1 Introduction

Beyond the focus of public attention, an unseen emergency continues to unfold. It does not fall dozens all at once, like a bomb, or carry away whole towns in the blink of an eye, like a flood. Rather it kills its victims, mostly infants and small children, largely unnoticed spiriting them away one by one from rural villages and urban slums in every corner of the developing world. Every day, this unremitting but seemingly invisible disaster claims the lives of more than 3,900 children under five, according to World Health Organisation. And for every child that dies, countless others including older children and adults suffer from poor health, diminished productivity and missed opportunity for education. What is behind this wholesale loss of life? It is the absence of something that nearly every reader of this study takes for granted, something basic, unremarkable, commonplace: toilets and other forms of improved sanitation and safe drinking water (WHO & UNICEF 2004).

After focusing objectives on economic growth during the UN Development Decades of the 1960's, 70's and 80's, in the Millennium Summit in 2000, the states of the United Nations unanimously reaffirmed their commitment to working towards a world in which sustaining development and eliminating poverty would have the highest priority. The Millennium Development Goals (MDGs) signal the enormous importance of poverty alleviation to the global community. The MDGs critically highlight the link among improved water supply, safe sanitation, better hygiene and poverty reduction. With the strong political process backing the initiative, the MDGs represent a once in a generation opportunity to make significant progress in the sector.

The Millennium development goal for sanitation, introduced at the Johannesburg World Summit on Sustainable Development at 2002, is to halve the number of people without adequate sanitation in 1990 by the end of 2015. Meeting this goal now requires that 2.4 billion additional people have adequate sanitation by the end of 2015 which means that 440,000 people per day from January 2001 to December 2015 get access to sanitation (Mara *et al.* 2006).

Though estimates indicate that some progress was made in most of the developing regions between 1990 and 2002, sanitation coverage remains low. In Southern Asia, for instance, in spite of an 85 % increase over that period, almost two thirds of the population still lacks access to improved sanitation. In parts of the developing world, the situation has actually deteriorated. Coverage decreased both in rural and urban areas in Western Asia, and in rural areas of Oceania and the Commonwealth of Independent States. Most people without access to sanitation are those hard to reach: people living in remote rural areas or in overcrowded slums and families displaced by conflict and famine. Of the 2.6 billion people using inadequate sanitation, over 2 billion are in rural areas.

These figures are large indeed. They require unprecedented action. If there is no improvement in the rate of progress made during the 1990-2002 period, the sanitation MDG will fall short of its target by some 1.3 billion people. Thus there is no time to waste if the sanitation MDG is to have any chance of success. Figure 1.1 illustrates the number of toilets needed to meet the sanitation target by 2015. The figure shows clearly that tremendous efforts are needed in Africa, South East Asia and South America.

However, even if the Sanitation MDG is achieved, the world cannot stand still. During 2001−2050 the global urban population is expected to increase from ~2.8 billion to ~5.6 billion, while the rural population will remain fairly stable (United Nations Environment

Programme, 2002). Thus, even if all 4.4 billion urban residents in 2025 are provided with improved sanitation, a further ~1.3 billion will require improved sanitation during 2026−2050. This period will see increasingly severe global scarcities in water, nutrients (especially phosphorus) and energy, particularly and most acutely in developing countries (Hunt, 2003). Human wastes will thus become an increasingly important resource, not least for small-scale and subsistence farmers in developing countries. Sanitation planning will have to change to reflect the growing economic importance of using both human wastes for energy production and waste-derived nutrients for both energy and food production.

