Faecal separation and urine diversion for nutrient management of household biodegradable waste and wastewater

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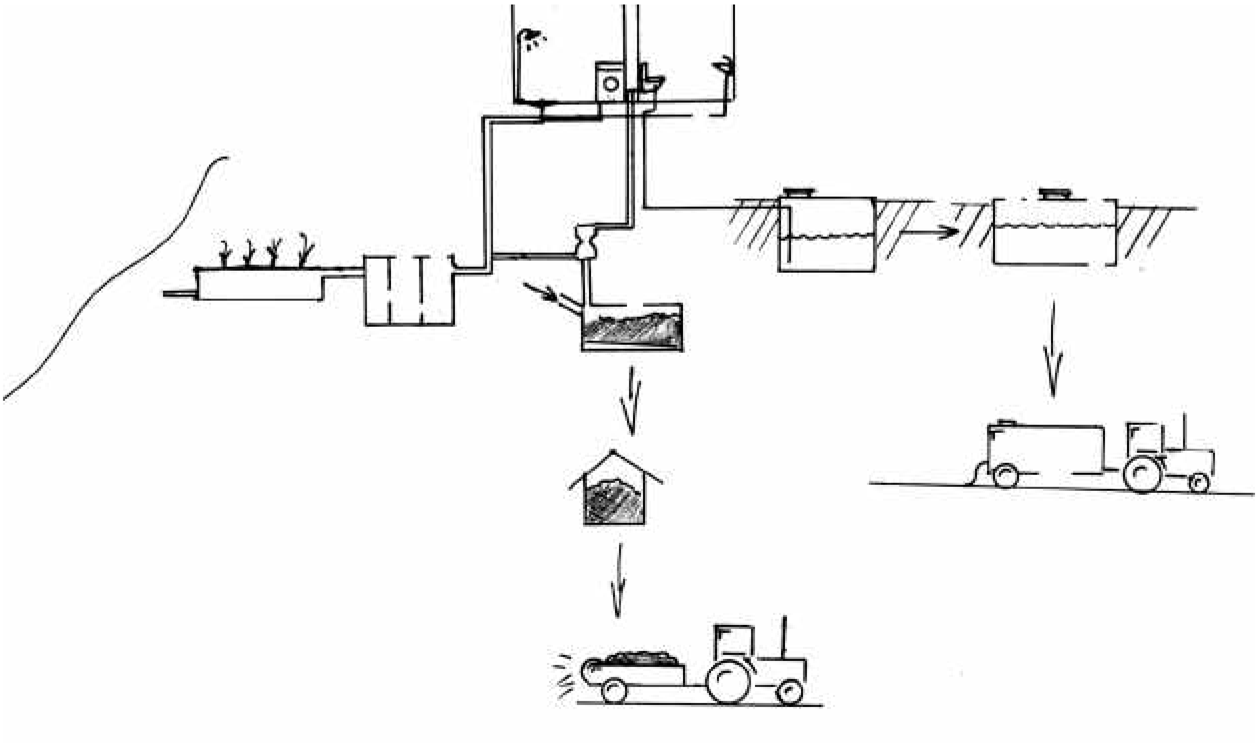

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Abstract

To create a sustainable society, the nutrients in household biodegradable solid waste and wastewater have to be recycled to agriculture. If the nutrients present in wastes from society were recycled, the use of fossil resources would decrease and so would the undesirable effects arising from discharge of nutrients to water recipients.

The main proportion of nutrients in the waste is to be found in the urine, faeces and the biodegradable solids. If all of these fractions are collected and recycled, 92% of the nitrogen, 85% of the phosphorus and 63% of the potassium out of the total flow of nutrients in the biodegradable fractions (urine, faces, greywater and biodegradable solids) would be recycled.

An easy way to collect the urine, which contains the majority of the nitrogen and a lot of the phosphorus and potassium originating from households, is to use a urine-diverting toilet system. So far, it has proved possible to collect up to 80% of the urine excreted using such a system.

In the collected urine mixture (urine and flushwater), there is a tendency for three layers to form. The middle layer, consisting of more than 90% of the total volume, has a composition comparable to the urine mixture if it were homogenized. The top layer, which is less than 5% of the total volume, has a lower concentration of nutrients than the middle layer while the bottom layer, also less than 5% of the volume, has a higher nutrient concentration than the other two layers.

When using a water-flushed toilet, it is possible after a short transport to capture the faecal nutrients by separating the faecal particles from the flushwater. High disintegration of the faecal particles, such as may occur in long or vertical transport, results in extraction and suspension of the nutrients, which decreases the amounts of nutrients it is by particle separation possible to separate and recycle.

Currently, faecal separation can be performed by Aquatron or filtration. The nutrient separation efficiency of the techniques depends on several factors. Aquatron separation was investigated in the laboratory with a short soil pipe transport and in the Ekoporten block of flats with a long transport through up to four floors to the separation in the basement. The investigation in Ekoporten showed that it was possible to separate about 60% of both nitrogen and phosphorus but only 45% of the potassium. In the laboratory study, 70% of all the nutrients were successfully separated. This indicates that the pipe transport distance should be as short as possible, especially the vertical drops, to enable as many of the faecal nutrients as possible to be collected.

One of the separation systems available on the market today is based on filtration with filters that are emptied every six to twelve months. Investigations in the laboratory of biological and chemical activity when faeces are submerged into water showed a rapid degradation of the faeces and extraction of the faecal nutrients, which indicates the importance of fast removal of the filter cake after separation. The laboratory study of filtration with immediate removal of the filter cake on average separated 70% of the faecal nutrients in to the separated solids.

If 80% of the urine is diverted and 70% of the faecal nutrients are separated and collected together with the biodegradable solids, 67%, 66% and 48% of the nitrogen, phosphorus and potassium respectively can be collected locally in an easily recycled fraction.

Urine diversion and faecal separation are simple and effective methods for collecting recyclable and unpolluted nutrients from wastewater. This increases the sustainability of society and decreases the degree of pollution resulting from nutrients being discharged to the water recipients.

List of papers

This thesis is based upon the following papers, referred to in the text by their Roman numerals. Paper II is appended and reproduced with kind permission of the publisher.

I. Vinnerås, B., Jönsson, H. & Weglin, J. (2001). The composition of biodegradable solid household waste and wastewater – flow of nutrients and heavy metals. Submitted to Bioresource Technology.

II. Höglund, C., Vinnerås, B., Stenström, T.A. & Jönsson, H. (2000). Variation of chemical and microbial parameters in collection and storage tanks for source separated human urine. Journal of Environmental Science and Health Part A: Environmental Science and Engineering. 35:1463-1475

III. Vinnerås, B. & Jönsson, H. (2001). The potential of faecal separation and urine diversion to recycle plant nutrients in household waste water. Submitted to Bioresource Technology.

IV. Vinnerås, B. & Jönsson, H. (2001). Faecal separation for nutrient management – evaluation of different separation techniques. Submitted to Urban Water.

Notes on the authorship of the papers:

In Paper I, the planning of the investigation was performed by Jönsson and Vinnerås, the sampling, interpretation and analysis of the results by Vinnerås and Weglin, and the writing was carried out by Vinnerås with revision by Jönsson.

In Paper II, the planning of the investigation was performed by all the authors, the sampling, interpretation and analysis of the results were performed by Höglund (emphasis upon microbiological parameters) and Vinnerås (emphasis upon chemical parameters), and the writing was carried out by Höglund and Vinnerås with revision by Jönsson and Stenström.

In Paper III, the planning of the investigation was performed by Jönsson and Vinnerås, Vinnerås and Weglin performed the sampling, Vinnerås carried out the interpretation and analysis of the results and the writing, with revision by Jönsson.

In Paper IV, the planning of the investigation was performed by Jönsson and Vinnerås, Vinnerås performed the investigation, the interpretation and analysis of the results and the writing, with revision by Jönsson.

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1 Introduction

All living organisms mainly consist of carbon, oxygen and hydrogen, which are found in excess in air and water from where they are initially taken up. Furthermore, living organisms contain a lot of nitrogen, phosphorus, potassium, calcium, sulphur and magnesium, which often are referred to as macronutrients. A lot of other elements in smaller quantities, trace elements, are also needed in small amounts for well-functioning biological systems.

In agriculture, when food is produced, the nutrients and trace elements are taken up from the soil and built into biological material. On harvesting crops or when meat is produced, these elements are taken from the fields and in most cases circulated on the farm. However some of the food is transported into the urban community, where a lot of it is eaten and some of it is disposed of as biodegradable solid waste.

Due to the one-way flow of food from the farms into the city, a deficit of those elements not occurring in surplus amounts will occur. These elements have to be compensated for in some manner. In the agriculture of today, mineral fertilisers of fossil origin often do this. Due to the decreasing reserves of fossil resources, nutrients have to be circulated between the city and the farms if we are to have a sustainable development of society.

The most common elements in mineral fertilisers are nitrogen, phosphorus and potassium, but in some areas other deficit elements are also added. If the biodegradable rest products from humans, e.g. urine, faeces and biodegradable solids, were recirculated, the need for fossil nutrient supplementation would decrease considerably and the sustainability of food production would therefore increase.

Of the food we eat, only a proportion of the carbon, hydrogen and oxygen contained in compounds is transformed in the body from solids or liquids into harmless gases. The remainder of the compounds consumed are excreted as solids or liquids, which in the Western world end up in the wastewater system. Some of the components excreted are harmless to the environment, while others have different degrees of environmental impact such as eutrophication by phosphorus and nitrogen compounds. To avoid this, the substances have to be removed from the wastewater before it is released to the water recipient.

The removal of nitrogen and phosphorus is effected by transformation of nitrogen compounds to nitrogen gas and chemical precipitation of the phosphorus followed by particle separation. The nutrients in the wastewater mainly originate from urine and faeces (Figure 1). If these two fractions were collected, the need to purify the water of nutrients would decrease drastically.

The flow of biodegradable solid and liquid wastes can be divided into four fractions, three liquid and one solid. The liquid fractions are urine, faeces and greywater, while flushwater used to flush the toilet can be included with the faecal and urine fractions. The solid fraction is the biodegradable solids, mainly consisting of food waste.

The nutrients from urine, faeces and biodegradable solids are mainly of biological origin and the nutrients in the greywater are mainly of mineral origin but all of the nutrients have to be disposed of in some manner. The best way to do this is by reuse of the nutrients as fertilisers, thereby increasing the sustainability both of the solid waste and wastewater treatment and of the agricultural production system. In the systems of the Western world, the fractions of urine and faeces are co-collected and transported in pipes with water (blackwater) and greywater to a treatment facility.

Conventional sewage treatment plants of today in Sweden are able to remove the majority of the phosphorus, more than half of the nitrogen but only small parts of the potassium from the incoming wastewater. The nutrients not removed from the wastewater are discharged to the recipient as a pollutant. Of the removed nutrients, most of the phosphorus and potassium are available for use as fertilisers. Some of the removed nitrogen will also be found as organically bound nitrogen that becomes plant available by mineralisation and some as directly plant available ammonia, while the rest is mainly emitted as N_2 gas. Pollution by heavy metals and organic pollutants in the recovered sludge decreases the value of the nutrients in the sludge.

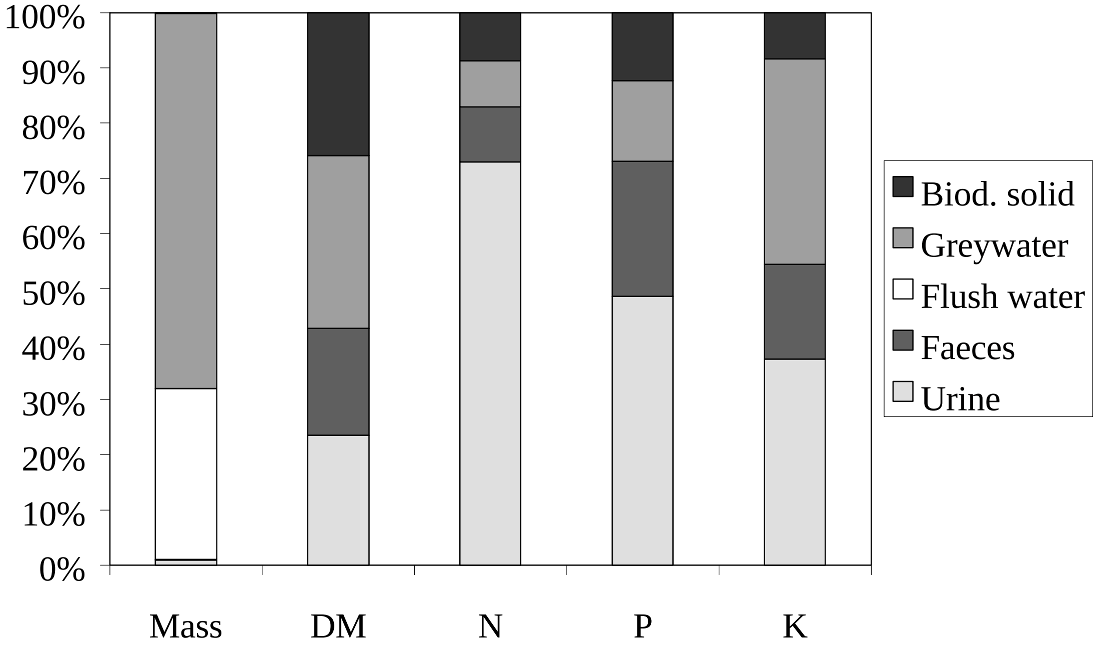

Figure 1. The distribution of mass, dry matter, nitrogen, phosphorus and potassium in the biodegradable household solid and liquids (Paper I).

Of the food purchased in Sweden, about 10% is not eaten (Paper I; NV, 1995) and thereby ends up in the waste as biodegradable solids. This corresponds well with the almost 9:1 relationship between the amounts of nutrients excreted in the urine and the faeces compared to the amounts in the biodegradable solids (Figure 1).

The main contributors of nutrients to the greywater are potassium- and phosphorus-containing detergents and potassium-supplemented salts, although the amount of phosphorus in detergents has decreased significantly during recent decades (Comber & Gunn, 1996).

Greywater contributes two thirds of the household wastewater volume (Figure 1). Greywater can be defined as water used for purposes other than flushing toilets, e.g. water used for washing, washing up, bathing and domestic cleaning. The greywater contributes the majority of the heavy metals to the wastewater (Figure 2), while only small amounts are found in the faeces and even smaller amounts in the urine. The content of heavy metals in the biodegradable solid waste is of the same magnitude as the content in the faeces.

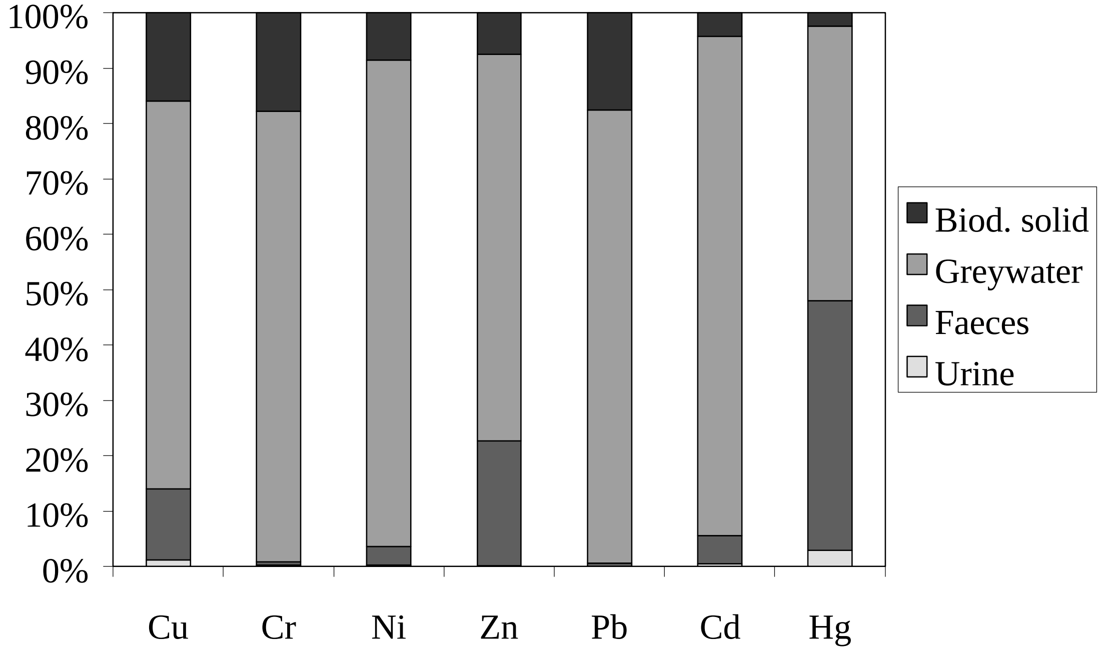

Figure 2. The distribution of copper, chromium, nickel, zinc, lead, cadmium and mercury in the biodegradable solids and liquids (Paper I).

If the fractions are collected separately, the treatment of each fraction can be adapted to the specific composition of each fraction. The urine and the faeces are two small fractions, according to their mass, containing a lot of unpolluted plant nutrients, potential resources that will become pollutants if they enter the water recipients.

2 Background

Up to the early 1970s a lot of descriptive studies were performed on the composition of human excreta. Most of the studies were performed in the field of medical and biochemical sciences, to get a better understanding of the biochemical pathways of our body. A lot of the studies were carried out on urine or faeces separately and seldom on both at the same time (Blatherwick & Long, 1922; Johnston et al., 1949; Johnston & McMillan, 1952; Jones Harp & Scoular, 1952; Vallee, 1959; Berger, 1960; Trémolières et al., 1961; Schroeder & Nason, 1971; Lentner et al., 1981; NV, 1995).

In the discussion about new types of sewage treatment systems that source separate the wastewater fractions, the interest in the composition of the different fractions has increased. The benefit of keeping the wastewater fractions separated is mainly their different composition and the treatment options for the fractions, where the urine mixture contains the majority of the nutrients in a water dissolved state and only a small amount of the heavy metals. The faeces are a very small fraction by mass, containing some nutrients and metals. The greywater is the largest fraction by mass, containing only small amounts of nutrients but the majority of the heavy metals (Paper I; NV, 1995; Koch & Rotard, 2000), and thereby also the concentration of substances. The composition of the biodegradable solid waste is comparable to that of the faecal fraction (Paper I).

2.1 Urine

2.1.1 Composition

The major proportion of the nutrients in the wastewater originates from the urine. Of the amounts consumed in food, about 80-90% of the nitrogen, 50-80% of the phosphorus and 80-90% of the potassium are found in this fraction (Berger, 1960; Schroeder & Nason, 1971; Lentner et al., 1981; Guyton, 1992; Frausto da Silva & Williams, 1997). All of the nutrients in the urine are in water-soluble forms and are thereby easy for microorganisms to digest and if not available for plants to take up easily transformed into plant available compounds (Kirchmann & Pettersson, 1995).

With the approximately 550 kg of urine excreted (Hellström & Kärrman, 1996) about 4 kg (NV, 1995) nitrogen are excreted per person (p) and year (y). The nitrogen is mainly found as urea (80%), ammonia (7%), creatine (6%) and the remaining part is in the form of shorter peptides and free amino acids (Lentner et al., 1981). The 365 g p^{-1} y^{-1} of phosphorus (NV, 1995)is mainly excreted as inorganic phosphates and one of their main purposes is to buffer the pH of the urine (Guyton, 1992). The 1.1 kg of potassium (NV, 1995) is, like sodium, mainly found in the urine as free ions (Berger, 1960).

Only small amounts of the heavy metals consumed will be found in the urine, generally 5% to 15% (Kehoe et al., 1940; Jones Harp & Scoular, 1952; Schroeder & Nason, 1971; Lentner et al., 1981; Vahter et al., 1991; WHO, 1991, 1992, 1995; Nordic, 1996; Frausto da Silva & Williams, 1997). Of the inhaled and consumed organically combined heavy metals, a larger proportion will be digested and therefore a larger proportion will be found in the urine. However, the fraction of heavy metals found in the urine is still small.

2.1.2 Urine diversion

During the latter part of the 20th Century, urine-diverting toilets were reinvented with the purposes of collecting the urine separately and thus providing a fraction of non-polluted nutrients and also of decreasing flushwater consumption. When analysing different sewage treatment alternatives using Life Cycle Analysis and Systems Analysis, it was shown that urine diversion was a good alternative with respect to water-recipient preservation, energy usage and nutrient recycling (Jönsson et al., 1998, 2000; Kärrman et al., 1999; Kärrman, 2000).

The double flushed urine-diverting toilet has two separate bowls, the urine being collected in a smaller front bowl and the faeces and toilet paper in a larger rear bowl (Figure 3). The urine mixture (urine and flushwater) is then transported in a separate soil pipe to a collection tank. After collection, the urine mixture is stored on site or transferred to a storage tank (Figure 4) for sanitation by storage, in Sweden for one to six months before usage as a fertiliser (Höglund, 2001).

