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Guidelines on the Use of Urine and Faeces in Crop Production

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Preface

These guidelines are based on our current knowledge of the use of urine and faeces in small- and large-scale cultivation. So far, the use of urine and faeces is limited around the world. Thus, these guidelines are based not only on the experiences of ourselves and others as documented in scientific journals, but also to a large part on experiences with similar types of fertilizer, e.g. compost and digestion sludge from solid biodegradable waste. Experiences derived from many appropriate and ambitious experiments around the world, even though not scientifically published and scrutinised, also inform these guidelines.

We want to highlight the many ambitious and well-performed experiments by Peter Morgan, Aquamor, Zimbabwe. We are grateful to Peter not only for sharing the results of these experiments, but also for assisting with this text and our reasoning and for sharing some of his pictures. In addition, we are very grateful for our fruitful discussions (mainly via e-mail) in which he has shared some of the insights he has gained in his research and development of ecological sanitation.

We are also very grateful to all the other experts participating in our reference group: George Anna Clark (Mexico), Sidiki Gabriel Dembele (Mali), Jan Olof Drangert (Sweden), Gunder Edström and Almaz Terefe (Ethiopia), Bekithemba Gumbo (Zimbabwe/South Africa), Li Guoxue (China), Edward Guzha (Zimbabwe), Watana Pinsem (Thailand), Caroline Schönning (Sweden) and Liao Zongwen (China).

Mary McAfee has rapidly and thoroughly checked our use of the English language and for this we are very grateful.

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A Summary of the Guidelines

Recommendations for agricultural use of excreta are based on knowledge of the nutrient content of the excreta, the amounts excreted, the composition and plant availability of the fertilizer and the treatment of the excreta, which influences their properties. Relationships and data that can form a basis for adapting the guidelines to local conditions are presented in the text. Urine and faeces are complete fertilizers of high quality with low levels of contaminants such as heavy metals. Urine is rich in nitrogen, while faeces are rich in phosphorous, potassium and organic matter. The amount of nutrients excreted depends on the amounts in the food consumed, and equations are presented for calculation of nitrogen and phosphorus in excreta based on easily-available statistics on the supply of food protein.

Excreta should be handled and treated according to the hygiene guidelines (Schönning & Stenström, 2004) before use in cultivation. Specific local recommendations for the use of urine and faeces in cultivation should be based on local recommendations for fertilization of crops. Application rates for commercial mineral nitrogen fertilizers (urea or ammonium), if available, can be used as a basis for recommendations on the use of urine. Before translating such recommendations to urine, its nitrogen (N) concentration should ideally be analysed. Otherwise, it can be estimated at 3-7 g N per litre. If no local recommendations can be obtained, a rule of thumb is to apply the urine produced by one person during one day (24 hours) to one square metre of land per growing season. If all urine is collected, it will suffice to fertilize 300-400 m^2 of crop per person per year with N at a reasonable rate. For most crops, the maximum application rate, before risking toxic effects, is at least four times this dosage. Urine also contains lots of phosphorus, and it will suffice to fertilize up to 600 m^2 of crop per person and growing season, if the application rate is chosen to replace the phosphorus removed, as for faeces below.

Urine can be applied neat or diluted. However, its application rate should always be based on the desired nutrient application rate and any potential need for supplementary water should be met with plain water, not diluted urine. To avoid smells, loss of ammonia and foliar burns, urine should be applied close to the soil and incorporated as soon as possible.

Urine is a quick-acting fertilizer whose nutrients are best utilized if the urine is applied from prior to sowing up until two-thirds of the period between sowing and the harvest. The best fertilizing effect is achieved if urine and faeces are used in combination with each other, but not necessarily in the same year on the same area. The amount of urine to be spread can be applied in one large dose or in several smaller doses, and under most circumstances the total yield is the same for the same total application rate.

For faeces, the application rate can be based on the local recommendation for the use of phosphorous-based fertilizers. This gives a low application rate, and the improvement due to the added organic matter is hard to distinguish. However, faeces are often applied at much higher rates, at which the structure and water-holding capacity of the soil are also visibly improved as an effect of its increased organic matter. Both organic matter and ash are often added to the faeces and they improve the buffering capacity and the pH of the soil, which is especially important on soils with low pH. Thus, depending on the application strategy, the faeces from one person will suffice to fertilize 1.5-300 m^2, depending on whether they are applied according to their content of organic matter or phosphorus. Faeces should be applied and mixed into the soil before cultivation starts. Local application, in holes or furrows close to the planned plants, is one way of economizing on this valuable asset.

These guidelines have been developed within the framework of EcoSanRes, an international network of ecological sanitation expertise funded by Sida, the Swedish International Development Cooperation.

Requirements for plant growth

The requirements for plant growth include light, water, a structure for roots to grow in and nutrients. The limiting factors regulating the growth of plants can be illustrated as in Figure 1. When the supply of the most limiting growth factor is increased, then other growth factors become important as limiting factors (Figure 1). If factors other than nutrients are limiting, e.g. water, light, pH, salinity, light or temperature, then adding more nutrients will not increase the yield.

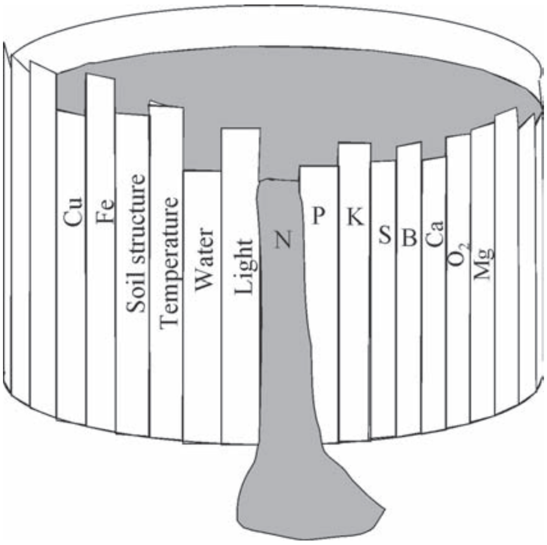

Figure 1. The limiting factors regulating the growth of plants can be thought of as the side planks of a barrel and the yield level as the level the liquid can reach before flowing over. If the most limiting factor is improved, e.g. here by addition of nitrogen, then some other factor will limit the yield at a higher level.

MACRONUTRIENTS

Elements essential for the growth of plants are called nutrients. The nutrients used in the largest amounts are the non-mineral elements, i.e. carbon, hydrogen and oxygen. These elements are mainly taken up as carbon dioxide (CO_2) from the air, and water (H_2O) by the roots. Increasing the supply of light, carbon dioxide, water and mineral nutrients from the deficiency range increases the growth rate and crop yield.

Nutrients can be divided into the two categories; macronutrients and micronutrients. The uptake of macronutrients is about 100 times that of micronutrients. The six elements normally classified as macronutrients are nitrogen (N), phosphorus (P), potassium (K), sulphur (S), calcium (Ca) and magnesium (Mg). These nutrients are mainly taken up from the soil by the roots in ionic form.

N is frequently the most limiting nutrient for plant growth and the use of N is usually higher than the total use of the other macronutrients and micronutrients together. N is taken up by the plant as ions of nitrate (NO_3^-) and ammonium (NH_4^+). The main natural sources of plant-available N are degradation of organic matter in the soil and N fixation by microorganisms living in symbiosis with the roots of legumes.

P is taken up by the plants as phosphate ions (at pH 5-7 mainly as HPO_4^{2-} and $H_2PO_4^-$). The natural supply of plant-available P comes from dissolution of soluble phosphates in the soil and from mineralization of organic matter.

The high water solubility of K often results in a good supply of plant-available K. However, many crops, such as vegetables, need large amounts of K and therefore additional K fertilization may improve plant growth. S is also highly water-soluble and most crops need it in somewhat smaller amounts than P. Yearly additions of S are often needed.

MICRONUTRIENTS

Micronutrients are as essential for plant growth as macronutrients, but are taken up in small (micro) amounts. The elements normally considered micronutrients are boron, copper, iron, chloride, manganese, molybdenum and zinc (Frausto da Silva & Williams, 1997; Marschner, 1997). Most of the micronutrients are needed for formation of different enzymes. These nutrients are normally available in sufficient quantities through initial soil content and mineralization of organic material. Only in special circumstances does scarcity of micronutrients limit plant growth. When human excreta are used as a fertilizer, the risk for such deficiency is minimal as excreta contain all micronutrients necessary for plant growth.

YIELD RESPONSE AND RESOURCE UTILISATION

Fertilization increases crop yield only if the plant nutrient supplied is one of the most limiting growth factors (Figure 1). No yield increase is to be expected when fertilizing crops that are mainly limited by factors other than nutrient supply, e.g. lack of water, too low or too high pH, etc. For maximum effect, it is important that the excreta are used in the most efficient way and this differs depending on the amount of available nutrients in relation to the available space and the fertilizer requirement per area unit.

There is sufficient area to utilize all of the nutrients to their full potential if the average application of plant-available N is below rate A in Figure 2, which is the rate up to which the yield increases linearly with increasing application. Rate A differs between different crops, regions and climates. If this rate is not known, then the application of the urine from one person during a full day per square metre (approx 1.5 litres of urine/m^2 and cropping season) can be used as a rule of thumb. This corresponds to application of approximately 40-110 kg N/ha.

When area is not a limiting factor, the full fertilizing effect can easily be gained from urine, even if the urine is applied at different dosages in different places, as long as the dosage in all places is below rate A (Figure 2).

The best fertilizing efficiency when area is so limited that the average rate has to be above A, is obtained by keeping the rate even over the whole available area, if all the crops have the same N demand. The yield increases when the application is increased from rate A to rate B (Figure 2). However, both the quantity and the quality of the yield are important and high rates of available N can also affect the quality, both positively and negatively. For example, the quality of wheat is generally improved by a high N dosage, while the quality of e.g. Irish potatoes may decrease since the tubers can become watery. However, the timing of the application is important here since the nutrient uptake by most crops decreases after the crop enters the generative phase, such as ear setting in maize.