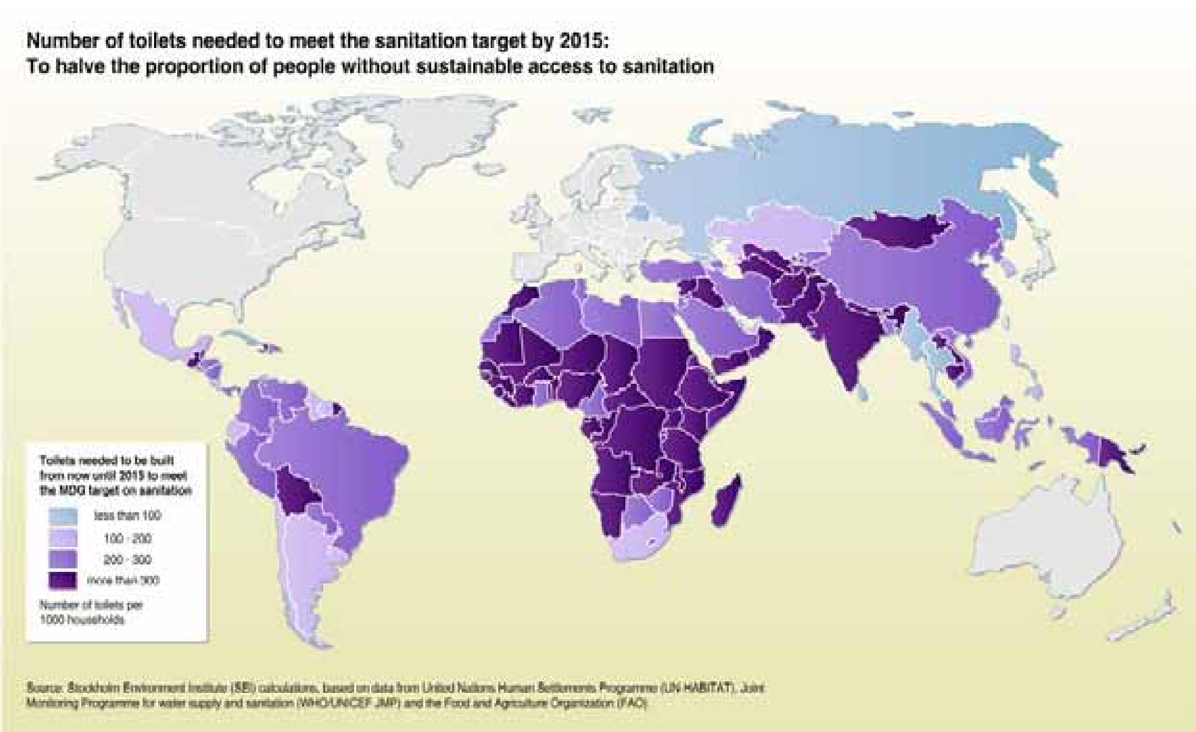

Figure 1.1: Number of toilets (per 1000 households) needed for the different regions to meet the Millennium Development goal in sanitation (Stockholm Environment Institute)

Many new urban areas will be created to house these increasing urban populations, and this offers the opportunity to develop more imaginative and more responsive sanitation arrangements, rather than continue with more of the same, whether the same be conventional sewerage or one of the current more ecological alternatives. It is with this long-term perspective that we develop a means of selecting sustainable sanitation arrangements, particularly for those currently most in need − poor and very poor households in developing countries (Mara *et al.* 2006).

Clearly, there is a need for an alternative, cost-effective and a sustainable paradigm of human waste disposal. The capital-intensive, material-intensive urbanisation process of the Western world is only feasible for rich countries, but not for the poor ones (Narain 2004). As a matter of fact, current sanitation technologies are very similar to those developed 100 years ago: transport the problem out of the residential area (Lens *et al.* 2001). What we believe to be the most sustainable solution today may not be the best one tomorrow due to new findings and the development of new technologies (Henze and Ledin 2001). Following this, ecological sanitation "ecosan" has emerged on the scientific and the political scene.

The term “ecosan” stands for ecologically and economically sustainable sanitation systems. It does not refer to a specific technology. It is used to describe a whole range of technologies and institutional arrangements, which addresses both, the issue of water scarcity and better sanitation. Ecological sanitation covers closed-loop systems of wastewater management, which concentrate on the principles of hygienically safe recycling water and nutrients as well as reducing the need for fresh water, presenting a holistic alternative to the conventional sanitation systems (Schmitt 2004).

