Working Paper:

A review of Terra Preta Sanitation with a focus on the research outcomes of TUHH

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"We have taken soils for granted for a long time. Nevertheless, soils are the foundation of food production and food security […]. Today, 33 percent of land is moderately to highly degraded […]. Further loss of productive soils would severely damage food production and food security, amplify food-price volatility, and potentially plunge millions of people into hunger and poverty. […]
Sustainable soil management, using scientific and local knowledge and evidence-based, proven approaches and technologies, can increase nutritious food supply."
(Da Silva 2015, pp. VI–VII)

Abstract

Terra Preta Sanitation (TPS) is an astonishing biowaste/sanitation system of a highly advanced ancient culture. It shows the great potential of soil building and nutrient recycling from excreta. Terra Preta Sanitation was and is developed through the inspiration from a rediscovered historic practice. TPS systems treat excreta and produces valuable soil amender. Such sanitation systems are capable to contribute to attaining particular Sustainable Development Goals of the UN. Findings of highly fertile soils in the Amazon region initiated research in this field of study. Archaeological research revealed that Terra Preta was produced from biowaste and excreta with charcoal powder additives and layers of pieces from broken ceramic. The Institute of Wastewater Management and Water protection (German: Institut für Abwasserwirtschaft und Gewässerschutz, AWW) of Hamburg University of Technology (TUHH) conducted research concerning the application of lactic acid fermentation (LAF) and vermicomposting, with a special focus on sanitization and process conditions. The AWW operated case studies in India, the Philippines and Ethiopia and developed implementation strategies for conventional and new sanitation systems. Moreover, the institute facilitated the design of a container toilet, adjusted to Terra Preta sanitation and to cultural requirements worldwide. LAF can make the collection over longer timespans odour free and sanitized at the same time. The downside is a demand in a sugar additive, however, this can be obtained from biowaste addition. This literature review gives an overview of the current state of research conducted at TUHH.

Keywords: Terra Preta sanitation, lactic acid fermentation, vermicomposting, dry sanitation

Table of Content

Introduction

Sustainable utilisation of natural resources is nowadays a central challenge in terms of food security and waste management. On the one hand, soils are depleted and nutrient rich humus is extracted due to extensive agriculture, while on the other, conventional sanitation systems are not equipped to recycle precious nutrients and give them back to the soil. One way to address this could be a rediscovered sanitation system from the Amazonas called Terra Preta (Portuguese for "dark soil"). Originally, this technique consists of urine diversion, lactic acid fermentation (LAF) with charcoal additives and subsequent vermicompostation by earthworms. LAF suppresses odour formation and sanitizes the excreta. Subsequent composting and vermicomposting additionally sanitize the substrate and nutrient rich humus is produced. (Factura et al. 2010) This product can be utilised as a soil amendment for non-food purposes in forestry or agriculture (Buzie & Körner 2015).

In recent years, there has been ongoing research on the Terra Preta solution at TUHH. The institute AWW has thoroughly worked on Resources Oriented Sanitation (also called Ecological Sanitation) in High-Tech and Low-Tech since around 20 years. AWW examined the Terra Preta approaches intensively, operated case studies, developed implementation strategies and facilitated the design of a container toilet suitable for Terra Preta sanitation. See more about the activities on www.tuhh.de/aww and www.terra-preta-sanitation.net.

Lactic acid fermentation (LAF)

Lactic acid fermentation is the first treatment step after the collection of faeces. LAF show several positive effects, like efficient odour suppression, significant pathogen reduction, as well as conservation of nutrients and organic matter (Yemaneh et al. 2012). The fermentation process has been researched in terms of sanitization degree and in terms of appropriate process conditions. LAF makes container toilets without biocides possible – these are far simpler than the alternative of urine-diverting dry toilets (UDDT).