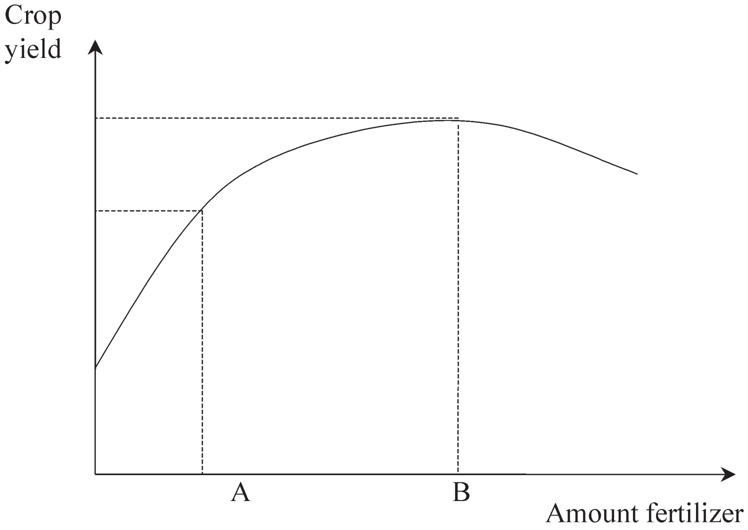

Figure 2. The effect on crop yield of increasing application rates of available N, e.g. in the form of urine. Up to rate A, the increase in yield is linear to the addition of urine. Between rate A and rate B, the yield still increases in response to the increased fertilizer application, but at a slower rate. Beyond rate B, additional fertilizer application becomes toxic and the yield decreases if the application rate is increased.

If no information is available on rate B, then a rate four times as high as rate A can be used as a rule of thumb, i.e. applying the urine from one person during one day on an area of 0.25 m^2, corresponding to an approximate application rate of 160-440 kg N/ha.

Even if the area is very limited, the average rate should never exceed rate B, above which additional amounts of N (e.g. urine) become toxic. The amount of urine that cannot be utilized as a fertilizer should be used in some other way, i.e. as an accelerating agent when composting. When used in this way, most of the N is lost, but the other nutrients remain in the compost and thus become available to plants.

Nutrients in Excreta

MASS BALANCE OF NUTRIENTS

Mass can neither be created nor destroyed, except in nuclear reactions, and this fact is the basis for sustainable plant nutrient loops. Such loops exist in nature and one example is the African savannah, where the plant nutrient circulation between vegetation and animals has been sustainable for such a long time that the giraffe have had time to develop its long neck! With ecological sanitation we strive to create nutrient loops in urban societies that are as sustainable as those existing in the rest of nature.

Consumed plant nutrients leave the human body with excreta, once the body is fully grown. While the body is still growing, some nutrients are taken up and integrated into the body's tissues. N is accumulated in proteins, P mainly in bones and muscles and K mainly in nerves and muscles. However, only a small proportion of the nutrients are retained in the body even when children and youngsters grow rapidly. Calculated from the average diet and weight gain for Swedish youngsters between the age of 2 and 17 years (Becker, 1994) and the composition of the human body (Garrow, 1993) the retention in the growing body during this period is approximately 2%, 6% and 0.6% for N, P and K respectively. Once the skeleton and muscles reach their full size, no more plant nutrients are retained and accumulated in the body.

Thus, the amount of excreted plant nutrients essentially equals that consumed. This has three important implications: 1) The amount of excreted plant nutrients can be calculated from the food intake, on which the data are both better and more easily available than on excreta. 2) If the excreta and biowaste, as well as animal manure and crop residues, are recycled, then the fertility of the arable land can be maintained, as the recycled products contain the same amounts of plant nutrients as were taken up by the crops. 3) Differences in composition of excreta between different regions reflect differences in the uptake of the consumed crops and thus in the plant nutrient supply needed for maintained fertility. Irrespective of the amounts and concentrations of plant nutrients in the excreta, one important fertilizing recommendation is thus to strive to distribute the excreta fertilizers on an area equal to that used for producing the food.

CONTENTS OF MACRONUTRIENTS IN EXCRETA

Only few measurements exist of the amounts and composition of human excreta and thus there is a need for a method to calculate the composition of the excreta from easily available data. Such a method, which uses the Food and Agriculture Organization (FAO) statistics (www.fao.org) on the available food supply in different countries, has been developed by Jönsson & Vinnerås (2004). This method uses equations derived from the FAO statistics and an estimation of the average excretion by the Swedish population (Table 1), where many large measurements on excreta have been made.

Table 1. Proposed new Swedish default values for excreted mass and nutrients (Vinnerås, 2002)

Parameter	Unit	Urine	Faeces	Toilet paper	Blackwater (urine+faeces)
Wet mass	kg/person,year	550	51	8.9	610
Dry mass	kg/ person,year	21	11	8.5	40.5
Nitrogen	g/ person,year	4000	550		4550
Phosphorus	g/ person,year	365	183		548

Based upon this estimation of the average excretion, on the food supplied to the Swedish population according to the FAO statistics and on statistical analysis of different foodstuffs, relationships (Equations 1-2) have been developed between the food supplied according to FAO and the excretion of N and P.

$$N = 0.13 * \text{Total food protein} \qquad \textit{Equation 1}$$

$$P = 0.011 * (\text{Total food protein} + \text{vegetal food protein}) \qquad \textit{Equation 2}$$

In Equations 1-2 the units of N and P are the same as those of the food protein. As is shown by Equation 2, there is a strong positive correlation between the contents of protein and phosphorous in the food stuffs. Furthermore, vegetal food stuffs contain on average twice as much phosphorus per gram of protein as animal ones, which is why the vegetal protein is counted twice in Equation 2.

These equations are useful for estimation of the average excretion of N and P in different countries. The input to such estimations are the FAO statistics on the food supplied, found on the FAO web page called "Nutrition Data – Food Supply – Crops Primary Equivalent". Examples of inputs and results of such estimations for a few countries are given in Tables 2 and 3.

Table 2. Food supply (crops primary equivalent) in different countries in 2000 (FAO, 2003)

Country	Total energy kcal/cap, day	Vegetal energy kcal/cap, day	Total protein g/cap, day	Vegetal protein g/cap, day
China, Asia	3029	2446	86	56
Haiti, West Indies	2056	1923	45	37
India, Asia	2428	2234	57	47
South Africa, Africa	2886	2516	74	48
Uganda, East Africa	2359	2218	55	45

Table 3. Estimated excretion of nutrients per capita in different countries (Jönsson & Vinnerås, 2004)

Country		Nitrogen kg/cap, yr	Phosphorus kg/cap, yr	Potassium kg/cap, yr
China, total		4.0	0.6	1.8
	Urine	3.5	0.4	1.3
	Faeces	0.5	0.2	0.5
Haiti, total		2.1	0.3	1.2
	Urine	1.9	0.2	0.9
	Faeces	0.3	0.1	0.3
India, total		2.7	0.4	1.5
	Urine	2.3	0.3	1.1
	Faeces	0.3	0.1	0.4
South Africa, total		3.4	0.5	1.6
	Urine	3.0	0.3	1.2
	Faeces	0.4	0.2	0.4
Uganda, total		2.5	0.4	1.4
	Urine	2.2	0.3	1.0
	Faeces	0.3	0.1	0.4

These estimations assume that the loss between the food supplied and the food actually consumed, i.e. the food waste generated, is of the same relative size in the different countries. This assumption is verified by Chinese data. The total excretion reported by Gao et al. (2002) for China was 4.4 kg of N and 0.5 kg of P. These values agree quite well with those calculated in Table 3, considering how difficult it is to do measurements representative of the excretion of a large population.

In Table 3, the total excretion has also been partitioned between urine and faeces and for this Swedish data have been used. In Sweden, approximately 88% of the excreta N and 67% of the excreta P are found in the urine and the rest in the faeces. The partitioning of nutrients between urine and faeces depends upon how digestible the diet is, as digested nutrients enter the metabolism and are excreted with the urine, while undigested fractions are excreted with the faeces. Thus, for countries where the diet is less digestible than in Sweden, the urine will contain somewhat less than 88% of the excreta N and 67% of the excreta P. For example, Chinese data (Gao et al., 2002) indicate that the urine contains approximately 70% of the excreta N and 25-60% of the P. To decrease the uncertainty on how the nutrients, especially P, are partitioned, more measurements are needed on the composition of excreta in countries with less digestible diets.

The digestibility also influences the amount of faeces excreted. In Sweden it is estimated at 51 kg wet mass (Vinnerås, 2002), in China measured at 115 kg/person per year (Gao et al., 2002) and in Kenya measured at up to 190 kg/person and year (Pieper, 1987). The faecal dry mass in Sweden is about 11 kg and in China 22 kg/person per year. The concentrations of nutrients are estimated from the amount of nutrients in the faecal matter and its mass.

The nutrient concentration of the excreted urine depends on the amounts of nutrients, which have been estimated above, and on the amount of liquid, which on average for adults can be estimated to be in the range of 0.8-1.5 litres per person and day and for children about half that amount (Lentner et al., 1981). Based upon this and other measurements, the proposed Swedish default value is 1.5 litres per person per day (550 litres/person, year; Vinnerås 2002), while Gao et al. (2002) for China report 1.6 litres per person per day (580 litres/person, year).

Urine is used by the body as a balancing medium for liquids and salts and the amount of urine therefore varies with time, person and circumstances. For example, excessive sweating results in concentrated urine, while consumption of large amounts of liquid dilutes the urine. Thus, to determine the application rate of urine as a fertilizer, the calculation should preferably be based upon the number of persons and days that it has been collected from, as this gives a better indication of the nutrient content than the volume.

CONTENTS OF HEAVY METALS AND CONTAMINATING SUBSTANCES IN EXCRETA

The contents of heavy metals and other contaminating substances such as pesticide residues are generally low or very low in excreta, and depend on the amounts present in consumed products. The urine is filtered from the blood by the kidneys. It contains substances that have entered the metabolism and therefore the levels of heavy metals in urine are very low (Jönsson et al., 1997; Jönsson et al., 1999; Johansson et al., 2001; Vinnerås, 2002; Palmquist et al., 2004). The content of these substances is higher in the faeces compared with the urine. The major reason for this is that faeces consist mainly of non-metabolized material combined with some metabolized material. The main proportion of the micronutrients and other heavy metals passes through the intestine unaffected (Fraústo da Silva & Williams, 1997). Even so, the concentrations of contaminating substances in faeces are usually lower than in chemical fertilizers (e.g. cadmium) and farmyard manure (eg. chromium and lead) (Table 4).

