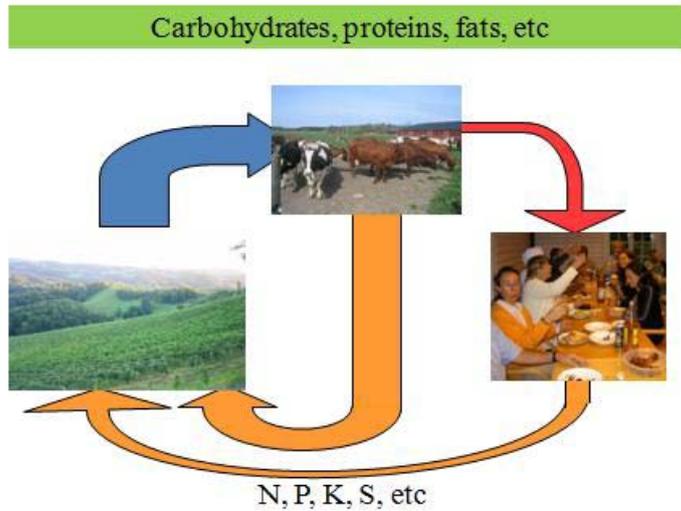


Lecture 4.1 Cycles of plant nutrients and water

How do plant nutrients and water flow in nature? How has these flows been changed by society?

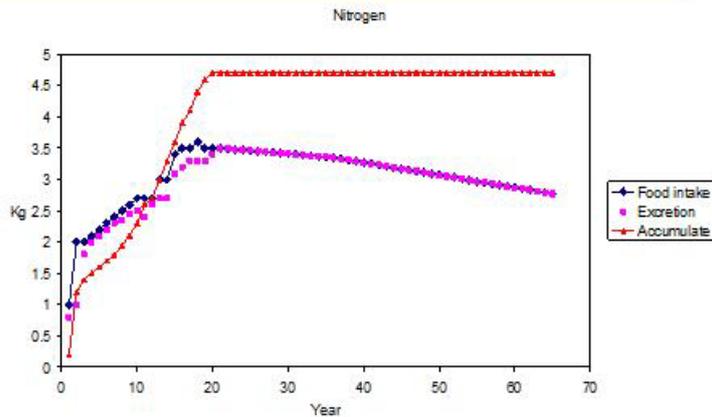
Goal: To be familiar with the natural cycles of plant nutrients and water and to know how different sanitation systems affect these cycles.

Ecological Alternatives in
Sanitation



Most natural ecosystems are sustainable over long time periods. The flow of nutrients are stable within the system as the consumed nutrients mainly are circulated on the field/forrest level with a smaller stream leaving for carnivores. The traditional flow for all is that the nutrient come back to the soil. Examples of such ecosystems are the savannah, the rain forest, the temperate forest etc. These systems have been running for very long time period and the losses have been small. However in last hundred years this natural internal flow of nutrients has been redirected and the nutrients from the main carnivore of today, the human are ending up in the water streams and lost into the ocean.

Accumulation of nutrients

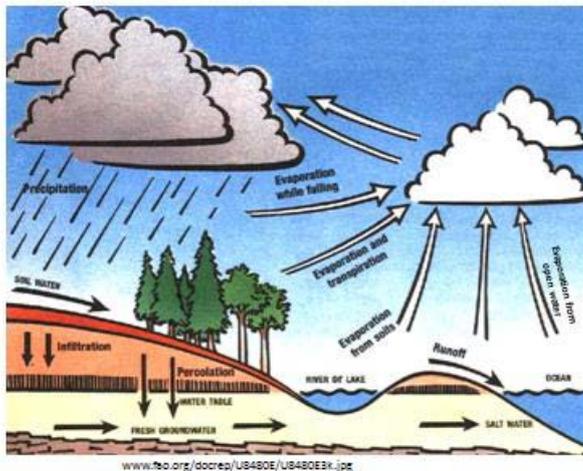


Note that while growing animals need to consume nutrients in the form of carbohydrates, proteins, fats etc., grown animals do not accumulate plant nutrients, like nitrogen, phosphorus, potassium and sulphur etc. Growing animal accumulates some of these nutrients in its body tissue, e.g. nitrogen in the form of proteins in the muscles and phosphorus in the skeleton, but even during this period only a very small fraction of the intake of these elements is accumulated. Once the animal is fully grown, it excretes as much of the plant nutrients as it consumes.

This is exemplified with this slide that shows the amount of nitrogen found in a average size human 80kg and an approximate consumption, excretion and accumulation of nitrogen during one life span.

Here we can see that small amounts of nutrients are accumulated during the first 20 years and after that the consumed nutrients are excreted as the body have reached a mass balance.

Hydrological cycle

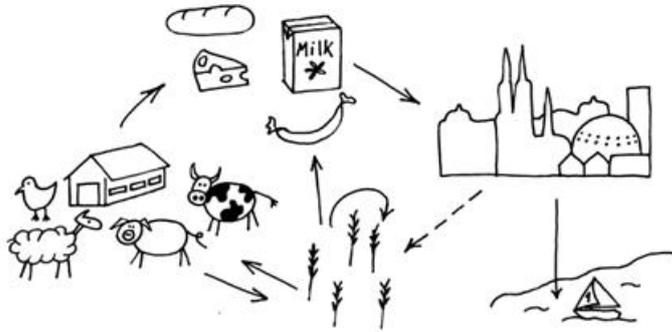


The natural hydrological cycle is driven by the sun. Water is evaporated and the precipitation, the rain, supplies fresh water to the soil and to the streams and lakes. In the soil, fresh ground water is formed and this feeds, together with surface runoff, streams and lakes.

While in a geological time frame, there is a clear coupling between the cycles of water and plant nutrient, the stable sustainable ecosystems are developed, and have evolved, to decouple these cycles as much as possible. The reason for this is that if the ecosystem loses a lot of plant nutrients by leaching, then it will be depleted of these and thus its production of plants will not be sustainable. Therefore, stable terrestrial ecosystems have developed to trap and utilise as much of the dissolved plant nutrients as possible. It is largely thanks to their efficient trapping of dissolved plant nutrients that fertile and productive terrestrial ecosystems so often coexist with clear streams and lakes which are not eutrophicated.

More about this is found in Chapter##

Linear flow of plant nutrients in present food chain



Contrary to the cyclic flow of plant nutrients in stable ecosystems, the flow of plant nutrients in our human society is almost entirely linear, at least as far as the flow of plant nutrients in food goes. The food plant nutrients flow, as constituents of the food, from agriculture to society. However, with conventional sanitation systems this flow is linear, not cyclic. When a water flushed sanitation system is used, the plant nutrients end up either in surface water causing pollution and eutropication. When a conventional pit system is used, the plant nutrients end up extremely concentrated in soil, far too concentrated for vegetation to be able to utilise them in any reasonable time. This is also the case when sewage sludge from well functioning sewage treatment plants are put in landfills. Usually this leads to a large part of the nitrogen leaching out, while the phosphorus mainly remains in the close vicinity of the deposit. In both cases, there is a severe risk of contaminating the ground water with nitrogen in the form of ammonium and nitrate and with pathogens.

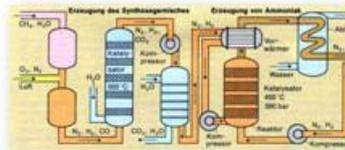
The linear flow of plant nutrients from the agricultural system leads to the soil being depleted of plant nutrient. Thus, to sustain good harvests, this linear flow of plant nutrients out of the agricultural system has to be counteracted by a linear flow in of plant nutrients and this flow is normally supplied by chemical fertilisers produced from non-renewable resources, e.g. raw phosphorus, natural gas and oil (for producing nitrogen fertilisers) and potassium deposits.

The losses due to leakage and erosion have to be counteracted by use of cultivation practises which minimize these losses. The loss of nutrients due to harvested crop and food should be counteracted by recycling the safely sanitised excreta and kitchen waste.

Thus, for improving the sustainability of food production it is important both to recycle the food lost with the harvested crop, which is done by recycling of safely sanitised excreta and kitchen waste and to use crop cultivation practices which minimize the nutrient losses due to erosion and leakage.

Fertiliser use

- 40% of global food is produced with mineral fertiliser
 - Mainly NPK
 - N= 95 MT*
 - P= 8,5 MT*
- Mineral fertiliser production
 - 1.2% of energy consumption
 - 1.2% of GHG emission
 - Lack micro-nutrient and humus



*FAO 2006

The large part of the flow of fertiliser nutrient into agriculture is lost on the way and does not end up in the amount of plant nutrients actually found in the food we consume. The main part of the nitrogen is lost in agriculture, mainly as nitrate leaching from the fields and nitrogen gas being denitrified in the fields. Some is also lost as N_2O , nitrous oxide and ammonia. The main part of the phosphorus remains in the soil and thus helps to improve its nutrient status. However, some is also lost from the fields mainly due to erosion but also leakage.

