to enrich soil and make it more productive is important for an agricultural country such as the Philippines. The potential of TPS as a means of secondary treatment for human faeces prior to its re-use in agriculture was investigated in Mindanao, Philippines in 2010 (Itchon et al, 2010). The study demonstrated the effectiveness of using the TPS approach as a secondary method of eliminating parasite ova from faeces collected in the vaults of urine diverting dehydration toilets. The total secondary treatment time for the entire process using TPS was shortened to six weeks after which the treated excreta was shown to be free of helminth eggs. The study also found out that the C:N ratio of the faecal material is low for the vermicomposting process and it is necessary to adjust the C:N ratio by adding organic materials with more carbon content. It is also noteworthy that after vermicomposting, assay of the vermicompost from both batches of vermicomposted dried faeces (with and without addition of bacterial mix and charcoal) showed remarkably similar macronutrient and moisture content. Both sample assays conformed to organic fertilizer standards set by the Philippine National Standards for Organic Fertilizer (DTI, 2008).

Aside from the advantages of creating terra preta to enrich soil and complete the carbon cycle, the fact that the process also shortens the time required to render human faeces safe for agricultural re-use is a very important finding for a developing country such as the Philippines. Earlier studies had shown that in developing countries, the issue of safe re-use of human excreta is often one of the principal barriers to completing the sanitation cycle primarily because of the high parasite load in faecal matter (Itchon et al., 2009; Phasha, 2005). Therefore, the potential of the terra preta sanitation process as an effective secondary treatment for excreta is a very important milestone for its re-use in the agricultural.

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Chapter VI: Another way to increase humus stable SOM founded in Asia

Haiko Pieplow

Figure 6.1: Pottery for fermentation belongs to every traditional private property in Korea. The fluid phase of the fermentation contains huge amounts of autochthonic microorganisms.

Another hypothesis of the genesis of Terra Preta, that is being discussed is the treatment of waste in big clay pots as illustrated in Figure 6.1. It is remarkable that the top layer which is rich in humus increased and leaching of humic material is obvious. For centuries large clay pots have been used for fermentation in Asia, especially in Japan, South China and South Korea.

The processes associated with the genesis of Terra Preta have been derived from the observations of natural processes. Charcoal has a disinfecting effect. With charcoal dust decay can be inhibited. Under tropical conditions decaying organic matter can cause inconvenience. Furthermore, they are a source of many and often lethal infections. In closed containers, untreated organic matter develops considerable amounts of gases, notably methane. This is accompanied by a large loss of nutrients. However, when transformed by fermentation, such as lactic acid fermentation combined with treatment with yeast and mould, the loss of carbon and nutrients can be minimized and the organic substance can keep its potential as multi-nutrient fertilizer. These ancient techniques for food preservation and preparation are common in all cultures worldwide; for example the German Sauerkraut, the Korean Kimchi or Japanese Haigoe and Bokashi, respectively.

A safe fermentation of organic waste, notably human and animal excrements, is ensured by introducing layers of 20% dust of charcoal, 30% excreta and 50% kitchen and garden waste to a pot. The necessary amount of charcoal dust can be produced daily during cooking without any difficulties. After the fermentation is finished, soil animals are allowed to enter the container and digest the fermented matter. Through their digestion, stable humus (SOM) is generated. After a successful humification, the containers are planted and high-yielding forest gardens can be formed. The roots of the plants may cause the containers to burst. This could provide an explanation why throughout the soil profile pottery fragments can be found. In the beginning the clay pots avoid leaching and dehydration of the organic material. Significantly less carbon and nutrients are lost compared with the more labour intense composting. Forest gardens are spread worldwide, too and can be managed successfully in small peasant structures. They can be established as mixed crops and raised beds close to the homes and be connected with a hygienic sanitation at once.

Figure 6.2: A sanitation facility in a public community garden in Seoul with fermentation pots and devices for humification by worms.

Figure 6.3: Historical urine diverting dry toilets from South Korea in a toilet museum in Suwon.

Module B: The Terra Preta Sanitation International Conference 2013

Torsten Bettendorf and Claudia Wendland

International Conference on Terra Preta Sanitation at Hamburg University of Technology (28.–31. August 2013), Foto © TUHH/Roman Jupitz.

B.1. Introduction

This second part of the publication is dedicated to the 1^{st} International Terra Preta Conference which was held from 29–31 August 2013 in Hamburg, Germany. The conference brought experts and interested people together who want to discuss about the fascinating ancient method of Terra Preta which has recently been rediscovered and is now being adapted for implementation to nowadays societies. More than 120 people from the different sectors, water/sanitation, agriculture, soil, energy, health, and journalists from 22 countries all over the world were present to show their research results and to share their experiences in the field of Terra Preta Sanitation.