Table 4. Concentrations of heavy metals (copper, zinc, chromium, nickel, lead and cadmium) in urine, faeces, urine+faeces mixture and in source separated kitchen waste, compared with farmyard manure (FYM) on organic cattle farms in Sweden both in μg/kg wet weight and in mg/kg P (calculated from SEPA, 1999; Vinnerås, 2002)

	Unit	Cu	Zn	Cr	Ni	Pb	Cd
Urine	μg/kg ww	67	30	7	5	1	0
Faeces	μg/kg ww	6667	65000	122	450	122	62
Urine+faeces mixed	μg/kg ww	716	6420	18	49	13	7
Kitchen waste	μg/kg ww	6837	8717	1706	1025	3425	34
Cattle org. FYM	μg/kg ww	5220	26640	684	630	184	23
Urine	mg/kg P	101	45	10	7	2	1
Faeces	mg/kg P	2186	21312	40	148	40	20
Urine+faeces mixed	mg/kg P	797	7146	20	54	15	7
Kitchen waste	mg/kg P	5279	6731	1317	791	2644	26
Cattle org. FYM	mg/kg P	3537	18049	463	427	124	16

A large proportion of the hormones produced by our bodies and the pharmaceuticals that we consume are excreted with the urine, but it is reasonable to believe that the risk for negative effects on the quantity or quality of crops is negligible. All mammals produce hormones and, during the course of evolution, these have long been excreted in terrestrial environments. Thus, the vegetation and soil microbes are adapted to, and can degrade, these hormones. Furthermore, the amount of hormones in manure from domestic animals is far larger than the amount found in human urine. Thus, even though theoretical estimations based on tests with fish have indicated a risk of ecotoxicity from oestradiol (Ambjerg-Nielsen et al., 2004) when applying urine, both fertilizer experiments and evolutionary history strongly indicate that there is no real risk.

By far the majority of all pharmaceutical substances are derived from nature, even if many are synthetically produced, and they are thus found and degraded in natural environments with a diverse microbial activity. This has been verified in ordinary wastewater treatment plants, where the degradation of pharmaceutical substances improved when the retention time was prolonged from a number of hours to a number of days. Urine and faecal fertilizers are mixed into the active topsoil, which has a microbial community just as diverse and active as that in wastewater treatment plants, and the substances are retained for months in the topsoil. This means that there is plenty of time for the microbes to degrade any pharmaceutical substances and that risks associated with them are small.

Concerning both hormones and pharmaceutical substances, it thus seems far better to recycle urine and faeces to arable land than to flush them into recipient waters. Since the aquatic systems have never before been exposed to mammal hormones in large quantities, it is not surprising that the sex development of fish and reptiles is disturbed when they are exposed to wastewater effluent. Furthermore, the retention time of the wastewater in the treatment plants is far too short for many pharmaceutical substances to degrade and recipient waters are also usually connected to water sources. Thus, it is not surprising that pharmaceutical substances have been detected for decades, not only in e.g. the recipient waters of Berlin but also in the groundwater, which is Berlin's source of drinking water (Herberer et al., 1998).

There are many indications that the possible risk from pharmaceutical substances in the agricultural system is small and far smaller than the risks associated with the present system. One such indication is that in many countries the human consumption of pharmaceuticals is small compared to that by domestic animals, as in most countries most commercial feeds contain antibiotic substances, added as growth promoters. Furthermore, the human use of pharmaceutical substances is small compared to the amount of pesticides (insecticides, fungicides, bactericides and herbicides) used in agriculture, which are just as biologically active as pharmaceutical substances.

COMPOSITION AND PLANT AVAILABILITY OF NUTRIENTS IN URINE

The urine has been filtered by the kidneys and contains only low molecular weight substances. At excretion, the pH of urine is normally around 6, but can vary between 4.5 and 8.2 (Lentner et al., 1981). Of the N, 75-90% is excreted as urea and the remainder mainly as ammonium and creatinine (Lentner et al., 1981). In the presence of urease, urea is quickly degraded to ammonium and carbon dioxide (Equation 3) and the hydroxide ions produced normally increase the pH to 9-9.3. Normally urease accumulates within the urine piping system and therefore the above transformation is very swift, usually within hours (Vinnerås et al., 1999; Jönsson et al., 2000).

$$\overset{\text{urea}}{CO(NH_2)_2} + 3\ \overset{\text{water}}{H_2O} \xrightarrow{\text{urease}} 2\ \overset{\text{ammonium}}{NH_4^{\ +}} + \overset{\text{hydroxide}}{OH^-} + \overset{\text{carbonate}}{HCO_3^-} \qquad \textit{Equation 3}$$

Ammonium is directly plant-available and an excellent N fertilizer, which is verified by the fact that urea (which is degraded to ammonium by urease in the soil) and ammonium are two of the most used N fertilizers in the world. Many crops prefer nitrate to ammonium, but this is no problem. Ammonium applied to arable soil is transformed within a few days to nitrate (Equations 4-6). In soils with very low microbial activity, these transformations take longer, since they are performed by microbes.

$NH_4^+ + 1.5\ O_2 \Rightarrow NO_2^- + 2H^+ + H_2O$ Nitrosomonas *Equation 4*

$NO_2^- + 0.5\ O_2 \Rightarrow NO_3^-$ Nitrobacts *Equation 5*

$NH_4^+ + 2\ O_2 \Rightarrow NO_3^- + 2\ H^+ + H_2O$ Cumulative transformation *Equation 6*

The plant availability of urine N is the same as that of chemical urea or ammonium fertilizers. This is to be expected, as 90-100% of urine N is found as urea and ammonium and has been verified in fertilizing experiments (Kirchman & Pettersson, 1995; Richert Stintzing et al., 2001).

The P in the urine is almost entirely (95-100%) inorganic and is excreted in the form of phosphate ions (Lentner et al., 1981). These ions are directly plant-available and thus it is no surprise that their plant availability has been found to be at least as good as that of chemical phosphate (Kirchmann & Pettersson, 1995).

K is excreted in the urine as ions, which are directly plant-available. This is the same form as supplied by chemical fertilizers and thus their fertilizing effect should be the same.

S is mainly excreted in the form of free sulphate ions (Lentner, 1981; Kirchmann & Pettersson, 1995), which are directly plant-available. This is the same form as the S in most chemical fertilizers and thus the fertilizing effect of S in urine and that in chemical S fertilizers should be the same.

COMPOSITION AND PLANT AVAILABILITY OF NUTRIENTS IN FAECES

As shown above, the major proportion of the nutrients excreted is found in the urine, which has an extremely low contamination of heavy metals. The faeces fraction also contains a lot of relatively uncontaminated nutrients. Compared with the urine, which has water-soluble nutrients, the faeces contain both water-soluble nutrients and nutrients that are combined in larger particles not soluble in water. Still, about 50% of the N and the majority of the K in faeces are water soluble (Berger, 1960; Trémolières et al., 1961; Guyton, 1992; Fraústo da Silva & Williams, 1997). P is mainly found as calcium phosphate particles, only slowly soluble in water (Fraústo da Silva & Williams, 1997). The K is mainly found as dissolved ions.

The plant availability of the nutrients in the faecal matter is lower and slower than that of the urine nutrients. This is due to the fact that the main proportion of the P and a large proportion of the N stem from undigested matter and this matter needs to be degraded in the soil to become available to plants. However the organic material in the faeces degrades and its content of organic N and P then becomes available to plants. The calcium phosphates also dissolve and become plant-available and these calcium phosphates ought to be as available as those supplied by chemical fertilizers. The K in faeces is in ionic form, which is directly plant-available. Thus, it is only for N that the availability of faecal nutrients is considerably lower than that of chemical fertilizers or urine. The high concentrations of P, K and organic matter in faecal matter can give substantial yield increases, especially on poor soils. The organic matter contributes in several ways: by improving the soil structure, increasing the water-holding capacity and the buffering capacity, and by supporting the soil microorganisms by serving as an energy source.

Hygiene treatment of urine and faeces – effects on plant nutrients

PRIMARY AND SECONDARY TREATMENTS

Urine is normally piped directly from the urine-diverting toilet or urinal to a collection tank or container. The hygiene quality of the collected urine is normally very high compared to that of faeces. The hygiene risks associated with diverted urine are mainly a result of contamination by faeces, which is possible in many systems.

Secondary treatment is only needed in large systems (i.e. systems where urine collected from one family is used to fertilize crops consumed by persons outside of that family) where the fertilization is done less than one month prior to harvest[1]. Separate storage is the most used method for secondary treatment as it is simple and cheap.

Faeces normally need both a primary and a secondary treatment before application, even if the distinction between these treatments is often diffuse. The primary treatment is that which

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[1] For more information see the hygiene guidelines (Schönning & Stenström, 2004).

occurs during collection, and in dry systems this normally occurs beneath the toilet during the collection period. The primary treatment has several objectives: a) to decrease the risk of odours; b) to decrease the risk of flies; and c) to decrease the hygiene risk, i.e. to reduce the number of potential pathogens in the faeces. In a dry system, this primary treatment can consist of the addition of ash after each defecation.

The secondary treatment occurs when the collection period is over and it can take place at the toilet (e.g. in a double vault toilet) or somewhere else. The main objective of the secondary treatment is to render the faeces hygienically safe. Another objective is to transform the faeces mixture into a state where it is odourless and visually non-repulsive. This means that it should no longer be possible to recognise pieces of faeces or toilet paper. This is important when the faecal product is handled manually but less important when the handling is mechanized.

There are several options for secondary treatment; composting, digestion, storage, chemical treatment and incineration. The thermophilic treatments (composting, digestion, incineration) for sanitation rely on all material reaching a sufficiently high temperature for a sufficiently long time to ensure pathogen die-off. This time ranges from seconds for incineration to days or even a few weeks for thermophilic composting. To achieve similar sanitation levels, the other treatments need more time and normally the die-off depends not only on temperature but also on a number of other parameters, such as humidity, pH, etc.

The treatment has effects on the content and plant availability of the faeces nutrients and this effect varies between the nutrients and the treatments. N and S can be lost as gases, N_2, SO_2 and H_2S, during some treatments, but the other nutrients remain in the treated product as long as no leachate is formed.

Primary treatment

Urine

From the urine-diverting toilet, the urine is piped to a collection vessel. Due to accumulation of urease, sludge forms where urine usually stands for a while, e.g. in the trap of the toilet, in pipes that are close to horizontal and in the tank. This sludge largely consists of struvite ($MgNH_3PO_4$) and apatite ($Ca_{10}(PO_4)_6)(OH)_2$). It is formed because the pH of the urine increases to 9-9.3 due to the degradation of urea to ammonium (Equation 4) and at this high pH the initial concentrations of phosphate, magnesium, calcium and ammonium are no longer soluble, but precipitate. Of the urine P, 30% or more is eventually transformed to sludge (Jönsson et al., 2000; Udert et al., 2003). If the pipes have a slope of at least 1% and are wide enough (for horizontal pipes ≥75 mm), the sludge flows to the collection vessel, where it forms a bottom layer. This is liquid and can be handled together with the rest of the urine.