Details on the data: Data given in million tonnes of pure nitrogen (N) and phosphorus (P) for year 2002/03 (Produced fertiliser. International Fertilizer Association (<http://www.fertilizer.org/ifa/>)).

The amount of phosphorus, 8,5 Mton, corresponds to 20 Mton of P_2O_5 .

The nutrient content

- Urine and faeces
- Average earthling (Indian)
 - 2400cal/pers, day
- Annual global nutrient consumption
 - N=20 MT 21%
 - P=2 MT 24%
- The cost of nutrients 1 kg N
 - Farmer 0.7€
 - STP 7€



If we look at the global scale regarding the nutrient content of the excreta from humans we have used an average number for food consumption. In this case we used the diet of one Indian person. The food consumption is based on the FAO statistics on food consumed in per person in India www.fao.org

Nitrogen: $0.13 \times \text{total protein supply per person}$

Phosphorus: $0.011 \times (\text{total protein} + \text{vegetal protein supply per person})$

Equations from: Jönsson et al. 2004

To compare the different costs for the plant nutrients in the wastewater the price of one kilogram of nitrogen have been compared for production and for removal. The production is the average retailer price in Sweden 2010 (no subsidies) that the farmer pay for nitrogen fertilizer. The fertilizer market is global and the price is similar wherever you buy the fertilizer. Many countries subsidize mineral fertilizers and the farmer pay lower prices. Often is this price the price that organic fertilizers are compared with when discussing the market for human derived fertilizers.

One alternative for this calculation is to include the cost of management of the consumed nitrogen also. In this calculation the price for nitrogen removal is based upon the treatment cost in an average Swedish sewage treatment plant where nitrogen are removed by nitrification and denitrification in a highly advanced treatment process. This can also be included in the calculation for fertilizer cost. If the system don't have the advanced treatment process it should not be included in the calculation, however, if it is possible environmental effects from pollution should be included.

Quality of ground water in Kampala

- Main water source – protected springs
- Main toilet system – dug pit latrin
- Most springs faecal contaminated

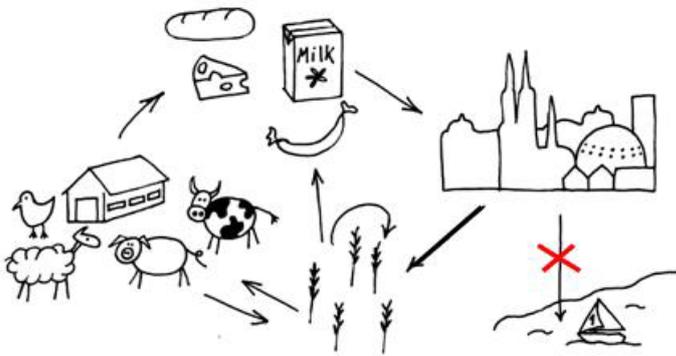


Kampala, the capital of Uganda is located on seven hills, on these hills there are several springs coming to the surface. In the valleys of the hills there are wet lands where standing water is found. The springs are the main water source for the majority of the inhabitants.

The main sanitation system for the area is dug pit latrines that are dug into the hills close to the houses. The placement of the latrines have not been associated with where the springs are located, so it is usual to find latrines just uphill to the spring.

This have lead to decreasing water quality from the springs and in an evaluation of the water quality of ten protected springs, faecal coliforms were found in all sampling of the springs and in 90% of the cases the count of faecal coliforms exceeded the WHO guidelines for drinking water quality (Haruna et al., 2005).

By closing the loop - both leakage and input are minimised



If the produced wastewater, that today are polluting the water recipients, are redirected from pollutant of the water bodies to a resource in food production there are two main gains.

First of all the pollution of the water recipients decreases as no more eutrophying nutrients enters. Together with this, also other pollutants in the water are stopped, e.g. pathogens and organic micropollutants that have major effects on the general water quality and specific on the drinking water quality.

Secondly as the nutrients are recycled back to agriculture the net loss of plant nutrients from agriculture will decrease and thereby will also the requirement for compensating nutrients decrease, this means that the need for virgin mineral nutrients to the fields is decreased and less fossil resources will be consumed.

Crop nutrient removal

Crop	Yield, kg/ha	Dry matter	N, kg/ha	P, kg/ha
Cereals				
Maize	4000	88%	51	9
Rice	4000	88%	45	11
Sorghum	4000	88%	56	9
Wheat	3000	88%	55	10
Wheat straw, crop above	4000	85%	16	2
Tubers etc				
Cassava root	20000	36%	32	1
Potatoes	25000	23%	83	13
Sweet potatoes	10000	59%	49	12
Others				
Banana fruit, ripe	25000	31%	67	8
Ground nuts, peanuts	1000	94%	37	4
Soybeans	1000	91%	54	5

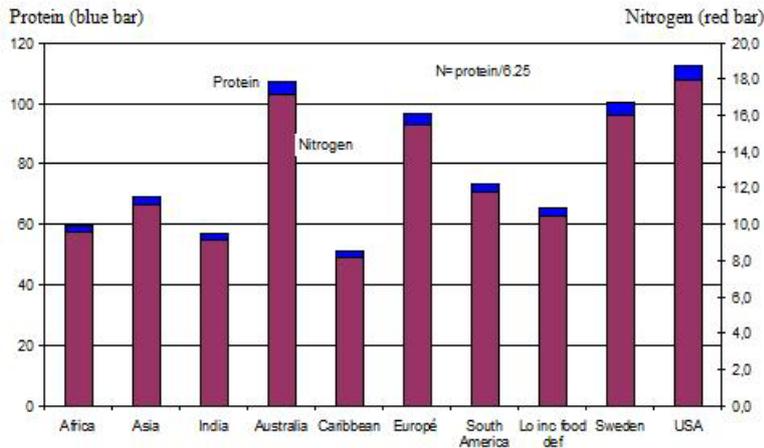
The table shows the amount of the plant nutrients nitrogen (N), phosphorus (P) and potassium (K) removed by the usable (as food or feed) crop with the given yield. This means that the amount of nutrients in removed crop residues is in addition to the amounts given in the table. The nutrient content in the table includes peels for crops with high moisture (bananas, potatoes, sweet potatoes & cassava root) but not for the others. Thus, the nutrients in the peels are neither included for groundnuts nor soybeans.

As shown by the table the amounts of nutrients removed by the crop are large, making it obvious that in the long run the nutrients of the soil will deplete, if the soil is not replenished with these elements.

The recommended fertilisation for certain crops and especially on certain soils can be radically larger than the amounts given in the table, especially for phosphorus, due to differing soil status and differing ability of the soil to deliver or immobilise nutrients. Many soils around the world are poor in phosphorus and to a large extent immobilises the phosphorus applied. The immobilised phosphorus is not lost, but can be seen as an investment towards a more fertile soil. However, on such soils the fertilisation recommendations for phosphorus can be up to 10 times as high as the amount removed by the usable crop.

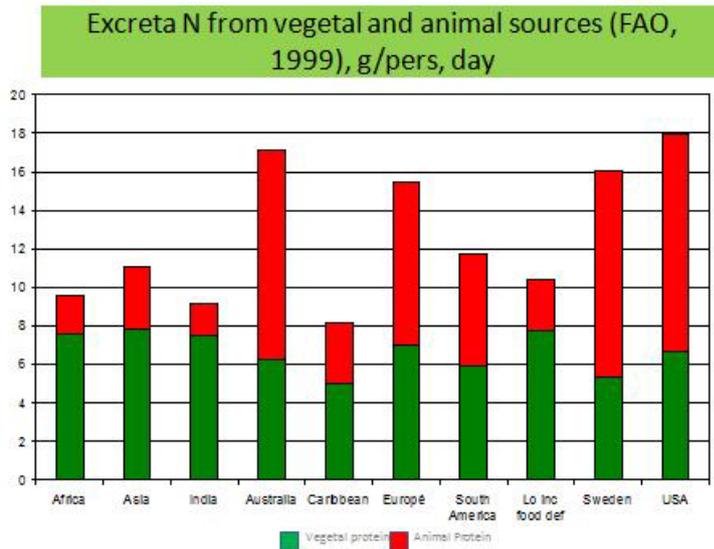
References for composition of crops: Machin, D.H., 1991; Simonsson, A. 1991; Leung, W.-T.W. 1968.