Sanitization

The sanitization degree of the feedstock is crucial for subsequent application of the products (Buzie & Körner 2015). The research undertaken by Factura et al. (2010) demonstrates general sanitization achievements of the Terra Preta Sanitation process (TPS), while Yemaneh et al. (2012) initiate more specific research concerning the sanitization in the LAF stage. Yemaneh et al. (2012) monitored E. coli as the sanitation indicator bacteria (SIB) and concluded that complete elimination is achieved in the lactic acid fermentation process. Further research by Yemaneh et al. (2014) confirms the removal of E. coli bacteria by LAF. In both cases, the E. coli colonies are determined using ChromoCult Coliform Agar. Factura et al. (2014) demonstrate in a field study a reduction of up to 50% Ascaris eggs (complete reduction after 60 days) and find no Taenia and Trichuris trichura bacteria after 30 days. Yemaneh & Itchon (2015) emphasise that low pH values due to lactic acid formation eliminate pathogenic microorganisms (MO) and antimicrobial compounds formed by lactic acid bacteria contribute to sanitization. Furthermore, Yemaneh & Itchon (2015) refer to publications that examine inhibition of pathogenic MOs besides E. coli. The research results are summarized in Table 1.

Table 1 Sanitation due to LAF

Authors	Microorganisms	Degree of elimination
Yemaneh et al. (2012)	E. Coli	Complete elimination after 5 (resp. 21) days with addition of 10% (5%) molasses
Yemaneh et al. (2014)	E. Coli	Complete elimination after 21 days with addition of 50% kitchen bio waste
Factura et al. (2014)	Ascaris eggs	50% reduction after 30 days Complete reduction after 60 days
	Taenia and *Trichuris trichura*	Complete reduction after 30 days

Process conditions

Factura et al. (2010) conducted basic research on process conditions for LAF. Analyses to improve process conditions for LAF were undertaken by Yemaneh et al. (2012). The authors researched suitable microbial inoculants, differing sugar supplement and modes of excreta collection. The process conditions were assessed based on the pH value, odour, E. coli and lactic acid formation. Yemaneh et al. (2012) concluded that the suitable microbial inoculant consisted of three lactic acid bacteria (LAB, Lactobacillus plantarum, Lactobacillus casei and Pediococcus acidilactici), that the optimal sugar supplement proportion was 10% mass fraction of molasses and that the LAF is a viable solution for all tested collection modes (combined and partially combined collection). Further examination that assessed the usage of kitchen waste as a low cost sugar supplement was conducted by Yemaneh et al. (2014). In this publication, it is stated that the application of kitchen waste, with a mass fraction of 40-50% in regards to wet weight of faecal matter, is appropriate as low cost sugar supplement. Moreover, this study evaluates additional parameters, the total amount of soluble nitrogen and ammonium nitrogen in the substrate during LAF. The findings of Yemaneh et al. (2014) regarding nitrogen compounds can hardly be compared to the findings of Factura et al. (2010) due to usage of different inoculants and additives. But it has to be remarked that most studies (Factura et al. 2010; Prabhu et al. 2014b) indicate an increase in ammonia (and ammonium respectively) independently from the chosen LAB after LAF, in contrast to the findings of Yemaneh et al. (2014).

Table 2 Process condtions of LAF

Authors	Process parameter	Adjustment
Factura et al. (2010)	Charcoal Additives (CA)	Charcoal (75%), stone dust (16% $CaCO_3$) and forest soil (9%)
	CA to faecal matter (FM) ratio as percentage of wet matter (WM)	Percentage of WM from 24-17%
Yemaneh et al. (2012)	Lactic acid bacteria	Lactobacillus plantarum, Lactobacillus casei and Pediococcus acidilactici
	Sugar supplement	10% (w/w) molasses
	Charcoal	10% (w/w) charcoal
	Microbial inoculant	10% (w/w) Lactic Acid Bacteria (LAB) inoculant
Yemaneh et al. (2014)	Sugar supplement	40-50% (w/w) kitchen waste as low cost molasses alternative

Lactic acid fermentation is well researched in terms of sanitization regarding E. coli bacteria. Other research concerning pathogen elimination could be conducted. Lactic acid fermentation operates well and shows satisfying results in odour suppression and stabilisation of organic matter (Factura et al. 2010).

Vermicomposting

The process of vermicomposting is subsequent to LAF. This composting technique aims to reduce pathogens and to contribute to a stable product through the digestion of the pre-fermented substrate by earthworms. Research reveals different results regarding the sanitization degree and examines suitable process conditions.