The ecological sanitation concept fits perfectly into the Millennium Development Goals, because its aims are to stop the non sustainable exploitation of water resources and develops strategies which enable an affordable and reliable water supply and sanitation at a regional, national and local level. There is a growing concern for ecological sanitation and this is giving a rise to innovations in the concept of “sewer-less cities” using new technological suitable systems which use extremely low amounts of water or no water at all and in which all wastewaters and solid wastes are recycled. Ecological sanitation is based on the traditional science of recycling and composting of human waste, but in a way that uses the best of modern science and technology to “sanitise” and match the convenience and public hygiene of the modern flush toilet (Narain 2004).

The most important issue that needs to be considered is that ecological sanitation must be a valid concept for the rich and not just for the poor. If ecological sanitation is cost effective aiming exclusively to serve the “unserved poor”, it will be an interim alternative that people will discard as soon as they become rich (Narain 2004).

The main and common element for applying “ecosan” is the collection and treatment of human faeces separated from the rest of the wastewater. The faecal matter is the smallest portion in the wastewater, but at the same time it contains the highest portion of pathogens and organic matter, compared to other wastewater streams. So if kept separated and treated in an appropriate way, it can provide a renewable energy and restore degraded soils. The mixing of faeces with a large amount of other wastewater streams is the crime that has often been committed has resulted and still results in the death of so many people. Now it is time to re-think, because faecal matter has got nothing to do with the water cycle but it belongs to the nutrient cycle (Otterpohl 2004). So, as conclusions drawn by scientists as well as by politicians were in order to make household nutrients available for recycling in agriculture, sanitary systems must be changed to allow decentralisation and separate treatment of the different wastewater streams (Niemczynowicz 2001).

Based on all these facts, this work will deal with the separate collection and treatment of human faecal matter as a component of ecological sanitation concepts.

This study investigates the possibility of combining two existing technologies for the separate treatment of faecal solids. The first technology is the so-called “Rottebehaelter” (pre-composting or rotting tank) technology. The Rottebehaelter uses the principle of cake filtration for the separation of faecal solids from the flush water. The filter medium used is either a filter bed or a filter bag. These systems are used in some rural areas in Germany, Austria and Switzerland. The faecal matter is retained in the filter bed or bag for a period of 6-12 months which results in a relatively dry product. This system has proven to be efficient in solid-liquid separation and collection/storage of solid matter from household wastewaters but perform only little treatment. Therefore, post-composting is required, in which the faecal matter is taken out of the bag to be further composted with other kitchen and garden wastes.

The second technology is the "vermicomposting" technology. Vermicomposting is the process in which organic materials are converted into humus using earthworms that break down the organic material and convert it to worm biomass and respiration products. The vermicomposting practice is not new, it started in the middle of the 20th century and the first serious experiments were established in the 1970's. There are already large amounts of literature reporting successful attempts for vermicomposting of various animal wastes as well as municipal wastes. However, the first attempts for using vermicomposting as a treatment method for the faecal matters were reported by Basja *et al.* (2002) followed by Gajurel (2003). The promising results reported by these authors have led to the need of more in-depth investigations about the mechanisms and kinetics of the vermicomposting process.

In this work, a number of important aspects of faecal matters vermicomposting were investigated:

- the influence of temperature on the kinetics of the vermicomposting process and the development of empirical equations explaining this influence,
- the influence of different earthworm densities on the kinetics of the vermicomposting process and the development of empirical equations,
- the influence of different earthworm species on the quality of the end product,
- the influence of vermicomposting process on water soluble and total nutrient contents,
- the influence of vermicomposting process on the degree of stabilisation and discussion of the different maturity criteria,
- the effect of $CaCO_3$ addition on the vermicomposting process and the final product,
- assessing the suitability of lab scale experiments for the prediction of quality parameters in pilot scale,
- assessing the economic feasibility of the concept.

To examine these aspects, lab scale experiments were conducted and operated for one and a half year. Furthermore, a pilot plant was operated for 2 and a half year.

