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*Review*

# Sustainable Sanitation—A Cost-Effective Tool to Improve Plant Yields and the Environment

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**Abstract:** Human urine and faeces are products formed every day in every human society. The volume and fertilisation value of urine is higher than that of faeces. This paper reviews data that urine has been used successfully as a fertiliser for cereals and some vegetables. According to the literature, urine fertilised plants may have produced higher, similar or slightly lower yields than mineral fertilized plants but they invariably resulted in higher yields than non-fertilised plants. There have been no microbiological risks associated with any products. The taste and chemical quality of the products are similar to plants treated with mineral fertilisers. Separating toilets, where urine and faeces are separated already in the toilet, could be beneficial not only in poor but also in the industrialized countries. A separating toilet could be installed also in old buildings and it could allow individuals to live in coastal areas, mountainous or other sensitive environments. In poor areas, urine fertilisation could increase food production also in home plots and reduce hunger. It could also combat water contamination and help to reduce diseases caused by enteric micro-organisms. If urine were to be viewed as a resource rather than a waste product, more families could be encouraged to install low-cost toilets which would especially improve the wellbeing of women.

**Keywords:** environmental health; enteric micro-organisms; fertilizer; natural resources; nitrogen; vegetables

## 1. Introduction

People all over the world need to adopt a more ecological life style, since we all live in the same planet with a limit on its resources, already we are over-consuming many natural resources, which may lead to financial and social crises. People need to cope with these realities *i.e.*, they need to consume less energy, water and other natural resources.

Hunger is mainly a problem in the tropical developing areas but there are also serious economic problems in some part of Europe and other "rich" areas. More sustainable sanitation could be one way to increase the plant yields in poor areas and more sustainable sanitation could also improve environmental health by improving water quality and food hygiene in large areas where there is no proper wastewater sewage system and treatment plant. This paper aims to highlight both of these aspects of ecological sanitation in different climates.

### *1.1. Sufficient Food at Moderate Prices for All to Reduce Hunger and Poverty*

A shortage of food has always been an important issue for mankind. Shortage of food and/or high food prices are still major issues for millions of families living in all continents including also some parts of Europe in spite of the Millennium Developing Goals launched by the United Nations and its members. Even the fear of a food shortage can be a powerful political weapon, and it was one of factors sparking the French revolution in 1789 and the Russian revolution in 1917 as well as countless other cases.

Today the demand of food and fodder is much higher than in previous times, since the human population is increasing and many people wish to consume a so-called Western diet with meat. For example the meat consumption per Finn was more than 70 kg in the year 2000, compared to less than 35 kg in 1960 [1]. All over the world there is also a higher need to produce more non-edible agricultural products such as medical or technological plants, biofuels, cotton and other fibres for increasing number of people. All these needs will increase the pressure to achieve greater agricultural production if the Millennium Development Goals [2] are to be met and hunger and extreme poverty are to be reduced by half by the year 2015.

Agricultural productivity has increased in industrialized countries as a consequence of many improvements including better fertilisation practices and the fact that there is the possibility to undertake all agricultural work at the most optimal time. In contrast, the agricultural productivity is still very low in many developing countries and in these places productivity needs to be increased as much as possible taking into account possible temporal shortages of water. The higher yields must be achieved with the existing resources and at low cost since it is unlikely that there would be the finances or even the fossil fuels to produce artificial mineral fertilisers and transport them to villages of developing countries especially if one is striving to reduce the emissions of greenhouse gases.

### *1.2. Sanitation as Basic Human Right Is Still Not Available for Many People*

Today almost half of the people living in the developing countries [3] and also 33.4 million rural inhabitants in the poorest parts of Europe live without access to safe sanitation [4]. If there is to be a more careful management of human excreta, millions of toilets will need to be built in order to provide improved sanitation for the more than 2.4 billion people who still do not have access to improved sanitation services [5] even though this is seen as a basic human right. In addition, sanitation can be unsatisfactory in many rural areas; there is no guarantee that it will not have a detrimental impact on the environment.