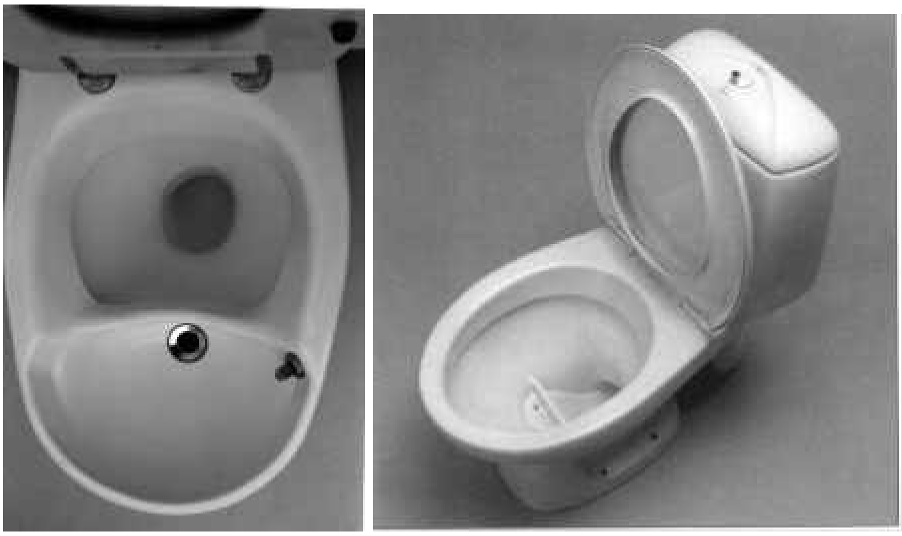

Figure 3. Two double flushed urine-diverting toilets, Dubbletten and WM-Ekologen DS

Several studies have been performed regarding how much of the potentially collectable amount of the urine is actually collected. These studies have shown that between 50% and 80% of the excreted urine is collected (Jönsson et al., 1997, 1999, 2000; Vinnerås, 1998; Lindgren, 1999). An important factor regarding the percentage collected is how well informed and conscientious the users are. It could be possible to collect more than 80% if the users are well informed and thus use the toilet correctly.

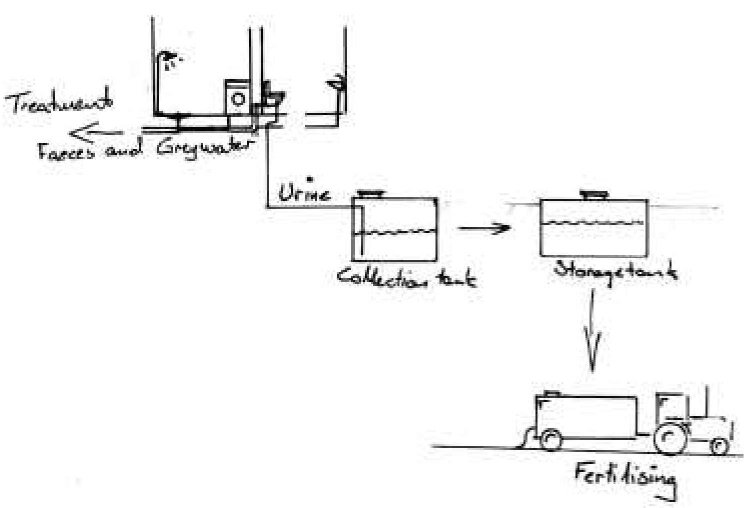

Figure 4. A urine-diverting wastewater system

Due to the low content of heavy metals in the urine (Figure 2), heavy metal contamination by other sources has a significant effect on the heavy metal content of the collected mixture. The two main contamination sources are corrosion from pipes and domestic cleaning water poured into the toilet (Paper I).

When the urine is collected, the urea content is normally biochemically transformed into ammonia and carbon dioxide and the pH is thereby raised from about 7 up to over 9. This reaction occurs as early as in the U-bend and the first metres of the soil pipe (Vinnerås et al., 1999; Jönsson et al., 2000). The content of free ammonia makes the urine mixture highly corrosive. Thus metals in the soil pipes will corrode and pollute the urine mixture. Use of metals should therefore be avoided in pipes and fittings.

2.2 Faeces

2.2.1 Composition

Faeces is by weight the smallest of the biodegradable waste fractions. Between 30 and 45 kilograms, wet weight, of faeces are produced per person and year. This corresponds to 10 - 15 kilograms of dry matter (Paper I; Lentner et al., 1981). The volume produced per person depends upon the composition of the food consumed. Meat and other foods low in fibre produce smaller volumes than food high in fibre (Guyton, 1992). On average, one stool per person and day is produced, but it varies from one per week up to five per day (Lentner et al., 1981; Pharmacia, 2000).

In Sweden, 8.5 kg of toilet paper are used per person and year (Anonymus, 1994), of which about 10% is expected to be used for other purposes and not thrown into the toilet. Thus about 7.7 kg p^{-1} y^{-1} of toilet paper will be collected together with the faeces (Paper I).

Of the nutrients from the food consumed, 10-20% of the nitrogen, 20-50% of the phosphorus and 10-20% of the potassium will be found in the faecal fraction (Figure 1), while the rest is found in the urine (Berger, 1960; Lentner et al., 1981; Guyton, 1992; Frausto da Silva & Williams, 1997). The distribution depends upon the composition of the food consumed, especially in the case of phosphorus where calcium regulates the amount of phosphorus available for uptake in the digestive system (Frausto da Silva & Williams, 1997).

Of the faecal nitrogen, about 17% is contained in the bacterial fraction and about 10% is found as ammonia from degradation of urea, peptides and amino acids. The remaining proportion of the nitrogen is found in different organic compounds such as uric acid and different enzymes or peptides. The nitrogen in the faeces is about 50% water-soluble (Trémolières et al., 1961).

Phosphorus is mainly found as granular calcium phosphates in the faeces (Frausto da Silva & Williams, 1997), but some phosphorus is found in organic compounds and a very small amount as soluble phosphorus ions (Lentner et al., 1981). Potassium is mainly found in its water-soluble ionic form (Berger, 1960).

The heavy metals, i.e. metals with a specific gravity above 4.5 (Greenwood & Earnshaw, 1998), can be divided into two fractions; proven essential elements and non-proven essential elements (Frausto da Silva & Williams, 1997). The main proportion of all heavy metals consumed passes through the intestine undigested, while many of the heavy metals inhaled are taken up by the body (WHO, 1991, 1992, 1995).

The heavy metals taken up are in time excreted in urine, faeces and sweat in different proportions for different heavy metals. Cadmium and mercury are to a large extent excreted in the urine, while the others to a large extent are found in the faeces. The trace elements Cu, Cr and Zn are also excreted via the sweat in relatively large amounts (Schroeder & Nason, 1971). However, due to the low digestion of consumed heavy metals, the main proportion will be found in the faecal fraction where they remain during the entire passage through the intestines (Vahter et al., 1991).

2.2.2 Faecal separation

Source separation and collection of faeces can be done either by collecting the faeces dry or, if a water closet is used, by separating the faeces from the flushwater after a short transport. To get a functional system where both the water recipient is protected and the nutrients are collected into reusable fractions, the urine has to be diverted and collected separately at source

(Paper III; Fittschen & Niemczynowicz, 1997; Del Porto & Steinfeld, 1999). This paper only deals with the separation of faeces from water after a short water transport.

The main idea of faecal separation is to keep the advantage of the flushed toilet and then after a short transport make it possible to recover the faecal nutrients in a fraction as small, undiluted and unpolluted as possible.

There are several commercial separation systems available on the market today. The two main types of systems used are filtration and Aquatron or in some cases a combination of both. The Aquatron system is based upon a combination of a whirlpool effect, surface tension and gravity; some systems also have a filter that increases the effect of the separation. The filtration systems available today are based on filters with a filter cake that complements the filter with a retention time of several months. In general, all these kinds of system are simple, robust and un-mechanised.

2.2.3 Blackwater

Blackwater is the denotation used for the flow when urine and faeces are kept together and separate from the greywater. Often blackwater is collected in a vacuum system and this kind of system has been used for decades on boats. One major advantage with these systems is that all the nutrients from the faeces and the urine are collected. One major disadvantage, however, is that the systems are highly mechanised and therefore need a lot of maintenance to function.

2.3 Biodegradable solids

The biodegradable solid waste is composed of solid food waste not eaten, but the liquid part of the food waste being found in the greywater. Due to higher amounts of heavy metals in the exterior parts of vegetables (McLaughlin et al., 1999) and bones and shells containing larger proportions of phosphorus and calcium compared to the average content in food, the parts of the food ending up in this fraction have a slightly different composition compared to that of the food consumed. In Sweden, this fraction is often collected separately and biologically treated, either at the house or at a central treatment plant.

2.4 Greywater

The greywater fraction is the largest wastewater fraction as regards both volume and dry matter content (Figure 1). Its contents of nitrogen and phosphorus are low, and the amount of phosphorus depends heavily on the usage of phosphorus-containing detergents. The potassium content is high, about 45% of the total content of potassium in the wastewater is to be expected in this fraction. It originates from detergents and potassium-supplemented salts, etcetera.

The main proportion of the heavy metals in household wastewater is found in the greywater. Main sources of the heavy metals are considered to be dust, extraction from metal-containing materials such as cutlery and machines, dyes of cloths, some phosphorus-based detergents and in some case building materials (e.g. Cd in PVC and Pb in paint) (Moriyama et al., 1989; Vahter et al., 1991; Kim & Fergusson, 1993; Comber & Gunn, 1996; McLaughlin et al., 1999; Koch & Rotard, 2000).

3 Objectives

The main objective of this study was to investigate the potential for collection of biodegradable solid waste and unpolluted wastewater fractions for recycling of their nutrients, to obtain sustainable handling of these fractions.

The specific purpose of the study was to identify the composition of biodegradable household solid waste and wastewater, identify chemical differences within the collected urine and identify the potential for local recycling of nutrients by using faecal separation.

Studies of the composition of the biodegradable household solid waste and wastewater were performed in parallel on the four fractions urine, faeces, greywater and biodegradable solids to determine the amounts in the different fractions and to identify the internal distribution of the fractions concerning mass, nutrients and heavy metals. The results are presented in Paper I.

To investigate if there were any internal differences in the collected urine mixture, the chemical stratification of the urine was analysed, and results of this are presented in Paper II. The study was performed in both collection tanks and storage tanks to see what happens in the urine mixture over time and to determine the best way of sampling to get representative samples.

The potential of faecal separation was studied and presented in Papers III and IV. The faecal separation was studied in the Ekoporten block of flats in Norrköping, where urine was diverted at the toilets and the faeces was separated in the basement by two Aquatron separators. The results are presented in Paper III. To compare different separation techniques, a laboratory study was performed mainly comparing small system separation by Aquatron and filtration. Flotation and sedimentation were also briefly studied, the results being presented in Paper IV.

4 Distribution of substances in the biodegradable solid waste and wastewater

The composition of the different fractions of biodegradable solids and liquids has often been studied one at a time (NV, 1995; Jönsson et al., 2000) or in some cases the composition of greywater has been calculated by withdrawing the other fractions from a mixed wastewater (NV, 1995).

In the study in Ekoporten, all fractions were collected at the same time to enable investigation of the composition and the internal distribution of the different fractions (Paper I). It was thereby possible to identify misplaced compounds in some of the fractions, e.g. urine in the faecal fraction and domestic cleaning water in the urine mixture and the faecal water. The misplaced quantities could then be deducted and added to the correct fraction.

According to the results from the study in Ekoporten and other studies, an updated norm for the composition of urine, faeces, greywater and biodegradable solids was proposed. The figures proposed to change are given in bold type in Table 1. These figures are the average that can be expected in the different waste fractions originating from Swedish subjects.

The volumes and composition of the fractions investigated are not exact figures but the average of what to expect from an average person in Sweden. The composition of urine and faeces depends on the diet of the subjects and to some extent on their metabolism. The composition of the biodegradable solid waste depends on how much of the food that is purchased is disposed of in this fraction. Finally, the composition of the greywater depends on several things, e.g. detergents used, extraction rate from machinery and heavy metal fallout.

Due to changes in the diet and usage of chemical household products, the norm has to be continuously updated to reflect the present composition of the biodegradable waste and wastewater fractions.

Table 1. A proposal for new Swedish norm values for amounts of mass, nutrients and heavy metals in the different fractions of biodegradable waste per person and year. The bold entries are those for which changes are proposed (Paper I)

Parameter	Urine	Faeces	Greywater	Biod. Solid	Total
Mass [kg]	**550**	**40**	**40 000**	80	**40 670**
DM [kg]	21.9	**18.0**	29.2	24.1	**93**
N [g]	4 015	548	**460**	482	**5 505**
P [g]	365	183	110	92	750
K [g]	**1 100**	**400**	**1 000**	224	**2 724**
Cu[mg]	37	402	2 190	**450**	**3 079**
Cr [mg]	3.7	7.3	**1 100**	241	**1 352**
Ni[mg]	2.6	27.0	**720**	**60**	**810**
Zn [mg]	16	3 942	**12 200**	**1 300**	**17 458**
Pb [mg]	0.7	7.3	1 095	236	1 339
Cd [mg]	0.4	3.7	**65.0**	3.1	**72.2**
Hg [mg]	**0.5**	**7.6**	**8.4**	**0.4**	**16.9**

5 Urine diversion

The system of urine diversion is based on a toilet that enables the urine to be collected separately (Figure 3). The different toilet models available today collect about the same amounts of urine, but the amount of diluting flushwater varies greatly between the different models and the size of the U-bend of the urine pipe (Hanaeus & Johansson, 1996). The single flushed urine-diverting toilet, where the faeces is collected dry seems to give the highest concentration of urine mixture (Olsson, 1995; Höglund et al., 1999).

The urine is collected with a small amount of flushwater used to clean the bowl after usage. The urine mixture is then collected in a tank and after storage used as a fertiliser (Jönsson et al., 1997, 2000).

5.1 Activity in the collected urine mixture

When the urine is collected and transported to the collection tanks via soil pipes, some chemical, biochemical and biological activity occurs (Paper II; Höglund et al., 1999; Vinnerås et al., 1999; Jönsson et al., 2000).

In the U-bend of the urine bowl and in the adjoining soil pipes, organic compounds in the urine, e.g. urea and peptides, are decomposed by microorganisms and enzymatic activity (Jönsson et al., 2000). This activity raises the pH due to ammonia formation.

Another chemical activity is precipitation of phosphates from the urine and metal ions from the urine and the flushwater (Vinnerås et al., 1999). The precipitation rate of metal phosphates increases in urine with higher concentrations of metal ions and with increased pH. Sediment with a high phosphorus content will be formed in the soil pipes. The sediment also contains a lot of active microorganisms. If the system is correctly built, the sediment will slowly be transported into the collection tank where it will form a bottom layer that contains higher concentrations of both nutrients and microorganisms (Paper II; Vinnerås et al., 1999).

The occurrence in the urine tank of sediment with a higher concentration of phosphorus gives a non-homogeneous urine mixture. The effect of different layers in the collected urine mixture is to produce non-homogeneous solutions that do not supply equal nutrient dosage during fertilising and that give rise to unrepresentative analyses if samples are taken in different layers (Paper II; Vinnerås et al., 1999). Therefore the vertical difference in chemical composition of the urine mixture was investigated to see if there were any layers in collection and in storage tanks (Paper II). Three different layers were detected in this study, a bottom layer, smaller than 5% of the total volume, containing higher concentrations of phosphorus and metals, a middle layer larger than 90% of the total volume with a composition more or less the same as the total mixed urine mixture and a top layer containing fewer nutrients and metals compared to the others.

Therefore a risk exists for miscalculation of the chemical composition of the collected urine mixture if samples are taken at the top or bottom of the mixture, where the concentrations differ and have a different internal distribution than the main part of the urine mixture or than a homogeneous urine mixture. Therefore, samples from collected urine mixture should be taken in the middle of the tank to get representative samples (Paper II). To get a representative result if the urine mixture analysed is made homogeneous by mixing, the tank has to be cleaned before it is filled. Otherwise old sediments will increase the content of nutrients, especially phosphorus, and produce misleading results.

Due to the small volume of the urine in the top and the bottom layers, the importance of a non-homogeneous nutrient supply when fertilising is small. However, if possible the urine mixture should be mixed before use as a fertiliser to provide a chemically homogeneous mixture.

5.2 The potential of the urine diverting system

The amount of urine mixture collected mainly depends on the time spent at the place where the urine is collected. There is a linear correlation between time and the amount of urine excreted, which provides the potential to calculate the percentage of urine collected per person and day even if the person did not spend all the time at home (Hellström & Kärrman, 1996). If the collected amounts are corrected to reflect a full-time resident, as if all of the time was spent at home or if all toilets used were urine diverting ones, the percentage of urine mixture collected differs widely, from 50% up to over 80% (Paper III; Jönsson et al., 1997, 1999, 2000; Vinnerås, 1998; Lindgren, 1999). It seems as if a combination of function of the toilet, motivation and knowledge are the reasons for the difference in how much is collected (Jönsson et al., 2000).

Thus, there is a potential for collecting more of the excreted urine if the users are better informed about the function of the system and about why they have the system, and also if initial problems with the design of the toilets are taken care of. This is similar to other recycling systems.

Due to the low content of heavy metals in the urine (Table 1; Figure 2) the effect due to contamination from other sources is great. The two main sources are corrosion of heavy metals from the soil pipes and the disposal of other liquids, such as domestic cleaning water, in the toilet (Paper I; Paper II; Paper III; Jönsson et al., 2000). Therefore, when building these kinds of systems, the materials that come into contact with the urine have to be free from metals, due to the corrosive nature of the urine mixture. The users of the urine diverting toilets also have to be informed about not disposing of domestic substances in the toilets. One major source of heavy metals is domestic cleaning water, due to the high content of heavy metals in dust (Kim & Fergusson, 1993). This contaminated the urine and faecal fractions in Ekoporten (Paper I; Vinnerås et al., 1999).

6 Faecal separation

The purpose of faecal separation from flushwater is to have the advantage of using a water-flushed toilet and still be able to collect a small fraction, according to its mass, containing the major proportion of the faecal nutrients.

These systems are all dependent on the fact that the nutrients remain in the particles that are separated. Therefore the fraction to be separated must contain as little water-solved nutrients as possible. The urine should therefore be diverted in the toilet to avoid its high load of water-solved nutrients.

6.1 Technical basis

The filtration system for faecal separation is based on a filter, often made of geotextile, through which the outgoing water is filtered. The interval between removals of the filter cake in the system is about half a year to a year. So the filter cake forms a complement to the filter and is therefore continuously washed during the retention time. With this kind of system there is a risk of major nutrient losses by mineralisation and extraction.

The Aquatron system separates the solids from the fluids directly when passing through the separator. The separation mechanism is based on the fact that the liquid follows the outer surface of the separator while the solids drop down in the middle (Figure 5)

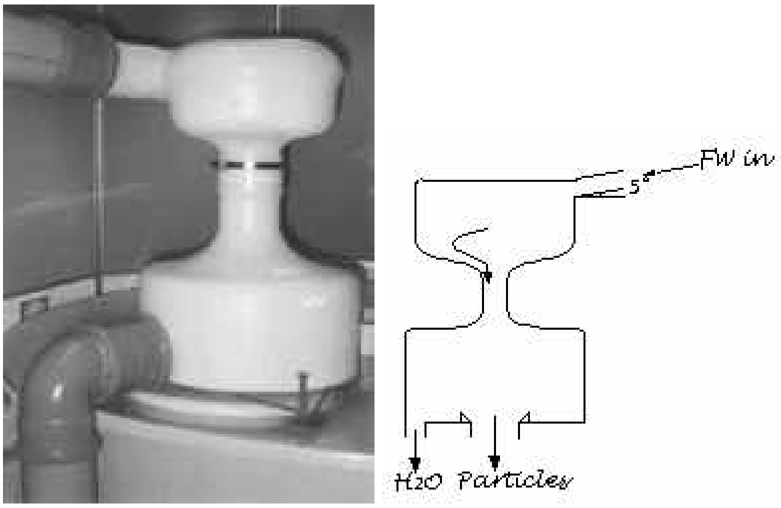

Figure 5. The faecal separator Aquatron and its function where the faecal water (FW) is separated into liquids and solids.

6.2 The study in Ekoporten

Ekoporten, situated in Norrköping in the southern part of Sweden, is a four-story block of flats, which was rebuilt during 1995. When rebuilding, the environmental effects and usage of resources were in focus. The house consists of 18 flats and during the measurements in the spring of 1999 there were 35 people living in the house. When the wastewater system was rebuilt, urine-diverting toilets were installed. The soil pipes for the different fractions of urine, faeces and greywater were kept separate. In the basement two Aquatron separators were installed to separate the faecal fraction into separated solids (SS) and separated water (SW). The SS fraction is diverted to a composting drum where it is composted, together with the biodegradable solid waste and sawdust. The SW is led into the greywater, which after passage through a septic tank is treated in a soil filter before it is discharged into a local water recipient. The separated urine mixture is collected and stored locally (Figure 6).