Provided that the sludge is handled and reused with the rest of the urine, neither the amount nor the availability of the nutrients is changed. The concentration of P in this bottom sludge can be more than twice as high as in the rest of the urine. Thus, this sludge can be utilized for crops with high P demands or handled with the rest of the urine. In the latter case, the fertilizer product should preferably be mixed before spreading to get an even dosage.

The high pH of the urine in the collection vessel, normally 9-9.3, coupled with its high ammonium concentration, means that there is a risk of losing N in the form of ammonia with the ventilated air (Equations 7 and 8). However, these losses are easily eliminated by designing the system so that the tank and pipes are not ventilated, but just pressure equalized. This also eliminates the risk of malodours from the urine system. Urine is very corrosive and therefore tanks should be made of resistant material, e.g. plastic or high quality concrete, while metals should be avoided.

$NH_4^+ + OH^- \Leftrightarrow NH_3(aq) + H_2O$ *Equation 7*

$NH_3(aq) \Leftrightarrow NH_3(g)$ *Equation 8*

Faeces – desiccation using additives

The most common primary treatment of faeces is collection in a ventilated chamber, often with some additive, such as plant ash, lime or dried soil. The additive should be dry and is normally far drier than the faeces, which at excretion have a dry matter content of around 20% whereas the dry matter content of dry soil and ash is normally 85-100%. Thus, the dry matter content of the mixture is far higher than that of the faeces, even if no air drying occurs. This increased dry matter content decreases the risk of odours and flies. It also reduces some pathogens and this effect is reinforced if the additive has a high pH, like lime or plant ash. The risk of flies is most efficiently reduced if the additive is applied in such a way that fresh surfaces of faeces are never exposed, i.e. if the additive is added after each defecation in such a way that it covers all fresh faecal surfaces.

The additives provide different nutrients. Plant ash is rich in K, P and calcium, and soil also contains these nutrients. These nutrients naturally contribute to the total amount of nutrients in the faecal mixture.

If the ash or soil is added after each toilet use, then the faeces dry rapidly, as moisture is transported to and shared with the dry additive. The high pH of ash and lime together with a rapid decrease of the moisture level of the faeces means that the biological degradation is small if sufficient additive is used. Thus, the losses of organic matter and N from the faecal mixture are small.

In the drying process, all nutrients except N and most of the organic matter are conserved. Some N is lost as ammonia and some very easily degradable organic matter also degrades and is lost as carbon dioxide and water. However, if the drying is fast the losses are small, as further biological degradation slows down and ceases when the moisture level decreases to low levels. In this case, it is only part of the water soluble organics and N, initially about 50% of total N (Trémolières et al., 1961), that is at risk of being lost. If the drying is slower, more biological degradation occurs and thus the losses of organics and N are larger.

Secondary treatment

Urine

Separate storage is a simple and cheap secondary treatment method for urine and the same processes occur in this storage tank as in the collection tank. As long as the tank is just pressure equalised, and not ventilated, neither losses of nutrients nor any changes in their availability can occur. The P content of the bottom sludge is high and this can be used for P-demanding plants, otherwise it should be mixed with the rest of the tank contents before spreading, in order to provide an even dosage.

The sanitation taking place when urine is stored separately can not be relied upon when the urine is co-stored with faeces, as faeces increase the number of pathogens and also both the buffering capacity and the organic matter. Thus, mixing with faeces simultaneously increases the need for sanitation and decreases the sanitation effect to the extent that it can no longer be relied upon.

Faeces

N and S are the nutrients at risk of being lost during the secondary treatment, and the important factors influencing their fate are the amount of aeration and degradation that occurs in the process.

Faeces – incineration

Incineration is a very aerobic process with essentially complete degradation of the organic matter. Thus, if the faeces are successfully and completely incinerated, then essentially all N and S is lost with the fume gas, while essentially all of the P and K remains in the ash. Like plant ash, the ash from successful incineration is a concentrated and hygienic fertilizer high in P and K. To make best use of this concentrated fertilizer it should be carefully applied (see the section "Faeces", subsection "Application technique" below).

Faeces – composting

Thermophilic composting

Thermophilic composting, like incineration, is a very aerobic process which relies on the heat from the degrading organic matter to reach the temperature desired, > 50ºC, for a number of days to ensure safe reduction of pathogens (Vinnerås et al., 2003a; Schönning & Stenström, 2004). A high rate of degradation is required if the compost is to reach this high temperature. The degradation requires much oxygen and the total weight of the required air for the composting process is usually several times that of the substrate (Haug, 1993). In successful composting, the pH of the substrate increases to 8-9, even if the initial pH is low (~5) (Eklind & Kirchmann, 2000; Beck-Friis et al., 2001, 2003). The pH increase is largely due to the ammonia formed as organic N (protein) being degraded (Haug, 1993; Beck-Friis et al., 2003).

The combination of ammonia, high temperature, high pH and high aeration means that N in the form of ammonia is lost. These losses are somewhat decreased if the C/N-ratio of the substrate is increased by use of additives high in carbon, e.g. leaves, straw or paper. However, if the C/N-ratio becomes too high (>30-35), then the composting is slowed down, impairing the attainment of the required temperatures. At C/N-ratios giving successful composting, the N losses usually are 10-50% (Eklind & Kirchmann, 2000; Jönsson et al., 2003). If latrine urine and faeces are composted together instead of just faeces, then the N input to the compost is increased some 3-8 times and most of the N from the urine is lost, because it is mainly in the form of ammonia, which easily escapes from the highly aerobic compost.

The main proportion (typically 90-95%) of the N in the finished compost is organic N (Sonesson, 1996; Eklind & Kirchmann, 2000). This organic N becomes plant-available only at the rate that it is further degraded in the soil. The remaining N, 5-10% of the total, is ammonium and nitrate, which are directly available to plants.

The availability of K, S and P in composted material is high. If leachate escapes during or after the process, due to rain or a wet substrate, then the most available fractions of these nutrients will be lost. Therefore, it is important that the composting is managed so that no leachate is allowed to escape.

A substrate based entirely on faeces is normally not enough to achieve thermophilic temperatures, especially if the faeces are mixed with ash or lime. Addition of supplementary, easily degradable substrates is needed, usually in amounts several times larger than the amount of faeces. This supplementary substrate can consist of e.g. food market waste, easily degradable industrial waste or source-separated kitchen waste. These additions influence the nutrient concentrations in the compost. In addition to this, excellent operation and maintenance is needed to sustainably achieve thermophilic operation.

Low temperature composting

Mesophilic composting and aerobic degradation at ambient temperatures, here collectively denoted low temperature composting, are best characterised as low temperature variants of thermophilic composting and these processes are just as aerobic. The products of these processes are, when mature, as degraded as those of thermophilic composting and the end products of aerobic degradation at these temperatures, carbon dioxide and water, are also the same. The final pH and the total N losses are similar, 10-50%, as in thermophilic composting (Eklind & Kirchmann, 2000), as is probably the plant availability of the final product. The two main differences between the two types of composting are firstly that the sanitation achieved through the elevated temperature in the thermophilic compost does not take place in low temperature composting, and secondly that the need for additional easily degradable substrate, as well as for extensive inputs to operation and maintenance, is decreased.

The above description of aerobic degradation largely holds also when the process takes place in the soil, as is the case for Arbor Loo and *Fossa alterna* (see footnote to Table 5). The ammonia loss from these processes might however be smaller than that of above-ground composting, since some ammonia may diffuse into the surrounding soil, be dissolved in the soil liquid and possibly be utilized by plants. It is especially advantageous if some crop is planted on top of the Arbor Loo or *Fossa alterna* pit. The crop requires moisture to survive, which means that ammonia diffusing upwards is also dissolved in soil liquid and utilized by plants. However, there is a risk of leaching losses of N during collection and processing in pits. This risk probably increases with the size of the pit and with the amount of urine deposited in it. For conventional pit latrines, this loss has, in eastern Botswana, been measured as varying between 1 and 50% (Jacks et al., 1999).

Extensive work has been done in Zimbabwe on low temperature composting of faeces (Morgan, 2003). Analysis of the humus extracted from shallow pits where soil is added to a combination of faeces and urine and allowed to compost, shows a material rich in all the major nutrients required for plant growth, compared to normal topsoil.

Table 5. Analysis of composted humus derived from Fossa alterna pit soil and Skyloo humus compared to a mean of various topsoils after incubation for two weeks

Soil source	pH	min-N ppm mg/kg	P ppm mg/kg	K ppm mg/kg	Ca ppm mg/kg	Mg ppm mg/kg
Local topsoils (mean of 9 samples)	5.5	38	44	195	3200	870
Skyloo humus (mean of 8 samples)	6.7	232	297	1200	12800	2900
Fossa alterna pit soil (mean of 10 samples)	6.8	275	292	1750	4800	1200

Mineral N was analysed by the Kjeldahl process for mineral N (nitrite, nitrate and ammonium) The classification of local soils in Zimbabwe: less than 20 ppm rates as low. 20-30 as medium, 30-40 adequate and ≥40 ppm "good". Therefore the soils produced from the Skyloo and *Fossa alterna* are very rich in mineral, plant-available N on this scale. The samples of topsoil used in the table above are in the adequate range.

P was analysed with the resin extraction process. This shows available P, not total P. Less than 7 ppm is regarded as low, 7-15 marginal, 15-30 medium, 30-50 adequate, 50-66 good, 67-79 very good and ≥80 ppm is regarded as high. The soils produced from Skyloo and *Fossa alterna* are also very high in P.

Ca, Mg and K were extracted with ammonium acetate.

The *Fossa alterna* is a twin pit toilet system in which soil, ash, leaves and excreta (urine plus faeces) are deposited in one of the two shallow pits (usually about 1.2 m deep). The use of the pits alternates at 12-month intervals, with only one pit being used at any one time, whilst the second pit is composting. It takes about one year or more for a family to fill a pit with the mix of ingredients. Thus this system allows for a continuous cycle of operation, with humus being excavated every year and the use of the pit alternating every year.