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1.1 Centralized sanitation concepts

1.1.1 Historical Background

In cities in industrialized countries, centralized urban sanitation systems (CUS) dominate. CUS systems are based on the collection and transport of wastewater via an extended sewer system to a centralized treatment plants (Lettinga *et al*. 2001). The reasons for their emergence were hygienic considerations. Decentralized sewage discharges and handling human excreta were found to cause major outbreaks of infectious diseases such as cholera (Reijnders 2001). The water closet that discharges into a sewer system was argued to be the solution of these problems (De Jong *et al*. 1998). Wastewater treatment systems originated as end of pipe measures to reduce the negative impacts of organic matter on surface waters into which sewers were discharged (Reijnders 2001).

Centralized wastewater treatment plants solve acute pollution problems efficiently and require relatively small treatment capacities per inhabitant. Gravity sewers can be a very energy efficient way of transport if they have reasonably small length per inhabitant. However, there are several disadvantages that become exceedingly important with today's world-wide promotion of this type of system with consideration of larger time scale (Otterpohl *et al*. 1997).

1.1.2 Drawbacks

Otterpohl *et al*. (2004) have pointed out that conventional wastewater management utilises a disadvantageous approach by mixing different flows in central sewerage systems. Urgent hygienic problems in the houses could be solved on one hand. On the other hand, water resources used for drinking water supplies are polluted at the source simultaneously. Consequently epidemics, which have been locally contained before, could now spread rapidly via the supply of drinking water.

Besides being very expensive in investment, maintenance and operation, conventional waterborne sanitation reveals shortcomings of greater importance. As water is used as a medium to transport the wastes, these systems are becoming increasingly more difficult to apply in regions of aggravating water scarcity, in arid zones and in poor countries (Werner *et al*. 2004).

The mixing of faeces and urine with flush water and greywater inhibits economic reuse of human excreta. The hygienically very dangerous, extremely small quantity of faeces contaminates large amounts of water via conventional flush toilets and sewerage (Otterpohl *et al*. 2004)

Centralized sanitation systems use clean water (mainly tap water) as the transport medium of domestic wastes which were originally relatively concentrated, for example, faeces. Moreover, very little, if any, recovery of useful products such as fertilisers (nitrogen, phosphorus or potassium) from human excreta is achieved. Conventional approaches to sanitation misplace these nutrients, dispose them of and turn the cycle into a linear flow (Winblad and Simpson-Hébert 2004). On the contrary, huge amounts of poorly stabilised and polluted sludge are generated which have to be disposed of or incinerated because they are not acceptable for agricultural reuse. Thus, the CUS approach is far from sustainability. The proper functioning of CUS systems depends on energy supply, computer hardware and so on, making them vulnerable to theft, sabotage and military attack in poor and politically unstable countries (Lettinga *et al*. 2001).

Narain (2004) has described modern sewage systems as ecologically mindless and iniquitous. This is because these systems waste natural resources: it use materials and energy, generate waste, and cause high health and environmental costs. They are highly capital intensive and divide the urban population into rich and poor, i.e. between people who can afford the expensive urban services and those who cannot. Wilderer (2001) has pointed out that the cost benefits of central systems diminish when the costs of building and maintaining the distribution and collection systems are taken into account, the cost of the installation of the water supply net and the sewer system are almost one order of magnitude higher than the cost of building the treatment facilities. According to Grau (1994), countries with an average annual per capita gross national product (GNP) of below US$ 1,000 not only lack the resources to construct treatment plants, but also cannot maintain them, even if these plants were constructed free of charge.

Of all the wastewater in the world, 95 percent is released to the environment without treatment (Niemczynowicz 1997). According to the WHO (2002), 1.1 billion people lacked access to improved water sources, which represent 17 % of the global population and 2.6 billion people lacked access to improved sanitation, which represents 42 % of the world's population. As a consequence, 1.8 million people die every year from diarrhoeal diseases, 1.3 million people die of malaria, 500 million are at risk from trachoma and 133 million people suffer from high density intestinal helminths infections. If sanitations provisions continue to be installed based on current standard, up to 5.5 billion people will be without sanitation by the year 2035, many of them will be living in crowded urban settlements (Niemczynowicz 1997).