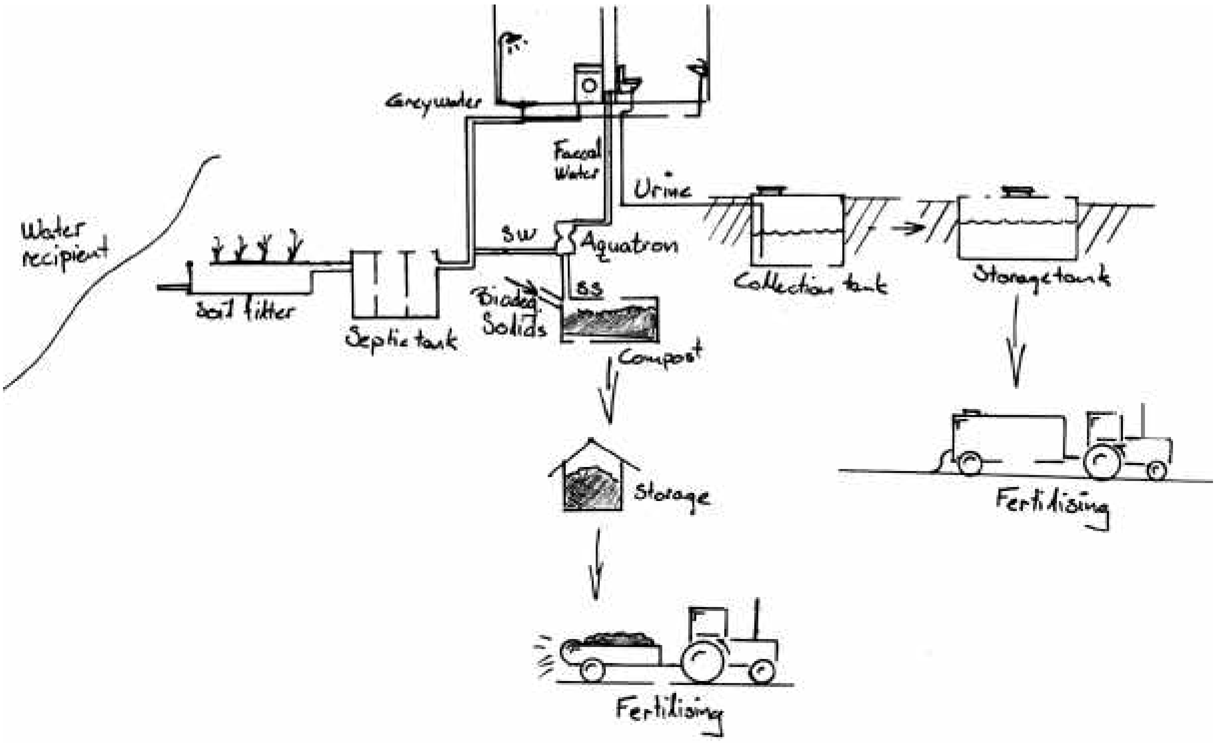

Figure 6. The wastewater system in Ekoporten.

In the Ekoporten study all the fractions of biodegradable waste and wastewater were collected and analysed. It was therefore possible to identify all of the flows and to allow corrections for misplaced components such as urine and domestic cleaning water (Paper I; Paper III).

The urine that was misplaced into the faecal fraction was deducted to enable calculation of the separation efficiency of the two Aquatron separators. Due to the different chemical forms, the nutrients nitrogen, phosphorus and potassium were separated by the Aquatrons into the fraction of separated solids (SS) in different percentages. Of the faecal nitrogen, which is mainly organically combined, more than 58% was found in SS, while the mostly inorganic phosphorus was separated to almost 58% and the mainly ionic potassium only to 45%. The different chemical form of the analysed elements is the reason for the different distributions of the elements (Paper III).

With the faeces, 13% of the used flushwater was collected. This gave a rather diluted fraction, with 0.2% dry matter content (Paper III). The high dilution comes from a combination of the disintegration of the particles and the large amount of flushwater used. The high disintegration allows more water to be absorbed into the particles and toilet paper absorbs a lot of water, giving a lower dry matter content, which also means more water into the SS fraction. Almost as many faecal flushes as urine flushes were performed, so a lot of water passed through the separator, giving a high water content in the SS fraction.

The faecal fraction was contaminated by domestic cleaning water poured into the toilets. This resulted in both a more diluted SS fraction and in an increased amount of heavy metals in the faecal fractions (Paper III). This emphasises the importance of not putting foreign materials in the toilet since they reduce the high quality of unpolluted recyclable nutrients. In conventional systems when all fractions are kept together this is not a problem since the material will be mixed into the wastewater in the system anyway. But in systems that recycle the toilet fraction, a good alternative for disposing domestic liquids has to be available to avoid this kind of contamination.

6.3 The laboratory study of faecal separation

To follow up the study in Ekoporten, a study in the laboratory was performed on the effects of different conditions before separation and different separation techniques. First, the effect on the faeces of submersion into water for different time periods and different oxygen supplies was investigated. The second part in the laboratory study consisted of investigations of the performance of different separation techniques (Paper IV).

When faeces are submerged in water, a rapid biochemical degradation of the faeces and a mineralisation of the nutrients occurs (Paper IV). The degradation of the faeces was monitored by measuring the redox-potential. The increased amount of ammonia also indicated the high biochemical activity (Figure 7). No significant differences in chemical degradation were found as a function of the amount of available oxygen. There was some tendency towards higher losses from samples where air was bubbled through the sample to get an aerobic environment compared to the samples that attained anoxic and anaerobic conditions (Paper IV). This was probably due to a higher reaction rate with oxygen present. Therefore it is important that the separation is performed as soon as possible after the faeces are submerged into the water, to retain as much of the faecal nutrients as possible in the particles and thus easily separable.

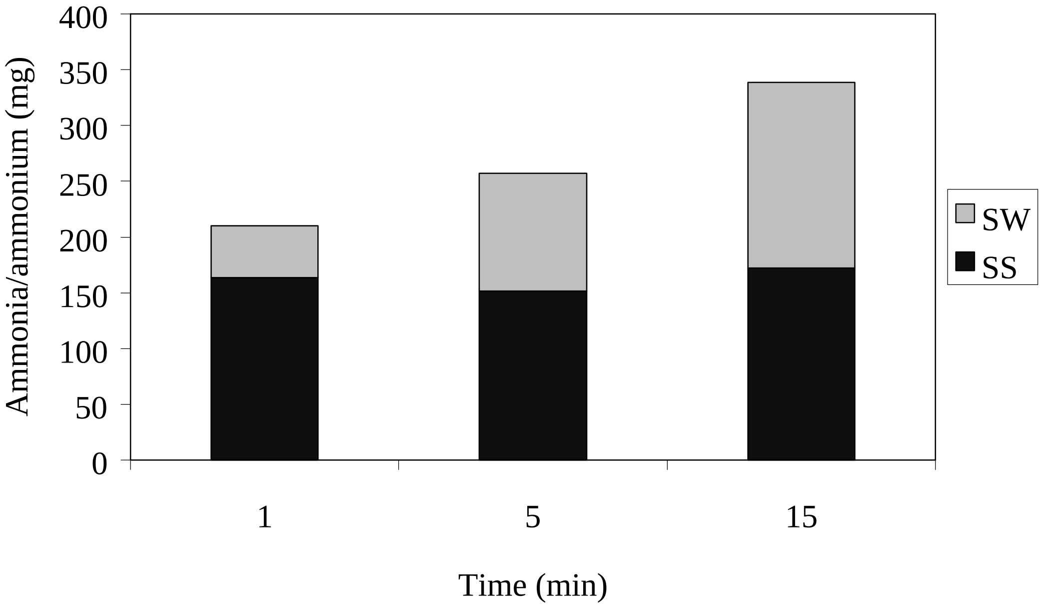

Figure 7. The total amounts of ammonia in the fractions of SW and SS after the faeces were immersed in water for 1, 3 or 15 minutes before separation.

Of the different separation techniques, filtration with instant removal of the filter cake and Aquatron were investigated closely, while sedimentation and flotation were discarded due to their inability to perform a fast and effective separation of the faecal particles from the water.

The filtration and the Aquatron showed similar separation efficiencies (Paper IV). The pattern of the separated amounts of nitrogen, phosphorus and potassium differed between the two separation techniques. The separation by Aquatron separated 70% of N, P and K into the separated solids (SS) fraction (Figure 8), which had a dry matter content of 10%. Filtration with 1mm pores separated 80% of the nitrogen, 72% of the phosphorus and of the 65% potassium was separated into the SS fraction, which had a dry matter content of 10%.

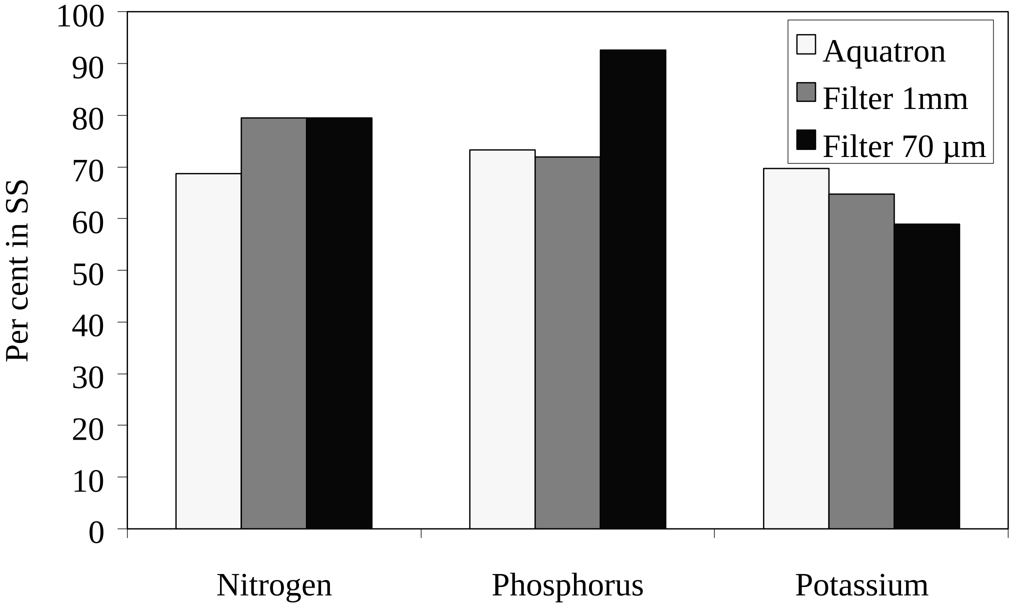

Figure 8. The amounts separated into SS when separating faecal water by 1 mm filter, Aquatron and 70 µm filter.

The difference in the distribution of the elements is due to how the nutrients are separated by the two techniques. By filtration, all particles larger than 1 mm are collected and, when a thin filter cake is formed, even smaller particles are captured in the filter. Thus the loss of nutrients occurs by extraction and suspended small particles. The nutrients not captured by the Aquatron are mainly nutrients still combined to larger particles suspended in the water that were not separated.

The best separation performance with regard to captured amounts of nitrogen and phosphorus was suction filtration via a filter with 70 µm pores performed in Part 1 of the laboratory study (Paper IV). After the faeces had been immersed in water for 15 minutes, 79% of the nitrogen and 92% of the phosphorus was recovered in SS (Figure 8). This indicates that the faecal phosphorus is found as small granules, mainly composed of calcium phosphates (Frausto da Silva & Williams, 1997) that are suspended in the water and thus not separated by filtration with large pores.

6.4 The potential of faecal separation

The difference in the performance of faecal separation by Aquatron in the two studies, in Ekoporten and in the laboratory, shows the importance of avoiding large vertical drops that disintegrate the particles and of minimising the number of flushes, which increase the dilution of SS (Paper III; Paper IV). Therefore, when the system is installed in buildings with more than one floor, the separated amount of nutrients will probably be higher if the separation is performed on each floor.

The Aquatron is a good system for local separation of faeces for nutrient recycling. The system contains no moving parts, which increases its robustness. Some problems still exist, however. The separation performance as regards the dry matter content varied a lot without any visual differences existing during the tests in Ekoporten (Paper III).

The rapid degradation of the faeces and the extraction of the nutrients show the importance of separating the faeces from the water as rapidly as possible. Otherwise the nutrients will be mineralised and extracted to the water and discharged to the wastewater system, from which they will have to be removed again. Therefore, filtration systems with a retention time of several months are tentatively not recommended.

To have a good separation performance of the faecal separation system, as many of the nutrients as possible have to be bound to particles. Therefore the urine with its dissolved nutrients has to be diverted by using urine-diverting toilets.

The best separation performance was achieved by suction filtration through filters with 70 µm pores (Paper IV). This kind of technique requires a lot of energy to perform the separation and the removal of the filter cake needs some kind of mechanical device, which renders this kind of system complex.

7 The potential for the techniques and their effect on the environment

With the sewage system of today, a lot of substances are discharged to the water recipients. Most of the phosphorus and the majority of the nitrogen are removed together with a small fraction of the potassium. If the main proportion of the nutrients could be collected and recycled locally at the houses, the central sewage treatment could be optimised for treatment of the greywater and the flow of polluting nutrients would decrease.

To get a well-functioning system in which the nutrients are collected, the urine diverting system is a good alternative and the nutrients collected are directly plant available (Kirchmann & Pettersson, 1995; Jönsson et al., 1997, 1999, 2000; Höglund et al., 1999).

With better information about how to use the urine diverting toilets and what the environmental impact is from using urine diversion, it will probably be possible to collect more than 80% of the urine nutrients and thereby collect more than 58% of the nitrogen, 39% of the phosphorus and 32% of the potassium in the biodegradable waste and wastewater from households (Figure 9). If it were possible to collect all the urine, the figures for N, P and K would be 73%, 49% and 40%, respectively (Figure 9).

If the urine diverting toilets with 80% diversion of the urine are combined with faecal separation where, as in the laboratory tests, 70% of the faecal nutrients were collected, 59%, 54% and 40% of N, P and K, respectively of the nutrients from the biodegradable waste and wastewater would be collected in small recyclable fractions (urine mixture and SS)(Figure 9).

If the biodegradable solids were collected together with 80% of the urine and 70% of the faeces, the collected recyclable nutrients from the households would be 68% nitrogen, 66% phosphorus and 48% potassium.

If a blackwater system or dry collection of the faeces were to be used instead, where all the urine and the faeces were collected, the amount of the biodegradable household waste and wastewater collected would be 83% of the nitrogen, 73% of the phosphorus and 55% of the potassium (Figure 9).

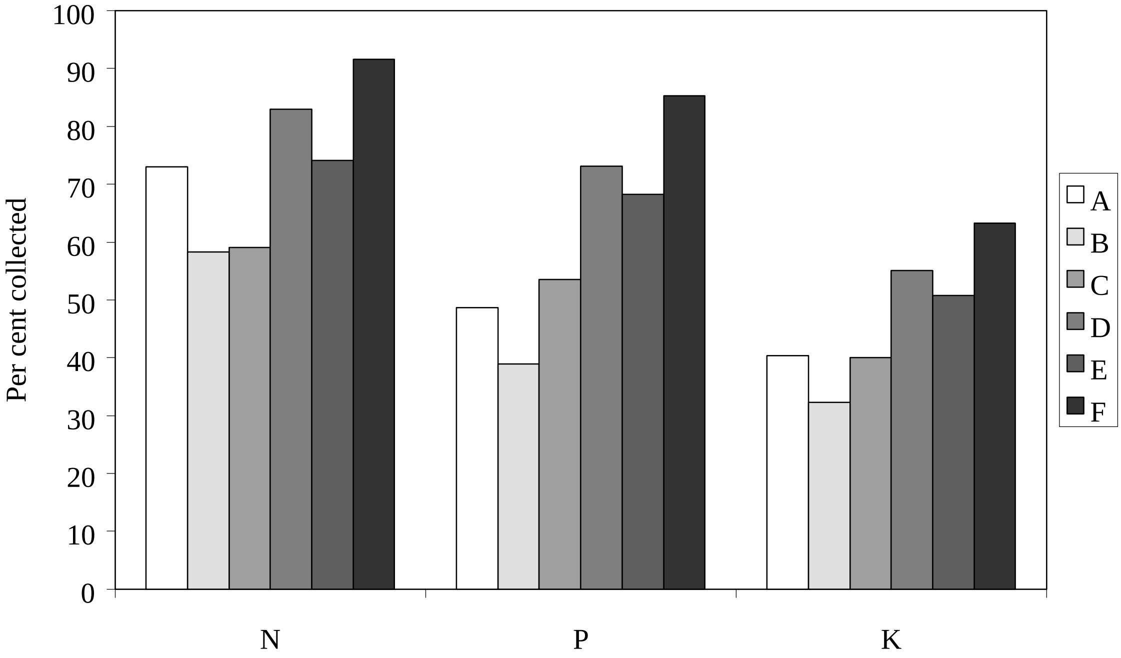

Figure 9. The potential of nutrients collected from the biodegradable solid waste and wastewater depending on separation efficiency, A=100% urine collected, B=80% urine collected, C=80% urine + 70% faeces collected, D=100% urine + 100% faeces collected, E=80% urine + 70% faeces + 100% biodegradable solids collected and F=100% urine + 100% faeces + 100% biodegradable solids collected.

If all of the urine, faeces and biodegradable solids fractions were collected, 92% of the nitrogen, 85% of the phosphorus and 63% of the potassium from the households would be available for recycling (Figure 9).

In an environmental perspective, a blackwater system combined with collection of the biodegradable solids would be the best alternative for recycling of plant nutrients from the households. Today there are no efficiently functioning blackwater systems available. Systems with urine diversion, faecal separation and separate collection of the biodegradable solids are effective alternatives with a high potential for recycling of nutrients.

8 Further studies

Due to the advantages with blackwater systems, the function of these has to be further investigated and developed. This is partially done within the development of the area “Hammarby sjöstad” in Stockholm.

Sanitation of the biodegradable solid waste, faeces and blackwater has to be done before recycling its nutrients. Techniques used today are mainly thermal treatments by pasteurisation and solid or liquid thermal aerobic or anaerobic digestion. These techniques are complicated, highly mechanised and require process knowledge for maintenance. For proper functioning the systems also have to be relatively big. In order to provide local recycling systems new techniques to maintain the hygiene has to be developed. These techniques should be simple, robust and resource saving. One easy way would be to sanitise the waste by chemical treatment, before transport from the place of collection. This technique could be used at each collection site, by the owner of the system.

The laboratory studies of Aquatron indicated a better separation of faecal nutrients and production of a drier separated solids fraction if the vertical and horizontal transports were shorter. To confirm this, studies of real systems with short transports, e.g. one-floor buildings, to verify the recommendation of installing a separator on each floor.

Flushed toilet paper will absorb a lot of water, a probable effect from this is an increased amount of water in the separated solids. During the laboratory study decreased dry matter was an effect by increased usage of flushwater. To see the effect on the separation efficiency depending on water and toilet paper usage studies with varied water and paper usage have to be performed.

To see if the separation technique using long-time filtration is an alternative for collecting and recycling of faecal nutrient, the technique has to be investigated with the focus on the amount of nutrients collected in the filters.

9 Conclusions

By using urine-diverting toilets, and if all of the urine produced is collected, it is possible to collect 88% of the nitrogen, 75% of the phosphorus and 55% of the potassium in household wastewater. This is a fraction containing from heavy metals unpolluted plant nutrients.

To collect even more nutrients and still have the advantages of flushed toilets, filtration or Aquatron faecal separation from the flushwater into a small solid fraction could, after a short transport, separate 70-80% of the faecal nutrients.

Urine diversion combined with faecal separation is a good alternative for removal of nutrients from the wastewater into unpolluted fractions that are easy to recycle to agriculture.

The performance of the separation depends on the degree of disintegration of the faecal particles. Disintegration will give larger losses of small particles and a higher extraction of nutrients from the particles due to the larger contact area. Therefore a longer pipe transport will decrease the nutrient separation efficiency when using Aquatron or filtration with 1 mm pores. Filtration with finer pores is not as sensitive to disintegration as regards its separation of phosphorus, but for nitrogen and potassium the effect is the same as for the other techniques.

In the collected urine mixture, three layers with different chemical compositions occur in the tank. The middle layer contributes more than 90% of the total volume. Therefore the layers do not have any major effects regarding the total dosage of nutrients when fertilising. Samples should be taken from the middle of the tank to get a good reflection of the composition of the homogeneous urine mixture or preferably, if the tank is cleaned before collection, the samples should be taken from a mixed homogeneous urine mixture.

Metals should be avoided in systems for diverted urine. The high pH in combination with the ammonia content in the urine will increase the corrosion of heavy metals, which will pollute the urine mixture and decrease the lifetime of the installation.

Domestic cleaning water is a considerable source of heavy metals and therefore in a system that recycles the toilet waste, domestic cleaning water should not be poured into the toilet since it will pollute the unpolluted fractions of urine and faeces.

The norm for the composition of the biodegradable waste and wastewater fractions depends on the food consumption and the usage of household chemicals. Therefore, the norm has to be continuously updated to reflect the present composition of the fractions of biodegradable waste and wastewater.

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The composition of biodegradable solid household waste and wastewater – flows of nutrients and heavy metals

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1 Abstract

The purpose of this study was to determine the composition (nutrients, heavy metals) and mass flows of the different fractions of biodegradable solid waste and wastewater and to compare these to present norms.

In the study the fractions of urine mixture (urine and flush water), faecal water (faeces, toilet paper and flush water), greywater and biodegradable solid waste from 35 people were measured and analysed during 35 consecutive days.

Based on the results, a proposal is made to update the Swedish norms for the composition of biodegradable waste, both liquid and solid, originating from households.

Key words: Nutrient, heavy metal, urine, urine diversion, urine separation, faeces, biodegradable household waste, greywater, wastewater standards.

2 Introduction

To evaluate the environmental impacts (mainly eutrophication) of households, and to compare different treatment alternatives for household wastewater, the quantities and composition of household wastewater and biodegradable solid household waste need to be known. For conventional sewage systems, it is enough to know the composition of the incoming mixed wastewater. However, if complementary sewage systems where the flows are already kept separated during collection are used (i.e. source separating systems), the composition of the different fractions has to be known. By having source separating sewage systems, it is possible to give specific treatment to each component flow. It is thereby possible to optimise the chosen treatment system, to achieve the best treatment for minimising the emissions from wastewater and for recovering unpolluted nutrients for recycling to agriculture and ultimately for preserving natural resources (Hanaeus et al., 1997; Jetten et al., 1997; Otterpohl et al., 1999; Skjelhaugen, 1999; Kärrman, 2000; Günter, 2000; Johansson & Gustafsson, 2000).

In this study we identified and quantified the composition of the different fractions of wastewater and biodegradable solid waste. The results obtained enabled us to propose new updated Swedish norms for the composition and quantities to be expected in the different fractions.

The study was carried out during 35 days in the ecologically reconstructed block of flats Ekoporten, with 18 apartments. The wastewater fractions urine, faeces and greywater and the biodegradable solid household waste were studied.

