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Terra Preta Sanitation: re-discovered from an ancient Amazonian civilisation - integrating sanitation, bio-waste management and agriculture

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Abstract The recent discovery of the bio-waste and excreta treatment of a former civilisation in the Amazon reveals the possibility of a highly efficient and simple sanitation system. With the end product that was black soil they converted 10% of former infertile soil of the region: Terra Preta do Indio (black soil of the Indians). These soils are still very fertile 500 years after this civilisation had disappeared. Deriving from these concepts, Terra Petra Sanitation (TPS) has been re-developed and adopted. TPS includes urine diversion, addition of a charcoal mixture and is based on lactic-acid-fermentation with subsequent vermicomposting. No water, ventilation or external energy is required. Natural formation processes are employed to transform excreta into lasting fertile soil that can be utilised in urban agriculture. The authors studied the lacto-fermentation of faecal matter with a minimum of 4 weeks followed by vermicomposting. The results showed that lactic-acid fermentation with addition of a charcoal mixture is a suitable option for dry toilets as the container can be closed after usage. Hardly any odour occured even after periods of several weeks. Lactic-acid fermentation alone without addition of bulking agents such as paper and sliced-cut wood to raise the C/N ratio is creating a substrate that is not accepted by worms.
Keywords Bio-waste treatment; nutrient recovery; terra preta sanitation; urban agriculture

INTRODUCTION

The way to sustainable management of natural resources is one of the greatest challenges of present time. The sustainability of society depends essentially from secured water and food supply and an intelligent management of wastes. Food, for example, is produced with extensive input of energy and resources. Nutrients are detracted from soils and needed to be replaced. Replacement is often done by artificial fertilisers which are produced with high energy input. The reduction of organic matter content by the degradation of humus is mostly not replaced to the required extent. This leads to a slow but steady degradation of soil and loss of fertility. Urban sanitation systems nowadays, with their sewers and treatment plants, are not designed to close material cycles and extracted nutrients are not directed back to the soil. If sludge from mixed wastewater is returned it has a lack of usable nutrients, the phosphate is to a large extent not accessible to plants because of strong bindings with metal salts from precipitation (UBA, 2001). Consequently, essential elements, especially carbon, nitrogen and phosphorus but also trace elements are lost, with consequent over-fertilisation of water bodies and the seas. Such form of waste disposal is not just water and energy consumptive, but also very cost intensive due to the necessary infrastructure and structural constructions. Particularly, the construction and maintenance of sewers demand enormous financial efforts and do require a high water input to avoid deposits and clogging. This approach of handling resources is in most situations not sustainable, neither it is feasible for expanding urban areas where energy and water resources are in short supply.

An analysis of a former civilisation in the Amazon, nowadays Brazil, reveals concepts which enable a highly efficient handling of organic wastes. Terra Preta do Indio is the anthropogenic black soil that was produced by ancient cultures through the conversion of biowaste and faecal matter into long-term fertile soils. These soils have maintained high amounts of organic carbon even several thousand years after they were abandoned (Lehmann et al., 2003b). It was recently discovered that around 10% of the originally infertile soils in the Amazon region was converted this way from around 7.000 until 500 years ago (Glaser, 2007). A hectare of meter-deep terra preta can contain 250 tonnes of carbon as opposed to 100 tones in unimproved soil (Lehmann et al., 2006). Figure 1 shows two soils, one (left image) having fallowed many years without charcoal and having a thin dark soil layer. The other soil (right image), located in the same region, has been under fallow for presumably a similar time period. However, because of the accumulation of charred biomass and other organic residues, terra preta subsequently formed giving it a deep, distinctly dark and highly fertile soil layer.

Figure 1: Photograph showing terra preta soils (Adapted from Günther, 2007)

One of the surprising facts is that this soil is highly productive without fertiliser addition still. From evidence of excavations and lab results it was concluded that this culture had a superior sanitation and bio-waste system that was based on source separation of faecal matter, urine and clever additives particularly charcoal dust and treatment steps for the solids resulting in high yielding gardening. Additives included ground charcoal dust while the treatment and smell prevention started with anaerobic lactic-acid fermentation followed by vermicomposting (Pieplow, 2008). Vermicomposting is a decomposition process involving the combined action of earthworms and microorganisms, and is a recent concept in the field of sustainable sanitation. An exhaustive review of the theoretical background of the vermicomposting process, mechanisms and practical application methods of vermicomposting are provided by Shalabi (2006) and Buzie *et al*. (2010, in press).