Total protein and nitrogen supply in grams per person and day (FAO, 2001) in different regions and countries



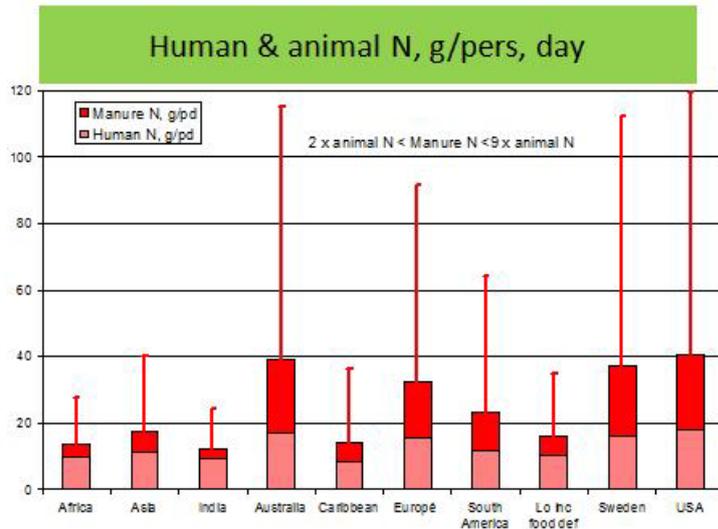
The consumption of protein differs by approximately a factor of 2 between different countries and regions. E.g. the supply of proteins in the Caribbean is around 50 grams per person and day, while the corresponding figure in the US is around 110 grams. Protein is normally calculated by multiplying the amount of nitrogen in the food stuff and then multiplying it by 6.25. Thus, the amount of nitrogen supplied to inhabitants in different countries and regions has been calculated by dividing the amount of protein supplied by 6.25. The food supplied does not entirely end up as food actually eaten as part of it ends up as kitchen waste, and thus the bars in the above diagram indicate slightly larger quantities than what is actually consumed and thus slightly more than what will be found in the excreta.

The diagram clearly shows that the amount of nutrients supplied by person and day is much larger in the developed regions of the world than in the developing. The amounts of protein, and thus of nitrogen, supplied is far larger in e.g. Australia, Europe, Sweden and the US than in e.g. Africa, India and the Caribbean. The amount of nutrients in the excreta is one argument stressing the urgency to close the nutrient loop in the developed countries. However, as seen in the next diagrams, it is even more urgent to close the nutrient loop in the developing regions.



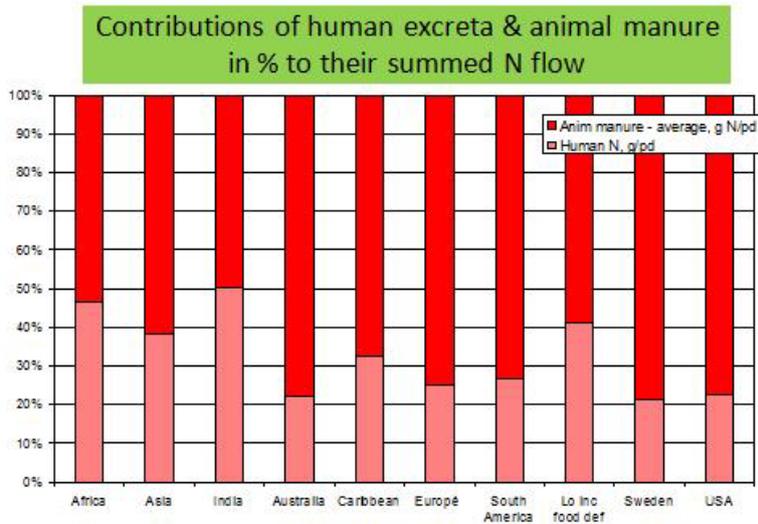
The diagram shows that the amount of vegetal protein (in green) supplied per person and day is fairly constant in different regions, between approximately 35 and 50 grams per person and day. And it is higher in most developing regions than in the developed regions. In the developed regions the vegetal protein is supplemented by large amounts of animal protein. The animal protein (in read) has accumulated in the animals and the efficiency for this accumulation is low. Its variation can be approximated as usually between 10 and 30%, meaning that 2 to 9 times the amount of nitrogen in the animal protein has been excreted as manure from the growing animal. Thus, the total flow of nitrogen in animal manure and human excreta in society can be calculated.

You can get the data for your country/region from www.fao.org, FAOSTAT-Nutrition, Food Supply, Crop Primary Equivalents.



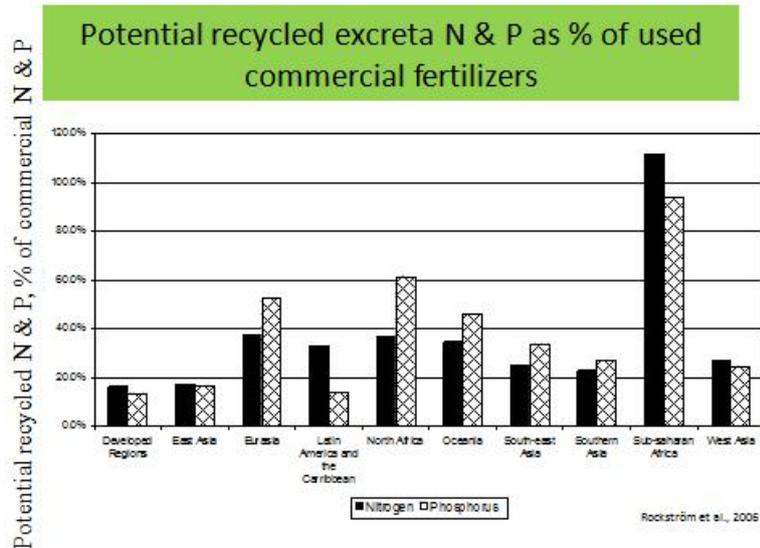
The total flow of nitrogen in animal manure and human excreta in different societies. In the calculation, imports and exports has been neglected, i.e. it has been assumed that the food supplied in a region also is produced in the same region.

As seen from the diagram, the proportion of the nitrogen flowing with human excreta to the flow of nitrogen in excreta and manure is far less for the developed regions than for the developing regions, due to the large flows of nitrogen with animal manure in the developed regions. Thus, the excreta nutrients are far more important for the plant nutrient flow in the developing regions than for the developed regions. This is even more so, as the farmers in the developed regions can afford to use chemical fertilisers and thus they can replace the losses of plant nutrients from the fields. In the developing regions however, many farmers can not afford chemical fertilisers, which means that the soil can rapidly be depleted of nutrients. This, together with the data in the above diagram strongly indicates that it is of utmost importance for food security to close the nutrient loop in the developing regions, that it is of utmost importance to introduce Ecosan sanitation systems in these regions.



As seen from the diagram, the contribution by the human excreta flow to the combined flow of N is far larger in the developing regions of the world, 40-50% in Africa & Asia and in countries with low income and food deficiencies. In the developed regions on the other hand, Australia, USA and Europe, the contribution from the human excreta is far less, 20-25%, which indicates that it is far more crucial to close the nutrient loop in the developing regions than the developed ones. This is especially so, as the farmers in the developed regions supplement the nutrient flow in manure and excreta with chemical fertilisers, while many farmers in many developing regions can not afford chemical fertilisers.

On the data: the flow of N in animal manure has been calculated as 5.5 times the amount of N consumed in the form of animal protein.



The above diagram gives another argument why it is of utmost importance to introduce Ecosan in the developing regions. In many of these regions, the excreta nutrients corresponds to, and thus theoretically can replace, a larger fraction of the chemical fertilisers used, than in the developed regions. E.g. in North Africa, Euroasia and Oceania, the plant nutrient content of the excreta corresponds to approximately 40 to 50% of the chemical nitrogen and phosphorus fertilisers used and in Sub-saharan Africa the excreta nutrients even corresponds to more than 100% of the chemical plant nutrients used, while in the developed regions the excreta nutrients corresponds to approximately 15% of the chemical fertilisers used.

References

Haruna R., Ejobi E., Kabagambe EK. 2005, The quality of water from protected springs in Katwe and Kisenyi parishes, Kampala city, Uganda

Jönsson, H., Richert Stintzing, A., Vinnerås, B. & Salomon, E. 2004. Guidelines on use of urine and faeces in crop production. Report 2004-2, Ecosanres, Stockholm Environment Institute. Stockholm, Sweden. Download:
<http://www.ecosanres.org/PDF%20files/ESR%20Publications%202004/ESR2%20web.pdf>

Machin. D.H., 1991. Overview of needs and justification for use of roots, tubers, plantains and bananas in animal feeding In: Machin, D. & Nyvold S. Roots, tubers, plantains and bananas in animal feeding, FAO Animal production and health paper 95

Simonsson, A. 1991. Fodermedel till svin. Husdjur Rapport 69, SLU Info.