The present Swedish norms for the quantities and composition of urine and faeces are laid down by the Swedish Environmental Protection Agency (NV, 1995) and are based on Swedish food consumption data for 1995 combined with studies of human excretion. Most of the excretion studies are presented in Lentner et al. (1981). The values in Lentner et al. (1981)

are an amalgamation of measurements, made mainly between the 1920s and the 1960s. The majority of these measurements were made with a very small selection of the population and during short periods and in many cases only one of the fractions, urine or faeces, was measured.

The present norm for greywater is based on samples from 16 apartments in an eco village during seven days, in combination with calculations from analyses of flows in other systems (NV, 1995).

For the biodegradable solid waste, a norm for the quantity and composition was proposed in 1996 by Sonesson and Jönsson (Sonesson & Jönsson, 1996). More recent analysis of source separated biodegradable solids (Eklind et al., 1997) showed a much lower content of the non-essential metals lead, cadmium and mercury and this is probably due to decreased flows of these metals in society. During recent years, several measurements have been performed that indicate a need for upgrading of the norms for urine (Jönsson et al., 1997, 1999, 2000).

2.1 Liquid biodegradable waste

The biodegradable waste produced in households can be divided into a solid and a liquid fraction. The liquid fraction can then be divided into three different flows by origin; urine, faeces and greywater.

External sources of contamination are a risk worth considering when using sewer systems to collect the different fractions, especially for urine and faeces. The two main sources of pollution are liquids poured into the sewers (e.g. domestic cleaning water poured into the toilet) and contamination from corroding material (e.g. copper corroding from pipes). Increased concentrations of copper in diverted urine (40 times the norm) have been found to originate in half a metre of copper pipe connecting the urine bowl of the toilet with the soil pipes in the walls (Jönsson et al., 1997, 2000).

2.1.1 Urine

The amount of urine excreted varies; the present Swedish norm is 365 litres per person and year. However, a more recent study has shown an average of 548 l $p^{-1}y^{-1}$ (Hellström & Kärrman, 1996).

The nitrogen in the urine when excreted is mainly found as urea (80%), ammonia (7%), creatinine (6%) and the remaining part is mainly free amino acids or shorter peptides (Lentner et al., 1981). If the urine is collected separately in a sewage system, the main proportion of the nitrogen will be biologically converted into free ammonium (Vinnerås et al., 1999). The conversion of the organic nitrogen to mineral ammonia will also have a major effect in decreasing the dry matter content of the collected urine from about 21.9 kg per person and year (NV, 1995) to less than 7 kg (Jönsson et al., 1999).

Phosphorus in the urine is mainly found as phosphates (Lentner et al., 1981) and more than 95% is inorganic. Between 50% and 80% of the phosphorus consumed is excreted via the urine, where it buffers the pH. The potassium is mainly found as free ions, the excreted amount in the urine corresponding to 80 to 90% of the dietary intake (Berger, 1960).

The content of heavy metals in the urine is very low compared to the content in the faeces and the greywater. The heavy metals can be divided into two types; one of proven essential metals, e.g. Cu, Zn, Ni, and the other of metals not proven to be essential, e.g. Hg, Cd, Pb. Of the heavy metals consumed, generally less than 10% are excreted via the urine, e.g. for Cu and Ni 3%, Zn 5%, and Pb 7% (Lentner et al., 1981). However mercury differs and about 75% is excreted via the urine (Lentner et al., 1981).

2.1.2 Faeces

Of the three-wastewater fractions, faeces is the one with the smallest mass flow. About 30 to 45 kilograms, wet weight, of faeces are produced per person and year, corresponding to 10 to 15 kilograms of dry matter (Lentner et al., 1981; NV, 1995). The amount of faeces excreted depends on the composition of the food consumed. Meat and other food low in fibre produces smaller volumes than food high in fibre (Guyton, 1992). On average in Sweden, one stool per person and day is produced, but the rate varies from one per week up to five per day (Lentner et al., 1981; Pharmacia, 2000). About 8.5 kilograms of toilet paper are used per person and year (Anonymus, 1994). Not all of the paper is not thrown into the toilet but at least 90% (7.7 kg $p^{-1}y^{-1}$) can be expected to end up in the toilet.

Next to urine, the largest proportion of nitrogen and phosphorus in the biodegradable household waste (both liquid and solid) is found in the faeces. The amounts of nutrients and heavy metals in the faeces and in the urine reflect the composition of the food consumed (Vahter et al., 1991).

Of the faecal nitrogen about 50% is water soluble (Trémolières et al., 1961) and about 17% is contained in the bacterial fraction. About 10% is found as ammonia, from degradation of urea, peptides and amino acids. The remaining fraction is found in different organic compounds such as uric acid and different enzymes (Lentner et al., 1981).

The faecal phosphorus is mainly found as calcium phosphates (Frausto da Silva & Williams, 1997), but some phosphorus is found in organic compounds and some as solute phosphorus ions (Lentner et al., 1981). Potassium is mainly found in its water-soluble ionic form (Guyton, 1992).

On average, more than 90% of the heavy metals consumed are excreted via the faeces and most of them have not been digested at all. Of the metabolised heavy metals, approximately 50% is excreted via the faeces and the rest mainly via the urine (Vahter et al., 1991).

2.1.3 Greywater

Greywater is the water used in the household, not including the water used in the toilets; e.g. water for washing dishes and clothes, showering and domestic cleaning. This part of the household wastewater corresponds to about 75% of the total wastewater flow when a conventional toilet system is used. The Swedish norm for greywater is 55 m^3 per person and year.

The amounts of macronutrients in the greywater are generally considered low. During the second half of the last century, detergents containing phosphorus were used, thereby increasing the amount of phosphorus in the fraction. During the 1990s this kind of detergents became less common, due to an increased awareness of the risk of eutrophication in recipient waters (Huheey et al., 1993). However, some of the liquid detergents available today use potassium as a saponifier. Some potassium in the greywater fraction also originates from food, e.g. food ingredients and potassium-supplemented table salt.

The content of heavy metals in the greywater is high in relation to the total content in the liquid and biodegradable solid household waste. The concentrations of heavy metals are, however, generally quite low, as a result of the large water volume. The origins of the heavy metals are mainly considered to be dust, extraction from metal-containing materials such as cutlery, dyes of cloths, some phosphorus based detergents and in some case building materials (e.g. Cd in PVC and Pb in paint) (Vahter et al., 1991; Kim & Fergusson, 1993; Comber & Gunn, 1996; McLaughlin et al., 1999).

2.2 Biodegradable solid waste

Biodegradable solid waste consists of source separated household waste. The amount of biodegradable waste according to the norm is on average about 80 kg per person and year (Sonesson & Jönsson, 1996) corresponding to 27 kg of dry matter (Eklind et al., 1997).

In the biodegradable solids, the N content is about 10% and the P and K contents about 17% of the amounts in the urine and faeces together. This agrees well with the assumption that about 10% of the food purchased is thrown away (NV, 1995). All nutrients are not evenly distributed in the food. Therefore a larger part of the phosphorus ends up in the biodegradable solids compared to the nitrogen. Scraps such as bones contain a lot of phosphorus and are always thrown away.

The content of heavy metals also agrees with the assumption of 10% being thrown away and 90% eaten. However, as for phosphorus, the waste contains more than 10% of the heavy metals. This is due to larger concentrations of heavy metals in the removed exterior- and root parts of plants and vegetables (McLaughlin et al., 1999). There is also some risk for contamination by misplaced substances and objects. Therefore, the biodegradable solid waste contains more than 10% of the heavy metals compared to the content in the urine and the faeces.

3 Materials and methods

This investigation was carried out in the Ekoporten block of flats, which was reconstructed with special consideration for the environment, i.e. emissions, recirculation of nutrients, materials used and conservation of natural resources. The house is four storeys high and consists of 18 flats and a communal area on the top floor. During the investigation, 35 people lived in the house, 34 adults and one 10-year-old boy. The sewage system is divided into three sub-systems; one for greywater, one for faecal water (faeces, toilet paper and flushwater) and one for urine mixture (urine and flushwater). These systems have separate pipe systems in the house. All flats are equipped with the urine-diverting toilet Dubbletten (Jönsson et al., 1997).

The study was carried out during a period of 35 days in the spring of 1999, and was divided into three periods of 11, 12 and 12 days, respectively. The total mass flows and the composition with respect to dry matter, nutrients and heavy metals were collected, weighed and analysed for the urine mixture, faecal water, greywater and biodegradable solid waste. Due to measurement problems, the duration of the measurements for greywater during Period One was 5 days, during Period Two 12 days and during Period Three 12 days. The faecal water was collected into two different fractions, separated solids and separated water. The duration of the measurements for separated solids during Period One was 10 days, during Period Two 12 days and during Period Three 11 days, while for the separated water all measurement periods were 11 days.

The number of flushes, both of the urine- and the faecal-bowl, were measured using electronic counters attached to the flush buttons according to the method described by Jönsson et al (1997). The water usage per faecal flush was noted and the water usage per second of the urine flush was determined. During the measurement periods, the inhabitants recorded the time they spent at home using protocols.

3.1 Sampling

During the study the urine mixture was collected in a one cubic metre plastic tank. At the end of each period, before sampling, the urine mixture was mixed by pumping and simultaneously the walls of the tank were scraped to ensure representative samples (Höglund et al., 2000). To avoid ammonia loss during the 10 minutes of mixing and sampling, the containers were covered with plastic sheets. After sampling, the samples were stored at –20°C until the analyses were performed. The collected volume was determined by weighing.

The faeces were collected in two separate fractions, separated water and separated solids. However, in this investigation these two fractions were added together after collection and treated as a single faecal water (FW) fraction.

The separated water (separated by two Aquatron separators (Vinnerås & Jönsson, 2001)) was, just as the urine, collected in a one cubic metre plastic tank. The flow of separated water was on average slightly less than 1,000 litres per day. The separated water was sampled once or twice a day, depending on the volume collected. The mixing procedure was the same as for the urine mixture. The sampling was done each day by taking weight proportional samples, ten grams per 100 kilos of separated water. Directly after sampling, all samples were stored at –20°C until the analyses were done.

The separated solids fraction was collected below the two Aquatron separators in a 120 litre plastic bin. The flow of separated solids varied from 50 to 210 litres per day. Sampling was done once or twice a day, depending on the volume collected. The separated solids were weighed and then mixed mechanically for ten to fifteen minutes with a large electric plaster mixer, until the mixture was homogeneous. The sampling was done after the mixing, taking weight proportional samples each time. One gram per kilogram of collected separated solids was taken. The samples were stored at –20°C until analysis.

The greywater was conveyed to a one cubic metre plastic tank. When the water volume was 0.700 m^3, a volume of 0.600±0.010 m^3 was pumped out automatically. Two inductive switches sensitive to the water level controlled the pump. The volume of greywater was calculated from the number of times the collection tank was emptied. From the outlet, a bleed stream was led to a 25-litre collection container. Once every day sampling was done from the 25-litre container. The size of the sample was proportional to the amount of the greywater collected each day. Ten grams of greywater were taken for each emptying cycle. Before sampling the container content was mixed by shaking. The collected samples were stored at -20° C until analysis was done. The amount of greywater entering the collection tank during emptying was estimated and corrected for, from the average flow of greywater each day.

The solid biodegradable waste was collected in a plastic bin placed in front of the normal disposal point. The bin was emptied once every second day. After weighing, the biodegradable waste was emptied on a tarpaulin where it was mixed and made into a pile. The pile was then divided into eight equally sized sections, from which two opposite sections were removed. The procedure of making a pile and removing two eights was repeated until only 10% of the waste was left. The remaining biodegradable waste was then stored at –20°C until it was ground in a mincer with 12 mm holes. After grinding, the samples from the respective period were mixed before samples were taken for analysis. These ground samples were stored at –20°C until analysis.

All samples were taken in triplicate, poured into three different sampling containers and then analysed separately. The daily samples of separated solids and separated water and greywater were added to the frozen main samples for each measurement period.

3.2 Analyses

Phosphorus, potassium and the metals, except cadmium and mercury, were analysed using ICP-AES (Perkin Elmer) after the sample was resolved in nitric acid. Samples for mercury and cadmium analyses were prepared in the same way but analysed with ICP-MS (Perkin

Elmer). Nitrogen was analysed for using elemental analysis according to the Dumas principle. Analysis was performed on triplicates of each sample. When calculating total means, the results from the three periods were weighted according to the length of each period.

4 Results

The average time spent at home was 13.9 hours per day, i.e. 58% of the day (Table 1). During this time the urine bowl was flushed 4.6±2.9 times per person and day and the faecal bowl was flushed 4.5±2.9 times. Half of the time both bowls were flushed within the same minute.

The collected volumes and the compositions of the investigated fractions are given in Table 1. In the discussion the values are recalculated to amounts per person and year for full day persons i.e. if they spent 24 h per day at home. This was done by extrapolating the two toilet fractions (urine mixture and faecal water) linearly for the time spent at home, since other studies have shown a linear correlation between the excretion of urine and time when considering more than 12 hours per day (Hellström & Kärrman, 1996). According to a Gallup survey done by Pharmacia (2000) the stools are almost evenly distributed over the day, with a slight predominance of being performed at home.

Table 1. Collected daily amounts and the concentrations of elements in the urine mixture, faecal water, greywater and biodegradable solid waste (average±standard deviation)

Parameter	Unit	Urine mixture	Faecal water	Greywater	Biod. solid
Volume	kg/day, 35p	45.9±5.3	1 006±19	3 640±1645	7.9±2.4
TS	g/kg	8.51±0.93	0.66±0.09	0.57±0.49	261±24
N	g/kg	2.49±0.60	0.10±0.01	0.016±0.003	6.86±0.09
P	g/kg	0.28±0.05	0.125±0.001	0.004±0.001	1.10±0.21
K	g/kg	0.98±0.21	0.49±0.01	0.040±0.005	2.40±0.19
Cu	mg/kg	1.82±0.35	0.057±0.003	0.11±0.02	3.70±0.20
Cr	mg/kg	0.013±0.002	0.004±0.001	0.009±0.007	3.19±3.54
Ni	mg/kg	0.040±0.007	0.006±0.001	0.008±0.002	0.41±0.07
Zn	mg/kg	0.18±0.08	0.26±0.02	0.13±0.06	8.01±0.67
Pb	mg/kg	0.019±0.011	0.025±0.004	0.014±0.007	2.47±2.27
Cd	µg/kg	0.58±0.24	0.34±0.11	0.30±0.12	33.1±21.5
Hg	µg/kg	0.43±0.24	<0.15$^{\alpha}$	<0.10$^{\alpha}$	<2.5$^{\alpha}$

α) Less than given detection limit.

The two other fractions (greywater and biodegradable solid household waste) were not expected to depend on the time spent at home, at least if more than 50% of the time is spent at home. Therefore they have not been corrected for the time spent at home.

5 Discussion

The nitrogen:phosphorus ratio of the urine mixture was nine and not the expected eleven (Höglund et al., 2000). The reason for this was probably the nitrogen losses when handling the samples before analysis. One factor that might have increased the nitrogen loss as ammonia emission was the handling of the samples by freezing and melting the samples. The low temperature can cause extraction of minerals from the water, giving a higher concentration of ammonia in the liquid phase. Earlier studies of the urine mixture from Ekoporten (Höglund et al., 2000) showed a nitrogen:phosphorus ratio of 12. The nitrogen content of the urine mixture was therefore calculated based on the phosphorus content and a nitrogen:phosphorus ratio of eleven.

5.1 Mass flow

The largest volume and most of the dry matter was found in the greywater. The volume collected, 38 m^3 p^{-1} y^{-1}, was only two thirds of the present Swedish norm, 55 m^3 p^{-1} y^{-1}, (NV, 1995). In the study by NV (1995), greywater from an ecological village was collected and the collected volume was the same as in our study. So, by using water-conserving equipment the inhabitants used considerably less water (30%) compared to the present Swedish norm. However, teenagers are often claimed to use a lot of water and no teenagers lived in the house during the measurement period.

The second largest fraction by volume was the faecal water. The urine diverting toilets used 25% less water than conventional toilets would have used, with the same number of flushes. However, by only flushing the faecal bowl after each stool, it would have been possible to save 70% of the water used by a conventional toilet.

By using water conserving equipment, taps and double flushed urine diverting toilets, the inhabitants made a saving of more than 30% of the normal water usage. This can be compared to 15%, which is the approximate water saving in most systems that recycle wastewater (McIntosh, 1996; Neal, 1996; Dixon et al., 1999).

5.2 Flows of the macronutrients nitrogen, phosphorus and potassium

All of the urine excreted at home was not collected in the urine bowl as intended. Some urine was instead collected in the faecal bowl. According to the Swedish norm, combined with the time spent at home, not as many urine-derived nutrients (nitrogen, phosphorus and potassium) were collected (Hellström & Kärrman, 1996; Hanaeus et al., 1997; Jönsson et al., 1997, 2000; Faouzi et al., 1998). This, combined with the higher than expected amounts of nutrients in faeces according to the present norm, proved the misplacement of the urine.

Approximately 32% of the urine is estimated to be collected in the faecal bowl (Vinnerås & Jönsson, 2001). Since the purpose of this paper was to check the validity of the Swedish norms, the urine that was estimated to be misplaced was deducted from the faecal water and added to the urine fraction.

Table 2. Measured values in Ekoporten (En) in grams per person and year compared to the Swedish norm values (SN) for nitrogen, phosphorus and potassium in the different fractions of biodegradable waste (NV, 1995; Sonesson & Jönsson, 1996)

Parameter	Urine mixture		Faecal water		Greywater		Biod. solid		Total	
	En	SN	En	SN	En	SN	En	SN	En	SN
Nitrogen	3741	4015	632	548	613	365	566	549	5552	5477
Phosphorus	340	365	126	182	162	109	91	104	719	761
Potassium	1186	913	537	365	1449	182	198	255	3371	1715

After deducting the estimated urine value from the faecal water and adding it to the urine mixture figure, the amounts of nutrients collected in the two toilet fractions agree fairly well with expected amounts according to given norms and earlier studies (Table 2) (Lentner et al., 1981; NV, 1995; Hellström & Kärrman, 1996; Hanaeus et al., 1997; Jönsson et al., 1997). However, the collected amount of phosphorus in the faecal fraction differed from the amount expected according to present norms. This difference is probably due to differences in the diet compared to the average Swedish diet. This is also, to a lesser extent, reflected in the collected urine mixture.

It is important to include the effect of the time the people spend within the system per day when estimating the nutrient flow of the different toilet fractions. The excreted amounts are approximately linear compared to the time spent at home if more than 50% of the time is spent there (Hellström & Kärrman, 1996; Pharmacia, 2000).

The flows of potassium in the three wastewater fractions were larger, especially for the greywater, and differently distributed to the Swedish norm, while the flows in the solid waste agreed fairly well. Total potassium flow (3.34 kg p^{-1} y^{-1}) was 100% larger than the norm value. About 43% of the potassium was found in the greywater, which is much more than the present norm. The reason for these large flows is probably an increased use of potassium, for example in liquid detergent and as a supplement in table salt. Jönsson et al. (1999) have also noted the increased amount of potassium in urine compared to the norm. The difference in collectable amounts of potassium seems to be a general one, therefore the present norms ought to be increased.

5.3 Heavy metals

The total flow of heavy metals was in most cases lower and in some cases much lower than the present norm values. The major discrepancies were found in the greywater, while in the urine (Jönsson et al., 1997, 2000) and in the faeces the flow of heavy metals was larger than expected from earlier measurements and present norms (NV, 1995).

Earlier studies have shown much smaller amounts of heavy metals in the urine (Jönsson et al., 1997) and the norm values for heavy metals in the faeces are also lower than those measured here (Lentner et al., 1981; Faouzi et al., 1998). The present norm is based on the average Swedish diet but the amount of heavy metals in Swedish society has decreased during recent years, and so has the dietary intake of heavy metals. The amounts in the urine have been well determined by earlier studies, where no contamination was detected (NV, 1995; Jönsson et al., 1997, 1999, 2000) and the amounts of heavy metals in the faeces can therefore be calculated from the amounts of heavy metals consumed minus the amounts found in the urine.

The reason for the large amounts in the toilet fractions was probably heavy metal-containing domestic cleaning water being poured into the toilets. A lot of heavy metals are found in dust from households and thereby in domestic cleaning water. It is not possible to remove more than 10% of particles 10 µm in diameter by vacuuming. Instead, these small particles have to be removed in some other way, e.g. by scrubbing or wiping (Månsson, 1992). Therefore a lot of heavy metals will be found in the domestic cleaning water. This was especially obvious for lead, which probably partly originated from leaded fuel used at the airport nearby and deposited on surfaces in the homes.

No alternatives were available to the inhabitants of Ekoporten other than to pour the domestic cleaning water into the toilet. This is the probable explanation for the large amounts of heavy metals found in the urine and the faecal fractions. However, these metals belong to the greywater. To get a good image of the content in the investigated fractions, the misplaced amounts of metals from the domestic cleaning water were mathematically moved to the greywater. The surplus of heavy metals in the urine (except copper) and in the faeces was deducted from these fractions and added to the greywater where it belongs (Table 3).

The reason for not adding the copper from the urine to the greywater is the high corrosion rate of copper from the half metre pipe that connects the toilets to the soil pipes inside the walls as described in Vinnerås et al. (1999). The high ammonia content in the urine, after biological degradation of urea, increases the corrosion of metals (Greenwood & Earnshaw, 1998; Vinnerås et al., 1999). Half a metre of copper pipe in the urine pipe system caused the high copper concentration in the urine mixture compared to the Swedish norm (Table 3). When calculating the excretion of copper, the excess of copper was therefore deducted from the urine but not added to the greywater.