Leaching of enteric micro-organisms, nitrogen and phosphorus from rural habitation also occurs in Europe. The nitrogen present in human urine is degraded via ureolysis first to ammonia and then via nitrification to nitrite and subsequently to nitrate. The very high nitrogen loads originating from human and animal excreta can mean that the nitrite concentration of the raw waters being treated by small water works often exceeds the permitted limit also in "clean" areas [6]. Nitrite is known to be a health risk especially for embryos and newborn infants and animals.

## 2. Reaching the Millennium Development Goals in a Sustainable Way

The construction of Western style water toilets which are based on continuous access to tap water and wastewater treatment plants is not possible in many areas, since there is not enough fresh water and these devices would be very expensive to build and operate. Therefore sanitation must be arranged with affordable technology according to the economic situation of the local people or local government. The sanitation could be achieved by decentralised eco-sanitation especially in rural areas and in peri-urban areas.

If human and animal excreta were to be treated/composted and used as a valued fertiliser and not allowed to contaminate water, it would be possible to protect water bodies and to increase crop yields in a cost-effective way. Much research work has been done with animal manure using different treatment methods [7] and animal manure is generally considered to be acceptable for use as a fertiliser. Therefore this paper concentrates on human excreta.

Human excreta have traditionally been used as a fertiliser in European cities, towns and rural areas. Water toilets were not allowed in the last decades of the 18th century in Malmö (Sweden) [8] and in Copenhagen (Denmark) [9]. One argument against this toilet technology was the loss of fertilisation value of excreta and another argument was spreading of cholera and other enteric diseases since there was no effective wastewater treatment and the enteric toilet wastewaters were simply lead to channels or into other surface waters. Though this may seem very old fashioned, this is still done in many areas where domestic houses with a water toilet simply discharge their enteric wastewater into water sources.

The major nutrient components *i.e.*, nitrogen, phosphorus, potassium and many micronutrients consumed in the human diet are excreted in human urine and faeces with only a small proportion stored in cells or excreted via respiration or sweat [10]. Human urine is thus a rich nutrient solution with nitrogen in the form of urea, phosphorus as phosphate and potassium in an ionic form, *i.e.*, components very similar to those present in commercial mineral fertilisers. It is often stated that human urine contains some 90% of nitrogen, and 50–65% of phosphorus and 50–80% of potassium excreted from the human body with almost all the rest being excreted in faeces [11,12]. Urine also contains considerable amounts of chloride [13] which has been present in food and which might impact on the fertilisation value of urine.

Pure urine when urinated is normally rather hygienic since it contains very few enteric micro-organisms [14] even if pathogens are present and can sometimes be excreted in urine, those few micro-organisms can be destroyed rather easily simply by natural increase the pH of urine [15]. Therefore urine can be used safely within a few days after collection if it is applied onto the soil around the root area—not directly onto the plant to avoid burning damage. The fertilisation is best done during the early growth phase and possibly divided into two—five fertilisation stages and not used less than one month before harvesting so that enteric micro-organisms can be eliminated [16].

Theoretically urine could contain: (a) *Salmonella typhi* and some other *Salmonella* bacteria if this bacterium group were present in blood in the acute phase, (b) *Mycobacterium tuberculosis* if tuberculosis had infected the kidneys, and (c) *Schistosoma haematobium* causing bilharziasis [17,18]. However, the more usual ways for transmission are contamination by faeces with salmonellas, by the respiratory route for mycobacteria and by walking in fresh water contaminated with the bilharziasis parasite in some tropical countries. There do not appear to be any scientific reports indicating that these micro-organisms can be transmitted by vegetation growing in soil which has been contaminated by urine from diseased individuals.

Every year, an individual consuming a Western diet produces about 500 litres of urine thought in tropical climates this amount might be less since more water is lost through sweating and possibly also due to too low consumption of drinking water and therefore the urine excreted in tropical countries could be more concentrated. If the urine in those tropical countries were to be concentrated, then this would not favour the survival of enteric bacteria since ureolysis would be more effective and the pH would become rapidly alkaline and furthermore micro-organisms survive less well at higher temperatures than at lower temperatures [15,19].