The Skyloo is a single vault urine-diverting toilet where the urine is led off and contained for future use as a plant fertilizer and the faeces drops into a container such as a bucket in the shallow vault. Soil and wood ash are added to the faeces after each deposit. When the bucket is nearly full, its contents are moved to a secondary composting site where more soil is added and the mix kept moist. This process makes a rich compost after a period of time.

Faeces – storage

Storage in a dry state at ambient or increased temperature is another possible secondary treatment. The pathogen reduction increases with increasing ambient temperature (Moe & Izurieta, 2004). If the moisture level is kept low, <20% during the whole storage, then the degradation is low and so are the losses of N and organics. These substances are conserved and, after incorporation into the soil and moistening, they are degraded in the same way as the material in a mesophilic compost or an Arbor Loo. Furthermore, since the degradation takes place in small volumes in moist soil planted with a crop, the risk of ammonia or leachate losses is virtually eliminated.

Faeces – digestion

Anaerobic digestion at thermophilic, mesophilic or ambient temperatures is another option for secondary treatment of faeces. Digesters are closed and all inflowing substances leave them either with the biogas and/or with the digestion residue. In the digestion, a large proportion of the organic matter is degraded to biogas (methane and carbon dioxide). A large proportion of the organic S is mineralizsed from proteins, and some of this leaves the process as hydrogen sulphide contaminating the biogas. A large proportion of the organic N is mineralized from proteins and thus the N of the residue consists largely (50-70%) of ammonium (Berg, 2000), the remainder being organic N. Ammonium is directly plant-available and the availability of the other plant nutrients is also good. Digestion residues should be handled with care so as not to lose the ammonium as gaseous ammonia.

Faeces – chemical sanitation

Sanitation of faeces can also be achieved by mixing them with urea. This urea is degraded to ammonium by the urease that naturally occurs in the faeces. Thus, this process probably functions best if the faeces are in the form of a sludge, which can be mixed. In the sludge, equilibrium is established between ammonium and ammonia (Equation 7). Ammonia is toxic to microbes and the reduction of pathogens is very good in the process (Vinnerås et al., 2003b). Additions such as ash and lime that increase the pH during primary treatment push Equation 7 towards the right side and thus increase the sanitizing effect. This treatment needs to be performed in a closed container. The process resembles storage in that no degradation of the faeces takes place and therefore neither organic matter nor N is lost. They are all left for the microbes in the soil to thrive on after application of the sludge as a fertilizer. The ammonium content of this sludge is higher than that of urine and digestion residue. Thus, it ought to be an excellent fertilizer but, like digestion residue, it needs to be handled with care to avoid ammonia losses.

Recommendations for Use of Urine and Faeces in Cultivation

A starting point when deciding the application rate of urine and faeces is the local recommendation for use of conventional N (preferably urea or ammonium fertilizers) and P fertilizers[2]. If local recommendations are not available, a starting point can be to estimate the amounts of nutrients removed by the crop. For a few crops the removal per metric ton of harvested edible fraction is given in Table 6. These amounts should be multiplied by the estimated harvest to get the amounts of plant nutrients removed.

Table 6. Amounts of N, P and K (kg/ha) removed per metric ton of harvested edible fraction for different crops (Swedish Food Authority, 2004)

Crop	Amount kg/ha	Water content %	N kg/ha	P kg/ha	K kg/ha
Cereals					
Maize, dry*	1000	10	15.1	2.1	2.9
Maize. fresh	1000	69	6.2	1.1	2.9
Millet	1000	14	16.8	2.4	2.2
Rice. unpolished	1000	12	12.4	3.0	2.3
Sorghum	1000	11	17.6	2.9	3.5
Wheat	1000	14	17.5	3.6	3.8
Others					
Green beans. fresh	1000	90	2.9	0.4	2.4
Irish potatoes	1000	80	2.9	0.3	4.7
Lentils. dry	1000	12	38.4	3.8	7.9
Onions	1000	91	1.9	0.4	1.9
Pumpkin	1000	92	1.6	0.4	3.4
Red beans, dry	1000	11	35.2	4.1	9.9
Soybeans, dry	1000	10	59.5	5.5	17.0
Spinach	1000	94	3.0	0.3	5.6
Tomatoes	1000	93	1.4	0.3	2.1
Water melon	1000	91	1.0	0.1	1.2
White cabbage	1000	92	2.2	0.3	2.7

* USDA, 2004.

It is important to remember that an application rate corresponding to the amount of nutrients removed by the edible fraction of the crop is lower than the application rate needed for highest crop yield, especially on soils of low fertility. The fertilizer supplied has to provide nutrients for the root system, crop and crop residues removed from the field, and there are usually some additional losses of N, K and S in particular through leaching, and of N also through volatilization. Some nutrients are also lost if the waste from processing the crop is not recycled to the field as fertilizer. Another important aspect is that added P is usually sorbed by the soil, especially if the soil is poor in P. Therefore the amounts calculated from Table 6 give the minimum application level needed for maintained fertility. Higher application rates, often

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[2] For further discussions on the subject of application rates, see the Sections "Urine" and "Faeces" below.

twice as high, are needed to simultaneously increase the fertility of the soil, which is needed to get a high yield off poor soils. However, if N is supplied to N-fixing crops, e.g. beans and peas, their N-fixing ability is not fully utilised.

URINE

General considerations

Urine is a valuable source of nutrients, used since ancient times to enhance the growth of plants, notably leafy vegetables. There are different ways of using urine. The most obvious is to use urine directly to fertilize crops and this is the use on which recommendations are given below. Another possibility, which entails large ammonia losses, however, is to use urine for improving the composting process of carbon-rich substrates. Recommendations on the use of different composts are given in the Section "Faeces". Several different process options for concentrating or drying the urine have been presented, but the use of these products is not treated in this text.

The following text presumes that the urine is handled according to the hygiene guidelines given for urine (Schönning & Stenström, 2004).

Fertilizing effect of urine

Urine used directly or after storage is a high quality, low cost alternative to the application of N-rich mineral fertilizer in plant production. The nutrients in urine are in ionic form and their plant-availability compares well with chemical fertilizer (Johansson et al., 2001; Kirchmann & Pettersson, 1995; Kvarmo, 1998; Richert Stintzing et al., 2001). Urine is best utilized as a direct fertilizer for N-demanding crops and leafy vegetables. If crop- and region-specific recommendations are available for the use of N fertilizers (urea, ammonium or nitrate), a good starting point for how to use urine is to translate the recommendations to urine. The translation is simplified if the N concentration of the urine is known. If it is not then, as a rule of thumb, a concentration of 3-7 grams of N per litre of urine can be expected (Vinnerås, 2002; Jönsson & Vinnerås, 2004). Urine also contains large amounts of P and K, but due to its large content of N, its P/N and K/N ratios are lower than in many mineral fertilizers used for vegetable production.

The yield achieved when fertilizing with urine varies depending on many factors. One important aspect is the soil condition. The effect of urine, just as that of chemical fertilizers, is probably somewhat lower on a soil with a low content of organic substances than on a soil with a high organic content. Experience shows that it is beneficial for soil fertility to use both urine and faeces or other organic fertilizers on the soil, but they can be used in different years and for different crops.

Dilution

Urine can be applied neat (without dilution) or diluted with water, which is practised in many places. The level of dilution varies between approximately 1:1 (1 part water to 1 part urine) to 10:1, and 3:1 seems common. Dilution implies increasing the volume to be spread and thus the labour, the equipment needed, the energy use and the risk for soil compaction are all increased.

Dilution has the advantage of decreasing, or eliminating, the risk of over-application, of applying urine at such high rates that it becomes toxic to the crop. However, irrespective of whether the urine is applied diluted or neat, urine is a fertilizer and should, just as the much more concentrated chemical fertilizers, be applied at the rate corresponding to the desired application rate of N, while additional water should be applied according to the needs of the plants. Thus, urine can be applied neat, or even concentrated to the soil, which then is irrigated according to crop water requirements. The urine can also be diluted into the irrigation water at a rate that depends on the need for nutrients and water by the crop. The application of a water/urine mix normally needs to be interspersed with irrigation with water only.

Diluted urine should be handled in the same way as urine. In order to avoid smells, loss of ammonia, generation of aerosols, burns and possible contamination on plants by remaining pathogens, urine should be applied close to, on or incorporated into the soil. Foliar fertilization is not recommended.

In areas where salinisation of soils is a problem, urine fertilization is only recommended if it gives a good yield increase. If salinization is by far the most limiting factor, other improvements are needed for increased soil fertility than application of urine.

Application time

In the early stages of cultivation, good availability of all nutrients is important to enhance growth. In large-scale crop production, normal fertilizing strategy is application of nutrients once or twice per growing season. If fertilizer is applied only once, this should normally be carried out prior to or at the time of sowing/planting. If the crop is fertilized twice, the second fertilization can be performed after approximately 1/4 of the time between sowing and harvest, differing depending on the needs of the crop.

The crop can also be continuously fertilized, e.g. if the urine is collected in smaller containers and used more or less directly. However, once the crop enters its reproductive stage it hardly takes up any more nutrients. An example is maize; fertilizer applied until the plants are setting ears is well utilized, but after this stage the uptake of nutrients from the soil declines, as at this stage the nutrients are mainly relocated within the plant (Marschner, 1997). This is fully appreciated in recommendations on use of chemical fertilizers. For example, in Zimbabwe, where maize is harvested 3-5 months after planting, the recommendation is to fertilize it three times, but no later than 2 months after planting.

As a rule of thumb, fertilization should stop after between 2/3 and 3/4 of the time between sowing and harvest. Some vegetables, notably the leafy ones, are harvested before they reach their reproductive stage and therefore fertilizer applied closer to the time of harvest can be utilized. However, a waiting period of one month between fertilization and harvest is very advantageous from a hygiene point of view and recommended for all crops eaten raw (Schönning & Stenström, 2004).

An often stressed aspect is the risk of leaching of nutrients. In regions where there is heavy rainfall during the cropping season, repeated applications of urine may be an insurance against losing all the nutrients in one rainfall event. However, it should always be remembered that the leaching after fertilization is small compared to the leaching from a pit latrine or from letting diverted urine leach into the ground close to the toilet.

The total applied amount of urine and whether it should preferably be applied once or several times also depends on the N need of the plant and its root size. Root size varies widely between different crops (Figure 3). Plants with inefficient or small root systems, e.g. carrots, onions and lettuce, can benefit from repeated applications of urine throughout the cultivation time (Thorup-Kristensen, 2001).

