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# Fertiliser products from new sanitation systems: Their potential values and risks

Martina Winker [a,*], Björn Vinnerås [b,c], Andreas Muskolus [d], Ute Arnold [e], Joachim Clemens [e]

[a] Institute of Wastewater Management and Water Protection, Hamburg University of Technology, 21071 Hamburg, Germany
[b] Department of Energy and Technology, Swedish University of Agricultural Sciences, Uppsala, Sweden
[c] National Veterinary Institute, Uppsala, Sweden
[d] School of Biological Sciences, University of Southampton, Southampton, United Kingdom
[e] Institute for Crop Science and Plant Nutrition, University of Bonn, Karlrobert-Kreiten-Straße 13, 53115 Bonn, Germany

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ABSTRACT

The plant nutrients consumed in human society today are lost through the established wastewater treatment systems in industrialised countries as well as via insufficient or non-existent handling of sewage in the developing world. New sanitation systems have been designated to overcome this failure. The source separated wastewater streams collected within these systems contain a high nutrient content, and can be used as fertiliser as well as soil conditioner after appropriate storage and/or treatment. Application in agriculture with existing techniques is feasible. However, pathogens and pharmaceuticals contained in these fertiliser types are a potential hazard. Nevertheless, storage and appropriate treatment can minimise the risks. The products deriving from these systems have a high potential to preserve available plant nutrient resources and deficiencies in agriculture as well as being able to substitute synthetic plant nutrients and at the same time prevent unwanted environmental nutrient over-enrichment.

## 1. Introduction

New sanitation systems are focusing on treatment of domestic wastewater streams. Such new systems are of increasing importance especially for areas without sufficient wastewater treatment and those experiencing water scarcity or high fertiliser prices. Water usage can be drastically reduced as flush water becomes practically negligible by implementation of new sanitation techniques such as dry toilets, vacuum systems and separation of domestic wastewater streams. Moreover, wastewater streams can be collected and treated appropriate to their specific requirements and nutrient recovery and at the same time pollution management can be simplified. New wastewater products with promising characteristics are emerging, thereby enabling the substitution of synthetic plant nutrients made from fossil resources. The new products can be used as fertilisers in agriculture either directly or after respective treatment. Additionally, recovery of nutrients gains importance due to the finiteness of mineral resources such as phosphorus (Driver et al., 1999) and due to the increase of energy prices as e.g., energy is required for the production of nitrogen fertilisers. These tendencies lead to a continuous increase of fertiliser prices which put farmers especially in poorer countries under severe financial pressure and high degrees of dependencies.

Engineers have already designed pilot plants to treat wastewater and to recycle nutrients for >100 inhabitants e.g., Lübeck-Flintenbreite, Germany (Otterpohl et al., 1997), Linz SolarCity, Austria (Steinmüller, 2006), or Erdos Eco-Town, China (Lixia et al., 2007). Although the utilisation of nutrient rich fractions as fertilisers is implemented in these projects, overall little is known about their quality, their nutrient availability, and their potential risk through contained pollutants. Their nutrient contents and other characteristics differ significantly from sewage sludge which is very well-known and thoroughly investigated. Additionally, it is important that existing agricultural equipment can be used for field application. To match the capabilities of existing fertiliser application technologies, a product is needed which can be applied in quantities of 10–50 $m^3$ $ha^{-1}$ (liquid), up to 40 t DM $ha^{-1}$ (solid), as well as 100–600 kg $ha^{-1}$ for granulates (Finck, 1979). The nutrient availability of a fertiliser of organic origin is mainly defined by whether single nutrients are present in mineral form or bound to carbon compounds. Organically fixed nutrients need to be mineralised in order to be taken up by plants.