Human faeces contains less nutrients and its volume is approximately one tenth of that of urine [12]. Faeces contains many enteric micro-organisms, most of which are anaerobic. The intestinal channel is strictly anaerobic so that many of the micro-organisms which have grown in the well balanced (pH, temperature, redox potential) optimal conditions cannot thrive outside of the human body. The faecal micro-organisms consist of many (possible thousands) groups of bacteria, viruses, fungi and protozoa. Even clinically healthy individuals may excrete some enteric pathogens in their faeces e.g., *Salmonella* [20]. Normally these micro-organisms are not able to multiply outside of the human body though they can survive and still be infective. Due to this rich microbial flora, especially the potential presence of pathogens, human faeces must always be sanitised before use in agriculture or horticulture *i.e.*, efficient composting is one of the best ways to achieve this goal. The entire faeces must be held at a temperature of more than 50 $^{o}$C at least for several days in order to ensure the destruction of pathogens [16]. Dry faeces alone or mixed with some plant residues can be composted much better than a wet mixture of urine and faeces, since composting consumes oxygen which cannot penetrate deeply into the wet mixture.

*Toilets Allowing a Sustainable Use of Excreta as Fertilisers*

A toilet allowing a sustainable and safe re-use of excreta without high needs of water, chemicals or electricity can be defined as an eco-toilet. They can either separate urine and faeces in seat or squatting pan to different fractions or they can collect these fractions together to a compost tank but this paper deals with separating eco-toilets, which are available in many commercial models and there are also non-commercial designs. Some models require space on two floors so that the faeces storage tank is situated in the basement under the floor and urine is usually transferred to a specific tank outside the building. Some toilets can have a small faeces container under or behind the toilet seat. Some toilet models are so streamlined that they can be installed in old buildings without the need to undertake major reconstructions.

A separating squatting pan (used often in Asia or Africa) could cost about 10–15 €. The toilet superstructure can be made by local people at minimal cost. Urine has to be led with a plastic tube to a jerry-can or to an irrigation can (total less than 3 €) and used soon as fertilizer. Typically the price of a composting toilet or a separating toilet seat can be estimated to vary between 50 and 1,600 €, while a small wastewater treatment plant (e.g., the alternative available in Finland) can cost 7,500 €. If there is a need to have pure urine or problems with too wet pit toilet contents, one can think domestic urinals which can be made from 3 € (self-made) though the top-line commercial models can cost 600 €. The prices of squatting pans, separating seats and urinals are taken from www-pages of German Gtz [21]. Composting toilets with large composting tanks are more expensive and thus will not be discussed in this paper.

Today there are at least more than 5 million eco-toilets in different countries including more than 2 million dry toilets with urine separation in China [22] and there have been other large-scale sustainable sanitation projects in other Asian countries, Africa or Latin America [22]. Many large-scale eco-toilet programmes have been either totally or partly subsided. There are also many un-subsided eco-toilet programmes not reported on the Gtz list such as those in Västanfjärd (Finland) in Baltic Sea archipelago who have collaborated with our own research group and donated human urine (some of the results presented in Table 1).

The impact on the landscape of an eco-toilet would be minimal—it would need only a relatively small soil filter to treat bath and kitchen washing wastewaters. A separating eco-toilet or other composting toilets would be a good option if the household is situated far from sewage networks such as in hilly or mountainous terrain where the connections to sewage networks would be very expensive, perhaps impossible. Eco-toilets represent a good option if there is a shortage of fresh water or a risk of contaminating well waters since many separating toilet models use no water while other models use 100–200 mL per visit.

Most eco-toilets do not need any electricity. The place of the toilet must be carefully chosen in the building so that smells from the toilet and its faeces container do not drift into the living rooms. The frequency when the toilet has to be emptied is dependent on the size of faeces container, but this procedure is not very unpleasant if the composting can be already underway in the container or if faeces has been mixed with some plant material. Emptying of urine has to be done mainly during the early phase of the vegetation period when the need for fertilisers is at its highest.