The conference was organized by the Institute of Wastewater Management at Hamburg University of Technology (TUHH) and the international NGO network WECF. Supporting institutions were the Institute of Environmental Technology and Energy Economics at TUHH, the German WASH Network, UNESCO IHE, the International Water Association (IWA), the Sustainable Sanitation Alliance (SuSanA) and the demonstration center for decentralized wastewater treatment BDZ.

The conference was under the patronage of the German Ministry of Environment, Nature Conservation and Nuclear Safety and co-funded by the Deutsche Bundessstiftung Umwelt (DBU).

Prior to the conference, the presenters on the conference had to undergo a two-step review process. First the abstract was reviewed and then the full paper. Each submitted full paper was reviewed by at least three experts. Their feedback had to be included in their revised paper by the authors.

B.2. The Scientific Committee

The scientific outcome of the conference is strongly related to the personal engagement of the scientific committee. Thus special thanks for the commitment and meticulous work especially during the review process belongs to:

- Håkan Jönsson (Sweden)
- Piet Lens (the Netherlands)
- Martin Kaltschmitt (Germany)
- Kerstin Kuchta (Germany)
- Gina Ichton (Philippines)
- Massimiliano Fabbricino (Italy)
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- Vishwanath Srikantaih (India)
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- Oliver Christ (Germany)
- Günter Langergraber (Austria)
- Ina Körner (Germany)
- Bruno Glaser (Germany)
- Zifu Li (China)
- Monika Krüger (Germany)
- Ralf Otterpohl (Germany)

B.3. The Papers of TPS-IC 2013

In the following list the authors and titles of their contributed papers are assembled in chronologic order of the conference program.

All papers are accessible for free download via the TPS homepage: **http://www.terra-preta-sanitation.net/downloads.**

Number	Author(s)	Titel
00	B. Glaser	Potential and constraints of Terra Preta products for soil amelioration and climate change mitigation
01	T. Theuretzbacher, S. Stranzl, E. Smidt and G. Langergraber	Investigation on Terra Preta like products on the german-Austrian market
02	N. Andreev, M. Ronteltap, B. Boincean and P. Lens	The effect of a terra preta-like soil improver on the germination and growth of radish and parsley
03	H. Factura, J. Medalla, M. Masgon, A. Miso, G. Itchon, R. Gensch, C. Buzie and R. Otterpohl	The Implementation and Practices of Terra Preta Sanitation in the Tropics – The Experiences from Xavier University Ateneo de Cagayan, Cagayan de Oro City, Philippines
04	M. Prabhu, M. Horvat, L. Lorenz, R. Otterpohl, T. Bettendorf and S. Mutnuri	Effect of terra preta compost on growth of Vigna radiate
05	S. Böttger, I. Töws, J. Bleicher, M. Krüger, H. Scheinemann, E. Dorgeloh, P. Khan and O. Philipp	Applicability of Terra Preta produced from sewage sludge of decentralized wastewater systems in Germany
06	D. Meyer-Kohlstock and E. Kraft	The integration of Terra Preta Sanitation in European nutrient cycles Options for alternative policies and economies

08	T. Schütze and P. Thomas	Terra Preta Sanitation – a key component in sustainable urban resource management systems
09	R. Wagner, N. König, R. Schatten, K. Rößler and K. Terytze	Utilization of organic waste in the Botanic Garden Berlin by producing and applying biochar substrates – Introduction and first results of the terraboga project
10	R. Kuipers, A. Balkema and S. Flapper	Socio-economic assessment of ecological sanitation and the logistics of nutrient recycling in the Philippines
11	M. Bulbo, A. Yemaneh, T. Amlaku and R. Otterpohl	Assessment of availability of Terra Preta Sanitation precursors in Arba Minch, Ethiopia
12	X. Liu and Z. Li	Energy balance analysis of the cattle manure slow pyrolysis process
13	E. Someus	REFERTIL: reducing mineral fertilizers and chemicals use in agriculture by recycling treated organic waste as compost and bio-char products
14	B. von Herzen, H. Fallside, L. Talsma, J. Lehmann, J. Atnafu, P. Csonka, A. Vallabhaneni and L. Krounbi	Biochar Conversion of High-Moisture Human Solid Waste at Community Scale
15	C. vom Eyser, K. Palmu, R. Otterpohl, T. Schmidt and J. Tuerk	Product quality of hydrochar from sewage sludge in terms of micropollutants
16	G. Itchon, A. Miso and R. Gensch	A field trial of terra preta sanitation in Mindanao, Philippines
17	M. Stöckl, P Roggentin, T. Bettendorf and R. Otterpohl	Assessment of hygienisation of faecal matter during terra preta inspired vermicomposting by qualitative identification of Salmonella spec.
18	A. Walter, T. Bettendorf, M. Stöckl, I. Franke-Whittle and H. Insam	Screening of the microbial community in charcoal and microbe- amended vermicomposts