Hence, nowadays wastewater products originating from new sanitation systems are thoroughly investigated regarding these aspects. Currently, urine, blackwater, compost from faecal matter, and struvite seem to be so far the most important new fertiliser products derived from source-separated wastewater. They could potentially cover more than 10–20% of the German and 20–30% of the Swedish fertiliser demand. For developing countries the contribution through products from new sanitation systems to

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[*] Corresponding author. Tel.: +49 40 42878 2982; fax: +49 40 42878 2684.
*E-mail addresses:* m.winker@tuhh.de (M. Winker), a.clemens@uni-bonn.de (J. Clemens).

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the national application of mineral fertilisers would be even larger. For example in sub-Saharan Africa, the annual excreta production corresponds to more than 100% of the local application of mineral fertilisers (Rockström et al., 2005).

## 2. Methods

Data on fertiliser products from new sanitation systems were collected by a literature review. The scientific papers and reports discuss the nutrient contents and availabilities, the concentrations of pollutants such as heavy metals, pharmaceuticals, and pathogens, the quality of the products, and their solid/liquid as well as mineral/organic properties referred to as fertilising type (FT). It has to be stated explicitly that in this paper fertiliser types are not evaluated according to their origin as mineral or organic fertiliser but to their nutrient binding form. So, e.g., urine is described as mineral FT.

Moreover, a mass flow model (Rieß, 2003; modified by Hammer and Clemens, 2007) to estimate pollutant fluxes to agricultural fields along with the provided nutrients was extended with the additional data of the literature review. Hence, the respective parameters chosen for nutrients, heavy metals, and organic pollutants were checked and replaced in the case of more recent or thoroughly analysed data.

The model bases on the assumption that a certain amount of nutrients and organic matter is required on a long term average for maintenance of soil fertility. The necessary nutrient inputs are defined as nutrient equivalents (NE). Seven NEs are needed to supply arable fields with sufficient fertiliser. According to the concentrations of these nutrients in the substrates, always one of them limits the application rate – otherwise the field would be over fertilised – and defines the quantity finally applied per hectare. This rate is used to calculate the corresponding pollutant fluxes.

The fertiliser application was limited in the case of pig manure by phosphorus, of cattle manure by organic matter, and of urine by sulphur to avoid over-fertilisation. Urine was chosen as the first indicator substance out of the fertiliser products derived from new sanitation systems. It is the only product where complete information is available for the categories of TS or DM, COD, as well as the three macronutrients nitrogen (N), phosphorus (P), and potassium (K) (see Table 1).

## 3. Results and discussion

### 3.1. Nutrients and heavy metals

Detailed information for the fertiliser products originating from source-separated wastewater streams and having been identified as being important during the literature screening is given in Table 1. The products were sorted according their specific fertiliser type (see Section 2). Additionally, the fertiliser suitability of the wastewater products in comparison to different common crops i.e., cereals and potatoes is shown in Fig. 1. The graph shows very well the specific properties of each fertiliser due to its position within the triangle. That is the ammonia solution is located in the upper edge as it only contains N while struvite is found on the left side due to its high P content. A mismatch of fertiliser compositions and crop requirements can generally be balanced by adding single nutrient mineral fertilisers such as ammonia solution. However, as P and K can be stored in soil to a larger extent than N, some oversupply of these nutrients might be acceptable in single years as long as the long term balance is right.

### 3.2. Urine

Urine is perhaps the most promising product as it contains relatively high concentrations of N (up to $9\,\mathrm{g\,N\,l^{-1}}$), P (around $0.7\,\mathrm{g\,P\,l^{-1}}$) and other nutrients such as K, sulphur (S), and micronutrients. Although its pH is around 9 after storage (Udert et al., 2003), it shows low $NH_3$ emissions (<10% of applied N) after field application compared to liquid slurry due to its quick infiltration (Rodhe et al., 2004; Simons, 2008). Urine can be used as a multi component mineral fertiliser (Muskolus, 2008) and is easily applied with conventional equipment available at the farm. Additionally, its characteristics are well investigated compared to other products derived through new sanitation systems.