Vermicomposting alone has been proven to be highly efficient for treatment of faecal matter (Basja, 2002; Shalabi, 2006; Yadav 2008; Buzie et al., 2010, in press) but the initial silage process makes the combination superior than other combined processes. There is first qualitative experimental evidence, that it is not only lactic-acid fermentation but also some other organisms like *Bacillus subtilis* in combination with the addition of some thin wood particles that is leading to a better compost quality. Research on practical application of the principles of modern Terra Preta Sanitation (TPS) has shown that it is possible to convert in a hygienic and sustainable way biowaste and faecal matter into highly fertile humus-like material. TPS makes use of lacto-fermentation and vermicomposting in a two-stage process. One of the main advantages is that the lacto-fermentation works efficiently and stable without air exchange and produces no offensive odours.

Integration of the anaerobic dry toilet and vermicomposting thus promises to be an ideal approach for managing wastes even generated by urban households. The product, terra preta, can address the problems of soil degradation and food insecurity common in many areas across the world. TPS may allow the design of highly resource efficient houses and housing areas with added value in urban agriculture that can be combined with local grey water reuse. Thus it can close regional cycles and improve hygienic conditions and soil fertility in a sustainable manner with the creation of local added value. In addition to macro-nutrients the issue of micro-nutrients has to be addressed. In important agricultural soils around the world, micronutrient deficiencies are: Zn (49%), B (31%), Mo (15%), Cu (14%), Mn (10%), and Fe (3%) (Graham, 2008). These are the essential micronutrients of plants. They are needed by plants in minute amounts that is why they are called micronutrients but they function equally important with the macronutrient requirements of plants (e.g. N,P,K). Human health requires plants for food that have all these substances, too. Especially Zn and Fe deficiencies are very common and contribute heavily to child death according to WHO.

The objective of this study is to investigate the suitability of the TPS toilet as an alternative sanitation option. Therefore, we monitored the dry toilet under anaerobic conditions. We focused on analysing standard chemical and biochemical properties of the toilet products to evaluate their stability and maturity, and establish nutrient status. The fate of pathogens during vermicomposting of faecal matter is of much importance in the discussion about reuse-oriented sanitation concepts. Therefore, in investigating the TPS concept as an alternative technology for faecal matter treatment, due attention has been given to the hygienic safety of the product.

MATERIALS AND METHODS

The experiments, which were conducted in the laboratory of the Institute of Wastewater Management and Water Protection at the Hamburg University of Technology (TUHH), consisted of three phases: collection, lactofermentation (LF) and vermicomposting. The main materials used were simple buckets with air-tight lids (without provision for urine diversion), urine bottles, ground charcoal, stone dust and inoculums (IC). Three independent experiments were conducted, each involving the three phases as stated above. In the collection phase, faecal matter (FM) was collected during a two week period with addition of charcoal additive (CA) (charcoal, stone dust and soil) at each usage. The LF phase involved pre-stabilisation of the collected material during a 4-week period where the bucket was closed air tight and stored at a temperature of 20°C, whereas the vermicomposting phase involved aerobic decomposition of the pre-digested material by the combined action of earthworms and the waste's natural flora. The CA consisted of roughly 75% ground charcoal (<1mm), 16% calcium carbonate ($CaCO_3$) and 9% forest soil (related to dry matter). The moisture content of CA was adjusted to 16% by addition of water in order to get a dispersible mixture without dust formation.