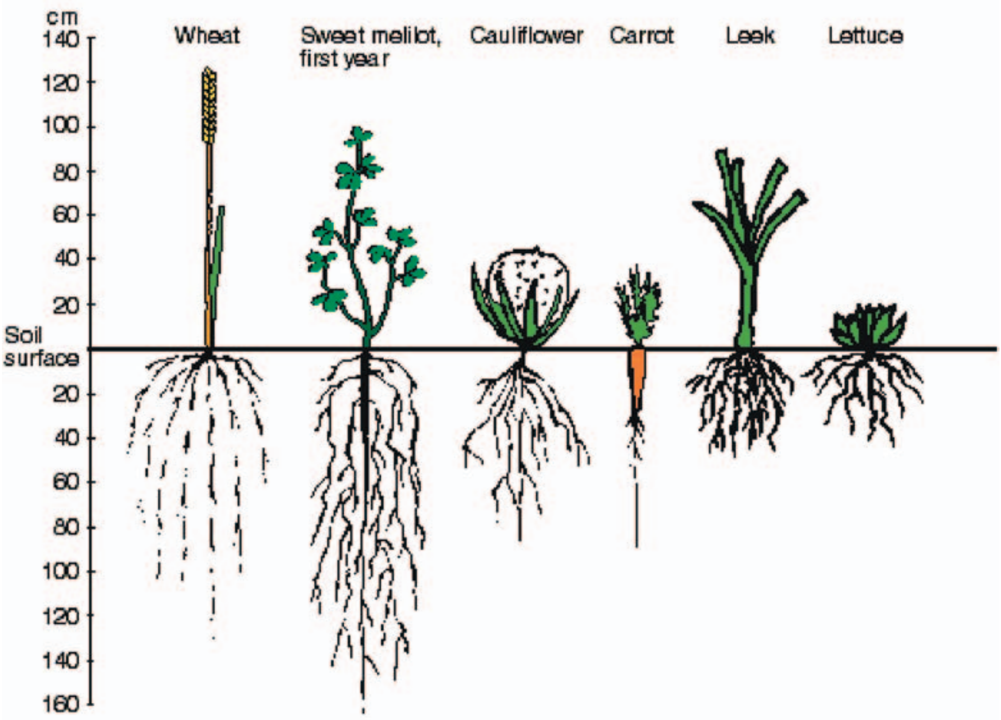

Figure 3. Root size of vegetable crops. Drawing: Kim Gutekunst, JTI.

Storage in soil

In regions where there are definite cultivation periods followed by dry periods, storage of urine nutrients in soil is an alternative if the storage capacity is insufficient. This is carried out by applying and incorporating the urine into the soil during the dry season, followed by normal cultivation during the cropping season. The idea is that the main portion of the nutrients remain in the soil and become available for the plants during the growing season. Further investigations are needed to determine the loss and availability of nutrients, especially N, to crops during and after such storage. Results from the Society for Urban Development in East Africa (SUDEA) in Ethiopia, as well as from Zimbabwe, indicate that the method is an interesting alternative to storing the urine in containers until the cropping season, even though the N loss might be fairly high. During one such experiment where the urine nutrients were stored for 28 days in the soil, the loss of mineral N was found to be 37% (Sundin, 1999). An additional advantage of soil storage is that the labour of applying the urine is carried out during the dry season, which is normally less labour-intensive than the cropping season.

Application technique

For best fertilizing effect and to avoid ammonia losses, the urine should be incorporated into the soil as soon as possible after the application, instantly if possible (Johanssson et al., 2001; Richert Stintzing et al., 2001; Rodhe et al., 2004). A shallow incorporation is enough, and different methods are possible. One is to apply urine in small furrows that are covered after application. Washing the nutrients into the soil with subsequent application of water is another option.

Figure 4. Spreading of urine is easily done with an ordinary watering can. Vegetables fertilized with urine, Sweden. Photo: Håkan Jönsson, SLU.

When spreading urine, it should not be applied on leaves or other parts of the plants, as this can cause foliar burning due to high concentrations of salts when drying. Spraying urine in the air should also be avoided due to the risk of N loss through gaseous emissions of ammonia (Johanssson et al., 2001; Rodhe et al., 2004) and the hygiene risk through aerosols.

Drip irrigation using urine as a fertilizer is another possible application technique. However, when this technique is used, measures must be taken to avoid blockages due to precipitation of salts forming sludge because the total amount of precipitation often increases after dilution as water normally contains some magnesium and calcium.

Some crops, e.g. tomatoes, are sensitive to having all their roots exposed to urine, at least when plants are small, while on many crops no negative effect is seen at all. Therefore, before the sensitivity of a crop is known, it is wise not to simultaneously expose all the roots of the plant to urine, be it neat or diluted. Instead, urine can be applied either prior to sowing/planting or at such a distance from the plants that the nutrients are within reach of the roots, but not all of them are soaked. For annual plants this distance may be about 10 cm.

Application rate

A starting point for the dimensioning of urine application is the local recommendations for use of commercial mineral N fertilizers, preferably urea or ammonium fertilizers. If such recommendations are not available, another starting point can be to estimate the amounts of nutrients removed by the crop, which for some crops are given in Table 6.

Urine can be recommended for most crops. Since it is especially rich in N, it may be wise to give priority to crops that have a high value and that respond well to N, such as spinach, cauliflower, ornamental flowers and maize. However, there is no reason not to use urine, if there is enough, as a fertilizer to other crops, as experiences from all over the world show good results.

Experiences

Human urine has been used as fertilizer in small-scale gardening for a long time in many places around the world, though its use is mostly not documented (Figure 5).

Figure 5. Gooseberries, blackcurrants and roses fertilized with urine in a garden in Uppsala, Sweden. Photo: Håkan Jönsson, SLU.

Urine has been tested as a fertilizer on greenhouse-grown lettuce in Mexico (Guadarrama et al., 2002). There were treatments comparing urine with compost, a urine-compost mixture and no fertilizer at all. The application rate was 150 kg of total N per hectare in all treatments, except for the unfertilized one. Urine gave the best yield of lettuce, due to its high availability of N. Similar results are reported for other vegetable crops.

Urine was tested as a fertilizer on barley in Sweden during 1997-1999 (Johanssson et al., 2001; Richert Stintzing et al., 2001; Rodhe et al., 2004). Results showed that the N effect of urine corresponded to about 90% of that of equal amounts of ammonium nitrate mineral fertilizers.

In field trials on organic farms during 1997-1999, human urine was tested as a fertilizer on spring grain and winter wheat (Lundström & Lindén, 2001). For winter wheat, applications were made in spring in the growing crop. A comparison with dried chicken manure and meat + bone meal was made. Human urine corresponding to 40, 80 and 120 kg N/ha increased the grain yields of winter wheat by, on average 750, 1500 and 2000 kg/ha, respectively. Dried chicken manure gave yield increases of, on average, about 600, 1100 and 1500 kg/ha, respectively. Dried meat + bone meal gave the smallest yield increase: about 400, 800 and 1200 kg/ha, respectively. On average for all three N fertilization levels, the increase of the winter wheat yields was 18 kg grain per kg N for human urine, 14 kg for dried chicken manure and 10 kg for meat + bone meal. These data show that the plant availability of N in urine is higher than in chicken manure and meat + bone meal, which is to be expected since chicken manure and meat + bone meal all have a higher fraction of organically bound N. For spring wheat, yield increases and N utilization were lower, probably due to high levels of plant-available N in the soil at the start of the cultivation period.

Figure 6. Spreading of urine before sowing of barley, as well as urine-fertilized barley at an early stage. Photo: Mats Johansson, VERNA.

Urine has been tested as a fertilizer on barley and ley in both greenhouse and field trials in Germany (Simons & Clemens, 2004). The urine in some treatments was acidified in order to reduce ammonia emissions and microbial contamination. The results from field trials showed that the fertilizing effect of urine was higher than that of mineral fertilizer in production of barley. There was no difference in yield between plots fertilized with acidified urine and untreated urine.

Urine has been tested as a fertilizer on Swiss chard in Ethiopia (Sundin, 1999). The yields of the fertilized plots were up to four times that of those unfertilized. Urine has also been tested as a fertilizer on cotton and sorghum in Mali (Dembele, pers. comm.). Results are promising and the trials continue during 2004.

Urine has been tested as a fertilizer on amaranth in Mexico (Clark, pers. comm.). Results show that a combination of urine and poultry manure gave the highest yield, 2,350 kg/ha. Chicken manure alone gave a yield of 1,900 kg/ha. Human urine alone gave a yield of 1,500 kg/ha and the unfertilized control gave a yield of 875 kg/ha. The amount of N applied was 150 kg N/ha for the three treatments. Soil sampling showed no differences between treatments regarding physical or chemical characteristics.

In a field trial in Sweden in 2002, different application strategies for urine as a fertilizer on leeks were tested (Båth, 2003). Fertilizing with urine gave a three-fold yield increase. Neither yield nor nutrient uptake was significantly affected by whether the same total amount of urine was applied in two doses or whether it was divided into smaller doses applied every 14 days. The N efficiency (i.e. N yield – (N yield in unfertilized plots)/added N), when using human urine was high, ranging from 47% to 66%. This is on the same level as when mineral fertilizers are used. N efficiency for most other organic fertilizers, e.g. compost, is normally between 5 and 30%.

Table 7. Results of a field trial using human urine as a fertilizer for leeks. There was no statistically significant difference between treatments A, B and C (after Båth, 2003)

Treatment	N rate kg/ha**	Yield ton ha*	N yield kg/ha**
A Urine every 14 days	150	54	111
B Urine twice	150	51	110
C Urine every 14 days + extra potassium	150	55	115
D Unfertilized	0	17	24

* ton/ha= kg/10 m^2
** kg/ha= gram/10 m^2

Figure 7. Field trials using urine as fertilizer to leeks. Photo: Anna Richert Stintzing, VERNA.

Plant trials with urine have been carried out with various vegetables in Zimbabwe (Morgan, 2003). Plants were grown in 10-litre cement basins and fed with 0.5 litres of a 3:1 water/urine mix three times per week. Unfertilized plants were cultivated as a comparison. The increase in production was large but no statistical analysis was performed.

Figure 8. The spinach to the left is unfertilized. The spinach to the right is fertilized with urine diluted with three parts of water to one part of urine applied two times per week. Photo: Peter Morgan, Aquamor.