### 3.3. Urine based fertiliser products

Many different systems for concentration of nutrients contained in urine have been investigated (Pronk et al., 2007; Tettenborn et al., 2007; Maurer et al., 2006). In most cases, these systems are high-tech solutions with a series connection of different treatment steps. So far, the most promising one is struvite precipitated from urine as a rather pure mineral. Simons (2008) found that 88% of the precipitate was present in form of ($Mg(NH_4)PO_4$). In contrast, a struvite product precipitated at a wastewater treatment plant consisted of 46% crystallised struvite only. About 40% of the P was available in form of magnesium phosphate hydrate ($Mg_3(PO_4)_2 \cdot 22H_2O$). The two substrates showed similar P-availability for grass but plant availability of P was 25% lower for clover from struvite originating of urine.

### 3.4. Blackwater

Blackwater – a liquid mixture of urine, faeces, flush water, and toilet paper – is the base for a multicomponent fertiliser which contains considerable amounts of carbon. Compared to urine, it normally contains nutrients in lower concentrations, mainly due to dilution by flush water during collection. However, on a societal level, the total nutrient recovery from a blackwater system is higher due to collection of a larger proportion of the nutrients. Before usage, a treatment is needed to stabilise and sanitise the material.

**Table 1**

Properties of wastewater products originating from source-separated wastewater streams presented along their fertilising types. Additionally, the level of knowledge for these products is indicated by + (well-known), (+) (known to some degree), and – (unknown). n.r. stands for not relevant.

| Fertilising type (FT) | Product | Level of knowledge | TS (%) | COD ($\mathrm{g\,l^{-1}}$) | N ($\mathrm{g\,l^{-1}}$) | P ($\mathrm{g\,l^{-1}}$) | K ($\mathrm{g\,l^{-1}}$) | Reference |
|---|---|---|---|---|---|---|---|---|
| Liquid mineral | Urine | + | 1.5–3 | 4–11 | 1.8–17.5 | 0.2–3.7 | 0.7–3.3 | Meinzinger and Oldenburg (2008) |
| | Concentrated urine e.g., Urevit | (+) | | 10 | 11 | 0.65 | 5.7 | Boller (2007) |
| | Ammonia solution | (+) | | | 120 | n.r. | n.r. | Tettenborn et al. (2007) |
| Liquid organic mineral | Digestate | – | $\leqslant 1$ | 2.8 | 1.5 | – | 0.14 | Wendland (2008) |
| | Untreated sludge blackwater | – | | | | | | |
| Solid mineral | Struvite | (+) | | | 60 | 130 | n.r. | Calculated stochiometrically |
| Solid organic | Compost | – | | 100 | 5–20 | 2–4 | 3–10 | Simons et al. (2005) |
| Solid organic mineral | Sludge with DM > 20% | – | | | | | | |