Leung, W.-T. W. 1968. Food composition table for use in africa. Nutrition Program, National Center for Chronic Disease Control, Health Services and Mental Health Administration, Public Health Service, U.S. Department of Health, Education, and Welfare, 9000 Rockville Pike, Bethesda, Maryland 20014 U.S.A.

Rockström, J., Nilsson Axberg, G., Falkenmark, M., Lannerstad, M., Rosemarin, A., Caldwell, I., Arvidson, A. & Nordström, M. 2005. Sustainable Pathways to Attain the Millennium Development Goals. Stockholm Environmental Institute, Sweden.

Chapter 4 module 2 Treatment of excreta for safe reuse

How should urine and faeces be treated for safe handling and reuse in crop cultivation? How can organic material from households be co-treated?

Goal: After the lecture the student should know the principles, prerequisites and main characteristics, properties, advantages and disadvantages of treatment by incineration, ammonia and storage of faeces and storage of urine.

Incineration



Chimney

Removable top through which faeces are fed into the incinerator

Access door through which the stove is opened and loaded inside after firing

- Quick and simple method
- Faeces are applied in the stove
- Require external fuel
- **Is quick and gives a product, the treatment of which can be verified by the eye**

Incineration can be performed in a stove supported with an underlying fire, the one on the picture is a stove locally produced in Uganda where you heat up the stove by incinerating sewage dust. When reaching high temperatures the faeces are entered into the stove and a quick degradation occurs within minutes. During the incineration the material is transformed into ash, and the treatment assures that all material is treated in high temperatures. As the material is degraded the function of the degradation can be verified by the eye if there is no organic material remaining and thereby no risk for remaining pathogens.

This type of simple incinerators are cheap and are efficient enough for be used at municipal level for faecal incineration as it according to Niwagaba 2009 can be used for incinerating the faeces from at least 500 persons.

Incineration - function

- To avoid odour, moisture should not be above 10%
- Large amounts of non-organic material calls for additional fuel
- Very efficient pathogen reduction
- Mass of faeces reduced by more than 90%



When excreted the faeces hold a moisture content of approximately 80%, for incineration the material required to be dried to 10% moisture only. If the material contain more moisture there is an overlying risk for strong odour during the incineration. In most cases the faeces can be sun dried in a thin layer (10cm) on soil. In some areas there are toilets available that dry the faeces directly in the toilet or on a sun heated conveyor belt behind the toilet.

If the faeces are covered with inert material after defecation, e.g. ash or sand, this has to be considered as the inert material can kill the fire upon addition, therefore additional fuel will be required to manage this. Another way to go is to replace some of the inert material with organics, e.g. saw dust.

The high temperatures result in efficient reduction of pathogens in the material as no organisms stands the high temperatures reached in the stove. The efficiency of the incineration can be evaluated just by looking at the outcomming material as if some material is not well degraded there is risk for pathogens.

The faeces are significantly reduced in mass and volume by the incineration, approximately 10% will remain of the initial material. Inert material will not be affected of this.

Incineration - nutrient transformations

- N: All is lost – most as N_2 , but some as NO_x
- P: Partly fixed – availability probably 30-70% of that in chemical fertiliser
- K: high availability
- S: lost to air as SO_x
- Ash is a concentrated K fertiliser containing large amounts of P
- Can be reused as amendment in toilet

The heat in the stove will affect the chemical composition of the material as the incineration will lead to thermic oxidation of the material. Almost all carbon will be lost as well as all the nitrogen and the sulphur. Nitrogen will mainly be lost as N_2 , which is the same form as you find nitrogen in the atmosphere and some will be found as NO_x which is a toxic pollutant that also can increase acidification. Sulphur is mainly lost as SO_x which is an acidifying compound.

Phosphorus will not be lost, but the availability for plants will decrease as a result of the incineration. About 30-70% of the plant availability will be lost during the process, so even if the phosphorus remains in the ash the effect on plants is less compared to mineral fertilisers as only parts of the phosphorus in the ash will be mineralised during the coming ten years after application. Potassium will remain in the ash with high plant availability.

The ash can be used as a potassium fertiliser that contain large amount of phosphorus, that is only partially plant available. Another use can be to recycle the ash as amendment in the toilet after defecation.

Storage of faeces

- Biological degradation during storage
- Final product look like soil
- Risk for pathogenic survival
- Current recommendation
 - $>20^{\circ}\text{C}$ >1 year
 - $<20^{\circ}\text{C}$ >2 years
 - Restriction in usage



Long term storage is the most common treatment alternative practiced for faeces collected in Ecosan systems. It is often also called composting, and in this case the composting occur under low temperatures and therefore called storage. The degradation of the material occurs slower at lower temperature, the optimal temperature for composting is 55°C .

The storage can be performed in the toilet, in the resting vault of a double vault toilet. But it may as well be performed on another place e.g. external container or in a pile. Like in the picture above it is good to have the opportunity to cover the storage during rain assuring to minimise surface run off, and thereby spreading unsanitised faeces in the environment. Additionally animals should be kept off the storage, this means all animals like dogs, chicken, pigs, rodents and wild birds. These animals either be sick themselves if there is a disease that infect both animal and man (zoonose) or it is carried by the animal back into the houses where it again can infect humans.

Whatever the temperature of the compost is the final result look more or less the same, even if there is not the same hygienical quality as high temperatures (i.e. $>50^{\circ}\text{C}$) are required for assuring proper inactivation of pathogens. The low temperature stored material will have a lower assured hygienic quality as several pathogens can survive for years at ambient temperatures. And the current WHO recommendations (WHO guidelines) for faecal storage is over one year at temperatures above 20°C and for over two years at lower temperatures. Still after this time there is risk for remaining pathogens and restrictions in the use as fertiliser should be used. This means that the stored faeces should not be used as fertiliser for food that is consumed raw, e.g. lettuce and tomato.

Ammonia treatment

- Uncharged ammonia is toxic to all organisms
 - animals, plants, bacteria, viruses and parasites
- The ammonia distributes by itself through the material
- The ammonia can be added as urea or as ammonia(aq)



Chemical treatment is traditionally performed by addition of lime or ash. Studies have found that these two additives are both hard to work with and the effect is unsure as the additive is only working upon contact and is not distributed by itself within the material. The pH needed for efficient reduction using lime is at least 11 for most organisms and for the one that have strong survival against high pH, e.g. *Ascaris* spp., the pH needs to be above 12. Ammonia on the other hand has shown a good ability to distribute itself within the material. Ammonia is utilised in most nitrogen fertilisers and is used by biological life but at too high concentration on uncharged ammonia (NH_3) the ammonia becomes toxic (Ward, 1962). Ammonia are in equilibrium between NH_3 and NH_4^+ with a pKa at 25°C of 9.2 and during the treatment the high concentrations of NH_3 inactivates pathogenic organisms. When the material then is transferred to the soil, the pH is buffered and the main part will be in the form of NH_4^+ that is non-toxic and available for uptake of bacteria and plants. The ammonia in the treatment is borrowed for sanitising before it is returned into the soil as fertiliser. As the ammonia gets into the NH_3 form it is also found both as a gas and a water-solved substance. This combination supports the distribution of the ammonia in the material. However it also lifts the importance of performing the treatment in a closed container avoiding the ammonia to leave as air emissions.

The ammonia can be added to the material intended to treat either as urea (the most common mineral fertiliser in the world) or as water-solved ammonia. The ammonia will result in a higher pH than urea as the degradation of urea in addition to ammonia produces carbonate that will buffer the pH.

Ammonia treatment

- Urea is enzymatic degraded to ammonia
- $\text{CO}(\text{NH}_2)_2 + 2 \text{H}_2\text{O} \Rightarrow 2\text{NH}_3 + \text{H}_2\text{CO}_3$
- $\text{NH}_4^+ + \text{OH}^- \Leftrightarrow \text{NH}_3(\text{aq}) + \text{H}_2\text{O}$
 - $\text{pKa}=9.25$ at 25°C
- $\text{NH}_3(\text{aq}) \Rightarrow \text{NH}_3(\text{g})$
- Upon addition pH reach 9
 - the higher the pH, the more $\text{NH}_3(\text{g})$, the more toxic

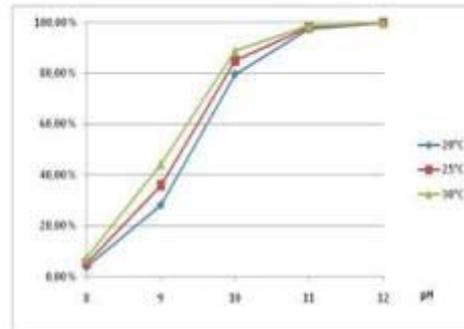


When the urea is added to the faecal matter it will be degraded by naturally occurring enzymes. The enzyme, urease, is a very common enzyme found in bacteria as well as in humans and plants. The degradation of urea produces one carbonate and two ammonia molecules. This degradation will increase the pH and at high additions the top pH reached is 9-9.5. Higher pH results in more efficient reduction of unwanted microorganisms as the sanitisation is regulated by the free ammonia (NH_3) concentration. The pKa of ammonia (the pH where you find an equal distribution of ammonia and ammonium in the material) is 9.25 at 25°C .