Table 8. Average yields (grams fresh weight) in plant trials with urine as a fertilizer to vegetables in Zimbabwe (Morgan, 2003)

Plant, growth period and number of repetitions n	Unfertilized plants g	Fertilized, 3:1 water/urine application 3x per week g	Relative yield fertilized to unfertilized
Lettuce, 30 days (n = 3)	230	500	2.2
Lettuce, 33 days (n = 3)	120	345	2.9
Spinach, 30 days (n = 3)	52	350	6.7
Covo, 8 weeks (n = 3)	135	545	4.0
Tomato, 4 months (n = 9)	1680	6084	3.6

FAECES

General considerations

While the total amount of nutrients excreted with faeces is lower than with urine, the concentration of nutrients, and especially P and K, is high in faeces and, when used as a fertilizer, faecal matter can give significant increases in plant yield. P is particularly valuable for the plant in its early development and important for good root development. In addition to supplying macro- and micronutrients, faeces contain organic matter, which increases the water-holding and ion-buffering capacity of the soil, serves as food for the microorganisms and is important for improving soil structure. However, the risk for high concentrations of pathogens in faeces is large and thus it is critical that the faeces are handled in such a way that the risk of disease transmission is minimized. The relevant hygiene guidelines (Schönning & Stenström, 2004) should be followed.

Fertilizing effects

It should be noted that faeces contribute to crop production both by their fertilizing effect and by their soil-improving effect. The fertilizing effect of faeces varies much more than the effect of urine. This is mainly due to the fact that the proportion of N that is in mineral form in the faeces varies largely between the different treatment strategies, as mentioned above. Another reason is that different additives are used in the different treatments and these additives contribute to the total content of nutrients and organic matter in the treated faecal product. Finally, the content and properties of the organic matter in the treated faeces differs widely between the different treatments.

The soil-improvement effect consists of increased buffering capacity, moisture-retaining capacity and contribution to food for microbial activity. All of these are related to the addition of organic matter and to some extent mineral substances in ash to the soil system. The soil improvement effect varies according to the same principles as stated above.

Ash

Incineration of faeces results in ash with high contents of P and K as well as the other macro- and micronutrients. However, N and S are lost with the fume gas. Thus, ash is a PK fertilizer with micronutrients and a high pH, increasing the buffering capacity of the soil. The plant availability of the nutrients in ash is good as long as the incineration temperature is not high enough for the ash to melt. If so, then the availability of the plant nutrients probably decreases drastically.

The amount and content of ash that is generated from the incineration varies. Depending on the choice of primary treatment, additions of ash, soil, lime or other dessication materials can be made, which affects the incineration. Additional fuel may also be needed. Ash and lime contribute towards the pH-increasing effect of the product, a most desirable effect since the pH of most soils is below the optimal, 6-7 for most crops. On soils with very low pH (4-5) this is a very important effect for cropping and also for getting the full benefit from fertilizing with, for example, urine, which has been shown both in Uganda and Zimbabwe.

Compost from thermophilic or low-temperature composting

In many respects, composting functions like a slow and partial incineration mediated by microbes. Often some 40-70% of the organic matter and somewhat less of the N are lost. Remaining N is mainly, often about 90%, in organic form and this only becomes plant-available at the rate of degradation, which is slow as the remaining organic matter is more stable than the initial organic matter. This stable organic matter improves the water-holding and buffering capacity of the soil. The P is also to some extent, but far less than N, bound in organic forms, while the K is mainly in ionic form and thus plant-available. Compost should be applied as a complete PK fertilizer or as a soil improver.

Additions of organic waste in the composting treatment, just as additions made in the primary treatment, naturally affect the amount and characteristics of the compost.

Dried faeces from desiccation and storage

If the drying is fast and a low moisture level is achieved, the losses of both organic matter and N are small. Most of the organic matter is conserved and upon application it both improves the soil and serves as food for the soil microbes. Thus, compared to composting, dry storage of the faeces recycles more organic matter and N to the soil, but the organic matter is less stable. Dried faecal matter is a complete PK fertilizer, which also contributes considerable amounts of N.

Residues from anaerobic digestion

In anaerobic digestion, approximately the same proportion of organic matter is degraded as in composting, 40-70%, but the mineralized N is not lost, as it largely is in composting. Instead, the N remains as ammonium in the digestion residue. Some 40-70% of the N found in the residue is in the form of ammonium, which is readily plant-available. Thus, for most crops digestion residue is a well-balanced, quick-acting and complete fertilizer (Åkerhielm & Richert Stintzing, in press). To most digestion processes, additional substrates such as animal manure and household waste are added, which naturally affects the amount and composition of the digestion residue.

Chemical treatment with urea

When faeces are treated with urea, the ammonia content is elevated to high levels, as high or higher than in neat urine. The large content of P and K in the faeces means that this is still a well-balanced and complete fertilizer. The urea-treated faeces should be applied according to their content of mineral N. Ash and other additions during the primary treatment contribute to the properties of the product.

Application time

Irrespective of how the faeces have been treated, they should be applied prior to sowing or planting. This is because the faeces contain large amounts of P and the availability of P is very important for good development of small plants and of roots. The faeces need to be applied in such a way that they come in contact with the soil solution, which can dissolve and transport the nutrients to the roots. Thus, the faecal products need to be well incorporated into the soil, and this should be done before the sowing/planting in order not to disturb the small plants.

Finally, faeces initially contain lots of pathogens and therefore several barriers are desired between these and the food crop, to minimize the risk of disease transmission via food crops fertilized with faeces. The secondary treatment is one such barrier, and application and thorough covering of the treated faeces before sowing/planting is another barrier against disease transmission. Avoiding faeces as a fertilizer to vegetables eaten raw is a third barrier against disease transmission. In climates with a dry season before the cultivation period, the faecal product may be spread during the dry season or at the end of the preceding growth season.

Application technique

Two of the largest benefits of faeces are its content of P and organic matter. To make full use of these, the faecal matter must be applied at a depth where the soil stays moist, because the P only becomes available to the plants at the rate that it dissolves in the soil liquid. Likewise, the water-holding and buffering capacity of the organic matter are fully utilized only in moist conditions. Thus, the faecal fertilizer product, irrespective of whether it is in the form of ash, compost, digestion residue or treated slurry, should be applied at such a depth and in such a way that it is well covered by the upper layer of the soil. However, the rooting depth of plants is limited, and if faeces are applied at depths exceeding the rooting depth, the plant nutrients will not be available to the plants.

The application technique differs depending on the desired application rate. If the desired application rate is high, i.e. large amounts are available in relation to the area to be fertilized, the faeces can be dug into the soil in a layer which is covered by surface soil not mixed with any faecal product, forming a bed. If the application rate is very large, it is advantageous if the layer is mixed with some underlying soil before being covered by surface soil. Digging is used in the small scale, while in the larger scale ploughing is preferred, since it covers the product well with unmixed soil. If the desired application rate is low, the faecal product is preferably applied in furrows covered by unmixed soil. At lower application rates, the faecal product can be applied in holes close to where the plants will be growing. The size of the furrows or holes depends on the product to be spread. They naturally need to be larger if the product to be spread is desiccated and stored faeces with a high content of toilet paper, than if it is ash. The faecal product should always be well covered and placed in such a way that is within reach of the roots but not their only growing medium.

The ammonia content of digestion residues and urea-treated slurry is high. These products should be stored, handled and applied in such a way that ammonia losses are minimized. This entails storage in covered containers and rapid incorporation into the soil. Ash is a concentrated fertilizer and should be carefully distributed to utilize its nutrient content in the most effective way. Spreading ash evenly may be difficult. It is simplified if mixed with a bulking agent such as sand or dry soil.

The use of faeces in the production of trees is an example of how application in a hole can be used for perennial crops. When planting a tree, dried, composted or incinerated faeces may be used to increase soil fertility. A suitable way to spread the faeces is to mix in a shovel of dried or composted faeces with the soil in the pit that has been dug for the planting of the tree. This will stimulate its early growth.

Figure 9. Sabtenga, Burkina Faso. Mango tree fertilized with faeces at planting and doses of urine regularly during the growth season. Photo: Anna Richert Stintzing, VERNA.

Application rate

The rates at which most faecal products can be applied span a large interval. The two most beneficial effects to be gained from most faecal products are their supply of P and of organic matter. The main benefits from these effects are gained at very different application rates. The P excretion with faeces is large, in Sweden about 0.2 and in China 0.2-0.3 kg/person per year, and if P is applied at the removal rate of the crop, then the faecal matter from one person is enough to fertilize some 200-300 m^2 of wheat at a yield level of 3000 kg/ha per person. However, in many places, the soil is so devoid of P that the recommended application rate is 5-10 times the removal rate, and in this case the faecal matter from one person in a year contains enough P to fertilize 20-40m^2. Thus, on soils with low levels of P, the faecal matter from a family of five can supply 100-200 m^2 of wheat with P at a yield level of 3000 kg/ha. At this high application rate, most of the P will remain in the soil, improving it.

When it comes to the organic matter content in the faecal product, higher rates of application are needed to achieve effects on the soil system that will in turn give higher yields, as is shown below.

The amount of excreted organic matter in faeces in many countries seems to be in the range of 10 kg (Sweden) to 20 kg (China) per person per year. In addition, in Sweden about 8 kg/person per year of toilet paper is used. If the toilet matter is included in the faecal compost, the resulting compost, after losses of some 40-70% of the organic matter, contains about 10 kg of organic matter per person per year in faecal compost in both China and Sweden.

The dry matter of the topsoil on one square metre and down to 25 cm depth weighs around 300 kg. If the initial content of organic matter in the soil is 1%, then one square metre of topsoil contains 3 kg of pure organic matter. This level of organic matter is a product of soil properties, cultivation history and climate. To instantaneously increase the organic matter of the soil to 3%, the addition of another 6 kg of organic matter per square metre is needed. This level of application corresponds to applying the faecal production from one person during a year to an area of 1.5-3 square metres of land. Consequently, the production of faeces from a family of five would supply 7.5-15 square metres of land with organic material. This application rate, which means applying a lot more phosphorous than is removed by most crops, is an example of high rate application of faeces to achieve the main goal of improving the organic content of the soil.

However, high and stable organic matter content of the soil is only accomplished over longer periods of time. The organic matter in the applied material, e.g. dried faeces or compost, is not as stable as the humus of the soil and will degrade in the soil. The advantage of this is that the more that it degrades, the more plant nutrients are mineralised and become plant-available. The drawback is that this degradation means that the content of organic matter decreases and therefore continued applications of organic matter are needed in order to permanently raise the soil organic matter content.