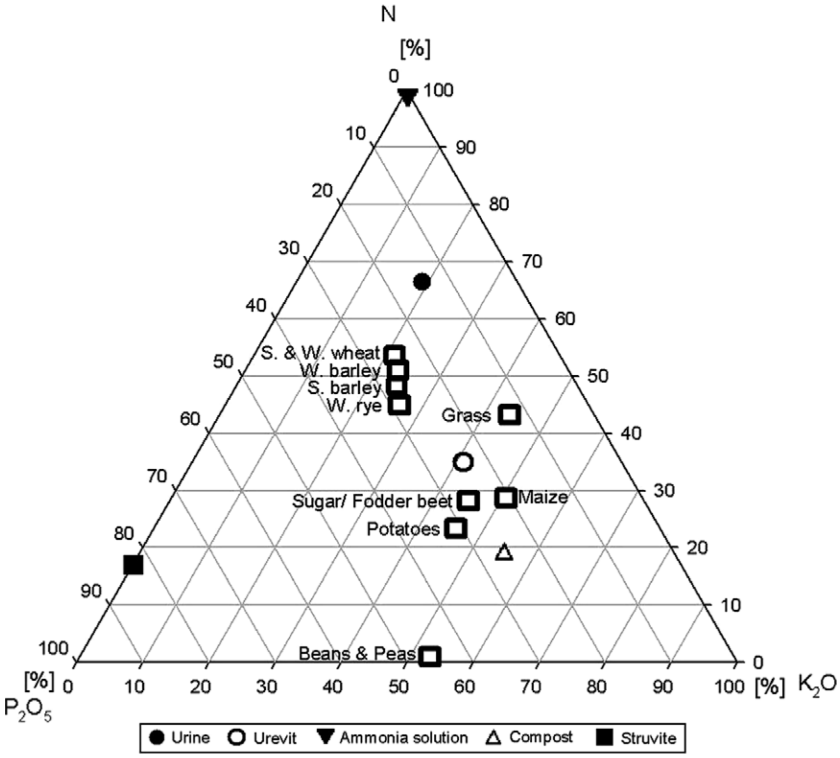

**Fig. 1.** Nutrient compositions in fertilising products from new sanitation systems and nutrient requirements of common European crops. P is shown as $P_2O_5$ and K as $K_2O$ to achieve a better visual distribution in the graph. Data for wastewater products are taken of Table 1, for crops out of MAFF (2000).

### *3.5. Blackwater based fertiliser products*

Anaerobic treatment turns blackwater into a digestate. Carbon contents in the digestate are reduced compared to blackwater. The magnitude of this depends on the degradability of the input material and specific process characteristics (retention time, temperature) as well as the presence of inhibitors. However, in most cases, during collection the blackwater is diluted and additional organic energy input is needed for a functional process e.g. via the addition of manure or solid organic waste. The digestate still contains all nutrients with minor losses of N and S as some $NH_3$ and $H_2S$ leaves the digester with the biogas. Anaerobic digestion also raises the share of mineral N (ammonium) on total N due to both mineralisation of organic nitrogen and reduction of N-fixing carbon compounds. In an additional treatement step, nutrient recovery and concentration from the digestate becomes possible by evaporation or precipitation (Alp and Otterpohl, 2008). Such a step has the advantage of creating a completely new product with no connection to the original matter as well as a volume reduction.

The blackwater can also be treated with ammonia sanitisation where the potential pathogens present can be inactivated using urea or ammonia additions (for details see below). Ammonia treated material contains a high N content which limits the application rate.

### *3.6. Faecal matter*

The separation of solid faecal matter – collected in dry sanitation systems, is not implemented in Europe in large scale but in many developing countries. As blackwater this fraction requires treatment for stabilisation and sanitisation. The nutrient concentration in the faecal matter is comparable to the urine but the fraction is only one tenth the size and the plant availability is significantly lower as most nutrients are organically bound. Along with the faeces other substances can be found that affect the fertiliser value and treatment options available, e.g., inert material for anal cleansing such as stones and covering material such as ash.

### *3.7. Faecal based fertiliser products*

Solid compost mainly derived from faecal matter and maybe mixed with organic food waste, has a lower nutrient content compared to urine, especially the concentration of plant-available N is low. Due to the low N availability of compost (grouped under the FT "solid organic"), it is normally used as soil conditioner instead of fertiliser.

Additions such as ash complicate composting of the faecal material as it is hard to reach good hygienic standards. (Niwagaba et al., 2009a,b). Similar accounts for vermicomposting which normally results in nutrient-rich compost after 2–4 months of treatment (Simons, 2008; Shalabi, 2006). Another disadvantage of vermicomposting is its management – it needs steady supervision to guarantee an appropriate functionality. Moreover, ammonia sanitisation is also an alternative treatment for the faecal fraction (for details see section "pathogens").