Two ICs were investigated, sauerkraut (pickled sour cabbage) juice and a commercial product 'effective microorganisms' (liquid EM A). The decomposition was monitored using standard chemical parameters (moisture content, volatile solids, pH, electric conductivity, soluble total organic carbon, TOC, as well as N and P compounds). Analyses were conducted using standard methods as described in the German "Methods Book for the Analysis of Compost" (BGK, 1994), whereby extractions with $CaCl_2$ solution (for determination of pH, TOC and N compounds), CAL solution (for phosphorus compounds) and deionised water (for electric conductivity) were carried out. Mass balances in collected faeces and added CA were also determined at the end of each phase. A pilot set-up similar to the lab-scale experiments has been in operation and maintained by one of the authors (H. Pieplow) in his own home for more than two years. Faeces were collected separately from urine. The composition of the charcoal additive used for faeces during the collection period was the same as in the lab experiments conducted in TUHH. Using simple bucket with air-tight lid the faeces were subjected to anaerobic condition with added effective microorganisms (LF phase) for at least 4 weeks and then followed by vermicomposting at his backyard for another 6 months. Results from the lab-scale analyses were compared with the pilot trial. Additionally, included in the results and discussion is a data on concentrations of sanitation indicator bacteria for vermicomposting by Buzie *et al.* (2010, in press).

RESULTS AND DISCUSSION

During the collection phase of the three experiments no uncomfortable odour was observed during usage particularly when ICs were incorporated in the CA. This shows that the CA combined with ICs was effective in odour adsorption.

Table 1. Total mass (TM) in the bucket, used CA, and collected faecal matter (FM) in gram with their corresponding dry matter (DM) percentage as well as the ratio of CA to FM as percentage of wet matter (WM) and number of entries (n.o.e.) in experiments 1, 2 and 3.

	TM	CA	FM	CA/FM	n.o.e.
Exp. 1	4443 (27.9%DM)	859 (83.3%DM)	3584 (14.7%DM)	24.0% WM	23 (155 g FM/usage)
Exp. 2	6650 (31.5%DM)	1040 (84%DM)	5610 (17.1%DM)	18.5% WM	36 (175 g FM/usage)
Exp. 3	6930 (29.1%DM)	1020 (83.5%DM)	5911 (16.8%DM)	17.3% WM	28 (211 g FM/Usage)

As shown in figure 2 only slight changes in DM and organic dry matter (oDM) occured in the collection (FM) and LF phases in all three experiments. This implies that no remarkable changes took place in the material during LF phase. In the pilot samples a notably higher mineral residue was observed (almost equal DM and oDM in terra preta, TP) and a reduction of 60% to 42% oDM between LF phase and vermicomposting (TP) was measured. Reasons for the higher mineral content in the LF pilot scale samples were most probably due to a higher content of stone dust and clay minerals added in the CA. Furthermore, bio-waste was added to the faeces before LF phase started.

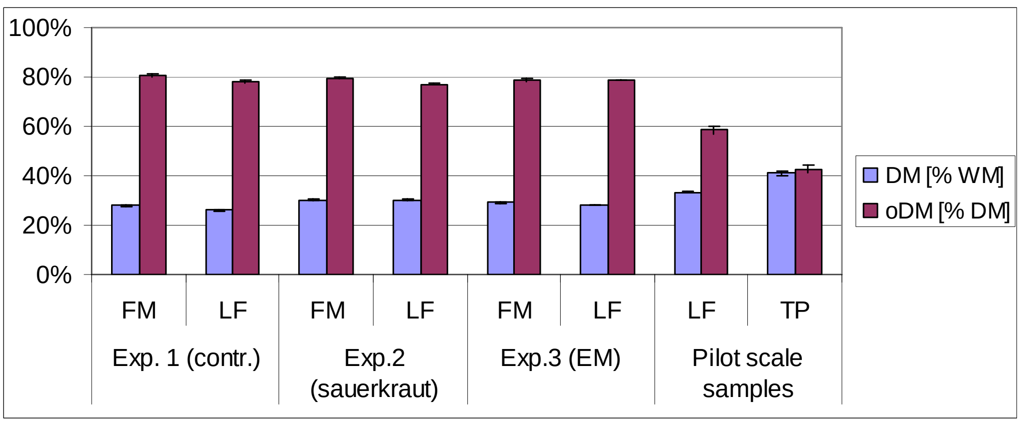

Figure 2. Percentage of dry matter and organic dry matter in fresh and lactofermented faeces in the three experiments as well as in samples from the pilot scale.