The ammonium ion (NH_4^+) is always solved in water while the ammonia (NH_3) is in equilibrium between water solved (aquatic) formed and gaseous form.

Ammonia distribution as %NH₃

- The distribution depends on
- Temperature
- pH

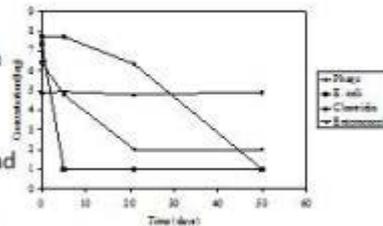


The distribution of ammonia is connected to the pH as well as the temperature, at higher temperatures the larger proportion of the ammonia will be uncharged at the same pH.

However, the dominating factor regulation the proportion uncharged ammonia is connected to the pH as when the pH drop below 8 there will only be a small fraction, less than 10%, that is found as uncharged ammonia, irrespective of the temperature. At pH closer to 12 all of the ammonia will be uncharged at all temperatures.

Ammonia treatment

- Closed vessel required
- Temp. >20°C
 - High effect on all pathogens esp with NH₃ >50mM
- Temp. <20°C
 - Low effect on Ascaris and viruses
 - High effect on bacteria
- No effect on spore formers



Due to the high volatilisation of ammonia the treatment needs to be performed in closed containers avoiding losses of ammonia.

At temperatures above 20°C ammonia treatment results in very efficient reduction of all kinds of pathogenic microorganisms including bacteria, viruses and parasites. The higher the ammonia content the more efficient the treatment. Empirical studies have showed that at level of free ammonia above 50mM you find higher efficiency compared to lower concentrations.

Spore forming bacteria is not affected, however there is no spore forming human pathogens in the faecal matter, only opportunistic ones and these are also found in many other places in the environment. Additionally, spore forming bacteria are not affected by any other conventional treatment of biowaste.

At ammonia levels below approximately 50mM NH₃ the rate of inactivation decreases fast, especially for the non bacterial organisms. At temperatures below 20°C the inactivation of bacteria is still very fast in presence of ammonia while the inactivation of parasites and viruses occurs at a much slower speed in relation to the ammonia content compared to temperatures above 20°C. When performing treatments at temperatures below 20°C there cannot be any assurance for proper inactivation of virus and parasites and therefore other measures to protect from disease transmission needs to be taken. These measures can be restriction in usage and measure to assure minimal risk for spreading diseases during application e.g. wearing protective clothing and gloves. The main part of the organisms in the groups of parasites and viruses are restricted to one host i.e. they are not zoonoses, with some exceptions e.g. Hepatitis E, Ascaris spp, Cryptosporidia. Read more about other barriers in chapter 3.

Ammonia treatment - in praxis

- Lower dosage \Rightarrow longer time needed for treatment
 - 0.6% N-NH₂ Dr-salmonella=6d
- Temperature
 - Higher temperature \Rightarrow faster die-off
 - Main effect on enzymatic activity
- In large scale ammonia cheaper than urea and more efficient



To use ammonia for treatment of manure there are several environmental factors that need to be considered. The first is that treatments below 20°C do not inactivate viruses and parasites at a reasonable speed and the treatment needs to be longer than one year. Therefore it is better to have a short treatment combined with restrictions in the use. More information about different barriers for disease transmission can be found in chapter 3.

When lowering the ammonia concentration the treatment time needs to be prolonged as the time for treatment is connected to the ammonia concentration. The effect it has is that the inactivation is slower and thereby also the D-value. The D-value is the decimal reduction for a certain organism, i.e. the time for a 90% reduction. The reduction is given as 90% reduction even if most treatment requires larger reduction to assure that not disease causing microorganisms survive the treatment. The required reduction is correlated to other barriers and the determined quality of the starting material, these are often combined with risk assessments, further described in chapter 3. When the temperature increases will also the enzymatic activity increase and thereby also the speed of the degradation of urea.

In small scale application the usage of urea are simple as urea are a common chemical substance (the most common mineral fertilizer in the world) and it is harmless. The activity comes upon the degradation into ammonia and carbonate. In larger scale water solved ammonia can be used instead of urea, as the ammonia result in higher pH and less ammonia is needed for similar sanitisation effects. On the other hand, ammonia is a toxic substance that needs to be handled with care. Therefore the ammonia application for treatment is more suitable for large scale mechanized treatment systems.

Ammonia treatment - recommendations

- | | |
|---|---|
| <ul style="list-style-type: none"> • For human consumption <ul style="list-style-type: none"> – T>20°C <ul style="list-style-type: none"> • 2% urea • 8 weeks – T>30°C <ul style="list-style-type: none"> • 1.5% urea • 4 weeks | <ul style="list-style-type: none"> • For fodder/non-food <ul style="list-style-type: none"> – T<20°C <ul style="list-style-type: none"> • 1% urea • 12 weeks – T>20°C <ul style="list-style-type: none"> • 1% urea • 1 week – T>30°C <ul style="list-style-type: none"> • 1% urea • 1 week |
|---|---|

Most pathogenic organisms are very selective regarding the organisms they infect. Most of the parasites and the viruses are species selective while there are several important pathogenic bacteria that infect several species, this is called that they are zoonotic organisms. This makes it important for understanding the differences regarding how you should manage the excreta when reusing it in agriculture. If the reuse is for fertilization of food intended for human consumption there has to be assurance that the strongest human pathogens are dealt with during the treatment. Several studies have been performed looking close into the inactivation rates of a set of organisms and the most hardy organism for chemical treatment, as well as for many other treatments are the intestinal worm *Ascaris* spp. Therefore the recommendation for treatment of material intended for human consumption is based upon 4 log₁₀ inactivation of *Ascaris*. At temperatures below 20°C there are no significant reduction of *Ascaris*, independent of treatment method and the recommendation is that if the treatment is performed below 20°C the material should not be used for fertilization of human food. Above 20°C the best effect is from addition of 2% urea combined with eight weeks storage. Increasing the addition of urea makes the material to contain very high concentrations of nitrogen and awareness of the risk of nitrogen losses needs to be taken. Some commercial systems use up to an average of 4% urea for sanitizing fecal matter. This leads to faster reduction of the pathogens and the current recommendation with 4% addition is one month treatment. When increasing the temperature the time of treatment can be reduced significantly and addition of 1.5% urea requires 4 weeks of storage for safe reuse as fertilizer. With higher urea addition the time of storage can be reduced too.

When the excreta are used in fodder cropping agriculture the focus is removal of zoonotic organisms assuring no spreading of disease to other species. Less urea is required for efficient treatment within reasonable time. If the urea content is increased then the time of treatment can be decreased. The main focused organism for spreading of zoonotic diseases is *Salmonella* spp. and the time for treatment are based upon removal of 6 log₁₀ organisms during the time of treatment. When treating the material according to this recommendation the people performing the treatment need to be aware of that the fertilizer still may contain human pathogens and that precautions according to this should be taken.

Ammonia treatment - nutrient transformations

- N: left in initial form NH_3 = high availability
 - Buffered in soil to $\text{pH} \sim 7$ = no toxicity
- P: Probably similar to chemical fertiliser
- K: high availability
- High content of organic substances
- **Ammonia treatment gives a fertiliser with very high fertilising value**

During the ammonia treatment the nitrogen will remain in the form of ammonia, as long as it is not ventilated as air emissions. The ammonia will then have high plant availability when added to the soil, the high ammonia concentrations needs to be taken into concern when fertilizing and rapid incorporation into the soil as fast as possible is to recommend. When in the soil the pH of the material is buffered by the soil which leads to less ammonia and more ammonium. Thereby, the material will not be toxic anymore and a high quality fertilizer is found in the soil. The potassium in the material is both in the form of organic phosphorus and as calcium phosphates and thereby have relatively high availability. Potassium is mainly found in the liquid phase as potassium ions and thereby of very high plant availability.

The treatment will not affect the organic components of the treated material and thereby this is a treatment method for recycling high concentrations of organic material from the faeces.

Ammonia treatment

- Pro
 - Increases fertilising value
 - High content of organics
 - No mixing necessary after initial mix
 - No risk for regrowth
- Con
 - Corrosive
 - Smelly
 - Require closed container
 - Risk for ammonia emission at application

The ammonia treatment is one of the most reliable treatment alternatives available for treatment of toilet fractions as it at room temperature assure an efficient removal of pathogenic organisms. The ammonia addition will increase the fertilizer value of the treated material as the ammonia will not be consumed during the treatment.