Sanitization through vermicomposting

As mentioned in the LAF chapter, the degree of sanitization of the feedstock is crucial for the subsequent application of the products (Buzie & Körner 2015). A general sanitization degree of TPS was demonstrated by Factura et al. (2010). Buzie-Fru, Otterpohl & Müller (2010) evaluated the feasibility of the vermicomposting technology as a method for faecal matter (FM) and state on the basis of SIB that sanitization of FM with and without earthworms mostly results in pathogen decline. Earthworms lead to higher pathogen reduction (Buzie-Fru, Otterpohl & Müller 2010). Based on US-EPA guidelines, the end products are rated as sanitization Class B. Buzie-Fru, Otterpohl & Müller (2010) give a comprehensive background to the process of vermicomposting. Stöckl et al. (2014) assess the sanitization of FM during vermicomposting, especially concerning *Salmonella*. It is shown that acidification contributes to *Salmonella London* elimination and thermal sanitization is more efficient than the digestion of earthworms (Stöckl et al. 2014). Whereas Buzie-Fru, Otterpohl & Müller (2010) promote limited use of end products, Stöckl et al. (2014) are more strict and do not recommend vermicomposting as a safe method for sanitization regarding *Salmonella*. The authors recommend further studies to enhance the vermicomposting technique or prior sanitization (see LAF sanitization). Walter et al. (2014) examine MOs at certain levels of vermicomposting phases. The study underlines the concerns regarding remaining pathogens after vermicomposting for 88 days. Factura et al. (2014) demonstrate in a field study an elimination of parasite ova after the vermicomposting process with prior LAF. The main research results are summarized in Table 3. Buzie & Körner (2015) insist explicitly that faecal matter (vermi-) composts should not be used for food production due to sanitization insecurity.

Table 3 Sanitization due to vermicomposting

Authors	Microorganisms	Degree of elimination
Buzie-Fru, Otterpohl & Müller (2010)		*Earthworm participation vs. composting process*
	E. Coli	99.98% vs. 45.46% reduction
	Faecal coliforms	99.98% vs. 49.26% reduction
	Enterococcus faecalis	99.99% reduction vs. 24.72% increase
	Salmonella spp	99.76 % vs. 74.57% reduction
	Shigella spp	99.69% vs. 99.71% reduction
	Enterobacter spp	99.98% vs. 56.81% reduction
Factura et al. (2014)	Parasite ova	Zero presence
Stöckl et al. (2014)	Salmonella	No complete reduction after 88 days due to vermicomposting
		Microarray technology analyses concerning the absence or presents of MO:
Walter et al. (2014)	Acinetobacter	Absent in EM and RM sample
	Enterococcus sp.	Present after 33 days, absent after 88 days
	Flavobacteria	Absent in EM and RM sample
	Pseudomonas	Absent in EM and RM sample
	Salmonella sp.	Present after 33 days, absent after 88 days
	Stenotrophomonas maltophilia	Present
	Xanthomonas	Present
	Xylella	Present

Process conditions

Buzie-Fru, Otterpohl & Müller (2010) conducted basic research on process conditions for vermicomposting. Earthworms (*Eisenia fetida /foetida*) are intoxicated by human faeces as a consequence of high nutrient content of excreta, ammonia production and anaerobe conditions (Buzie-Fru, Otterpohl & Müller 2010). Buzie-Fru, Otterpohl & Müller (2010) recommend 70% moisture content and temperatures between 20-25°C as optimal. The authors propose further research on the C/N ratio. Factura et al. (2010) came to similar results and aim to improve the environmental conditions by adding bulking agents like wood chips or paper, to raise the C/N ratio. Bettendorf, Stöckl & Otterpohl (2014) conducted experiments with a varying mixture of raw materials for vermicomposting and adjusted the molar C/N ratio to 31,5. Raw materials used are faecal sludge, charcoal, grass, wood, overlaid fruits and vegetables (OFV) and pot soil. The aim of the experiments was to evaluate the vermicomposting process in terms of physio-chemical product characteristics dependent on raw composition. Bettendorf, Stöckl & Otterpohl (2014) show that the vermicomposted product based on their raw composition is a stabilized and fertile soil enhancer. A study conducted by Walter et al. (2014) evaluate the effects of amended starter communities by two microorganism colonies (Effective Microorganisms (EM) and Reckin laboratory mix (RM)). It is indicated that the deployed MOs have no substantial effects on starter communities. Walter et al. (2014) recommend characterisation of the whole microbial community to gain a deeper understanding of the composting process in TPS. Buzie & Körner (2015) give a comprehensive overview on composting and vermicomposting. A wide range of feedstock is presented, sanitization is discussed, (vermi-) composting techniques are explained and a concluding comparison of the two techniques is drawn (Buzie & Körner 2015).