With regards to soluble N and P (as illustrated in figures 3 and 4) almost all changes from FM to LF in experiments 1, 2 and 3 showed similar pattern. However a big difference was observed between the LF and TP pilot scale samples in terms of soluble N (figure 3). The very low content of soluble N in TP could be interpreted as a result of a strong binding of N to the humus matrix of the TP material.

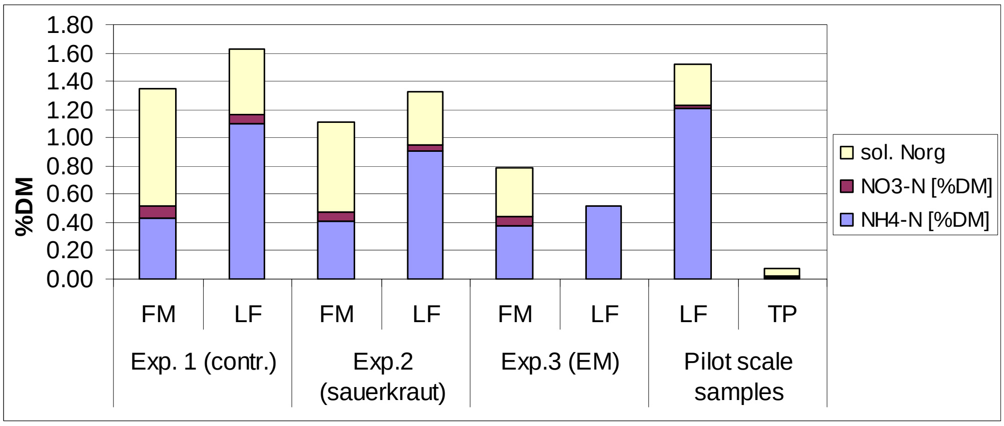

Figure 3. Percentage of soluble N species in fresh and lactofermented faeces in the three experiments as well as in samples from the pilot scale.

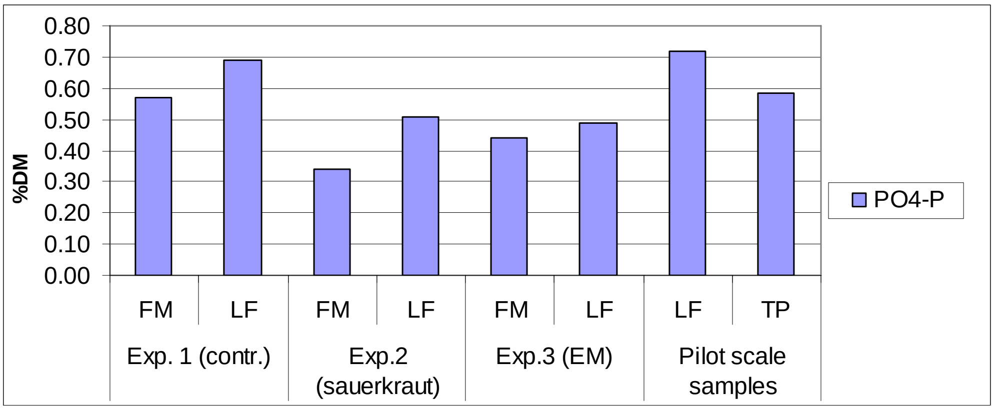

Figure 4. Percentage of soluble P in fresh and lactofermented faeces in the three experiments as well as in samples from the pilot scale.

Testing the lactofermented faeces for vermicomposting, the worms had shown intolerance and died within 24 hours of exclusive contact with the material. It is assumed that the absence of suitable co-substrates like bio or garden wastes and the abrupt change of substrate conditions caused the death of the worms. In contrast to the laboratory trials in TUHH the LF material (in the pilot scale) were spread on an on-going vermicomposting pile and so the worms adapted easily. This research will be continued. In the subsequent investigations measures to eliminate substances toxic to earthworms will be implemented. A possible explanation for the mortality of earthworms in the lacto-fermented substrate was the release of ammonia (NH_3) which is known for its toxicity to living organisms. The release of high levels of NH_3 was expected owing to the low carbon to nitrogen (C/N) ratio of the substrate. We plan to correct this problem by adding bulking agents, mainly wood chips to raise the C/N ratio and improve aeration that facilitates the escape of released NH_3.