Table 3. The flows of heavy metals in Ekoporten (En) in the different fractions of biodegradable waste, mg p^{-1} y^{-1}*, and the present norm values (SN) (NV, 1995; Sonesson & Jönsson, 1996)*

	Urine mixture		Faecal water		Greywater		Biodeg. Solid		Total	
	En	SN	En	SN	En	SN	En	SN	En	SN
Cu mg	37[α]	37	402[α]	402	3648	<2190	306	549	4391	<3177
Cr mg	4[α]	4	7[α]	7	426	<1825	263	137	701	<1973
Ni mg	3[α]	3	27[α]	27	428	<1095	33	82	491	<1207
Zn mg	16[α]	16	3346	3942	6486	<18250	661	3570	10510	<25779
Pb mg	0.7[α]	0.7	7.3[α]	7.3	991	<1095	203	275	1202	<1378
Cd mg	0.4[α]	0.4	3.3	3.7	14.4	<219	2.7	8.2	20.8	<231.3
Hg mg	0.4	1.1	<1.9[β]	23.0	<3.8[β]	<21.9	<0.2[α]	2.8	<6.3[β]	<48.7

α) Set to norm value when correcting for misplaced greywater

β) Less than given detection limit.

The majority of the heavy metals were found in the greywater. However, these amounts were still much lower than the norm values (NV, 1995). The flows of the non-essential heavy metals cadmium and mercury were considerably below present norms Table 3). In the solid biodegradable waste, the greywater and in the separated water (one of the two faecal water fractions) no mercury was detected at all, therefore the detection limit was used to calculate the total flow of mercury. However, for mercury the values are uncertain because of the risk for point discharges by dental fillings and by free mercury used in the households, e.g. thermometers, which were probably missed during this study. The amount of lead was not reduced as much as the amounts of cadmium and mercury. The probable reason was an airfield nearby where leaded fuel was still being used, which increased the surface depositions of lead.

The second and third largest flows of heavy metals were found in the faecal water and in the biodegradable solid waste. In these two fractions the metal flows were still considerably lower compared to the flows in the greywater.

The smallest flows of heavy metals, except for mercury, were found in the urine mixture. The flows were in most cases considerably lower than in the other fractions.

Table 4 is our proposal for an upgraded norm to be used when discussing and calculating the total mass and the concentrations of nutrients and heavy metals in the different fractions of biodegradable waste from households. This table is based on the present Swedish norm values (NV, 1995) and measurement of all the biodegradable fractions in Ekoporten, a house with 35 inhabitants during 35 consecutive days. Where the discrepancy was large when comparing the measured flows with present norms, and not explainable by local circumstances, a new norm value is proposed in-between the present and the measured values.

Table 4. A proposal for new Swedish norm values for amounts of mass, nutrients and heavy metals in the different fractions of biodegradable waste per person and year. The bold entries are those for which changes are proposed

Parameter	Urine	Faeces	Greywater	Biod. Solid	Total
Mass [kg]	**550**	**40**	**40 000**	80	**40 670**
DM [kg]	21.9	**18.0**	29.2	24.1	**93**
N [g]	4 015	548	**460**	482	**5 505**
P [g]	365	183	110	92	750
K [g]	**1 100**	**400**	**1 000**	224	**2 724**
Cu[mg]	37	402	2 190	**450**	**3 079**
Cr [mg]	3.7	7.3	**1 100**	241	**1 352**
Ni[mg]	2.6	27.0	**720**	**60**	**810**
Zn [mg]	16	3 942	**12 200**	**1 300**	**17 458**
Pb [mg]	0.7	7.3	1 095	236	1 339
Cd [mg]	0.4	3.7	**65.0**	3.1	**72.2**
Hg [mg]	**0.5**	**7.6**	**8.4**	**0.4**	**16.9**

The norm for the mass of the urine has been increased by 50%, according to the results from this study and other recent studies showing 550 kg as the amount to expect (Hellström & Kärrman, 1996; Jönsson et al., 1997, 1999).

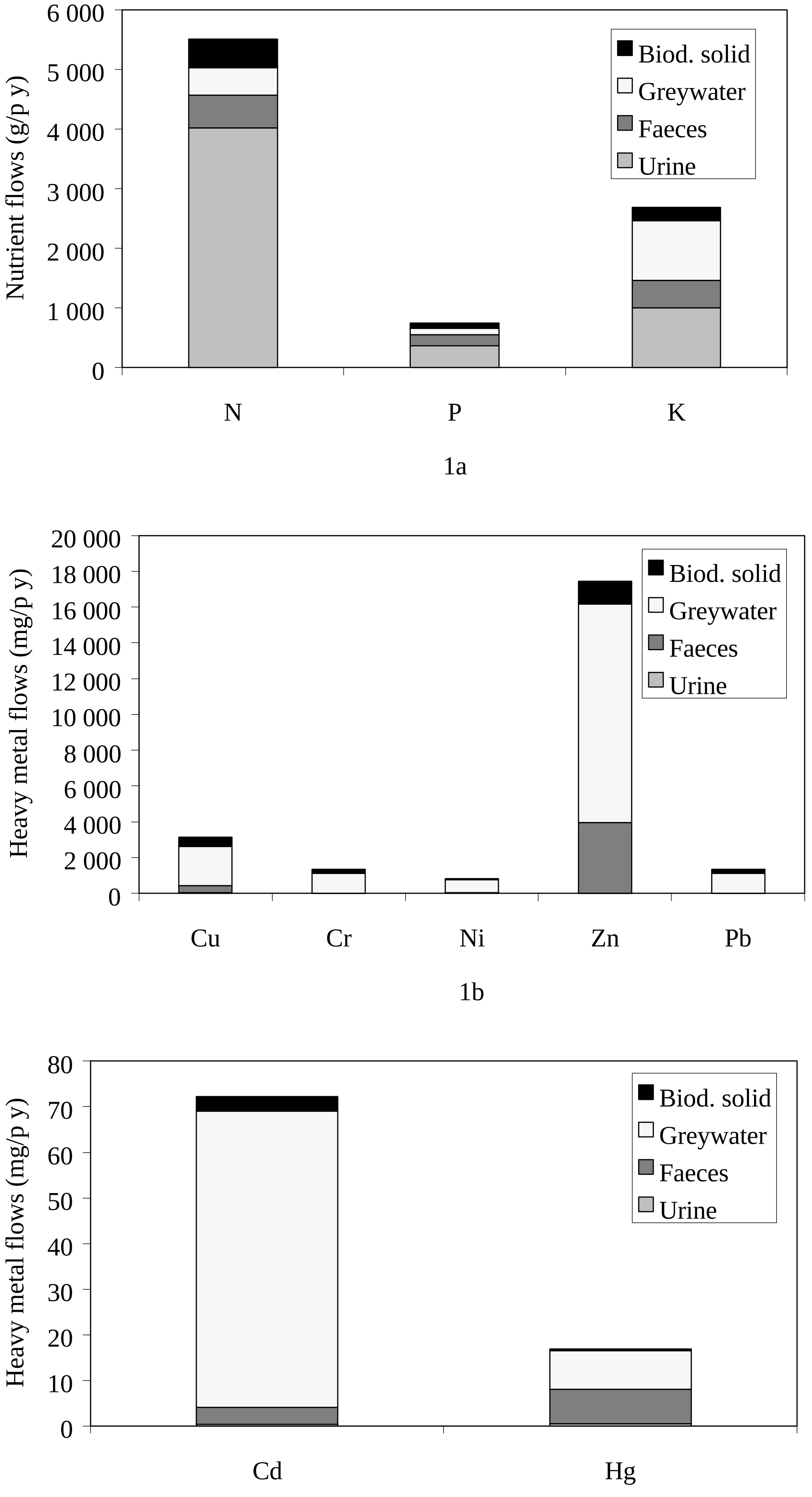
The total mass of the greywater has been reduced. Newer and more water conserving equipment requiring less water is likely to be used in the future. The proposed flow is based on this measurement and the measurement done by NV (1995), which showed similar water consumption. Recent studies of water consumption in some Swedish households show figures for greywater production figures similar to the proposed values (Hellström & Johansson, 2001).

We propose reducing the total mass of the faeces by 10% to 40 kg per person and year. Of the collected mass, 17.5% (7 kg) is toilet paper and the rest is faeces.

It is proposed to reduce the dry mass of the faeces and toilet paper fraction to 18.0 kg per person and year. Even if a considerably lower mass was collected during this measurement, the impact from this on the proposed norm is not especially great. The lower mass collected can be caused by three major factors; biological degradation of the collected matter, a decrease in dietary fibre in the food giving less dry matter in the faeces and less usage of toilet paper compared to the norm, especially if not all toilet paper used is disposed of in the toilet. In Trémolières et al. (1961)a much lower value is given for excreted faecal mass from seven males (7.7 kg $p^{-1}y^{-1}$) compared to the present norm (12.8 kg $p^{-1}y^{-1}$). Of the proposed amount of dry matter, 60% comes from the faeces and 40% from the toilet paper.

A proposal is made to slightly increase the norm for nitrogen in greywater. No valid explanation for the difference between the present norm and the measured value was found. The coefficient of variation for the measured values was only ±7.5%, so the measured values were quite stable. Because of these two factors, the proposed new norm is closer to the old norm than the measured value.

It is proposed to increase the norms for potassium in all wastewater fractions. Earlier measurements of diverted urine indicated that the norm for potassium was underestimated (Jönsson et al., 1999, 2000). The proposed values are between the measured value and the old norms for all liquid fractions. The proposed new norms for nitrogen, phosphorus and potassium are illustrated in Figure 1a.



1a

1b

1c

Figure 1. The proposed new Swedish standards for the composition of wastewater and biodegradable solid waste with respect to (a) N, P,K, (b) Cu, Cr, Ni, Zn, Pb, (c) Cd and Hg given per person and year.

The local influence of copper in the liquid fractions is due to a difference in the incoming water, especially from corrosion in the pipes. Therefore, the standards for copper in the wastewater have not been changed.

The proposed values for chromium, nickel and zinc in the greywater are the averages between the present norm and the values from the present measurement. The large changes to the norms are necessary because of the big differences from present norms, which were 3 to 4.5 times higher than the measured values. The present norms are mainly based on a single, not as extensive, measurement and calculated values from other flows, where corrosion from the pipework and some industries could have been included (NV, 1995). The proposed new norms for copper, chromium, nickel, zinc and lead are illustrated in Figure 1b.

The proposed values for cadmium and mercury in the greywater and mercury in the faecal water are close to the measured values. These major changes are due to increased sensitivity of the analyses as a result of improved technology and the norm is mainly based on detection limits. The difference between the measured values and the old norms were about one power of ten. For mercury there is a risk of point discharges not included in present measurements, and the proposed values include this effect. The proposed new norms for cadmium and mercury are shown in Figure 1c.

The proposed values for copper, nickel, zinc and mercury in the biodegradable solid waste are close to the present norms. The smaller influence from the measured values is because the present norms are based on several measurements of biodegradable solid wastes from different places. The differences between the measured values and present norms in the case of these three metals were so large that the norm value had to be updated.

The proposed value for mercury in the urine has been decreased to the measured value. This value is the measured value for mercury in the urine; the old norm value was based on the detection limit. The detected value is therefore a more valid value for use as the norm than the detection limit.

6 CONCLUSION

Using double flushed urine diverting toilets and water conserving equipment, the inhabitants used 30% less water than the present Swedish norm for household water consumption.

For the urine, changes to the norm for mass, potassium and mercury are proposed. The mass and the potassium are increased, while the mercury content is decreased.

For the faeces, changes to the norms for the mass, dry matter, potassium and mercury are proposed. For the mass and the dry matter, a slight decrease is proposed, mainly due to a change in the diet. For potassium it is proposed that the norm be increased, as for all the liquid fractions.

For the greywater, changes to the mass, nitrogen, potassium, chromium, nickel, zinc, cadmium and mercury values are proposed. The mass is decreased by 27%, while the values for nitrogen and potassium are increased. For the heavy metals, values for chromium, nickel and zinc are decreased somewhat and for cadmium and mercury the new proposed values are decreased significantly.

For the biodegradable solids, we propose that the norm values for the heavy metals nickel, zinc, cadmium and mercury be slightly decreased.

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The performance and potential of faecal separation and urine diversion to recycle plant nutrients in household waste water

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1 Abstract

In household wastewater and biodegradable solid waste, the main proportion of the plant nutrients are found in the toilet water (i.e. in urine and faeces). In order to recover the majority of these nutrients, with the purpose of decreasing the emission of eutrophicating agents and of increasing their recycling, present waste and wastewater systems have to be changed. The major proportion of the nitrogen (>70%), phosphorus and potassium (>50%) can be collected separately by using urine-diverting toilets and almost all of the nutrients in this fraction are immediately plant available. If the faeces are also collected, up to 85%, 75% and 75% for N, P and K respectively can be recovered and recycled. The faeces can be collected dry or, as in the system investigated here, separated from the flushwater used for transport.

This study was carried out at an ecologically renovated house with 18 flats. The toilets used were of a double flushed urine-diverting type. The faeces were flushed from the toilets using water and then separated from the flushwater using two parallel Aquatron separators in the basement. The Aquatron separates by a combination of a whirlpool effect, gravitation and surface tension. Nitrogen and phosphorus from the faeces were separated to 73% and 58%, respectively, to the dryer fraction, indicating that this method is an alternative when aiming to recover faecal plant nutrients while still wanting to use water flushed urine-diverting toilets.

Key words: faeces, urine, faecal separation, urine diversion, nutrient recirculation, supplementary wastewater treatment.

2 Introduction

The purpose of the present study was to evaluate the system of urine-diverting double flushed toilets combined with Aquatrons for faecal separation and recovery of human waste nutrients. An ecologically reconstructed house with 18 flats was monitored for 35 days. The quantity and composition of different wastewater flows (urine, faeces and greywater) and of solid biodegradable household waste were studied and are presented in Vinnerås et al. (2001). This paper presents some results concerning the toilet water from the households (faecal water and urine mixture) and highlights the separation of faecal water into separated solids (SS) and separated water (SW).

Household wastewater has three major constituents; greywater, urine and faeces. In Swedish houses, these are normally mixed and piped together into one sewer. The total volume of water used in households is about 73 m^3 per person and year (NV, 1995; Hanaeus et al., 1997).

The major contributor to the plant nutrients nitrogen, phosphorus and potassium is the toilet water (urine and faeces) (Figure 1). If a urine-diverting toilet is used, the urine, containing a large fraction of the plant nutrients, is collected separately. Simultaneously, flushwater is saved (Jönsson et al., 1997).

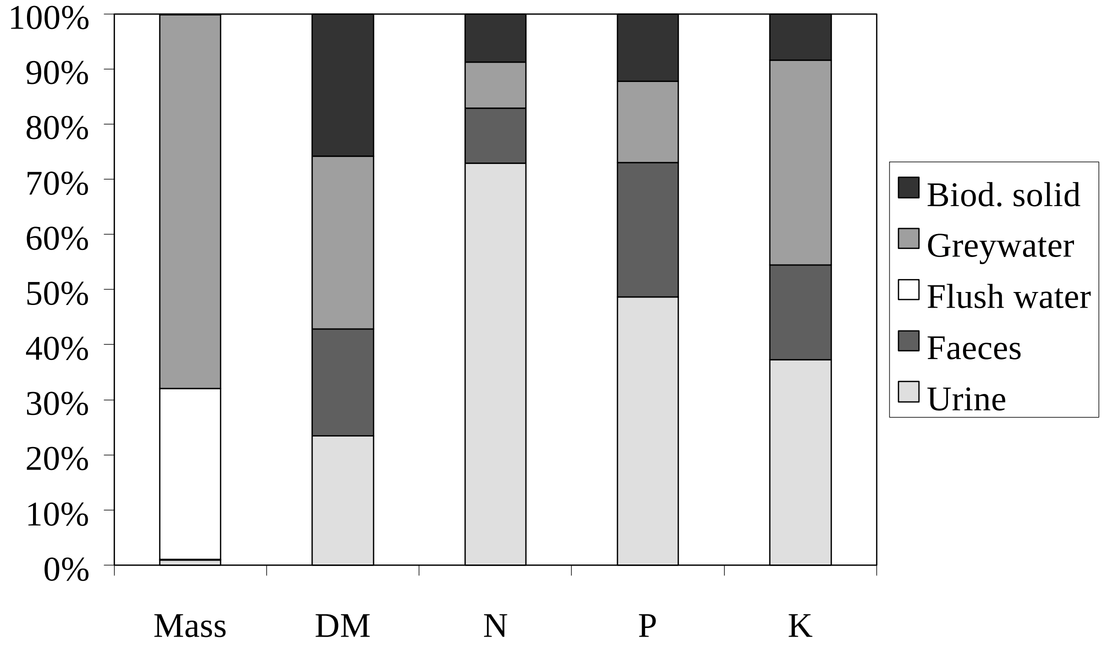

Figure 1. The distribution of mass, dry matter (DM), nitrogen (N), phosphorus (P) and potassium (K) in solid organic household waste and household wastewater constituents (Kärrman et al., 1999).

If all the toilet waste is recirculated to agriculture, between 75% and 85% of the nitrogen, phosphorus and potassium from the households will be used as a resource instead of being a potential pollutant to the environment. By storing before usage, the urine will be sanitised and approved for use as a fertiliser (Höglund, 2001). The majority of the potential pathogenic microorganisms excreted are found in the faeces. The faeces must therefore be treated to remove potential pathogens before usage in agriculture.

Of the total mass flow per person and year (73 m^3), approximately 55 m^3 is greywater, i.e. water used for washing, showering and cleaning, and the remaining 18 m^3 is toilet water. The flows of macronutrients in the greywater are about 5% of the nitrogen, 15% of the phosphorus and 10% of the potassium from the total household flow (Figure 1), while the major proportion of heavy metals is found in the greywater (NV, 1995; Kärrman et al., 1999).

2.1 Heavy metals

Dietary consumption of heavy metals, especially those such as lead, mercury and cadmium that are non-essential, is low, leading to low concentrations in the excreta. A rule of thumb which is often given is that more than 90% of the heavy metals consumed, both ingested and inhaled, are excreted in the faeces (Vahter et al., 1991; WHO, 1993). The main proportion of heavy metals consumed passes through the intestines without being metabolised. Major sources of heavy metals in the solid biodegradable waste and wastewater flows are dust, dyes and cutlery. This is one of the reasons why the major proportion of the heavy metals is found in the greywater (Kehoe et al., 1940; Vahter et al., 1991).

2.2 Diverted urine

In Sweden, the average time spent at home by a person is about 15 hours per day, which gives about 400-500 litres of diverted urine mixture collected per person and year (Jönsson et al., 1999). The volume collected depends on the amount of flushwater used and this mainly depends on the toilet model used. The urine mixture contains approximately 1.5-2 kg nitrogen, 0.15-0.2 kg phosphorus and 0.4-0.5 kg potassium per person and year (Jönsson et al., 1997, 1999).

The plant availability of the nitrogen and the phosphorus in the diverted urine is high (Kirchmann & Pettersson, 1995). The nitrogen is comparable to mineral fertiliser or just a little bit poorer and the phosphorus is also comparable to mineral fertiliser or even a little bit better.

The heavy metal content in the urine fraction is generally very low. Due to the high concentration of ammonia and the high pH in the urine, metals used in the urine sewer pipes are easily corroded and thereby contaminate the urine mixture (Vinnerås et al., 1999; Höglund et al., 2000).

2.3 Separated faeces

The second largest contributor of nitrogen, phosphorus and potassium to household wastewater is faeces. The plant availability of this nitrogen is probably lower than that of mineral fertiliser since only about 50% of the nitrogen is extractable with water (Trémolières et al., 1961). The remainder of the nitrogen is incorporated into organic matter and bacteria (Lentner et al., 1981). The plant availability of the faecal phosphorus might also be lower as compared to mineral fertiliser, since a considerable fraction is found in granulated particles mainly bound to calcium (Frausto da Silva & Williams, 1997) and the rest exists mainly as organic bound material, e.g. bacteria. Only a small fraction of the faecal phosphorus can be found as free phosphate ions.

Conventional toilets in Sweden today are water closets using approximately six litres of water per flush and the majority of the urine-diverting toilets use water to flush both the urine (0.1 litres per flush) and the faecal fraction (4-9 litres per flush).

One way to get a dry, and thus compact, faecal fraction is by using dry urine-diverting toilets. The urine diversion decreases the volume of the faecal fraction and its smell, giving two fractions that are easy to handle (Fittschen & Niemczynowicz, 1997). However, many people accustomed to the present flushable toilets do not think that dry toilets are equally acceptable.

Another technique for obtaining a compact faecal fraction when using a double flushed urine-diverting toilet is to separate the faecal particles from the flushwater. In this paper, the separation technique investigated is the Aquatron.

2.4 Faecal separation

One way to recover the nutrients contained in the faeces is to separate the faeces from the flushwater after just a short transport in the sewer.

A technique for removing some dry matter and nutrients is to use a three-chamber septic tank. In Sweden, the accumulated sludge is removed once a year. However, due to decomposition of organic matter and anaerobic conditions, the main fraction of the bound nutrients is dissolved into the wastewater and transported down the system. Only a small fraction of the material is accumulated in the septic tank. The anaerobic environment dissolves phosphorus and the greenhouse gas methane is emitted (Philip et al., 1993). The concentrations of heavy metals in the septic sludge are high (Svenson & Mattson, 1999).

Another technique for separation of the total solids and nutrients from the wastewater is by using an Aquatron separator locally to separate faecal particles from flushwater (Figure 2).