As stated above, each person consuming Western diet each year produces some 500 litres of urine. Pure, undiluted urine formed in Finnish separating eco-toilets and preserved for several months contained 8.56 g $L^{-1}$ nitrogen as ammonium and 2 g $L^{-1}$ phosphorus as phosphate [23]. If some water is used, then the urine fraction is more diluted and its nitrogen concentration can be even less than 1 g $L^{-1}$ [13].

Irrespective of whether urine would be diluted or not, the annual urine of some 20–25 individuals would be needed in order to obtain the 100 kg N $ha^{-1}$ and 15 kg P $ha^{-1}$ needed to fertilise one yield of cereal in this hectare. Another way of estimating this value is that about 400 $m^2$ land area is needed to dispose carefully the urine of one person as a fertiliser if only one annual yield is possible. For grasslands, which have a higher nitrogen need, the urine formed by one person would fertilise about 200 $m^2$.

## 3. Urine as a Fertiliser

Pure human urine has been studied as a fertiliser in only a few scientific experiments. In pot experiments, nutrients from urine were shown to have the same effect as industrial fertilizers [24]. The yields of barley grown in Sweden were similar as those treated with the same amount of nitrogen from mineral fertiliser [25] and the ammonia losses were moderate if harrowing was done soon after urine application [26]. Cattle urine gave a better germination yield than human urine in barley and cress tests [27].

In Finland, cabbage [13], outdoor cucumber [14] and red beet [28] produced as good or higher yields than those treated with mineral fertiliser. Pumpkin outdoors [23] and tomato grown in a greenhouse [29] fertilized with urine led to clearly higher yields than those grown without fertilisation, but less than those produced with mineral fertiliser. The taste and chemical content of cucumber, cabbage, pumpkin, tomato or red beet are very similar compared to those treated with mineral fertiliser. Furthermore, there was no enteric microbial contamination in the edible parts of the plants. The chloride content of vegetables fertilised with urine has sometimes been higher but on the other hand, the nitrate and nitrite contents have been lower than those fertilised with mineral fertilisers or non-fertilised plants. In cabbage experiments, there was less damage caused by insects [13] compared to mineral fertilisation whereas willow trees cultivated for biofuel and fertilised with urine experienced more rust and insect damage than the non-fertilised willows but urine fertilisation still resulted in better growth than non-fertilisation in spite of this damage [30]. Not only edible plants but also non-edible plants can be cultivated using human urine as fertiliser and thus roses have grown well in the Indonesian climate [31].

### *In Tropical Developing Countries, Urine Would Be an Especially Useful Fertiliser*

Hunger and extreme poverty are two common scourges in many tropical developing countries in spite of the fact that climate would allow three or four annual crops to be obtained from the same soil plot. Very low agricultural productivity is one cause of hunger and this low agricultural productivity is attributable to the fact that almost no fertilisers are in use and also many working days are lost due to enteric diseases and hunger. In turn, the enteric diseases can mainly be traced to a failure to treat properly human faeces.

Sustainable sanitation would be a convenient way to obtain at least some fertilisers for use in rural areas where many people are so poor that their daily income is less than 2 $ [2]. Annually the urine of one person can contain some 3–4 kg of nitrogen. If one calculates its value as nitrogen fertiliser then this amounts to 3–6 € with the phosphorus being less than 1 €. Even these small sums of money are important in the poor villages of developing countries since transportation possibilities are so limited that the rural shops do not sell any fertilisers. Poor people cannot travel even to the nearest town to buy fertilisers though rich farmers in the same village might use mineral fertilisers. Thus the poor usually cultivate their crops in plots without any fertilisers and thus the yields are low. Many African soils are known to lose their fertility when there is no fertilisation so that the yield and erosion can consume some 10–15 kg P $ha^{-1}$ [32]. Consequently agricultural yields are declining even thought families need to produce more food for their own consumption as a way of staving off hunger.

The spectre of the hunger and shortage of food might have been the reason that poor rural Nepalese, often illiterate women, were receptive to the idea of using human urine to increase food plant yields. On the contrary the richer people were more likely to say that this does not belong to their culture [33].