The effect of the ammonia is that all microbiological activity is stopped by the treatment and thereby no organic matter is degraded. The concentration of organic matter will remain the same as prior to the treatment and a large quantity of organic matter can be recycled to the soil. This is of major importance in areas with poor soil as increased organic matter will increase the buffer capacity and the water holding capacity of the soil.

After the addition and the initial mixing, no further mixing will be required as the ammonia will keep the distribution within the material by using chemical forces striving for an equal concentration throughout the material.

As the ammonia will remain in the material during the treatment there is no risk for regrowth as the repressive effects will continue to be present as long as the ammonia remains. If the ammonia is ventilated off, there will be a risk for contamination and regrowth, depending on how long the treatment have prolonged.

Therefore is it important to keep the treatment in a closed container assuring that no ammonia is lost via ventilation during the treatment. This is also for keeping the fertilizing value, since the fertilizing value will also decrease if the ammonia is lost during the treatment. The ammonia will also increase the smell of the material and if it is ventilated smell will occur around the area of storage. The same is for the application of the treated material as fertilizer. During the application it is to recommend that the application is performed as close to the ground as possible and that it is incorporated into the soil directly after application to keep the ammonia emissions as small as possible, both regarding the loss of fertilizer and the smell.

The ammonia is corrosive and metal containers will corrode during the treatment and the recommendation is to use plastic materials for this kind of treatment.

Urea treatment in use

- Peepoo
 - Single use
 - Biodegradable
 - Self sanitising toilet
 - Contain 4g urea
 - 4 weeks $T > 20^{\circ}\text{C}$ safe to use
 - 2 weeks $T > 30^{\circ}\text{C}$ safe to use



Photo: Camille Wirsén (www.peepoo.com)

One commercial use of the ammonia treatment is the peepoo system. Peepoo is a single use self sanitizing biodegradable toilet. The toilet is in the form of a bag, which is placed over a small can or held by hand for urination or defecation. The material is biodegradable so after collection sanitisation and incorporation into the soil the bag will be degraded biologically.

The sanitation in the peepoo is performed by 4g of urea placed in the bottom of the peepoo and upon contact with faeces the urea are degraded by the natural occurring enzymes and turned into ammonia that sanitise the content. The treatment will be performed above 20°C for unrestricted use as fertilizer. At 20°C and above four weeks of storage are enough for sanitizing the content while the time of treatment can be halved if the temperature is increased by 10°C to 30°C .

Storage of urine

- Approx. 90% of N in fresh urine is urea
- Enzymatic degradation to ammonia
- pH increase from 7 to 9
- Pathogens inactivated by ammonia
- Sanitation faster at high temperature and high concentration.



The process for sanitisation in urine is the same as you find from ammonia/urea addition to faeces or faecal sludge. The major difference is that the urine do not require any addition of urea as the nitrogen in the urine (7-8g/L) will mainly be found in the form of urea that are degraded during the collection by bacteria naturally existing in the collection system. This enzymatic degradation with the enzyme urease, transform the urea into ammonia and carbonate. The degradation leads to an increase in the pH from approximate neutral (pH 7) to a basic pH of approximately 9. This increase in the pH leads to an increased concentration of uncharged ammonia in the solution that will act as a sanitizing agent. The higher the temperature the more efficient the treatment will be and for unrestricted use of the urine as fertilizer the treatment needs to be performed above 20°C.

Storage of urine

- Urea \rightarrow ammonium/ammonia
- $\text{CO}(\text{NH}_2)_2 + 3 \text{H}_2\text{O} \Rightarrow 2 \text{NH}_4^+ + 2 \text{OH}^- + \text{CO}_2$
- pH 6 – 7 \Rightarrow 8.8 – 9.4
– $\text{NH}_3/\text{NH}_4^+$ pKa=9.25 at 25°C
- **Precipitation as metal phosphates (in pipe and tank)**

- $\text{NH}_4^+ + \text{OH}^- \Leftrightarrow \text{NH}_3(\text{aq}) + \text{H}_2\text{O}$
- $\text{NH}_3(\text{aq}) \Leftrightarrow \text{NH}_3(\text{g})$
- \Rightarrow **Minimum ventilation!!**

During the storage the urea will transform into ammonia and carbonate. The pKa for ammonia at 25°C is 9.2, this means that at this pH half of the ammonia will be in the form of uncharged NH_3 while the remaining 50% is in the form of ammonium ions NH_4^+ . Increasing the pH leads to increased concentration of ammonia while decreased pH leads to increased ammonium formation. The formation is balanced with formation of hydroxide ions and carbonate ions. When increasing the temperature the pKa will decrease, i.e. you will find higher concentrations of uncharged ammonia, and the opposite for decreased temperature.

During the collection you will have formation of metal phosphates, the main two are magnesium and calcium phosphates, MgNH_4PO_4 and $\text{Ca}_x(\text{PO}_4)_z$, as Mg and Ca are commonly found in drinkingwater. If other metals are present, e.g. copper from the piping you will also find copper phosphates in the sediments. When using thin piping 50mm or less there is a major risk for sludge building, especially when having small slopes.

The ammonia will be found in equilibrium between ammonium ions, watersolved ammonia and gaseous ammonia. If the gaseous ammonia are ventilated off new $\text{NH}_3(\text{g})$ will be formed and if this continues a major loss of nitrogen will occur. Therefore it is important that the collection system are closed and not ventilated. No ventilation is required as the liquid in the pipe will not flow in a plug flow, as in conventional systems. As the pipe is never filled with liquid there are no need for ventilation and the ventilation will only lead to ammonia losses and smell to the surrounding.

Urine storage recommended times

- Faecal contamination main source of pathogens
- Storage $>20^{\circ}\text{C}$ 6 month no restrictions in use
- Storage $<20^{\circ}\text{C}$ 2 month not to crop consumed raw



The main transmission route for pathogenic organisms in urine is from faecal contamination, further information in Chapter 3. Therefore, if the urine is collected from urinals only, the risk for disease transmission is considerably less compared to urine collected from sorting toilet systems where the risk for faecal contamination is much higher. If the urine is collected in urinals the recommended storage time can be considerably shortened, as a rule of thumb by 75%. For efficient reduction of pathogens the urine should not be too diluted as major dilution leads to less efficient sanitisation. As a rule of thumb is that you should have at least 40 mM uncharged ammonia in the urine for efficient sanitisation of all potential pathogenic organisms. One example for reaching 40mM ammonia is pH 8.8 and an ammonia concentration of 2.8g N/L at 20°C .

For using the urine to crops intended for human consumption the storage has to be performed above 20°C as some of the human pathogenic organisms are not reduced at lower temperatures. At 20°C for unrestricted use the recommended treatment time is 6 month of storage, and then the urine can be used for fertilization of lettuce. When increasing the temperature the time of storage can be decreased.

At temperatures below 20°C the recommended use is not to use the urine for crop intended for raw human consumption, while 2 months of storages is enough for inactivation of zoonotic organisms that may be present in the urine.

Urine storage - nutrient transformations

- N: Plant availability of N in urine is very high, similar to chemical ammonium fertiliser
- P: Similar availability as chemical fertiliser
- K: Similar availability as chemical fertiliser
- **Urine is a fertiliser with uniquely high availability for being a biological fertiliser**

During the storage will, as mentioned above, the urea enzymatically be transformed into ammonia. As the urine is an easy flowing liquid will the risk for ammonia emissions to the air be minimal as the liquid quickly will be incorporated into the soil, even better effect are from application systems with direct incorporation or cultivation directly after application.

The nitrogen in urine is very plant available and similar to other ammonia fertilizers, e.g. urea and ammonia sulphate.

Phosphorus and potassium in urine are both comparable to mineral fertilizers and the urine can be considered to be a mineral fertilizer of biological origin.

Hygiene and composting

- Main effect from heat
 - Require $T > 50^{\circ}\text{C}$
 - WHO guidelines 1 week
- Other effects
 - Stabilisation of material
 - No easy available organics
 - Competing microbiota
- Risk for regrowth

Composting is the most common treatment method for faecal treatment. The composting itself is not any guarantee for proper sanitisation. During the process the organic material are degraded into a humus soil like material, that can, if the treatment have not been performed correctly still be potentially pathogenic.

The only assurance for safe sanitisation during composting is actually that the process reach temperatures high enough for removal of potential pathogens. As a rule of thumb for the composting treatment is that the material should reach above 50°C for proper inactivation, at temperatures below this you should be aware of the risk for growth of bacteria. The more stabilized the material are the lesser the risk for growth. The WHO guideline stipulate that the treatment over 50°C should continue for at least one week. The inactivation at this temperature is faster but there is risk for areas with lower temperature where the reduction is less, e.g. surface areas and larger particles where it takes time for the material to reach an equal temperature. To increase the temperature of the composting by increasing the energy content of the material to be treated food waste can be used.