### *3.8. Other products from new sanitation systems*

Sludge with a dry matter content >20% summarises various sediments emerging during collection and treatment of source separated wastewater streams. This sludge is very diverse depending on its origin and respective storage/treatment and normally of organic and mineral character. Detailed investigations do not exist as of yet.

The existing knowledge on the plant availability of nutrients contained in these fertilising products from new sanitation systems is still limited. For most of the discussed FTs only estimations were possible which are presented in Table 2. It has to be

**Table 2**
Expected nutrient availability of the various fertilising types presented for the three macronutrients N, P, and K.

| Fertilising type (FT) | Expected availability (%) | | |
|---|---|---|---|
| | N (in year of application) | P (3 year crop rotation) | K (3 year crop rotation) |
| Liquid mineral | 100 | 100 | 100 |
| Liquid organic mineral | $N_{mineral}$ + approx. 10% of $N_{organic}$ | 100 | 100 |
| Solid mineral | 100 | 100 | 100 |
| Solid organic | <10 | 100 | 100 |
| Solid organic mineral | $N_{mineral}$ + approx. 10% of $N_{organic}$ | 100 | 100 |

pointed out that the three macronutrients N, P, and K are discussed along different time periods to provide an overall picture. While nitrogen availability is given on an annual basis, phosphorus and potassium were considered for a crop rotation of 3 years. In general, all mineral and water soluble compounds in fertilisers are plant available immediately. In addition, mineralisation processes of the organic fraction occur and release further N over time in the form of ammonium. Therefore, it is important to know which N fraction is mineral and which is organic in order to estimate the nutrient availability and the resulting fertilising effect.

The application of liquid substrates might be associated with ammonia emissions, as they may contain relatively high ammonium concentrations and high pH-values, up to 9. However, the liquids infiltrate the soil immediately and thereafter ammonia emissions end. Ammonia emissions from urine (FT “liquid mineral”), the most sensitive fertilising product regarding this type of emissions, are lower than emissions from animal slurry (FT “liquid organic mineral”) (Simons, 2008). However, the application technique needs to be adjusted to the high ammonia content of urine, i.e., application close to the soil preferably in combination with soil incorporation, and the low level of total solids.

Heavy metal concentrations are low in all products of domestic origin as no industrial wastewater is included. The only exceptions are sludge from septic tanks and compost (Simons et al., 2005). Threshold values of heavy metals in composts may be reached due to the decreased content of organic matter after degradation. Nevertheless, loads to agricultural fields are at least ten folds lower in comparison with animal manure (Fig. 2) and for chromium and copper even 100 folds lower. Certainly, only urine was compared in the model. Use of heavy metals in households can result in a large impact on the urban-derived fertiliser (Vinnerås et al., 2006).

### 3.8.1. Organic micropollutants

All fertilising products derived from domestic wastewater streams can contain organic micropollutants such as pharmaceuticals used for human medication and substances originating from cleansing agents, personal care products, etc. as their original wastewater streams do (Eriksson et al., 2003; Lienert et al., 2007; Ronteltap et al., 2007; Tettenborn et al., 2007). Hence, an appropriate treatment (Gajurel, 2007; Maurer et al., 2006; Tettenborn et al., 2007) is required in order to eliminate these unwanted and potentially harmful substances before the product can be used as fertiliser. Until now, no detailed investigations on concentrations of organic micropollutants in fertiliser products have been carried out except from stored urine (Tettenborn et al., 2007) and further products originating from this source such as struvite (Ronteltap et al., 2007). In this aspect, further research for the other potential fertilising products is urgently needed and recommended. Especially, as certain treatment techniques show promising properties to create clean products with high potentials to be applied in agriculture such as struvite precipitation (Ronteltap et al., 2007) and steam stripping (Tettenborn et al., 2007).