Financially well-to-do families may possess a water toilet. Usually human excreta is lead from these toilets either to septic tanks or directly into drainage channels which can then become polluted by enteric micro-organisms, phosphorus or/and nitrogen as was reported to occur in South Asia [34]. Septic tanks pollute groundwater with micro-organisms, nitrate and nitrite. Both groundwater and drainage channel waters are used without any purification as drinking water or for cooking. Channel waters are also used for irrigation both for non-edible or edible plants and many of which are consumed without cooking.

Many poor families do not have any toilet and urination and defecation have to be done outdoors. It is not unusual to see fresh human faeces near to villages and even inside the village if there is an empty plot. Agricultural fields, river banks or drainage channel areas near villages can also be used as defecation spots. Therefore it is easy to understand that enteric micro-organisms can spread and cause disease, even death.

If human urine were to be used as a fertiliser, the crop yields could be increased as was evident in work conducted in India, Bangladesh and Sri Lanka [34] though there were no scientific experiments with controls. If urine were valued as a useful fertiliser, then many rural and peri-urban families could be persuaded to build a simple toilet where plain urine could be collected and stored. The storage of urine should not pose a problem in the tropics since cultivation can be started at any time and three or four crop yields per year can be obtained from the same plot. Therefore also the area needed for fertilisation by the urine produced by one individual is much smaller than that required in a Nordic climate.

In South-Asian culture, if a family had its own toilet, this could be especially important for women who without their own toilet often limit their eating and drinking to ensure that they only need to urinate or defecate during the hours of darkness so that they are not seen—at a time when they are vulnerable to be bitten by animals or suffering other accidents.

In tropical countries, solid faeces could be easily composted in latrine pits and in addition since its volume is rather small, the same latrine pit could be used for a long time. If there is more space in the home plot, then the pit could be covered with soil when full and a new pit could be dug and the light toilet structure would be moved to the new latrine location [35]. When the old pit site has been covered, it would be possible to use that site to cultivate the kinds of plants which have high need for fertilisers such as bananas [36, 37], fruit trees or firewood trees. If the home plot area is very small as may be the case in some peri-urban areas, it may not be possible to find a new site for the latrine and therefore the same site must be reused after emptying. In this case, it would be a good idea to divide the pit into two parts, using one side and allowing the other side to be composted so that emptying would be easier.

Table 1 describes some experiments, which show that human urine can give as good or better yields than mineral fertiliser when the same amount of nitrogen is applied. Pumpkin [23] and red beet [28] cultivated without fertilisation produced such small fruits or root that they were difficult to use in the kitchen and the red beet roots would not survive storage in the same way as the normal size roots.

**Table 1.** Outdoor yields achieved with different plants treated with no-fertilisation, mineral fertiliser or urine. ND = not done. NG = not given. Tomato yield and fertilisation estimated from the data of article.

| **Plants** | **Yields obtained with different fertilisers and applied urine N and mineral N (kg ha$^{-1}$)** | | | | **Climate** | **Reference** |
|---|---|---|---|---|---|---|
| | Fertiliser used | None | Mineral | Urine | | |
| Cabbage | Yield ton ha$^{-1}$ | 55.1 | 76.5 | 83.6 | Nordic | [13] |
| | Used N kg ha$^{-1}$ | 0 | 180 | 180 | | |
| Cucumber | Yield ton ha$^{-1}$ | ND | 25 | 30 | Nordic | [14] |
| | Used N kg ha$^{-1}$ | | 16.3 | 233 | | |
| Maize | Yield ton ha$^{-1}$ | 1.50 | 2.70 | 3.20 | African | [38] |
| | Used N kg ha$^{-1}$ | NG | NG | NG | | |
| Red beet | Yield ton ha$^{-1}$ | 1.3 | 6.4 | 7.1 | Nordic | [28] |
| | Used N kg ha$^{-1}$ | 0 | 133 | 133 | | |
| Tomato | Yield ton ha$^{-1}$ | 2.7 | 56 | 67 | African | [39] |
| | Used N kg ha$^{-1}$ | 0 | 400 | 400 | | |

## 4. Why Sustainable Sanitation Would Be Suitable?

One must remember that it is important to remove phosphorus from this effluent since it has been assumed that phosphorus resources will be exhausted after about 100 years [40]. Therefore ecological sanitation *i.e.*, recycling of essential elements, represents one possibility to save natural resources. It could be argued that ecological sanitation should be used more frequently also in the industrialized countries and it should be adapted also to suit the inhabitants of large cities with high population densities.