In all samples a pH between 7.5 and 8.1 was measured (Table 2). In experiment 1 and 3 a slight increase of the pH was observed from FM to LF phase, whereas in experiment 2 the pH was decreasing. Results imply that release of NH_3 was high and nitrification had also occured.

In line with the release of NH_3 an increase of electrical conductivity (EC) was also observed. It is remarkable that in experiment 3 (addition of effective microorganisms) negligible nitrate (NO_3-) concentrations were found in the extracts as compared to experiments 1 and 2 which was also similar with the LF pilot samples where also effective microorganisms were added.

Table 2. Results of the physical and chemical parameters in fresh and lactofermented faeces in the three experiments as well as in samples from the pilot scale.

	Exp. 1 (contr.)		**Exp.2 (sauerkraut)**		**Exp.3 (EM)**		**Pilot scale samples**	
Parameter	**FM**	**LF**	**FM**	**LF**	**FM**	**LF**	**LF**	**TP**
DM [% WM]	27.9	26.0	30.2	30.2	29.1	28.0	33.4	41.1
oDM [% DM]	80.6	78.0	79.6	77.1	77.1	28.3	58.6	42.6
Total Soluble N [%DM]	1.34	1.63	1.11	1.32	0.79	n.a.	1.51	0.08
Soluble Organic N	0.83	0.46	0.64	0.38	0.35	n.a.	0.29	0.05
NH_4-N [%DM]	0.43	1.10	0.41	0.91	0.38	0.52	1.20	0.01
NO_3-N [%DM]	0.09	0.07	0.06	0.04	0.06	0.01	0.02	0.02
Total P [%DM]	0.60	0.73	0.38	0.58	0.52	0.50	0.77	0.59
PO_4-P [%DM]	0.57	0.69	0.34	0.51	0.44	0.49	0.72	0.58
pH	7.69	8.01	8.01	7.78	7.52	8.17	8.07	7.58
EC [mS/cm]	2.01	3.03	1.78	2.90	1.99	2.4	4.02	1.7

Based on the amount of CA per DM added to the TPS an amount of 15 kg DM/cap/year is required to operate the TPS system. It would be between 6.3 and 20.4 kg DM of CA or in other words 4.7 to 15.3 kg charcoal per capita per year. In comparison with the equivalent energy input of 39.2 to 127.5 kWh (a heating value of 30 kJ/g for charcoal is assumed) it seems to be a high energy input but with respect to the corresponding fertiliser value of deriving TP with its benefits as a soil conditioner it seems more than justified.

Figure 5 shows the initial and final concentrations of six sanitation indicator bacteria (SIB) monitored in test units (with earthworms) and controls (without worms) during a 60 day period (Buzie et al., 2010, in press). There was a clear difference in SIB population profiles between the test and control systems. Although both systems exhibited reductions for all the SIB analysed, the reduction was more important when earthworms participated in the stabilisation process: (*Escherichia 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), and *Enterobacter spp* (99.98% vs. 56.81% reduction).