Table 4 Process conditions of vermicomposting

Authors	Process parameter	Adjustment
Buzie-Fru, Otterpohl & Müller (2010)	Moisture content	70%
	Temperature	20-25°C
	C/N ratio	20-25
Bettendorf, Stöckl & Otterpohl (2014)	C/N ratio	31,5 (calculated on molar base)
	Mixture of raw material 1*	FM: 35% sludge, 22% E0-earth, 19% grass, 13% OFV, 3% Wood, 9% charcoal
	Mixture of raw material 2*	FM: 32% sludge, 20% E0-earth, 18% grass, 12% OFV, 3% Wood, 15% charcoal
Factura et al. (2014)	C/N ratio	70:30 (equals 2,3)
Walter et al. (2014)	Microorganisms	EM and RM have no substantial effect on starter communities

**Readout from Figure 2; percentage in weight fraction (w/w)*

Research shows varying results in terms of sanitization success. Therefore, Buzie & Körner (2015) do not recommend TP product utilisation for food production. Further research to sanitization is advised (Stöckl et al. 2014; Walter et al. 2014). Process conditions to operate vermicomposting have been improved through further research. The vermicomposting process produces matured compost that serves as a valuable soil enhancer (Bettendorf, Stöckl & Otterpohl 2014). One major advantage in TPS is the combination of two sanitization steps.

Implementation of the Terra Preta system

The Terra Preta system is an integrated system and consists of more than LAF and vermicomposting. The implementation in terms of practical application in different regions and climates is necessary to prove reliability and to spread the idea of TPS. Furthermore, research of theoretical opportunities to implement TPS to conventional (CSS) and new systems (NSS) is crucial to provide strategies that can be integrated into existing structures. TPS offers many options and can also in the simplest form consist of sealed pit latrines put into LAF and regular collection.

Case studies

After basic knowledge of TPS (Factura et al. 2010) and its single constitutes (Buzie-Fru, Otterpohl & Müller 2010; Yemaneh et al. 2012) were fundamentally researched, studies were carried out by Bulbo et al. (2014), Factura et al. (2014), Prabhu et al. (2014b) and Yemaneh, Bulbo & Otterpohl (2015) which attempted to prove well-functioning implementation.

Goa, India

Prabhu et al. (2014b) tested TPS as an alternative solution for the management of primary sludge from the Birla Institute in Goa, India. Experimental setups with varying raw material compositions based on the research of Factura et al. (2010) were conducted. Raw materials used are sludge, charcoal, EM, soil and $CaCO_3$. In the vermicomposting phase earthworms die due to ammonia toxicity. Addition of dry grass cuttings kept the subsequently new added worms alive. As a result, Prabhu et al. (2014b) state that TP can be produced from primary sewage sludge. Contrary to Factura et al. (2010), Prabhu et al. (2014b) negate the necessity to separate urine and faeces. Prabhu et al. (2014b) do not give a recommendation for the most suitable raw material composition. In a different study, the effects of the produced Terra Preta on the growth of *Vigna radiate* are assessed by Prabhu et al. (2014a). The experiments show an increase of plant growth when TP is applied to soil in comparison to untreated soil (Prabhu et al. 2014a).

Cagayan de Oro City, Philippines

Factura et al. (2014) tested TPS system implementation in the tropical region of Cagayan de Oro City in the Philippines. In this project, urine diversion dry toilets with monthly collection were installed. The collected faeces were kept in storage facilities where they are protected from heat and moisture (Factura et al. 2014). Households use the collected urine in their backyards as fertilisers. Corncobs are added to adjust the C/N ratio to 2,3 to assure suitable conditions for vermicomposting. This differs significantly from the research of Bettendorf, Stöckl & Otterpohl (2014). Factura et al. (2014) conclude that TPS is effective in counteracting odours and providing a hygienically safe product for agricultural application.