There are other factors regulating the reduction of pathogens, e.g. competing microbiota, less available nutrients for the microorganisms. These factors are very hard to measure and therefor not that easy to include in an estimation of required treatment for sanitisation.

In composted material there is always a risk for either regrowth of pathogenic bacteria or growth after contamination, e.g. from bird dropping or from rodents. The more stabilised (further degraded) the material are the lesser the risk for growth.

More information on composing can be found in chapter 4 module 2.

Heat inactivation

- Most common treatment
- Only heat, removes all available organisms
 - Risk for re-growth of unwanted bacteria. First on site wins
- Combination of heat and stabilisation from removal of available carbon is better
- Moisture result in faster inactivation
 - Heat transport
 - Albumin p164 (haug)

Albumin watercont	aprox cog T
50	56
25	76
15	98
5	149
0	165

Heat inactivation is the most common hygienic treatment of human excreta. The combination of biological degradation and heat is good for decreasing the risk for regrowth of pathogenic bacteria. If heat treatment only is performed there is a high risk for growth of pathogenic bacteria as the material will attract vector animal, that may be ill or carrier of pathogenic organisms.

Combination of heat and stabilisation decreases the risk for pathogen transfer.

For most efficient heat transfer the moist heat is more efficient compared to dry heat. The example with the protein albumin shows the difference in temperature requirement depending of the water content and with less water the more heat is required for an efficient treatment. This is exemplified with the coagulation temperatures (cog T) for Albumin, where the coagulation temperature increases with decreasing moisture content.

Rule of thumb – hygiene treatment

- Reactor turn 3 times in high temp
- Pile or windrow turn 5 times in high temp
- Calculation of turnings for hygiene
 - $n_t = n_0 [f_c]^N$
 - n_t = number of surviving organisms
 - n_0 = number of initial organisms
 - f_c = fraction in cold zone
 - N = number of turnings

The number of turnings required in a treatment system is closely connected to the proportion of the reactor that does not hold high enough temperature for proper sanitisation. In a reactor this part is less than in a windrow and therefore the number of turnings required for proper reduction is less compared to the windrow.

For a proper hygienic quality of the end product the material in the reactor and the windrow should be completely mixed 3 and 5 times, respectively.

The number of required times of turning can also be calculated based on the equation where the initial numbers of organisms are set and based on the required removal the number of turnings can be calculated.

Anaerobic digestion

- 1-3 log₁₀ reduction
- Longer HRT and MRT
higher reduction
- Sedimentation in non-
mixed systems
(parasites)
- Additional treatment
required
 - Heat
 - Ammonia

Anaerobic digestion will not act as a functional sanitisation. Within the process of a mesophilic digester it can be estimated to have between 1 and 3 log₁₀ reduction during the treatment. The larger reduction is mainly connected to the retention time in the reactor for the digestate.

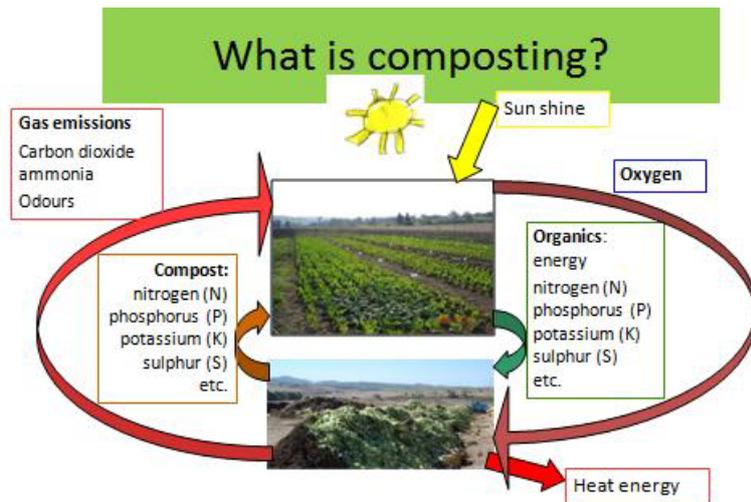
By increasing the temperature of the treatment or having an initial heat treatment prior to entering the reactor makes it possible to assure removal of unwanted organisms. The reactor design can also have effects on the removal of pathogens as long minimal residence time in the reactor increase the reduction. The same is for having plug flow reactors that allow parasite eggs to sediment during the treatment.

One post treatment alternative can be addition of ammonia or a base for performing an ammonia based sanitisation of the treated material.

Chapter 4 module 3 Treatment of faeces by composting

How should urine and faeces be treated for safe handling and reuse in crop cultivation? How can organic material from households be co-treated?

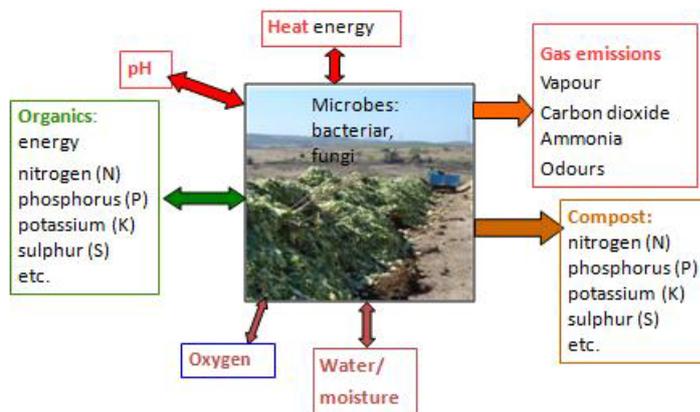
Goal: After the lecture the student should know the principles, prerequisites and main characteristics, properties, advantages and disadvantages of composting of faeces of kitchen waste.



Composting is microbial aerobic degradation of organic material. It is often subdivided into thermophilic and mesophilic composting, where thermophilic composting is performed at 40°C and above, while mesophilic composting is performed at temperatures below this. Composting is, as shown by the diagram, the reverse process compared to the photosynthesis. In the photosynthesis, organic matter is synthesised by the plants in a process driven by the sun. The plants synthesis many different types of organic substances, e.g. carbohydrates, proteins and fats, which contain a small fraction of the sun energy, which drives the process. The energy stored in the organics in turn drives the whole biological system consisting of herbivores and carnivores, but also the whole system of degrading microbes consisting of bacteria, fungi etc.

In the compost the opposite processes take place as compared to the photosynthesis. In the photosynthesis organic compounds are synthesised from carbon dioxide, water and plant nutrients driven by energy from the sun. In the aerobic degradation in the compost, the organic compounds are degraded by the microbes to carbon dioxide, water and plant nutrients, eg. nitrogen in the form of ammonia, phosphorus, sulphur etc. under the generation of heat.

The compost process?



To optimize the conditions for degradation, the conditions for the growth of the microbes have to be optimised. The composting microbes prefer moist but aerobic conditions with ample supplies of degradable organics.

As shown in the slide, the composting process itself changes its conditions. The heat released during the degradation increases the temperature and this in turn speeds up the degradation. The more of the heat released that is retained in the compost, the more the temperature is increased. Also the pH is affected, as this normally increases to around 8-9 during the process. If the substrate contains a lot of easily degradable organics like a compost containing lots of kitchen waste, then the pH might dip initially, down to about 4-4.5.

The degradation also consumes large quantities of oxygen, and good ventilation is needed to ensure aerobic conditions. The ventilation of an open compost is naturally created as the hot air in the compost expands, which makes it lighter than the surrounding air. The hot lighter air will then raise and create an under pressure of the compost, which is compensated by intake of air from the sides.

Due to the heat, the ventilating air is heated up and due to the ample supply of moisture it is saturated with moisture. This means that water is taken up by the ventilating air and therefore a good thermophilic compost is a drying process.

The plant nutrients contained in the organic substrate is largely mineralised in the compost and for a sustainable plant production, these nutrients should be recycled to the production of crops.