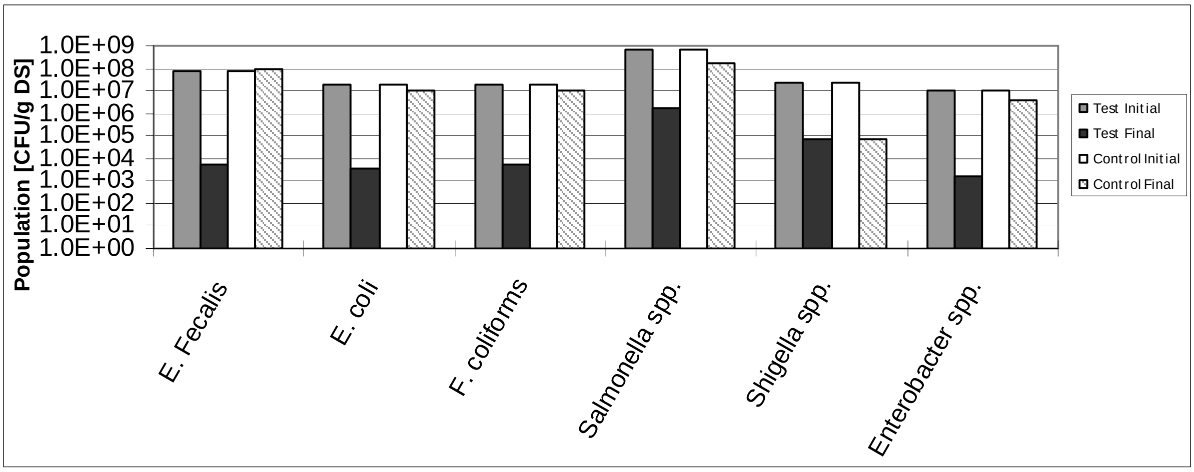

Figure 5: Sanitation indicator bacteria average decrease (shown in logarithmic scale) in the test and control systems during 60 days of treatment.

Similar results were reported by Flack and Hartenstein (1984). In an extensive study on the growth of *E. foetida* on microorganisms and cellulose, Buzie *et al.* (2010, in press) demonstrated that this earthworm grows similarly on gram-negative and gram-positive bacteria, and thus concluded that *E. foetida* is able to destroy human pathogens as well as non-pathogenic microbes by decomposing bacteria cell wall with a wide variety of polysaccharides. To meet United States Environmental Protection Agency (US-EPA) class B criteria, faecal coliform density must be below $2.0*10^6$ MPN/gTS or $2.0*10^6$CFU/gTS. In the present study, the density of faecal coliform in the final material (from test units) was $4.80*10^3$ which satisfied the requirement for class biosolids. The finding suggests that vermicomposting may be a feasible option for elimination of pathogens. Further investigations of the end-product by variation or prolongation of processing and storage times may provide improved results.

CONCLUSIONS

The re-discovery of a highly efficient low-cost sanitation system from an ancient civilisation in the Amazon combined with the latest development in urine diverting dry sanitation opens new pathways. Research is at the very beginning but results are promising. Application can be performed right away although there are a lot of open questions to fully understand the whole process. Lactic-acid fermentation is working so well and stable provided that inoculation is done. There are few reasons left for the desiccation of faecal matter that is now done in modern dry sanitation with numbers of installations exceeding a million. Adaptation of existing dry toilets is feasible where space requirements for the common double vault systems can be cut to half. The anaerobic, but oxygen-tolerating terra preta sanitation (TPS) offers smell free operation without ventilation pipes. Besides modification of the existing urine diverting dry toilets there are three more development lines for implementation: 1.) Upgrading pit-latrines as used by around two billion people; 2.) Simple bucket toilets with any kind of urine diversion that are closed air tight after defecation and addition of the charcoal with lactic-acid bacteria mixture and finally 3.) Well designed and comfortable urine diverting dry toilets with optional automatic addition of the conditioning/inoculation material. People suffering inadequate or missing sanitation can be served with one of the three types of installations. In the worst of situations as in slum areas a simple plastic bag would also be usable through avoidance of methane-fermentation in the silage process. The inoculation mixture can be multiplied at very low costs, but ground charcoal is a resource that is required. As in all on-site systems participatory planning (NETSSAF, 2008), proper utilisation of the end-products and well organised professional operation and maintenance is crucial for success. Quality of the end product will depend on avoidance of pollution at the source and in order to get good results in usage of the soil the dynamics of soil-plant interaction should be respected (Reckin, 2003). This implies that urine is not applied in a way that results in imbalances of plant nutrition that results to weaker plants. Research on urine treatment in a way that results in a balanced rich soil with a proper C/N-ratio will be crucial to achieve a well-functioning interaction of sanitation, biowaste management and agriculture.

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