Arba Minch, Ethiopia

Bulbo et al. (2014) studied the availability of precursors in Arba Minch (Ethiopia) to implement TPS. Precursors are human urine, faeces, biomass waste, manure, bones, biochar and process organisms. It is indicated that the limiting precursor for the TPS system in Arba Minch is charcoal. To enhance the availability of biochar, Bulbo et al. (2014) recommend further studies on the conversion of solid waste into biochar and the dual use of cooking stoves to produce biochar. Moreover, Bulbo et al. (2014) points out the high potential of TPS to improve and reforestation in the region. Evaluation of the microbiological quality of the end product should be conducted in the future (Bulbo et al. 2014). Yemaneh, Bulbo & Otterpohl (2015) presented their results concerning resource recovery and economic aspects of TPS in Arba Minch at the 2015 RANMIRAN conference (ed. Hamburg University of Technology 2015). Yemaneh, Bulbo & Otterpohl (2015) concluded that the TPS system produces a nutrient and organic matter rich vermicompost. Furthermore, biogas that is formed from human waste can be collected and utilised. Yemaneh, Bulbo & Otterpohl (2015) picked up the idea of Bulbo et al. (2014) to install wood stoves that produce bio char. It is deduced that fertiliser, soil conditioner and energy result in net benefit regarding monetary value (Yemaneh, Bulbo & Otterpohl 2015).

Theoretical implementation

Bettendorf, Wendland & Schuetze (2015) give a comprehensive overview of the subject matter and the integration of TPS. The wastewater streams separated by source are discussed. Furthermore, domestic wastewater flows and loads are exhibited. Moreover Bettendorf, Wendland & Schuetze (2015) discuss transport and collection systems of conventional (CSS) and new systems (NSS). At last, the implementation of TPS system to CSS and NSS was examined. Tangible NSS implementations are Blackwater Vacuum System, Dry Toilet System and “Loo-loop” System (Bettendorf, Wendland & Schuetze 2015).

Terra Preta is implemented in different regions with success regarding feasibility and outcome of the final product. However, Terra Preta faces limiting factors, such as the limited presence of charcoal. New concepts to implement TPS to existing systems are available. Application to new systems has been proven in pilot projects (Bettendorf, Wendland & Schuetze 2015).

Loolaboo – Terra Preta Toilet

The AWW institute facilitated an international toilet design award together with the World Toilet Organisation in 2012 with a total prize of $ 50.000. The winner was Sabine Schober from the Triften design studio with the Terra Preta toilet – Loolaboo (Otterpohl & Behrendt 2017). By enabling the user to either sit or squat on the toilet, the design is culturally acceptable worldwide (Otterpohl & Behrendt 2017). The Loolaboo meets requirements for the TPS system, since low amounts of water from a spray nozzle are required and LAF takes place in the storage tank (Otterpohl & Behrendt 2017). The tank is accessible through a hole in the back and a sliding mechanism seals the toilet (Otterpohl & Behrendt 2017). This concept won the 2012 WTO International Toilet Design Award (Otterpohl 2012). Figure 1 displays the design. A professional animation was produced for the design contest and is online on https://youtu.be/w_R09cYq6ys (search by Terra Preta).

Figure 1 Loolaboo - Terra Preta Toilet source: (Triften design studio n.d.)

Conclusion

Terra Preta addresses several Sustainable Development Goals (United Nations 2015) and has the potential to contribute to their success. Nevertheless, further research needs to be conducted.

Both process steps and implementation strategies of the Terra Preta are researched at the AWW institute of TUHH. Results indicate that TPS is a promising rediscovered ancient technology that closes the circle between sanitation issues and soil amendment. The LAF can be designated a stable process and vermicomposting was also analysed in detail with satisfying results. Several case studies proved a well-functioning implementation in different areas. However, as long as the TP are not entirely proven to be hygienically safe, the products should not be used on soils where food production is taking place. Studies that demonstrate a large-scale integration of TPS in conventional systems that widely operate in developed countries could be a future field of research. A strategic objective could be to raise public awareness of the fact that as much as a third of the total land is moderately to highly degraded and that 2,4 billion people lack improved facilities, as well as further repercussions of these issues. Basic education about the importance of well-functioning, of good water and soil quality could lead to broader acceptance to put high monetary and work intensive efforts to improve the current situation.

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