The supplies of fresh surface water and groundwater are becoming exhausted in many countries since agriculture requires so much water. Furthermore, it is not known how global climate change will change the global water cycles. For example, it seems evident that the snow cover in the Alps and Himalayas will be reduced and there is a fear that in the future that the great rivers originating from these mountains will provide less water *i.e.*, the irrigation water for fields feeding many millions of people will be unpredictable. Therefore the water economy of these areas must be improved. If a toilet uses 3–4 litres fresh water each time it is flushed, this is a level which is not only unsuitable but also non-sustainable in countries with dense populations and low water availability.

If each toilet flush uses 3–4 litres water, it also produces the same volume of wastewater contaminated with faeces and its enteric micro-organisms. Proper treatment of this wastewater requires a sewage system and a wastewater treatment plant. In areas with ancient cultures there are many important historical and religious sites which would make it impossible or difficult to construct sewage pipes to domestic houses even if money were available to construct those pipelines. A wastewater treatment plant as well as the wastewater pumps of sewage network, land area with connection to water bodies, and a secure and continuous supply of electricity are high budget projects. According to our own experiences, there are daily power cuts in Nepal, India, Sri Lanka, Bangladesh, Nicaragua and Tanzania and in addition large areas in these countries are not connected to the electrical network. Furthermore, there are no Western type wastewater treatments plants, even in the major cities.

## 5. There Is Still Work to Be Done

It has been shown that the use of pure human urine does not increase the risk of enteric micro-organisms in products and the products seem to be chemically safe, with respect to the main nutrients, though human urine does not match exactly the nutrient relations present in industrial fertilisers or animal manure [27]. One should not forget the risks of pharmaceutical residues and artificial hormones. Drugs can be present in urine and tiny levels have been analysed in wastewater treatment plants. However, it does seem that the residues of many medical compounds are degraded by soil microbial activity [41,42]. If pharmaceutical residues should pass into the soil via human or domestic animal urine used as fertiliser it is likely that they would mainly be degraded in soil. Some medical components are known to be excreted in urine and if the urine gains access to soil the drugs can be taken by vegetation but only in a few case and at low concentrations (less than 1 µg $g^{-1}$) have medical residues been found in plants [42]. This is a problem not unique to the use of urine as a fertiliser, even sophisticated wastewater treatment plants do not remove these drug residues.

Soil micro-organisms would be expected to be able to degrade natural human and animal hormone residues since those soil micro-organisms have encountered natural hormones in urine. Bacterial antibiotics and disinfectants, e.g., sulphadimethoxine can reduce the growth of some plants [43] and inhibit symbiotic nitrogen fixation since these antibiotics may be toxic for rhizobia bacteria [44]. Sulphadimethoxine is used in veterinary medicine but it now obsolete and no longer sold for instance in Finland [45].

## 6. Conclusions

1. Agricultural and health organizations should encourage people to use human urine as a fertiliser especially: (1) if it is an alternative to non-fertilisation of crops; (2) if there is no wastewater treatment plants and sewage systems and (3) if there is no continuous tap water and electricity.

2. More scientific research work should be done to study cultivation in the tropics using urine continuously to grow three or four crops annually in the same soil plots and comparing the yields to those grown without any fertilisation perhaps with local fertilisation methods. Urine should be considered as is a fertiliser—not irrigation water.

3. The possible effects of medical residues should be studied in greater detail. If this turns out to be a real risk, it may be necessary to limit the use of urine as fertilizer. One would predict that urine from an ordinary family may contain so little pharmaceutical residues that the risks are minimal [42].

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