The Aquatron separation technique uses a combination of surface tension, gravitation and a whirlpool effect. The water follows the outer surface of a vertical, hourglass-shaped separator across the waist and further along the expanding outer surface of the lower section, while larger particles drop straight down from the waist by gravitation. Thus two fractions, separated water (SW) and separated solids (SS), are formed (SP, 1992; Del Porto & Steinfeld, 1999).

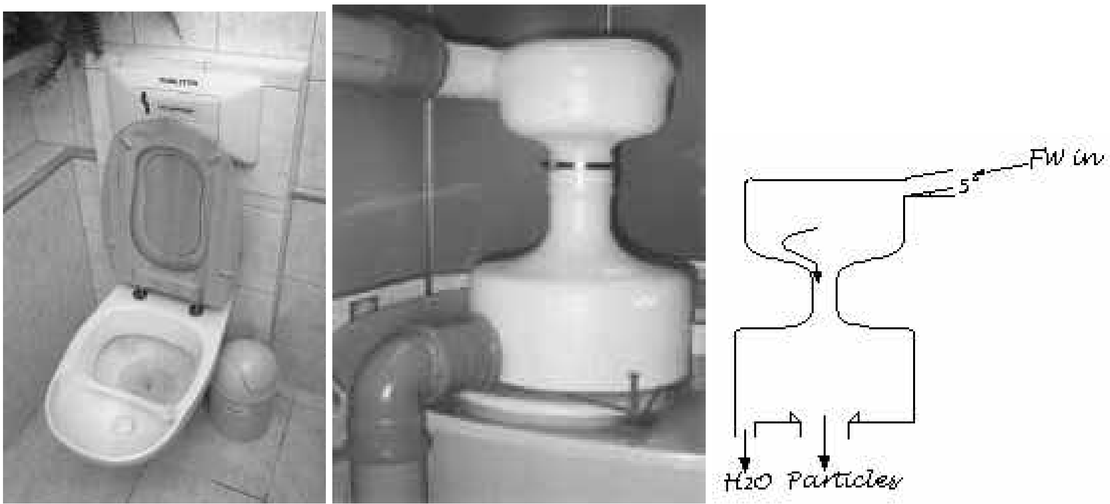

Figure 2. The urine diverting toilet Dubbletten™, the faecal separator Aquatron™ and a technical description of the function of Aquatron where the faecal water (FW) is separated into liquids and solids.

The separated water is normally diverted to the sewer and then piped with the greywater to a treatment facility, either a sewage treatment plant or an on-site treatment system, frequently a septic tank followed by a sand filter or an infiltration bed. The separated solids can be treated biologically, chemically or thermally. Biological treatment, e.g. composting, is most commonly used. Sometimes the separated solids are treated together with solid biodegradable household waste (Del Porto & Steinfeld, 1999).

3 Materials and method

This investigation was carried out in the Ekoporten block of flats, which was reconstructed with special consideration for the environment, i.e. recirculation of nutrients and saving of natural resources. The house is four storeys high and consists of 18 flats and a communal area in the attic. During the investigation, 35 persons lived in the house, 34 adults and one 10-year-old boy. The sewage system is divided into three subsystems; one for greywater, one for faecal water (faeces, toilet paper and flushwater) and one for urine mixture (urine and flushwater). These systems have separate sewers in the house. All flats are equipped with the urine-diverting toilet Dubbletten (Figure 2) (Jönsson et al., 1997).

The urine mixture collected is conveyed to two parallel collection tanks. When the tanks are full, after approximately a year, the urine mixture is pumped to a storage tank nearby.

The faecal water (faeces and flush water) is conveyed to two parallel Aquatron™ separators where the faecal water is separated into two fractions, separated water and separated solids. The separated water is conveyed, together with the greywater, to an on-site treatment system. The separated solids are conveyed to a composting drum where they are composted together with source separated solid biodegradable household waste and pellets of sawdust, which are used as a compost amendment.

The study was carried out during a period of 35 days in the spring of 1999, and was divided into three periods of 11, 12 and 12 days, respectively. The total mass flows and the compositions concerning dry matter, nutrients and heavy metals were measured and analysed for solid biodegradable waste, greywater, urine and faecal water as described in Vinnerås et al. (2001). Due to measurement problems, the duration of measurements of separated solids during Period One was 10 days, during Period Two 12 days and during Period Three 11 days, while for the separated water all measurement periods were 11 days.

The number of flushes, both of the urine- and the faecal-bowl, were measured using electronic counters attached to the flush buttons according to the method described by Jönsson et al. (1997). The water usage per faecal flush was noted and the average water usage per second of the urine flush was determined. During the measurement periods, the time spent at home by the inhabitants was registered using protocols filled in by the inhabitants.

3.1 Sampling

During the measurement period, the urine mixture was collected in a one cubic metre plastic tank. When the first period started, the urine sewer was reconnected to lead the urine to this external collection tank. At the end of each period, before sampling, the urine mixture was mixed using a high capacity pump and the tank walls were scraped with a rubber scraper to ensure a representative sample (Höglund et al., 2000). To minimise the ammonia loss during the ten minutes of mixing and sampling, the upper parts of the containers were covered with plastic sheets. Three parallel samples were taken of the urine mixture, as of all the other fractions. After sampling, the samples were stored at –20°C until the analyses were performed, one week after the end of the last measurement period. The amount of urine mixture was determined by weighing.

The separated water was also collected in a one cubic metre plastic tank. The flow of separated water was on average slightly less than 1,000 litres per day. The separated water was sampled once or twice a day, depending on the volume collected. The weighing and mixing procedures before sampling were the same as for the urine mixture. Weight proportional samples were taken each day; ten grams were taken per 100 kilos of separated water. All samples were stored at –20°C directly after sampling until the analyses were done.

The separated solids fraction was collected below the separators in a 120 litre plastic bin. The flow of separated solids varied from 50 to 210 litres per day. Sampling was done once or twice a day, depending on the volume collected. The separated solids were weighed and mixed mechanically with an electric plaster mixer for ten to fifteen minutes until the mixture was homogeneous. Sampling was done after the mixing, taking weight proportional samples each time. One gram per kilogram of collected solid fraction was taken. The daily samples of SS and SW were added to frozen main samples for each measurement period. All samples were stored at –20°C until analyses.

3.2 Analysis

The metals, except cadmium and mercury, were analysed for by using ICP-AES after the sample had been dissolved in nitric acid. For mercury and cadmium, the sample was prepared in the same way but analysed with ICP-MS. Nitrogen content was analysed using elemental analysis according to the Dumas principle. Analyses were performed in triplicate for each sample. The results from the three periods were weighted according to the length of each period.

4 Results

Collected amounts of macronutrients are given as grams per person per annum (g p^{-1} y^{-1}). Whenever measured values were compared with the expected excreted amounts, a correction for the time spent at home was made. The collection figures were linearly extrapolated to the amounts expected to be collected if the inhabitants had spent 24 hours per day at home. The inhabitants spent on average 13.9 hours per day, i.e. 58% of the day, at home.

The volume of urine mixture collected per person and year was 476 litres with a coefficient of variation of ±11%. The volume of faecal water (faeces and flushwater) produced per year was 11.0 m^3 (±7.7%), which was separated into 1.38 m^3 (±32%) of separated solids and 9.62 m^3 (±11%) of separated water.

When the collected amounts of nitrogen, phosphorus and potassium in the urine mixture were compared to expected amounts according to the nutritional data for Sweden in combination with previously determined excretion rates (Figures 1, 3) (Jönsson et al., 1999), on average 68% was collected (Vinnerås et al., 2001). The urine not collected is believed not to be separated i.e. it enters the rear, faecal, bowl, due to incorrect use of the toilet. This hypothesis is strengthened by the large recovery rate of nutrients in the faecal fractions when 24 h were spent at home: 1,829, 235 and 917 g p^{-1} y^{-1} for nitrogen, phosphorus and potassium, respectively (Table 1). The expected amounts when 24 h were spent at home, based on the average consumption in Sweden, were 548, 183 and 365 g p^{-1} y^{-1} respectively (NV, 1995; Hanaeus et al., 1997).

Table 1. Collected volumes and amounts of macronutrients in the three toilet fractions, urine mixture, separated solids, separated water and the sum of the two faecal fractions (faecal water), if 24 h per day were spent at home [g p^{-1} y^{-1}]

Parameter	Urine mixture		Separated solids		Separated water		Faecal water	
N^{α}	2 544	±430	609	±52	1 220	±195	1 829	±143
NH_4	2 209	±597	298	±53	887	±203	1 185	±148
P	232	±44	86	±16	149	±12	235	±22
K	807	±181	287	±24	630	±89	917	±72

α) One of the samples of the urine mixture from Period One was treated as an outlier and thus not included in the average value.

To estimate the efficiency of the separation of faecal water into SS and SW, the urine contribution to the nutrient content of the faecal water had to be corrected for. This meant that the assumed amount of urine in the faecal water, 32% of the urine, was deducted from the faecal fractions, in proportion to the masses in the two fractions. The nutrients deducted from the faecal fractions were added to the urine mixture (Table 2), which is the fraction into which all the urine should have been diverted if the toilets had been used as they should.

Table 2. The nutrients in the urine mixture, the separated solids, the separated water and the faecal water after the non-diverted urine was deducted and added to the urine mixture, if 24 h per day were spent at home [g p^{-1} y^{-1}]

Parameter	Urine mixture	Separated solids	Separated water	Faecal water
N	3 741	462	169	632
P	340	73	53	126
K	1 186	240	297	537

The nitrogen:phosphorus ratio in the urine mixture was nine and not the expected eleven (Höglund et al., 2000). The reason was probably nitrogen losses when handling the samples before analysis. The nitrogen content of the urine mixture was therefore adjusted up to a nitrogen:phosphorus ratio of eleven.

The amounts of heavy metals in the excreta (urine and faeces) are generally low, with a lower amount in the urine than in the faeces (Lentner et al., 1981; Jönsson et al., 1999). The amounts found in the urine mixture and the faecal fractions reflect the consumption pattern of the subjects.

5 Discussion

The following evaluations of the faecal separation were made after deducting the urine from the faecal water and adding it to the urine mixture. The urine mixture was corrected for nitrogen losses during the handling of the urine mixture to attain a nitrogen:phosphorus ratio of eleven instead of the detected nine. This was done since earlier measurements on-site showed a ratio of about eleven (Höglund et al., 2000).

Of the mass of the faecal water, 87% ended up in the separated water fraction and was treated in the wastewater treatment system together with the greywater. The remaining 13% (±32%) got separated as SS. This fraction also contained 37% of the dry matter (Figure 3). The high coefficient of variation for the SS fraction indicates a wide variation in separation efficiency. This was also observed visually during the measurements, since the dry matter content differed between different days.

The separation of inorganic matter into SS was as high as 50%, while only 23% of the organic matter was separated (Figure 3). One possible reason for the low separation of the organic matter was extraction of water-soluble compounds and dissolved particles. Inhabitants pouring domestic cleaning water into their toilets might be one source of the unexpectedly high amounts of inorganic matter found in the faecal water. The toilet paper was finely dispersed into small particles that were not separated. The paper mainly consists of organic material and this might be the reason for the difference in separation of organic and inorganic matter.

The expected amount of dry matter consisting of faeces and toilet paper was between 16.2 and 21.1 kg p^{-1} y^{-1} (Lentner et al., 1981), which was much higher than the collected 12.5 kg p^{-1} y^{-1} (Figure 3). The difference from the Swedish norm value for excreted amounts of faeces depends on the composition of the food consumed, where high intake of fibres increases the faecal mass. Decreasing fibre consumption in Sweden indicates that the lower of the two values is the more accurate one. The remaining difference between collected amounts and the norm value might be caused by a lot of reasons, such as lower excreted amounts, smaller amounts of toilet paper used compared to the Swedish average (8.5 kg, p^{-1}, y^{-1} (Anonymus, 1994)) and some biological degradation of small organic substances such as peptides. One other reason can also be that the degree of pre-treatment of the food consumed has increased since most of the reference values were determined mainly before 1965 (Lentner et al., 1981; NV, 1995). Increased pre-treatment of the food decreases the waste products left after passing the intestines.

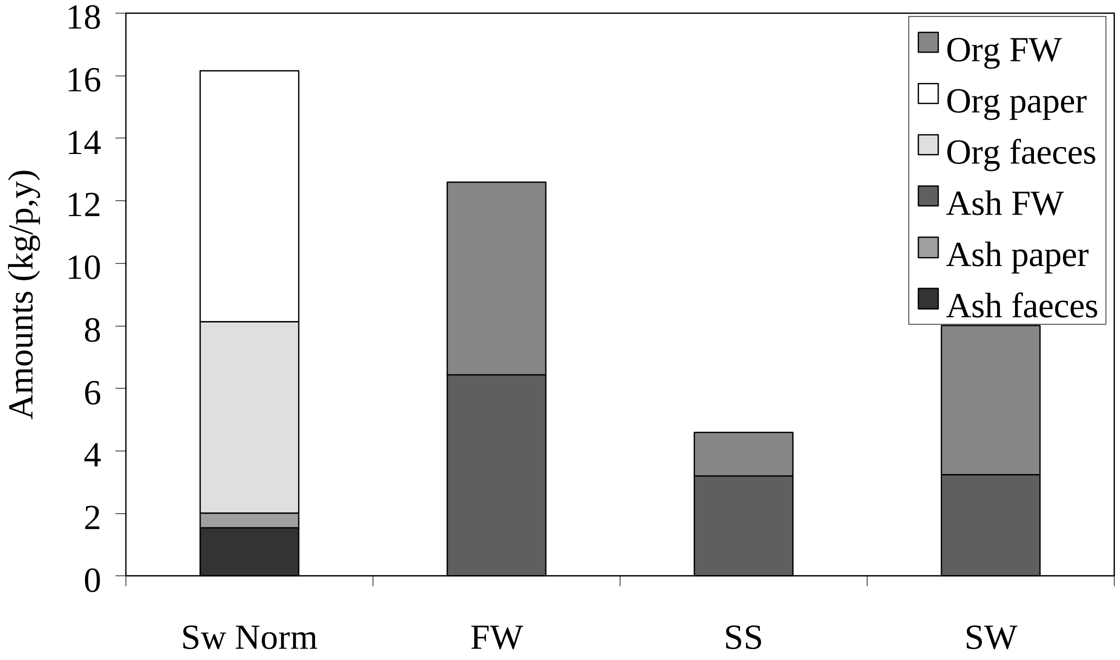

Figure 3. Distribution of dry matter, ash and organic material in the two fractions SS, SW and the sum of the two (FW) compared to the Swedish norm for faeces and toilet paper.

The collected amounts of dry matter in SS (4.6 kg $p^{-1}y^{-1}$) combined with the 13% of water that was separated gave a rather dilute fraction i.e. 0.2% DM. Between 10 and 20% of incoming water is normally to be expected in the SS fraction if the separation process does not have any specific dewatering devices (Zhang & Westerman, 1997). Therefore, it should be easy to increase the percentage of dry matter by decreasing the amount of flushwater used.

Of the nitrogen, between 59% and 73% corresponding to 484 and 462 g $p^{-1}y^{-1}$ (with 100% time at home) was separated into SS. The range is due to uncertainty in the analysis of the nitrogen content of the urine mixture, due to losses indicated by a nitrogen:phosphorus ratio of nine instead of the expected ratio of eleven (Höglund et al., 2000). The higher separation rate, calculated from a nitrogen:phosphorus ratio of eleven, is probably closer to the truth, indicating a high content of nitrogen in the separated particles. Even if about half of the faecal nitrogen content is extractable with water (Trémolières et al., 1961), only a minor part of the nitrogen was found in SW. This indicates only a small extraction of nitrogen during the transport.

Of the phosphorus, 58%, corresponding to 73.2 g $p^{-1}y^{-1}$ (with 100% time at home), was separated into SS. This is still higher than the separation of dry matter (36%). The reason for the lower percentage of separated phosphorus compared to nitrogen is probably due to some suspended small granular calcium phosphates and not as much organically combined phosphorus.

The separation of potassium to SS was 45%, corresponding to 240 g $p^{-1}y^{-1}$ (with 100% time at home). This is lower than the separation of inorganic matter. The reason for this is mainly due to the origin of potassium in the faeces. The potassium mainly originates from ion exchange reactions in the intestine. Therefore a lot of the potassium found is in the form of easily extracted water-soluble ions.

The distribution of N, P and K indicates a good separation of the faecal matter. However, between 27% and 55% of the nutrients were still neither separated nor collected. If the mechanical disintegration of the faecal particles in the sewers were less, the separation would probably be higher. An easy way to reduce disintegration is by shortening the length of the system, especially by decreasing the vertical drop of the faecal water (here it was up to four stories). Thus, the type of system investigated here is mainly of interest for small buildings or parts of large ones. In the building investigated, it would have been better if separators were installed on each floor. The separation of phosphorus can possibly be increased by chemical precipitation with for example calcium or iron ions, thereby making the phosphorus react and adhere to large particles, which are separated.

The major advantage of the Aquatron faecal separating system is its simplicity and robustness, since it has no moving parts. In this study, where the conditions for separation of faecal particles were unfavourable, more than half of the faecal nutrients were still separated into the separated solid fraction. Under more favourable conditions, i.e. less vertical drop, the separation would probably have been better. With a decreased usage of flushwater it is also plausible that the amount of water led to SS would have been less, thus increasing the percentage of dry matter content.

Visual observations revealed mainly large particles in SS and smaller ones in SW. The conclusion is that a lot of the nutrients are bound to separated large faecal particles. However, this contradicts the conclusion drawn by Zhang and Westerman (1997) and Möller et al. (2000) on animal manure, since they found that the main proportion of the nutrients are found in particles smaller than 0.5 mm. Their investigations were performed on cow dung, faeces and urine mixed and are thus a confirmation of the large amounts of liquefied nutrients in urine.

Nutrients should be used as fertilisers on agricultural land instead of eutrophicating natural waterways. The urine contains the main proportion of the nutrients from households. The urine can be diverted and the concentration of the urine mixture depends upon which urine-diverting toilet used and how it was installed. The composition of the collected urine in this study was similar to that in other investigations using the same toilet (Jönsson et al., 1997; Höglund et al., 2000). The only exception was the lower ratio of nitrogen to phosphorus which, according to Höglund et al. (2000) is expected to be eleven. In this study was it nine, indicating that some nitrogen loss probably occurred during the storage of the urine mixture before analysis.

The concentrations of heavy metals in the urine mixture and the faecal water were low. However, the collected amounts of the essential heavy metals and lead were higher than those expected from the average Swedish consumption (Table 3). The domestic cleaning water poured into the toilet by the inhabitants probably caused this. With correct information about how to use the toilet and better alternatives concerning where to pour domestic cleaning water, the heavy metal content of these fractions should be considerable lower.

Urine diversion has a major impact on nutrient recovery and on lowering the emissions to the water recipient body. If urine-diverting toilets are used correctly, about 80% of the nitrogen and 50% of the phosphorus should be recycled from the households as urine mixture. If the faeces are recovered, an even larger fraction of the nutrients will be recycled as a fertiliser. These two fractions, the urine mixture and the faeces, have very low concentrations of non-essential heavy metals e.g. Hg, Cd. The concentration of cadmium in the urine mixture per kg of phosphorus was lower than in mineral fertiliser claimed to be cadmium free. The concentrations of non-essential heavy metals in the faeces per kg of phosphorus were about the same as in normal Swedish mineral fertiliser.

Table 3. The collected amounts of heavy metals in Ekoporten (En) found in the urine, the two faecal fractions and the sum of the two faecal fractions compared to the Swedish norm (SN), if 24 h per day were spent at home [mg p^{-1} y^{-1}]

Parameter	Urine mixture		Separated solids	Separated water	Faecal water	
Source	En	SN	En	En	En	SN
Cu	1487	37	213	851	1064	402
Cr	10.3	16.1	17.6	50.6	68.2	7.3
Ni	32.7	51.1	36.8	71.5	108.4	27.0
Zn	147	172	1365	3499	4865	4015
Pb	15.3	8.8	37.5	424.6	462.1	7.3
Cd	0.48	0.88	1.53	4.84	6.36	3.65
Hg	0.30	0.37	1.12	<1.64	<2.75	23.0

Diverting the urine and separating the faeces and, after sanitation, using their non-polluted nutrients as a resource instead of emitting them to the environment as pollutants is one interesting option of moving towards a more sustainable society.

A major advantage with this kind of system is its lack of moving parts. Using a separate bowl diverts the urine and the faecal particles are removed in a separator with no moving parts. This should make the system robust.

6 Conclusions

The Aquatrons (using a whirlpool, gravitation and surface tension technique) in Ekoporten separated a SS fraction containing between 58% and 73% of the faecal nitrogen and phosphorus. This fraction contained 13% of the flushwater used. However despite this, the DM content of this fraction was only 0.2%. The separation of dry matter and nutrients would have been higher if the vertical drop had been less. This could be achieved by having a separator on each floor.

Larger amounts of heavy metals than expected were found in the faecal water. The reason for this was probably domestic cleaning water poured into the faecal bowl. This indicates the importance of using the toilet only for human excreta in this type of system.

Had the toilet used less flushwater and no domestic cleaning water poured into it, then the amounts of water and of heavy metals in the SS fraction would have been less.

To get the most positive environmental effects from using urine diversion and separation of the faecal water for dry treatment, it is greatly important to inform the inhabitants how to use a system like this correctly.

Despite its limitations, this system, using urine diversion and faecal separation by Aquatron, is a good alternative for environmental sanitation, which strives to use possible eutrophicating nutrients on agricultural land as fertilisers, instead of polluting adjoining waters.

7 Acknowledgement

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Faecal separation for nutrient management – evaluation of different separation techniques

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1 Abstract

The aim of this study was to evaluate the potential of different separation techniques for local recovery of faecal nutrients. Separation by Aquatron, filtration, flotation and sedimentation was tested in the laboratory.