19	P. Soewondo, A. Febriana, M. Handajani and M. Firdayati	Faeces Treatment By Lactic Fermentation Process and Future Perspectives of Terra Preta Sanitation Concept in Indonesia
20	A. Yemaneh, M. Bulbo, C. Schmale and R. Otterpohl	Investigation of Low-Cost Sugar Supplement for Lactic Acid Fermentation in Terra Preta Sanitation System
21	T. Bettendorf, M. Stoeckl and R. Otterpohl	Vermicomposting of municipal solid organic waste and fecal matter as part of Terra Preta Sanitation – a process and product assessment

Editors

Prof. Ralf Otterpohl is Professor of Civil Engineering and Director of the Institute for Wastewater Management and Water Protection at the Hamburg University of Technology (TUHH), Germany. He has more than 150 publications in peer review journals and edited and co-edited several books in his research field. He is also Co-owner of the consultancy Otterwasser GmbH, which specializes in computer simulation of large wastewater treatment plants and innovative water projects in Europe, Africa and the Middle East. He functions as Co-chair of the specialist group »Resources Oriented Sanitation« of the International Water Association (IWA).

Torsten Bettendorf is a Ph.D student at the Hamburg University of Technology. He is a Civil Engineer by training and has worked extensively over the past five years on resource efficiency in sanitation. His doctoral research investigates new sanitation approaches, focusing on the nutrient recovery and fertilizer production. He is currently supervising a range of undergraduate and graduate projects covering resource efficiency in sanitation. He has an extensive theoretical and practical understanding of the Terra Preta Sanitation system, from the system design through each of the processes to the final reuse options.

Dr. Claudia Wendland is a Water and Sanitation Specialist in the international NGO network WECF (Women in Europe for a Common Future). She facilitates and implements water and sanitation safety planning as well as re-use oriented sanitation systems together with local NGOs through community based approaches. Claudia has been consultant to WHO and UNECE and is active in the SuSanA (Sustainable Sanitation Alliance), the German WASH Network and the DWA (German Wastewater Association).

Terra Preta Sanitation Handbook – In brief

This first edition of Terra Preta Sanitation (TPS) handbook provides an authoritative account of the main theories of Terra preta formation and the principles of TPS concerning material recycling and soil fertility improvement. Written by foremost academics in the field of sanitation and soil science, the handbook takes full account of the extensive developments which have occurred since the outset of the ecological sanitation approach. There is a chapter on biochar as soil amendment, as well as detail treatment of key issues such as biochar production processes, co-application of biochar to soil and biochar effects in agroecosystems. The bulk of the text is dedicated to TPS systems and organic matter (bioresource) conversion technologies that generate Terra Preta – inspired products.

Thoroughly comprehensive – with dedicated chapters on all core topics – this handbook is essential reading for all students of Environmental engineering. It will also be welcomed as an invaluable reference work for academics and practitioners in the field.

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Editor
Deutsche Bundesstiftung Umwelt
An der Bornau 2
49090 Osnabrück
Postfach 1705
49007 Osnabrück
Tel.: +49 541 9633-0
www.dbu.de

Gesellschaft zur Förderung und Entwicklung
der Umwelttechnologien (GFEU e. V.)
at Hamburg University of Technology,
Institut of wastewatermanagement and
waterprotection
Eißendorfer Straße 42
21073 Hamburg
Tel.: +49 40 42878-3207
Fax: +49 40 42878-2684
Prof. Ralf Otterpohl

Women in Europe for a common future
(WECF)
St.-Jakobs-Platz 10
80331 München
Tel: +49 89 23239380
Fax: +49 89 232393811
www.wecf.eu
Dr. Claudia Wendland

Dipl.-Ing. Torsten Bettendorf

TerraPellet GmbH
Richard Linde Weg 21f
21033 Hamburg
www.terrapellet.de

Responsible
Prof. Dr. Markus Große Ophoff

Project leader
Franz-Peter Heidenreich

Layout
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Deutsche Bundesstiftung Umwelt
Postfach 1705, 49007 Osnabrück
An der Bornau 2, 49090 Osnabrück
Telefon: 0541 | 9633-0
Telefax: 0541 | 9633-690
www.dbu.de