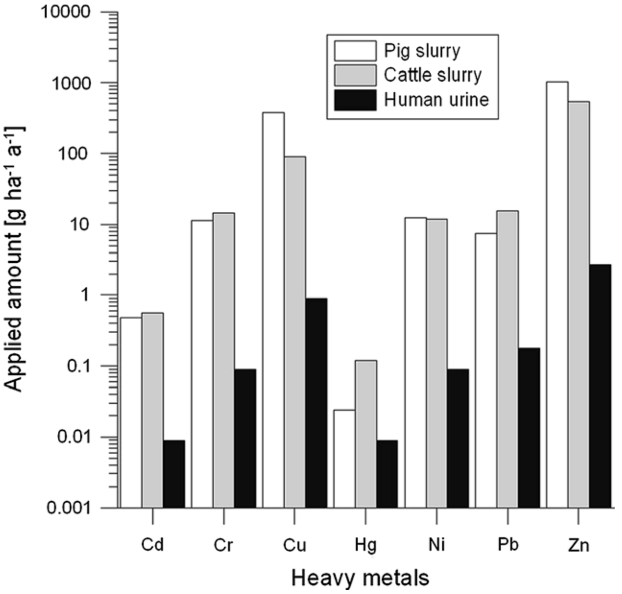

**Fig. 2.** Concentration of heavy metals applied via different fertilisers determined with the model of Hammer and Clemens (2007) which was adjusted with newly derived data.

Moreover, the model indicates that fluxes of antibiotics would be at least 100 times lower compared to animal manure (Fig. 3). The hormones do not show this clear picture but the trend points in the same direction apart from 17α-ethinylestradiol of which the applied amount would be higher from human urine than from cattle manure (Fig. 3). However, household derived fractions are likely to contain pollutants which are not found in animal manure. This needs to be considered when larger proportions of human excreta are recycled.

Additionally, investigations on the fate of organic pollutants in soil show so far that results derived of other areas e.g., via wastewater remediation (Ternes et al., 2007) cannot be adopted one by one. So far on-going research showed that sorption is a major factor influencing the behaviour of organic pollutants in soil. But when comparing pollutants contained in either water or urine and then applied to soils, the sorption behaviour of the pollutants is different. In the case of urine, a much lower amount is sorbed onto soil particles. Kujawa-Roeleveld et al. (2008) assumed the contained organic matter to be responsible for decreasing the capacity of soil to adsorb pharmaceuticals. While Lucas and Jones (2009) observed that urine is not affecting the sorption rate but enhancing desorption as well as hindering microbial degradation.

### 3.8.2. Pathogens

For a long time pathogens have been well-known to be a major constraint when using wastewater products in agriculture. Introducing recycling of domestic wastewater streams will always include a risk for new transmission routes of infectious human diseases. Source separation has the advantage of wastewater streams being separated and in most cases only marginally diluted, thus resulting in a manageable volume for the respective treatment. The main proportion of the pathogens is found in the faeces and only very few are excreted via urine (Feachem et al., 1983; Höglund, 2001). If the system includes the collection of faecal matter, the management of urine and greywater (wastewater of washing, bathroom, and kitchen activities) can be kept simple. Nevertheless, due to faecal cross-contamination in the toilet or urine excreted by infected persons, the risk of contamination with bacteria, viruses, and parasites exist for urine as well (Schönning