Adding highly degradable organic matter, e.g. dried faeces, means that a large proportion of the nutrients become plant-available but that the organic matter degrades quickly. Adding a more stabilized product rich in humus, e.g. compost, means that less N becomes plant-available but on the other hand the increase in soil organic matter is more durable. However, the amount of stabilized humus formed in the soil when the dried faeces are degraded is approximately the same as is formed in mesophilic composting. The difference is that there is a risk of losing the nutrients mineralized in the composting, while when the degradation takes place in the soil, these can be utilized by the plants.

There is little risk of negative effects when applying large amounts of P or organic matter to the soil. However, the following aspects should be considered at very high application rates. If there are carbon-rich easily degradable materials in the faecal product, there is a risk of plant-available N being used up by microorganisms in the soil, and therefore a short-term lack of N which may lead to yield depressions. If large amounts of lime or ash are used as additives, then there is a small risk of negative effects at very high application rates, due to too high (>7.5-8) resulting pH in the soil. Such a high pH is only a risk at extremely high application rates or if the initial pH of the soil is already very high. For products high in ammonium, digestion residue and urea treatment slurry, there is a risk of negative effects if the ammonium application is too high. Therefore, the application rate of these products should be based on knowledge of the ammonium concentration of the product and the desired application rate for N.

When the high application rates stated above are used, normally very impressive yield improvements are achieved, as the organic matter, pH and buffering capacity are increased and large stocks of P and K are supplied to the soil, enough to last for many years or even decades. However, these application rates are not resource-efficient with respect to use of nutrients in the faeces, even though the result is a very good effect on crop production.

The application rates in the examples stated above are in the approximate range of 20-150 tons of faecal product per hectare. Normal application rates for farmyard manure in agriculture are in the range of 20-40 tons per hectare.

Experiences

Composting

Extensive work has been done on low temperature composting of faeces (Morgan, 2003). In a series of experiments in Zimbabwe, vegetables such as spinach, covo, lettuce, green pepper, tomato and onion were grown in 10-litre buckets with poor local topsoil, and their growth was compared with that of plants grown in similar containers filled with a 50/50 mix of the same poor local topsoil mixed with an equal volume of humus derived from co-composted human faeces and urine. In each case the growth of the vegetables was monitored and the crop weighed after a certain number of days' growth. Table 9 shows the results of the trials (Morgan, 2003). These results show a dramatic increase in vegetable yield resulting from the enhancement of poor soil with the composted faeces and urine mix.

Figure 10. The onions to the left are unfertilized while those to the right are grown in a mixture of 50% poor sandy soil and 50% Fossa alterna compost. Photo: Peter Morgan, Aquamor.

Table 9. Average yields (grams fresh weight) in plant trials comparing growing in topsoil only, with growing in a mixture consisting of 50% topsoil and 50% Fossa alterna compost (Morgan, 2003)

Plant, soil type and number of repetitions	Growth period	Fresh weight topsoil only g	Fresh weight 50/50 topsoil/ FA*soil g	Relative yield fertilized to unfertilized
Spinach, Epworth soil (n = 6)	30 days	72	546	7 .6
Covo, Epworth soil (n = 3)	30 days	20	161	8 .1
Covo 2, Epworth soil (n = 6)	30 days	81	357	4 .4
Lettuce, Epworth soil (n = 6)	30 days	122	912	7 .5
Onion, Ruwa soil (n = 9)	4 months	141	391	2 .8
Green pepper, Ruwa soil (n = 1)	4 months	19	89	4 .7
Tomato, Ruwa soil	3 months	73	735	10 .1

* *Fossa alterna* soil

The effects are less pronounced on good and fertile soils. A literature review on experiences of compost used on such soils (Odlare, 2004) showed that at normal application rates of 30-40 tons of compost per hectare the immediate effects are small both on plant production and soil structure. Long term effects were mainly found. The application of compost results in an increased pool of organic N in the soil. This will slowly be mineralized, the rate depending on soil temperature, moisture and microorganisms. In total, about 20-30% of the N in the compost will become available to the plants over the years (Odlare, 2004). There are also long-term improvements in the soil structure and water-holding capacity. The best cultivation results will be achieved if the compost is applied together with mineral N in some form, e.g. in the form of urine.

Dried faeces from desiccation and storage

One way of recycling faeces to plant production is to plant trees in shallow pits filled with a mix of excreta, soil and ash. This is a traditional method in many African countries, even on deep pits. While the actual growth of trees on these pits has not been scientifically measured in comparison with trees growing on topsoil nearby, there are many reports of enhanced growth. The increased growth is due to the tree taking up nutrients from composted excreta held in the pits. Although the nutrient amounts in these pits are high and cannot be fully utilized by trees, even over decades, this is a simple and cheap ecological sanitation method, which hopefully can increase the interest in other methods where the nutrients are more efficiently utilized.

A field experiment has recently been started in Burkina Faso (Klutse, pers. comm.), where dried faeces are being used as fertilizer on trees such as mango and banana, Figure 11. A shovel full of faeces is mixed in with the soil in the pit just before the planting of each tree. No results are available yet.

Digestion residues

The effect of digestion residues has been investigated in Sweden (Åkerhielm & Richert Stintzing, in press) and India (Godbole et al., 1988). Results from Sweden show that digested food residues gave yields ranging from 72 to 105% of the yields with equal amounts of total

Figure 11. Fruit trees growing on Arbor Loo pits in Malawi. The Arbor Loo is shown in the background. Photo: Peter Morgan, Aquamor.

N in mineral fertilizer. Results from India show that over four years, digestion residues from small scale biogas plants gave higher or as high yields as farmyard manure or urea fertilizers, at equal levels of applied total N.

Concluding Recommendations

These guidelines are based on our current knowledge of the use of urine and faeces in small- and large-scale cultivation. During the coming years we anticipate the generation of a lot of new data on excreta fertilizer reuse. Therefore, these guidelines should be updated within a three-year period.

EXCRETA, GENERAL RECOMMENDATIONS

- Excreta should be handled and treated according to hygiene guidelines (Schönning & Stenström, 2004).
- Urine and faeces are both complete fertilizers of high quality and with low levels of contaminants such as heavy metals The best fertilizing effect is achieved if they are used in combination with each other, but not necessarily the same year on the same area.

URINE

- Urine is a quick-acting nitrogen-rich complete fertilizer. Its nutrients are best utilized if the urine is applied from prior to sowing, up until two-thirds of the period between sowing and harvest.
- Urine can be applied neat or diluted. However, the application rate should always be based on the desired nitrogen application rate and the urine or urine mixture should be handled in closed vessels and quickly incorporated into the soil, to minimize ammonia loss. Any potential need of supplementary water should be met by plain water, not diluted urine.

- The recommended application rate and time for chemical nitrogen fertilizers (urea or ammonium if available) is the best starting point for developing local recommendations on application rate and time for urine. For translating such recommendations to urine, its nitrogen concentration can be estimated at 3-7 g per litre, if no better knowledge exists.
- If no recommendations can be obtained, a rule of thumb is to apply the urine collected from one person during one day (24 hours) to one square metre of crop. If all urine is collected, it suffices to fertilize 300-400 m^2 per person. For most crops, the maximum application rate before risking toxic effects is at least four times this dosage.
- For most crops and under most circumstances, the yield is constant for the same total application rate, whether it is applied in one large dose or in several smaller ones. For crops with a small root system, it might be advantageous to divide the application, especially if the nutrient requirement of the crop is large and the main uptake is late in the growing season.

FAECES

- Faecal matter is especially rich in phosphorous, potassium and organic matter.
- Both organic matter and ash, which are often added to the faeces, increase the buffering capacity and the pH of the soil, especially important on soils with low pH.
- Organic matter also improves the structure and the water-holding capacity of the soil.
- Faeces should be applied and mixed into the soil before cultivation starts. Local application in holes or furrows close to the planned plants is one way of economizing on this valuable asset.
- For faeces, the application rate can be based on the current recommendation for the use of phosphorous-based fertilizers. This gives a low application rate, and the improvement due to the added organic matter is hard to distinguish. However, faeces are often applied at much higher rates, at which the structure and water-holding capacity of the soil are also noticeably improved.

Knowledge Gaps

There are many gaps in current knowledge concerning the use of urine and faeces as fertilizers. Lack of documented research in this area makes the development of set guidelines difficult. However, these products have been used in agriculture since ancient times, and there is a lot of undocumented knowledge based upon practice. Research on the use of urine and faeces as fertilizers is needed, especially in the following areas

- Nutrient effects of excreta on crops and soil
- Fertilization strategies and application techniques when using excreta
- Efficiency of storage of urine in soil
- Simple and resource-efficient sanitation techniques for faeces

Adaptation of these Guidelines to Local Conditions

These guidelines should be adapted to local conditions. Agricultural systems vary, as do the practices of humans from place to place. As a starting point, national data on nutrient content of urine and faeces as well as amounts excreted during a year can be developed based upon calculations according to the method described in the "Contents of macronutrients in excreta" section above, supplemented with relevant measurements.

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EcoSanRes

EcoSanRes is an international research and development programme sponsored by Sida (Swedish International Development Cooperation Agency). It involves a broad network of partners with knowledge/expertise in various aspects of ecological sanitation ranging from management and hygiene to technical and reuse issues. The partners represent universities, NGOs and consultants and they are involved in studies, promotion activities and implementation of projects in Asia, Africa and Latin America.

The network hub is Stockholm Environment Institute (SEI) which holds a formal contract with Sida. EcoSanRes has become an authoritative networking body within the field of ecological sanitation and also collaborates with other bilateral and multi-lateral organisations such as WHO, UNICEF, UNDP, UNEP, GTZ, WASTE, IWA, WSP, etc.

The EcoSanRes programme has three main components:

- outreach
- capacity
- implementation

The outreach work includes promotion, networking and dissemination through seminars, conferences, electronic discussion groups and publications.

Capacity building, is achieved through training courses in ecological sanitation and the production of studies and guidelines, with content ranging from eco-toilet design, greywater treatment, architectural aspects, agricultural reuse, health guidelines, planning tools, etc.

Implementation puts theory into practice with ecological sanitation pilot projects in diverse regions around the world. Because the most important factor to successfully implementing an ecosan system is local adaptation, EcoSanRes provides a logical framework for prospective pilot projects and insists the projects meet stringent criteria before approval.

EcoSanRes is currently running three major urban pilot projects in China, South Africa and Mexico. In addition preparations are being made to develop similar projects in Bolivia and India.

For more information about the partner organisations and programme activities please consult

www.ecosanres.org