In this study we found that the extraction of nutrients from the faeces to the liquid occurred rapidly. Therefore, to effectively separate the faecal nutrients and particles from the flushwater, the separation has to be performed locally, preferably at house level.

The Aquatron and the filtration gave a fraction of separated solids with 10% dry matter, which contained 70-80% of the incoming plant nutrients nitrogen, phosphorus and potassium. The other two methods investigated did not prove effective for local separation of faeces.

Using urine-diverting toilets, where all the urine is diverted, and collected and 70% of the faecal nutrients are separated locally, the potential for local nutrient recovery from the household wastewater is 88% for nitrogen, 75% for phosphorus and 55% for potassium, mainly in the form of directly plant available nutrients.

Key words: Faeces, Faecal separation, Nutrient management, Separation, Filtration, Aquatron, Sustainable sewage management

2 Introduction

In household wastewater the main proportion of nitrogen and phosphorus originates in the urine fraction (Figure 1). Using a urine-diverting toilet, the urine is easily collected separately at source. The other fraction worth recycling, according to its nutrient content, is the faeces (Vinnerås et al., 2001). The mass flow of the faecal fraction (faeces and toilet paper) is small, about 40-50 kg, person^{-1} year^{-1}, and to take advantage of this small mass for direct recycling the amount of diluting flushwater should be as small as possible. This can be combined with the advantage of the flushed toilet, if after a short pipe transport the faeces are separated into a dry fraction that contains the majority of the faecal nutrients and a liquid fraction containing the flushwater and some nutrients (Vinnerås & Jönsson, 2001).

A system with the potential to separate, collect and recycle a large fraction of unpolluted human excreted nutrients can consist of a double flushed urine-diverting toilet, which flushes the urine and the faeces into separate sewers. The faecal particles and the toilet paper are then, after a short transport in the sewers, separated again. Some advantages of this system are that the convenience of the water-flushed toilet remains, that the nutrients can be recovered with just minor pollutants and that it provides an easy way to recover the faecal nutrients (Del Porto & Steinfeld, 1999; Vinnerås & Jönsson, 2001). However, one prerequisite for recovery of the faecal nutrients by using solid-liquid separation techniques is that these nutrients remain in the separated particles.

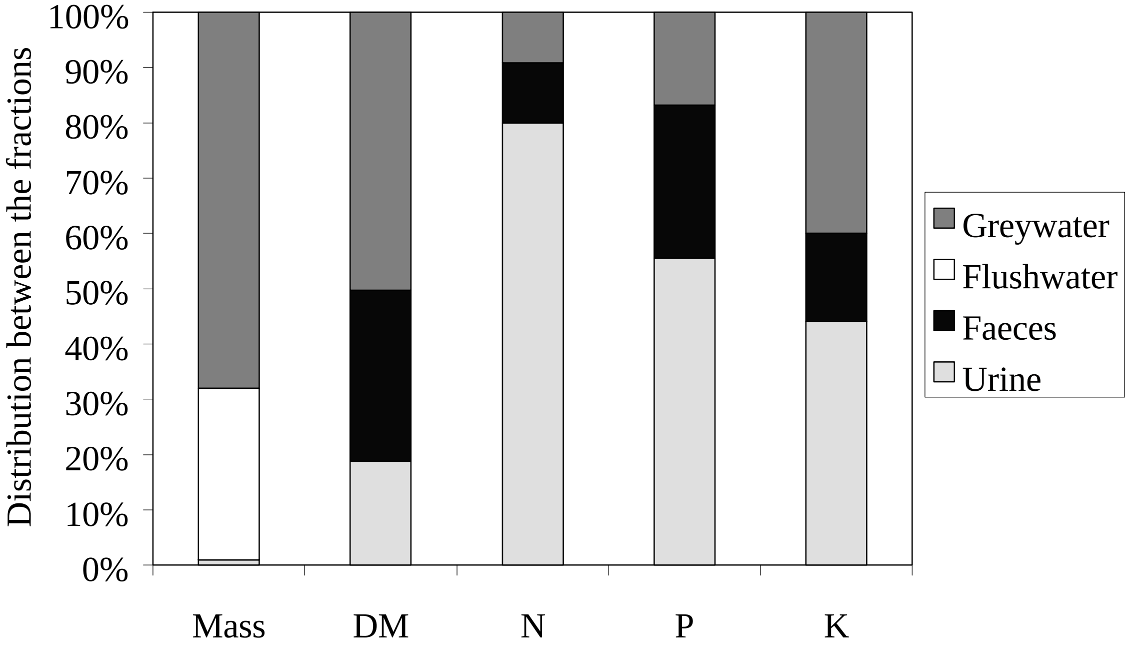


Figure 1. The distribution of Mass, DM, N, P and K in the three household wastewater fractions and the mass of flushwater.

In this study the potential for solid-liquid separation of faeces and water was evaluated with respect to nutrient recovery potential. The study was done in two parts; the first part consisted of an investigation of what happens after the faeces are immersed into the water. The second part of the study evaluated the separation of faeces and water in a controlled environment in the lab, using different separation techniques. The aims of these studies were to investigate the potential of different separation methods under different conditions.

Compared to the other biodegradable household waste fractions, the faecal fraction (faeces and toilet paper) is small if the flushwater is excluded. The 30 to 45 kilograms, wet weight, of faeces that are produced per person and year correspond to 10 to 15 kilograms of dry matter (Lentner et al., 1981; Vinnerås et al., 2001). The amount of excreted faeces depends on the composition of the food consumed. Meat and other food low in fibre produce smaller volumes than food high in fibre (Guyton, 1992). On average, one stool per person and day is produced, but it varies from one per week up to five per day (Lentner et al., 1981; Pharmacia, 2000). In Sweden, about 8.5 kilograms of toilet paper are used per person and year (, 1994). Not all of this paper is thrown into the toilet as some is used for other purposes, but at least 90% (7.7 kg $p^{-1}y^{-1}$) can be expected to end up in the toilet with the faeces.

Of the faecal nitrogen, about 17% is contained in the bacterial fraction. About 10% is found as ammonia, from degradation of urea, peptides and amino acids. The remaining part is found in different organic compounds such as uric acid and different enzymes (Lentner et al., 1981). The nitrogen in the faeces is to about 50% water soluble (Trémolières et al., 1961).

The faecal phosphorus is mainly found as calcium phosphates (Frausto da Silva & Williams, 1997), but some phosphorus is found in organic compounds and some as soluble phosphorus ions (Lentner et al., 1981). Potassium is mainly found in its water-soluble ionic form (Berger, 1960).

The three main macro plant nutrients nitrogen, phosphorus and potassium are differently distributed between the urine and the faecal fractions. Of the food consumed, 10-20% of the nitrogen, 20-50% of the phosphorus and 10-20% of the potassium will be found in the faecal fraction, while the rest is found in the urine (Berger, 1960; Lentner et al., 1981; Guyton, 1992; Frausto da Silva & Williams, 1997).

On average, more than 90% of the heavy metals consumed are excreted via the faeces and most of them have not been digested at all. Of the metabolised heavy metals, approximately 50% is excreted via the faeces and the rest mainly via the urine (Vahter et al., 1991). Some of the proven essential heavy metals, i.e. Cu, Cr and Zn, can be excreted in the sweat in relatively large amounts (Schroeder & Nason, 1971). When comparing the amounts of heavy metals in the urine and the faeces to the total flow from households, 10-30% of proven essential heavy metals (e.g. Cu, Cr and Zn) and less than 5% of Pb and Cd are found in the urine (Vinnerås et al., 2001). For mercury, where dental fillings are a considerable source (Engqvist, 1998), about 10% and sometimes more can be expected in the urine (Schroeder & Nason, 1971; Vinnerås et al., 2001).

To utilise the potential of the high nutrient content and the low heavy metal pollution of the urine and the faeces, these two fractions have to be collected separately without being mixed with greywater. Using systems where these materials are source separated achieves this.

During the pipe transport of the faeces from the toilet to the separator, some physical disintegration of particles occurs. This disintegration occurs due to vertical drops and turbulent horizontal transports. The drops are the main source of disintegration of the particles (Brown et al., 1996) and this is also indicated in the study by Vinnerås & Jönsson (2001) where the faecal particles were generally small after the transport in a four-storey block of flats to the separators in the cellar.

The faeces pass through the pipes somewhat slower than water and therefore a certain amount of flushwater has to be used (Brown et al., 1996). If too little is used, the faeces will block the pipes. However, Brown et al. (1996) studied the transportation dynamics in the pipe using artificial standard faecal stool (NBS), therefore is it hard to predict what happens in the pipe with real faeces. The NBC is a plastic cylinder 38 mm in diameter and 76 mm long with a specific gravity of 1.05 g, cm^{-3}.

Many methods are available for performing the solid-liquid separation. This study focuses upon four different methods: Aquatron separation, filtration, flotation and sedimentation. Of these methods, the Aquatron is developed for this kind of separation, while the others are general separation techniques slightly adjusted in the lab for this purpose.

The Aquatron separates the solids from the liquid using a combination of a whirlpool effect, surface tension and gravity. The system is described in detail by Del Porto et al. (1999)and Vinnerås et al. (2001). Vinnerås et al. (2001)investigated on-site separation in a four-storey block of flats where, when undiverted urine was corrected for, more than 60% of the faecal nitrogen and almost 60% of the faecal phosphorus were estimated to be separated by two Aquatrons into a drier fraction of separated solids (SS). In addition, 13% of the flushwater was separated into SS. Due to relatively large flushwater usage, the dry matter content of SS was low, 0.2%. With less usage of flushwater, a more concentrated fraction of SS would probably have been obtained.

No studies on filtration of faecal water were found, but many studies have been performed on separation of farmyard manure (Zhang & Westerman, 1997; Westerman & Bicudo, 2000; Möller et al., 2000). Filtration can either be performed by gravity or by using some kind of dewatering gadget, e.g. filter press, vibration or vacuum filtration. When filtrating manure by using gravitational filtration, about 10% of the incoming water is separated with the separated solids (Zhang & Westerman, 1997).

Systems for long-term filtration of particles from the faecal water are available on the market. The faecal material and the toilet paper are collected in a filter-bag and the filter cake is used as a supplementary filter until the filter-bag is emptied every six to twelve months. This system is presently being evaluated but no results relating to the filter are available as yet (Hellström & Johansson, 2001).

In septic tanks a combination of flotation and sedimentation is used for separation of particles from sewage water. During the long retention time of sludge in these systems, in Sweden up to one year, major losses of nutrients occur due to mineralisation and extraction when the separated material is biologically digested (Philip et al., 1993).

When using sedimentation and flotation to separate manure, the separated solids have a high water content (Cheremisinoff, 1995). Adding a chemical thickener is one way of producing a drier fraction and in most cases the treatment has to be done in several steps. The thickening can be done by an initial sedimentation or flotation, then addition of first lime and then polymers and finally thickening in a thickener to get a reasonable solid fraction (Westerman & Bicudo, 2000).

Another alternative for separating the faecal particles could be by using gas-induced flotation, where the particles are lifted to the surface by small air bubbles (0.01-0.1mm) and then scraped off (Cheremisinoff, 1995). The advantage with this method is that even small particles with slow sedimentation can be forced to the surface by the bubbles. One problem though is the decrease of density and surface tension caused by all the bubbles, which makes it more difficult to keep the larger particles floating, and if the bubbles are too big their own raise rate will prevent them from adhering to the particles (Cheremisinoff, 1995).

The purpose of this study was, in a controlled environment in the lab, to determine how rapid the biological degradation, mineralisation and extraction was when water and faeces were kept together and to evaluate the potential of different separation techniques. The main focus for the study was to identify the potential for recovery of faecal plant nutrients to a dry fraction for a wastewater treatment system based upon local nutrient recovery.

3 Materials and methods

The faeces used in this study were collected during one week from approximately 150 persons, mainly male, in their late teens or early twenties and in the Swedish military service. Collection was carried out outdoors at a constant temperature below zero degrees Celsius. The faeces were kept frozen until they were used in the laboratory. On the night before usage the faeces were brought into room temperature to assure that all material was thawed when used. The collected faeces contained some toilet paper but no or very little urine. As little toilet paper as possible was included in the samples for separation, but some was included for practical reasons. The avoidance of paper was to get as similar samples as possible.

3.1 Part 1: Biochemical activity and extraction of faecal nutrients

In the study of the biochemical activity after faeces were immersed into water, the effects of contact time and oxygen supply in the water on the overall extraction of nutrients from the faeces were studied.

Approximately 20 grams of faeces were immersed into 250 ml of water for 1, 5 or 15 minutes before the mixture was separated by suction filtration over a polyethene filter with 70 µm pores. The duration of the filtration was about five minutes per sample. All three time spans were tested with different oxygen supply to see if the nutrient extraction depended upon the amount of available oxygen. In the first trial, air was bubbled through the water to create aerobic conditions, these samples are denoted Air. In the second trial, the mixture was gently stirred to ensure only small amounts of available oxygen were present in the water and thereby to produce close to anoxic conditions, these samples are denoted Stir. In the third trial, N_2 was bubbled through the mixture to get anaerobic conditions, these samples are denoted N_2. The water used in the third trial was aerated with N_2 for more than five minutes before use to minimise the initial oxygen content.

To monitor the biochemical activity in the faeces-water mixture, the reduction and oxidation (redox) potential was continuously measured with a redox-potential probe **(**Hamilton, PROFITROAD Pt-ORP**)** during the tests.

Analyses were performed upon the fresh faeces, SS and SW. The nitrogen, ammonia, phosphorus and potassium contents were analysed.

3.2 Part 2: Separation of faeces from water after pipe transport

The second part of this study was carried out to investigate the potential for local separation of faecal nutrients from flushwater using different separation techniques. The idea was to simulate the effects from flushing the toilet and the following pipe transport in a system where the separation is performed just below the toilet. Depending on separation method used, different amounts of water and faeces were used. Techniques investigated were Aquatron, filtration and flotation. No experiments were performed on sedimentation due to several reasons given later in the discussion.

Before separation, the faeces and some of the water were gently mixed and poured into a pipe system consisting of a 1 metre vertical pipe connected to a 1 metre horizontal pipe by a 90° bend (Figure 2). Directly after pouring the mixture into the pipe, the rest of the water was also poured into the pipe.

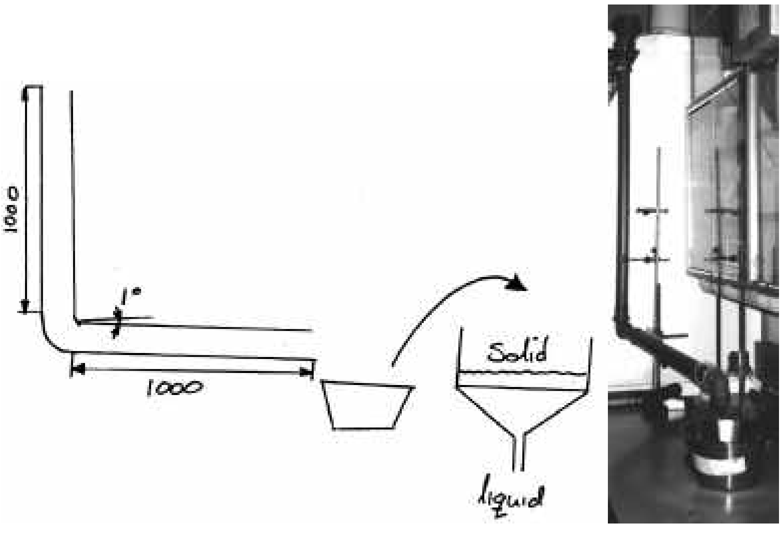


Figure 2. The system for filtration, a sketch and a picture of the system for pipe transport and filtration.

The amount of water and the pipe diameter were scaled down four times for the filtration and the flotation, which means that 1 litre of water and a pipe diameter of 55 mm were used. To get reasonable amounts of faecal matter to handle and separate, the amount of faecal matter was not decreased in the same proportions and almost 80 grams wet weight of faeces was used. After passage through the sewer, the material was collected in a vessel and manually moved to the separator.

The Aquatron system was used at full scale, meaning 110 mm pipes and 4 litres of water together with about 90 grams wet weight of faeces were used. The horizontal pipe was connected to an additional 1 metre horizontal pipe, which had a 5° slope leading directly to the Aquatron separator as prescribed by the manufacturer (Figure 3).

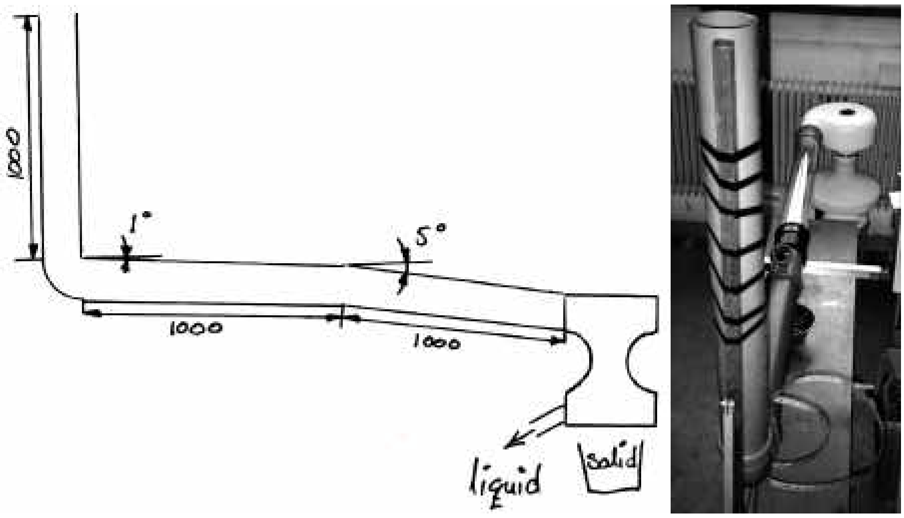


Figure 3. The system for Aquatron separation, a sketch and a picture of the system for pipe transport and the Aquatron separation.

The separation by flotation was performed in a 25-litre vessel where the bubbles were produced by air forced into wood, giving small bubbles (<1mm). The bubbles were produced at four places in the vessel. Water was continuously running through the system.

Analyses were performed upon the fresh faeces and the separated solids fraction. Losses to the separated water were then calculated from the difference between incoming and the separated solids. The nitrogen, ammonia, phosphorus and potassium contents were analysed.

3.3 Analyses

Phosphorus and potassium were analysed using ICP-AES (Perkin Elmer) after the sample had bee re-dissolved in nitric acid. Nitrogen was analysed using elemental analysis according to the Dumas principle. Analysis was performed on triplicates of each sample and from each separation technique, three samples were analysed.

4 Results

4.1 Part 1: Biochemical activity and extraction of faecal nutrients

The results of nutrient extraction for the three different treatments are presented in Table 1 for all three methods. Figures are given both for SS and for SW.

Table 1. Amounts (mmol) of nutrients in the separated solid fraction (SS) and in the separated water fraction (SW) as a function of contact time and oxygen supply. Air = aeration with air, Stir= stirred with a rod and N_2=aeration with N_2 gas

	N	NH_4^+	P	K
Air SS				
1 minute	54.5	8.2	6.0	6.9
5 minutes	67.8	7.7	10.4	7.0
15 minutes	91.2	12.3	18.6	6.9
Air SW				
1 minute	3.3	2.4	0.12	1.6
5 minutes	11.3	6.6	0.43	3.4
15 minutes	23.6	12.8	1.48	4.8
Stir SS				
1 minute	65.1	8.5	11.8	7.4
5 minutes	56.7	8.5	10.1	5.7
15 minutes	55.3	7.8	12.6	5.7
Stir SW				
1 minute	6.1	3.1	0.27	1.7
5 minutes	9.9	5.2	0.47	2.0
15 minutes	18.7	8.9	1.60	3.4
N_2 SS				
1 minute	75.6	10.6	14.3	9.2
5 minutes	64.7	9.1	12.4	5.7
15 minutes	56.7	8.6	14.0	6.8
N_2 SW				
1 minute	3.9	2.2	0.18	1.1
5 minutes	12.1	5.7	0.82	2.9
15 minutes	12.3	5.9	0.90	2.6

The redox potential was continuously monitored throughout the tests (Table 2).

Table 2. The redox potentials as a function of the time the faeces has been in contact with the water (mV)

Time	Aeration	No air	N_2
0 minutes	150	90	40
1 minute	130	30	-10
5 minutes	70	-30	-130
15 minutes	-40	-60	-250

4.2 Part 2: Separation of faeces from water after pipe transport

In the second part of the investigation, the separation of faeces from flushwater by Aquatron, a filter with 1 mm pores and a small-scale flotation was studied. The separation was done after passage of a 1 metre vertical and 1 metre horizontal pipe connected by a 90° bend. The amount of SS was compared to the amount of incoming material (Table 3).

Table 3. Separation of mass, dry matter and ash into SS by Aquatron and by filtration

Parameter	Wet weight G	Dry matter %	Ash % DM
Aquatron			
In	88.6±18.3	22.6±1.6	12.9±1.3
Out	177.0±57.8	9.3±1.9	13.7±0.5
Filtration			
In	77.1±17.9	22.6±1.6	12.9±1.3
Out	149.3±45.7	11.5±2.3	11.2±0.2

The concentrations of nitrogen, ammonia, phosphorus and potassium in SS compared to the incoming material are shown in Table 4.