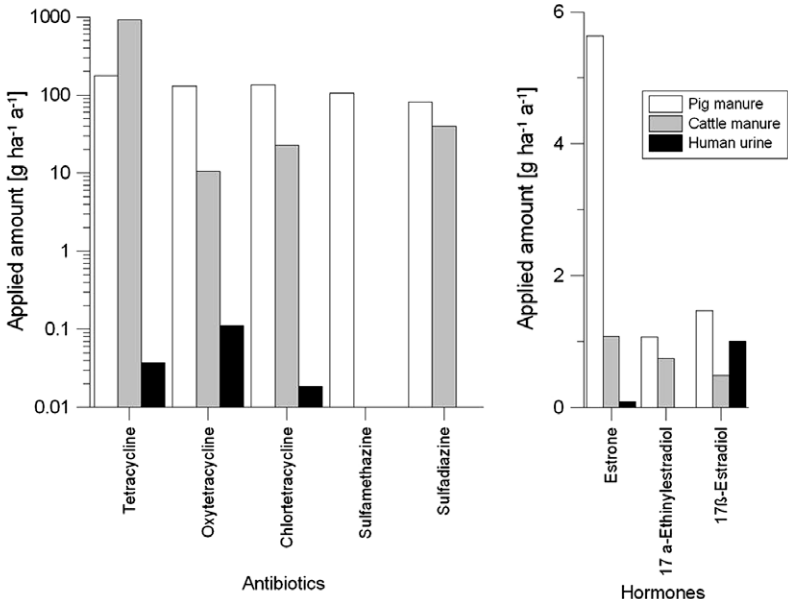

**Fig. 3.** Fluxes of antibiotics (left) and hormones (right) applied via different fertilisers determined with the model of Hammer and Clemens (2007) which was adjusted with newly derived data. Sulfamethazine and sulfadiazine could not be calculated as no data on human consumption was available.

et al., 2002). Consequently, treatment is necessary to minimise the risk of infection. For urine the present recommended minimum treatment is storage for 6 months without introducing fresh liquid (WHO, 2006). Pasteurisation (70 °C for 1 h) or an equivalent treatment is necessary for faecal matter and sludge (WHO, 2006).

Recent research looking closer into the effect of ammonia showed its high potential regarding an efficient sanitisation (Nordin et al., 2009, in press; Vinnerås et al., 2008a). Hence, the presence of uncharged ammonia in urine and its considerably low content of pathogens led to the conclusion that the required storage for undiluted urine is considerably shorter than stated in current recommendations (WHO, 2006) as long as the urine contains >2 g N $l^{-1}$ and holds a pH > 8.8 (Nordin et al., 2009, in press; Vinnerås et al., 2008a). Moreover, at lower N concentrations its agronomic value decreases together with an increased hygienic risk. These figures still include a very high safety margin. For usage on crops not consumed raw or for fodder crops two weeks to one month of storage is sufficient as the organisms infecting both animals and human beings will be inactivated after this period of time. So the risk for spreading of diseases to the environment is low. For usage on crops consumed raw, e.g. lettuce and cucumber, the storage needs to be performed at temperatures ⩾20 °C for safe removal of helminth eggs and viruses, where the bacteriophages MS2 and FiX are used as viral indicators (Fig. 4). As can be seen in Fig. 4, the decimal reduction (*D*) changes within the temperature interval of 14–24 °C and thereby results in significantly longer reduction times for lower temperatures at similar ammonia levels. In the case of >20 °C storage for two months, and of >30 °C one month is sufficient for a safe and unrestricted usage as fertiliser thereafter (Nordin et al., 2009; Vinnerås et al., 2008a).

Similar treatment of faecal matter is possible by external addition of urea for sanitisation. The addition of urea increases the pH (with addition of 1% wet weight an approximate pH of 9 is reached), and also the concentration of ammonia. These two effects increase the sanitisation rate (Nordin et al., 2009, in press; Vinnerås, 2007). The urea is enzymatically degraded into ammonia in contact with faecal matter which then efficiently inactivates pathogens (Vinnerås et al., 2003a). Using ammonia sanitation functions well at relatively low pH (pH 9) compared to other basic treatments (pH 12) and is still efficient in sanitisation. Addition of 2% of urea to faeces will require treatment of 2 months or 2 weeks at temperatures of 20–30 °C and above 30 °C, respectively (Nordin et al., 2009, in press). The advantage of urea addition is that the speed of pathogen inactivation can be controlled by measuring ammonia content and pH. Additionally, as long as ammonia is present no risk for recontamination of the treated material occurs and additional ammonia improves the fertiliser value of the treated material when applied to soil.