Otterpohl *et al*. (1997) have highlighted the disadvantages of the centralized flushing sewer system as follows (see figure 1.2):

- Nutrient losses even with the best affordable treatment plants are over 20 % for nitrogen and more than 90 % for potassium. The discharged nutrients are accumulated in the sea. P and K sources that are used to replace these losses are likely to run out within a time span of concern.
- High energy demand for destruction of the organic wastewater contents and for the nitrification. In addition, the synthesis of ammonia from nitrogen for production of fertilizer is very energy intensive.
- High pollution loads in the sewage sludge and missing potassium makes its use as an agricultural fertilizer often impossible.
- A high amount of water is necessary for flushing human wastes to the treatment plant (leads to disasters especially in water scarce metropolitan areas).
- Hygienic problems in receiving waters after combined sewer overflows and water treatment plants effluents. Severe problems without adequate treatment in low income countries (even existing often fail within a couple of years).
- Operation and rehabilitation costs for the drainage system and the sewage treatment plants are high.
- Little sense of responsibility for the water cycle and the fate of pollutants is developed on the users side due to the invisibility and invulnerability (mainly by dilution, not by final degradation of chemicals) of the wastewater infrastructure in the local environment.

Discussion on hormones, their mimics and emissions of medical residues by the users including those with endocrine effects (from widely used contraceptives) are showing another weakness of conventional sanitation systems. These substances reach receiving waters easily especially because of their polarity in combination with often very low degradation rates in conventional treatment plants (Otterpohl 2001).

As a matter of fact current sanitation technologies are very similar to those developed 100 years ago: transport the problem out of the residential area. They do not consider resource preservation or the reuse of residues and wastes. However, the innovation potential is very high; it is time to envisage this reality (Otterpohl *et al*. 2004). What we believe is the most sustainable solution today may not be so tomorrow due to new findings and the development of new technologies (Henze and Ledin 2001).

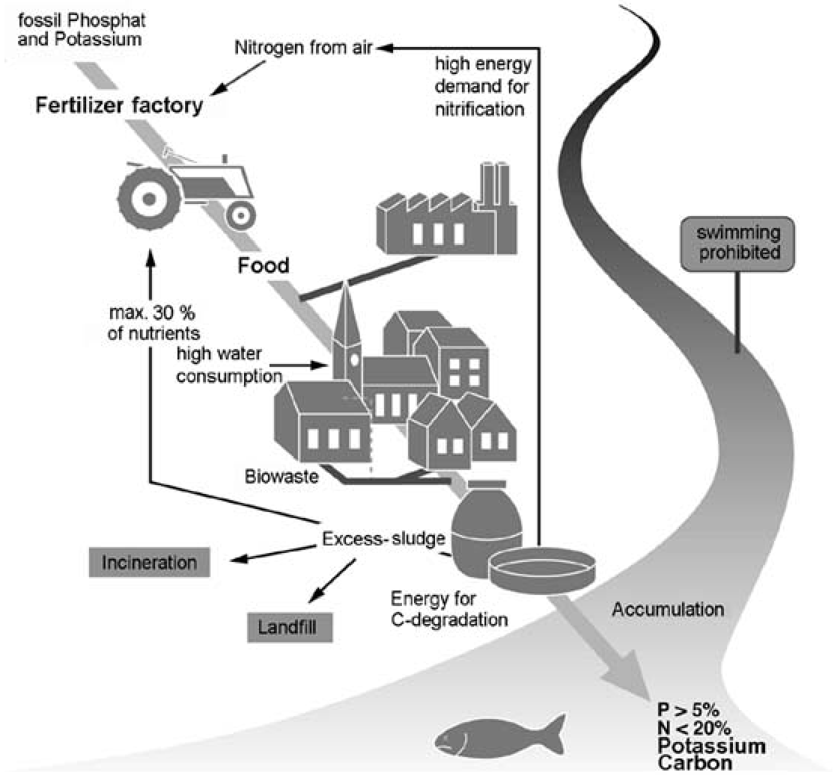

Figure 1.2: The linear flow system of the centralized flushing sewer system (Otterpohl *et al.* 1997)

1.2 Ecological sanitation

1.2.1 Introduction

An alternative approach to avoid the disadvantages of conventional wastewater systems is ecological sanitation. Key features of this approach are prevention of pollution and disease caused by human excreta, management of human urine and faeces as resources rather than as a waste, recovery and recycling of nutrients from human excreta. In natural world, excreta from humans and other animals play an essential role in building healthy soils and providing valuable nutrients for plants (Winblad and Simpson-Hébert 2004).