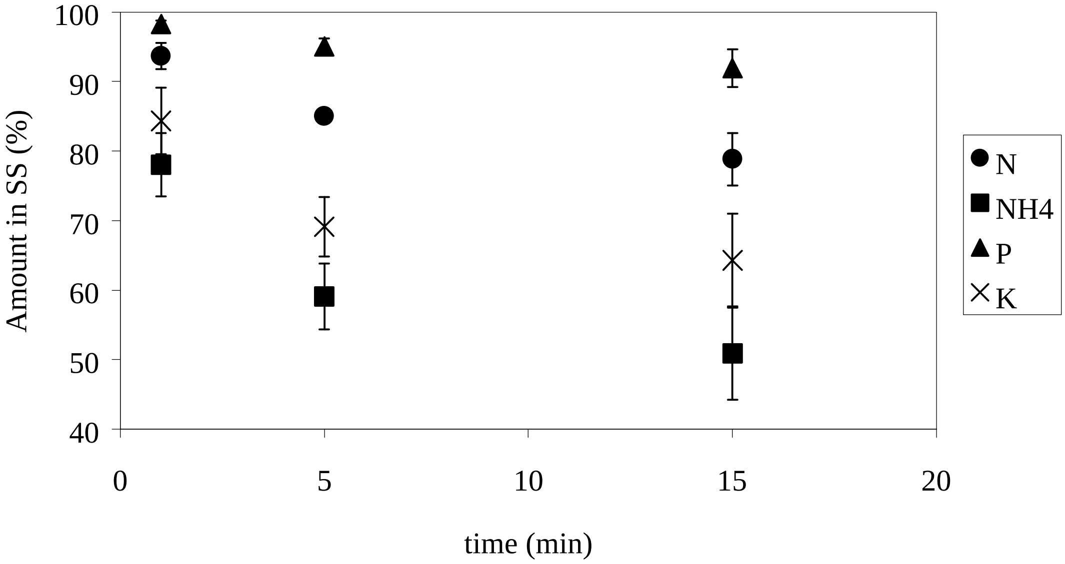
Table 4. The concentrations of nitrogen, phosphorus and potassium in the material used and in the collected solid fraction [mmol/kg wet weight]

Parameter	N	NH_4^+	P	K
Material in	1255±78	222±21	150±26	113±8
Out Aquatron	442±117	79±15	56±16	41±8
Out filtration	519±191	85±26	56±17	38±10

In the experiments with flotation, the system was not able to lift the large faecal particles, but instead broke them into small suspended ones, which left the tank with the outgoing water. Therefore no more results are presented from that part of the study.

5 Discussion

There were no significant differences between the three oxygen supplies in the water; therefore the extraction of investigated parameters is given as an average for all the three oxygen supply treatments (Figure 4). However, there was a tendency for a higher extraction rate in the two treatments with available oxygen (Air and Stir) compared to the N_2 one. This is probably due to the higher mineralisation rate of aerobic microbial and biochemical activity.



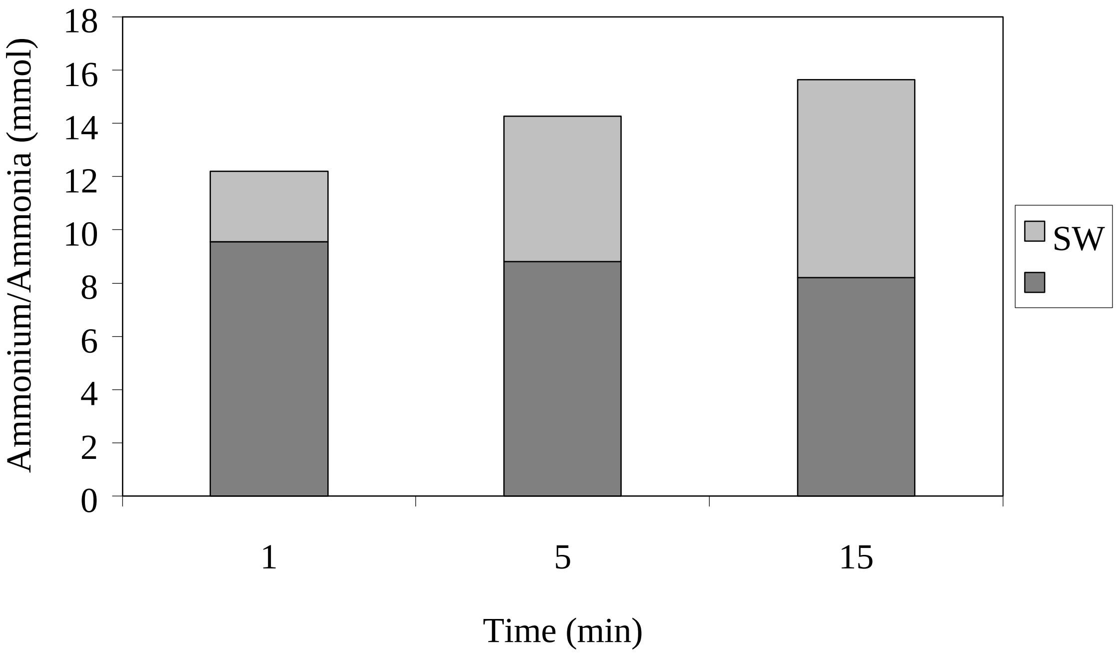


Figure 4. The average and the standard deviation of N, NH_4, P and K remaining in SS after immersing the faeces in water for different periods.

The increasing total amounts of ammonium with time compared to the initial amount (Table 1, Figure 5) indicate a relatively high biochemical activity. The increasing total amount of ammonium is due to decomposition of smaller amine-containing organic particles such as peptides, amino acids and urea. The molar NH_4^+:N ratio in SS was stable but the ratio in the liquid phase increased with time, indicating formation of ammonia, which is extracted to the liquid phase (Table 1, Figure 5).

Figure 5. The distribution and the sum of ammonia over time in the two separated fractions given as an average for all three treatments.

The decrease of the redox-potential after immersion of the faeces into the water was rapid in all samples, even in those aerated with air (Table 2; Figure 6). The largest drop in potential was in the samples aerated with N_2. The drop in potential shows that a rapid degradation of chemical compounds in faeces has occurred. This is what happens in septic tanks, where the biological and enzymatic activity is high and the sludge has a long retention time. This means that when the contact time between the faeces and the water increases, a lot of the initially captured nutrients will be dissolved into the water (Philip et al., 1993). Thus, if the aim of the separation is to recover faecal plant nutrients it is important that the faeces and the water are separated as soon as possible, since the nutrient recovery decreases rapidly with time.

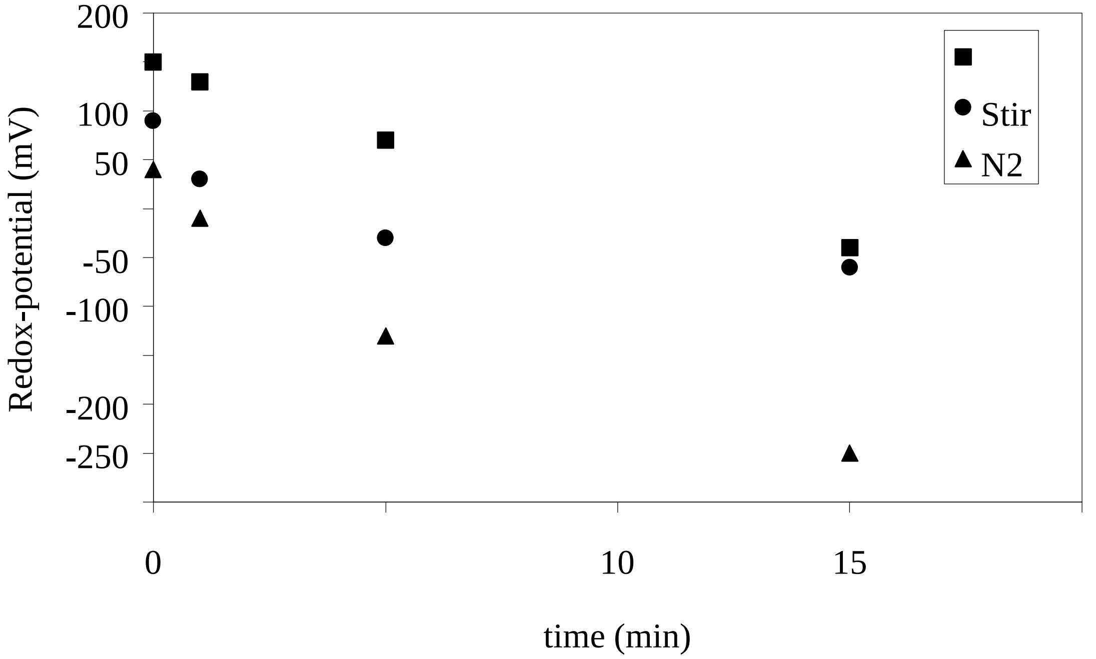


Figure 6. The change of the redox potentials as a function of contact time and oxygen supply (Air = active aeration, Stir=mixed by stirring, N2 = aeration by N gas)

time up to a year, the time combined with the repeated flushing of the filter cake implies that

evaluated yet, and thus there are no confirmative results available.

ts of the separated solids (SS) collected when separating with Aquatron and filtration respectively were similar to each other (Table 3), although with a tendency for

This is a considerably higher dry matter content than in the study by Vinnerås et al. where the dry matter content of SS was about 0.2%. The main reasons for the difference were

of soil pipes and thereby the degree of disintegration of faecal particles before the separation. In this study a 1

Ekoporten block of flats, which had four stories (Vinn . Due to the large disintegration caused by drops, high vertical drops should be avoided. In buildings higher than

any of the investigated separation techniques, if the separation were to be performed at each

To determine the effects of using more flushwater, a complementary study was carried out

n of SS contained 7.7% of dry matter. This shows the importance of keeping the volume of water

about 10% of incoming water will end up in the separated solids (. This rule seemed not to be applicable for the separation by Aquatron under our experimental

follow the material into SS when more toilet paper is used, due to the high absorption of water

The method used for this investigation concerning the distribution of nutrients was that only the fresh material and the fraction of separated solids were analysed. Some nitrogen and mass losses could therefore be due to degradation in the samples. To minimise this risk, all samples were kept deep-frozen until analysis and the dry matter content was determined immediately after the separation was performed.

The separation to SS of nitrogen, phosphorus and potassium when using the Aquatron was about 70% for all the three elements and about 80% of the dry matter was also collected in SS (Figure 7). The equal parts separated of nitrogen, phosphorus and potassium were not expected, due to the different chemical characteristics these three elements have in faeces. The nitrogen is mainly organically bound to larger particles, the phosphorus occurs mainly as granular mineral particles (calcium phosphates) and the potassium as free ions (Berger, 1960; Guyton, 1992)}} (Lentner et al., 1981).

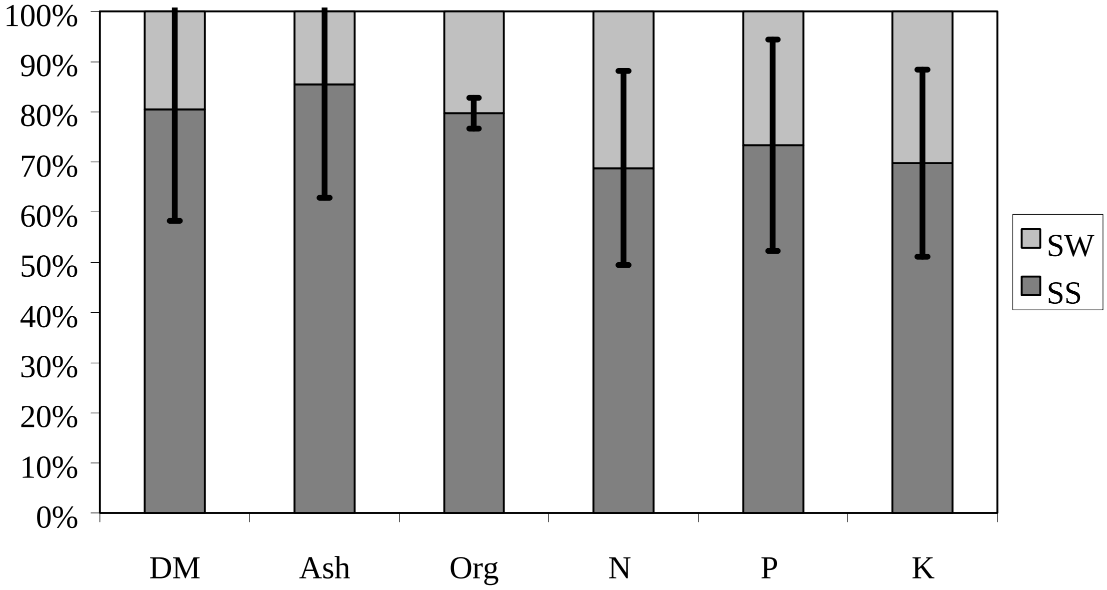


Figure 7. The distribution of DM, Ash, Org, N, P, K between the SW and SS fractions when using Aquatron.

The similar degree of separation indicates that smaller particles, mainly from disintegrated faeces, are not separated but end up in SW. This was also visually observed. It was also observed that only a minor extraction of nutrients occurred, mainly due to the rapid separation.

The separated solids from Aquatron have two distinct fractions, one with particles and one with water. This is a big difference compared to the filter cake, which consists more of solids containing a lot of free water. The distinct fraction of water in SS from the Aquatron separation indicates a potential for further dewatering and thereby getting a higher dry matter content. However, an increased loss of nutrients will also occur if water is drained from the separated solids.

One difference in separation of phosphorus and nitrogen between filtration in Part 1 of the study (Table 1, Figure 4) and filtration in Part 2 of the study (Figure 8) is that the P:N ratio in SS differed. More phosphorus compared to nitrogen was separated in Part 1 than in Part 2 of the study. The main factor causing this difference was the pore size of the filters, which was 70 µm in Part 1 and 1000 µm in Part 2.

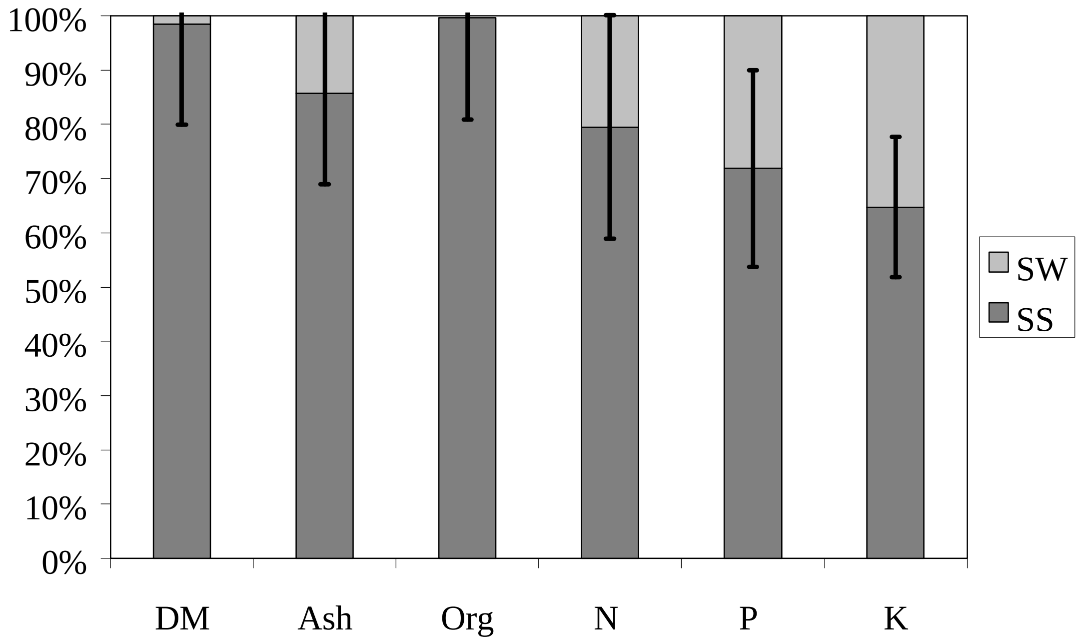


Figure 8. The distribution of DM, Ash, Org, N, P, K between the SS and SW fractions when using Filtration with a pore size of about one mm.

For phosphorus in particular, the effect of the pore size was distinctly noticeable. The highest fraction of phosphorus in SW in Part 1 was 9% (Figure 4) while in Part 2 it was 31% (Figure 7). The main part of the faecal phosphorus occurs as small calcium phosphate granules (Lentner et al., 1981; Frausto da Silva & Williams, 1997) and these were separated by the 70 µm pores but not by the 1 mm pores. A similar effect is seen for nitrogen, where the majority is organically combined (Trémolières et al., 1961).

SS, after separating the faecal water by filtration in Part 2, contained of the incoming nitrogen, phosphorus and potassium 80% nitrogen, 72% phosphorus and 65% potassium (Figure 8). No larger particles passed this separation and the nutrients lost were suspended or extracted into the liquid fraction. A larger part of the dry matter compared to the Aquatron system was collected into SS, more than 95% compared to 80% in the separation with Aquatron.

The difference in separation is confirmed by a tendency for a difference in the P:N and K:N ratios for the two separation methods used. This indicates that the Aquatron separation loses whole faecal particles while the filtration method has losses by extraction of nutrients from the particles. When the Aquatron is used in large systems, where the faecal matter is transported in long soil pipes, extraction of nutrients occurs, and the ratios between the different macronutrients (Vinnerås & Jönsson, 2001) look more like the ratios obtained for filtration (Figure 8).

Studies of suction-filtration were also carried out with pores smaller than 1 mm. When using filtration paper (with a flow rate of 1.67×10^{-3} m^3, s^{-1} m^{-2}) the filter was obstructed. Therefore, it is probably not possible to use filters with finer pores when separating faecal water due to the increased need for energy to drive the water through the filter fast enough to have sufficiently short separation time to keep the extraction low. A minor study of a filter with only a few 0.5 mm pores combined with suction resulted in a recovery of 90%, 54%, 48% and 44% of dry matter, nitrogen, phosphorus and potassium, respectively. The ratios of phosphorus and potassium to nitrogen were in the same range as for the gravitational filtration, indicating no difference in the composition of the separated mater.

Compared to the considerably higher recovery from gravitational filtration, the suction-filtration method is not to be recommended due to high nutrient losses and energy requirement. One alternative is to use really small pores such as during the studies with different retention times in Part 1, where 70 µm pores were used and relatively small fractions of the nutrients were lost. However, a lot of energy is needed to drive the liquid through the small pores of the filter and the system will also be much more complex, where not only the removal of the filter cake needs to be mechanised but also some kind of mechanism is needed to get pressure or suction to force the water through the filter. These high-mechanised systems are not suitable for a small scale local recovery where the system has to be robust and virtually maintenance free.

The differences between the two separation methods, Aquatron and filtration, concerning separation efficiency of faecal nutrients were small. Both systems were vulnerable for the disintegration of the faecal particles, especially the Aquatron system that does not separate small particles. Another effect of particle disintegration is the increased rate of nutrient extraction due to the increased contact area between the particles and the water.

The major difference between these two systems was that the filtration system tested was just a lab scale model while the Aquatron system was a full-scale commercial system for local separation of faeces. However, there are filtration systems for other purposes available today, and some kind of mechanical device is needed to remove the filter cake. The Aquatron is a system developed for faecal separation and has been tested on site and the system does not contain any moving parts, which increases its robustness. When installed correctly, the Aquatron combined with urine diversion seems to be a good alternative as a complement to provide a functional environmentally adapted sewage system that recycles pure nutrients and prevents pollution of the recipient waters.

No experiments were performed with sedimentation, due to the large variety in density of the faeces. Some of the faecal particles had higher and some lower density than water. Experiments with flotation were performed, but the decreased water density, due to the increased air supply, meant that the bubbles could not lift the relatively large faecal particles. Some of the bubbles were larger than 0.1 mm, which could have decreased the amount of smaller bubbles attaching to the particles. The only effect this flotation system had was to suspend, disintegrate and mix the faecal particles into the water fraction. It is an open question whether using pressurised air to saturate water and releasing the pressure in the flotation chamber would give a better performance of separating these large faecal particles. The retention time with such a system would be quite long and the amount of available oxygen in the liquid would also be high. Thus quick aerobic mineralisation would probably give considerable nutrient extraction to the water fraction. Therefore using flotation for local faecal separation is probably not to be recommended.

By using urine-diverting toilets where all the urine is diverted and collected and 70% of the faecal nutrients are locally separated, there is a potential for local recovery of 88% of the nitrogen, 75% of the phosphorus and 55% of the potassium of the total content in household wastewater. The separated and collected fractions have a small volume flow and contain mainly directly plant available and non-polluted nutrients.

6 CONCLUSION

About 70-80% of faecal nutrients are recoverable from the flushwater after a short pipe transport by using Aquatron or filtration. The recovered fractions in this study had a dry matter content of about 10%. If more flushwater is used, the dry matter content will probably be lower. Therefore as little water as possible should be used to get a fraction as dry as possible.

Due to disintegration of the particles and extraction of the nutrients, the longer the retention time the smaller the amount of nutrients to be found in the separated solid fraction. When faeces are immersed into water, the redox-potential drops rapidly. This indicates a high rate of biochemical activity and means that the faeces should be separated from the water as soon as possible.

Flotation and sedimentation are not functional techniques for local separation of faecal plant nutrients from flushwater.

The disintegration of the particles has a major influence on the efficiency of the separation. Much disintegration, i.e. small particles, gives less efficiency of separation, both by loss of small particles and by high extraction losses of nutrients.

The Aquatron is a commercial separation system adopted for separation of faeces from faecal water. The efficiency of the system depends on correct installation. The disintegration of faecal particles should be minimised. When using the system in a multi-storey building, one way of doing this is to install an Aquatron on each floor.

It is also possible to develop functional devices with similar separation performance based on gravitational filtration with continuous removal of the filter cake, but these systems will be more complex.

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