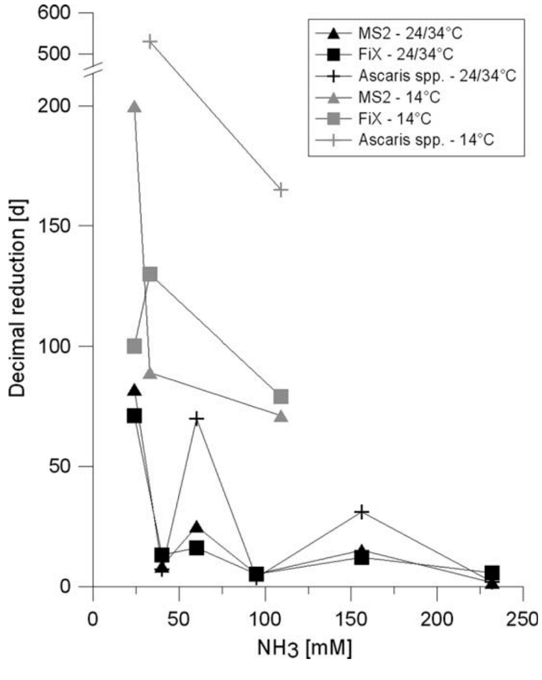

**Fig. 4.** The decimal reduction of *Ascaris* spp. and the bacteria viruses MS2 and FiX as models for animal viruses at 14, 24, and 34 °C in urine, (Nordin et al., 2009, in press; Vinnerås et al., 2008a). Lines always connect the dots of each single category.

Other treatment alternatives do not provide as assured sanitisation as ammonia. Composting offers a good pathogen reduction in areas with high temperatures (Vinnerås et al., 2003b; Vinnerås, 2007; Wichuk and McCartney, 2007), while only lower reduction rates occur in regions with lower temperatures. In some cases even growth of bacterial pathogens was observed (Sidhu et al., 2001). In anaerobic digestion the reduction of pathogens is limited and a reduction between 1 and 3 orders of magnitude can be expected in a mesophilic process, depending on different system management factors such as the minimal retention time and the hydraulic retention time (Vinnerås et al., 2008b; Yen-Phi et al., accepted for publication). Additionally, the hygienic performance of the mesophilic reactor can be improved by increasing the protein feeding of the reactor, reaching high ammonia levels within the reactor, and using the ammonia sanitisation within the process. This can be achieved by an ammonia content of 6 g l$^{-1}$ and pH 8 and, compared to the standard levels of 2–3 g l$^{-1}$ ammonia and pH 7 (Ottoson et al., 2008).

Moreover, further protection measures to minimise the risks drastically and allow the usage of these new fertiliser products can be: direct implication into soil decreasing the risk corresponding to a $2 \log_{10}$ reduction (WHO, 2006); immediate coverage of matter originating from faeces assuring minimal surface run-off; one month resting times between the last fertiliser application and harvest; protection clothes for field workers; awareness raising of all persons involved in the handling of the derived wastewater/fertilising products; and lastly appropriate monitoring of treatment methods (WHO, 2006).

## 4. Conclusion

Regarding the characteristics presented and the data analysed, it can be concluded that new fertilisers from new sanitation systems have a high potential to introduce a new and promising handling of our water and nutrient (re)sources. It has to be kept in mind that these new products have to be adjusted to the available application techniques in agriculture to guarantee a successful usage.

The implementation of new fertilising products always introduces potentially new transmission routes of infectious diseases or organic pollutants. Nevertheless, as long as we are aware of the inherent risks and address them with appropriate measures, usage of the fertilising products in agriculture should be possible. However, for many of the fertilising products deriving from new sanitation systems further research is required to fill still existing gaps of knowledge and gain further information to optimise handling, treatment, and usage of these products.

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