The starting point of the discussion about future is the feasibility and sustainability of sanitation. Serious planning might finish the common practice, that the system water closet-sewerage-wastewater treatment plant (WC-S-WWTP) is installed automatically without any serious discussions of alternatives (Otterpohl *et al*. 1999).

1.2.2 The need for ecological sanitation

Niemczynowicz (1997) has pointed out that new goal of water and sanitation should not only be the safe disposal of human residuals but also the reuse of nutrients from sanitary systems and organic parts of solid wastes in agriculture.

Separation of wastewater streams of different qualities and their respective appropriate treatment for reuse is common in industry and is fundamental for this new concept (Otterpohl *et al*. 1999).

According to Wilderer (2001) black water (faeces plus urine) is of major concern with respect to health risks. It may contain pathogenic organisms as well as pharmaceutical residues. Since the concentration of organic material is high, conversion into biogas appears to be attractive. Urine contains high amounts of nitrogen and phosphorus and could be used as a source for fertilizer production. Kitchen refuse is high in organic loads and can be converted into biogas and compost, potentially in combination with black water constituents. Compared to faeces, grey water is low in concentrations of organic compounds. Most, but not all, of the grey water components are easily biodegradable. This type of wastewater can be purified relatively easily and used thereafter for various purposes, for instance instead of drinking water for flushing toilets, for cleaning and irrigation. Figure 1.3 gives a typical range of specific mass flows (kg per capita and year) of the main constituents of household wastewater and their possible reuse options.

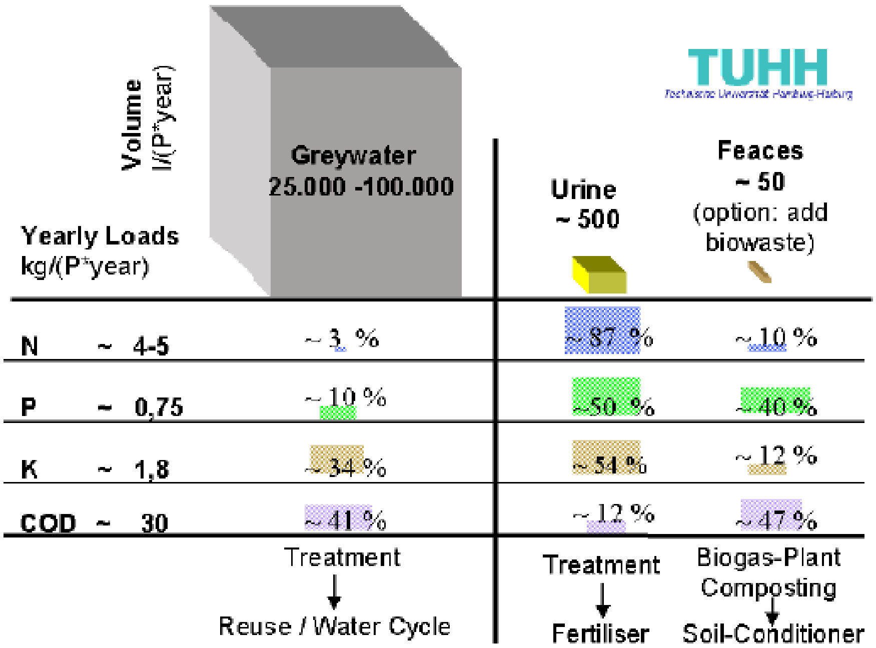

Figure 1.3: Characteristics of the main components of household wastewater and their potential reuse options (Otterpohl *et al.* 1997)

Sanitation systems can be designed to be more efficient; modern as well as classic technologies can be applied in source control systems. Sanitation can be considered as a production unit that provides high quality reuse water, safe fertilizers, and soil-improving material (including processed biowaste where appropriate). This could be called "resources management", because there will no longer be any wastewater (Otterpohl 2001). Future sanitation concepts should produce a rich organic fertilizer for agriculture rather than waste (Otterpohl *et al*. 1997). Niemczynowicz (1997) states that one person can produce as much fertilizer as necessary for the food needed for one person. This very optimistic view is limited to the production of crops and cereals one person needs. A more conservative view says that excreta of one person could replace about 50% of fertilizer needed for providing crops and cereals for this one person (Otterpohl 2005).

An idealised scheme of the general mass flows in a possibly ecological sanitation concept is shown in figure 1.4, where recovery of nutrients is possible, thus the flux scheme is no longer linear but a closed cycle.

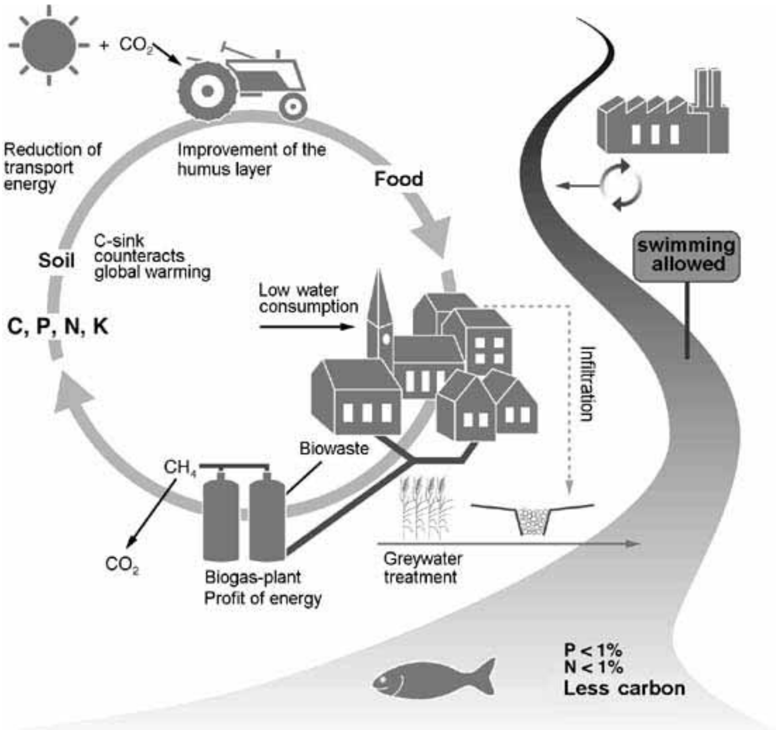

Figure 1.4: Scheme of the mass flux in ecological sanitation (Otterpohl *et al.* 1997)

1.3 Quantity, composition and hygienic properties of human faeces

Due to the fact that this work is focusing on the treatment of faeces, the quantity, bio-chemical composition and hygienic properties of faeces will be briefly reviewed.

1.3.1 Quantity

According to several researchers the dry weight of faeces can vary between 70 and 170 g/person/day (Roeleveld 2001). Europeans and North Americans produce daily between 100 and 200 grams (wet weight), whereas people in developing countries excrete an average daily wet faecal weight of 130-520 grams. Vegetarians generally show higher faecal weights than other groups, and faecal weights in rural areas are higher than in towns (Faechem *et al*. 1983).

Table 1.1: Total and dry weight of faeces and the average frequency of passing stools (Roeleveld 2001, Nudascher 2001)

Total weight of faeces (g/p/d)	Dry weight of faeces (g/p/d)	Frequency (l/p/d)	Reference
70-140	19-38	-	Bingham (1979)
106	-	-	Cummings *et al*. (1992)
170	44.2	1.2	Glatz and Katan (1993)
138	34	0.9	Cummings *et al*. (1996)
100-200	-	-	Belderok *et al*. (1987)
135-270	-	-	Gotaas (1956)
124	-	-	Geigy (1981)
-	27	-	Webb (1964)
-	35	-	SNV (1995)