Degradation – compost – digestion

Composting

- $C_6H_{12}O_6 + 6 O_2 \rightarrow 6 CO_2 + 6 H_2O + \text{bacteria}$
- $\Delta E = -3880 \text{ KJ/mol}$
- **Energy – appr. half to heat, half to bacteria**

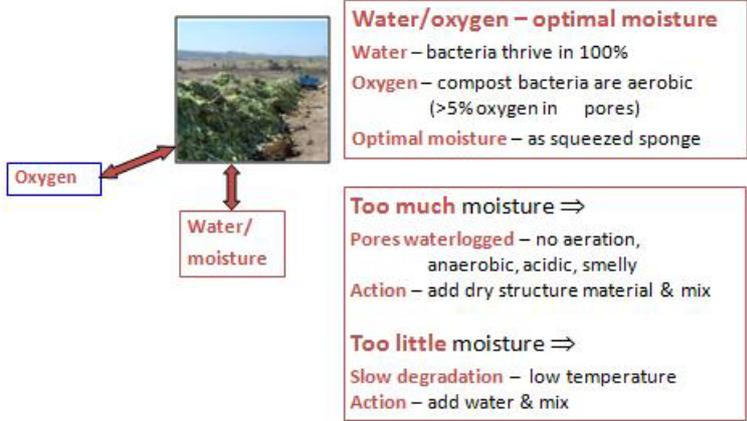
Digestion

- $C_6H_{12}O_6 \rightarrow 3 CO_2 + 3 CH_4 + \text{few bacteria}$
- $\Delta E = -405 \text{ KJ/mol}$
- **Energy – almost all remains in the biogas (-3475 KJ/mol sugar)**

The large heat energy surplus in the composting process means that lots of energy is released and that the bacteria grow very much – as much a half of the initial energy can go into the bacterial cell mass, but as there are several successions of bacteria in a compost, in the end, the bacterial population will contain less energy than this.

By comparison, far less energy is available for the microbes in the digestion process, and thus, they grow far slower and thus the whole process is slower and the heat released is not enough to really heat up the substrate.

Optimal conditions – moisture/oxygen



As air contains approximately 20,000 times more di-oxygen molecules per litre than water, it is important that the substrate is not too moist, because if it is, the oxygen supply will be limiting and the bacteria run out of oxygen. At the same time the microbes prefer an ample supply of water, as they live in the liquid film on the particles. If there is too much water the pores of the compost will be filled and block out the air to pass.

Thus, for most substrates a good compromise is a moisture content somewhere between 45 and 60% moisture. A simple test on the moisture level is the “fist test”. Squeeze some of the substrate in your hand. If drops of liquid appear between your fingers, then it is too wet. If the substrate falls apart in several pieces when you ease the squeeze, then it is too dry. If it stays in one piece when you ease the squeeze, but no liquid appears, then the moisture level is correct.

Optimal conditions - energy

- **Energy**
- **Sources – fast release:**
Carbohydrates, proteins, fats.
- **Lignin & cellulose** ⇒ slow release
- **Food waste** - rich in fast energy,
- **Faeces:** less energy, slower release
- **Woody waste** ⇒ slow release
- **Too much** fast energy ⇒
- **Oxygen** – goes easily anaerobic
acidic and/or **smelly**
- Action – add structure material & mix
- **Too little** fast energy ⇒
- **Too low temperature**
- Action – add food waste and/or insulate

The energy in the compost comes from the material and is released by the biological and biochemical degradation. The energy can be divided into two main categories, fast and slow energy. Food waste that contains carbohydrates (e.g. bread, sugar) proteins (e.g. meat, legumes) and fats (e.g. meat grease and oil) are rich in fast energy while garden waste contains more lignin and cellulose that is degraded slower and thereby contain less available energy.

Compared to food waste are faeces containing less fast energy as most of the energy has been taken up by the body.

Enough fast energy is needed for a high enough rise in temperature, if the temperature raises, the produced amount energy are larger than the energy lost from the compost via ventilation and the surface.

With too much fast energy the process will be so fast that there is risk for oxygen depletion and bad smell, this can most easily be dealt with by addition of better structure to the material and by mixing.

Too little energy content, i.e. no or slow increase in temperature can be compensated by addition of more high energy material such as food waste or by compensating the energy loss by improving the insulation.

Optimal conditions – C/N-ratio

- **C/N-ratio**
- **Sources of C:** the organics of the substrate.
- **Sources of N:** both organic nitrogen (protein) and inorganic nitrogen, e.g. NH_4^+ , in the substrate
- **C/N > 30** \Rightarrow
- **Process** – might be slowed down due to lack of N for bacteria
- **Action** – add N, e.g. faeces or urine & mix
- **C/N < 15** \Rightarrow
- **Process** – might smell ammonia – excessive losses of ammonia
- **Action** – add C, e.g. park waste & mix

The optimal C/N ratio in a composting process is between 10 and 30. In this range there is enough nitrogen per carbon for having an efficient process.

With high C/N ratio >30 the concentration of nitrogen is not sufficient for an efficient process and there is a risk for a slower process (degradation will still occur but not at the same rate as when having higher nitrogen concentration). Action to increase the activity is to add nitrogen to the compost, e.g. urine or faeces.

If the C/N ratio goes below 15 does it not really affect the process as the excess amount of nitrogen will be emitted as ammonia emission. This can result in smell problems and the easiest way of managing this is adding materials that contain low concentrations of N, e.g. garden waste.

Optimal conditions - pH

- thermophilic bacteria prefer pH > 6.5
- **Too high pH** (lots of lime)
⇒
- **Slow degradation** – low activity of bacteria
- **Action** – add food waste and/or wait
- **Too low pH** (lots of food waste) ⇒
Slow degradation
- **Action** – wait (especially if the compost is small) or add ash/lime

For a high degradation rate, the pH the optimal range is between 6 and about 10. If pH is below 6.5 and similarly the temperature is above 40°C, then the degradation is very slow.

When composting faeces that have been collected with ash or lime as coverage, the pH can be above 10 and therefore hamper the activity of the compost. This can be compensated for by diluting the material with more organics, e.g. food waste. One other alternative is to wait as the natural processes will decrease the pH as CO₂ from the surrounding air will be collected in the material and slowly decrease the pH.

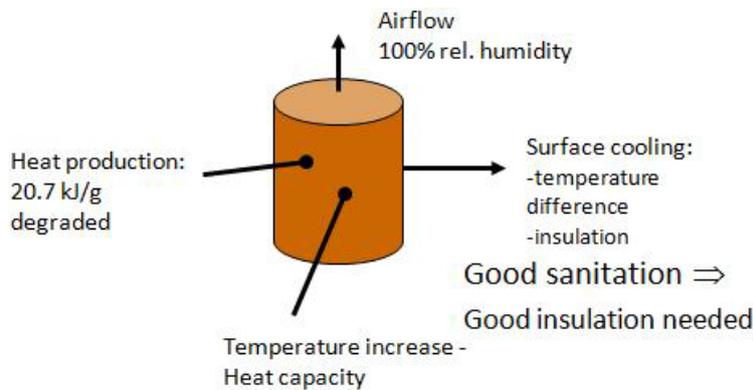
The compost pH can be too low if the material to compost has been stored and not enough air has entered the system. During the storage there will be anaerobic activities that are producing organic acids, which lower the pH. This will slow down the degradation as low pH has negative effect on the compost bacteria, especially if the temperature of the compost increases. To compensate for this is mainly to wait as the acids will be degraded and the pH will be neutralized. This can take time, especially in larger systems, and the compost pH can be compensated by addition of ash or lime.

Optimal conditions – temperature

- **Temperature** – for sanitation $>50^{\circ}\text{C}$,
- for fastest degradation approx. 55°C
- **Too low temperature**
Sanitation not ensured
- Action – **insulate** and/or add fast energy

A compost temperature of $50\text{-}55^{\circ}\text{C}$ is normally optimal for degradation. However, temperatures of 70°C and above can be reached and are preferable during sanitation to ensure that as much as possible of the material reaches temperatures above 50°C . For this it is also important that the compost is surrounded by well insulated walls. Further information about compost and sanitisation is presented in chapter 4 module 2.

Compost heat & scales



For good sanitation, as much as possible, and preferable all, of the substrate should reach a temperature above 50°C. For this, it is essential that the size of the compost is not too small and that it is well insulated. If it is small then the surrounding surfaces become large in relation to the volume and thus in relation to the heat evolved by the degradation in the compost. Thus, the smaller the compost is, the more important it is to insulate it well in order for it to reach at least 50°C.

Also for a big compost, a good insulation is important in order to maximize the proportion of the compost that reaches high temperatures. If it is not insulated, then essentially all surrounding surfaces will be cool, which means that a large proportion will not reach sanitising temperatures. If the compost is well insulated, then a far larger proportion of compost will reach sanitising temperatures.

Insulation crucial

- Theoretical heat loss
- Heat transfer coefficient:
 - non-insulated: $13 \text{ W } ^\circ\text{C}^{-1} \text{ m}^{-2}$
 - Insulated 10cm: $0.053 \text{ W } ^\circ\text{C}^{-1} \text{ m}^{-2}$
- so the heat resistance was 25 times larger for the insulated box .



Table: Highest and lowest peak temperature in each box

	Highest	Location	Lowest	Location
Insulated	75.0 °C	¼ depth, near center	57.6 °C	At the air inlet
Non-insulated	49.7 °C	¼ depth, near center	24.9 °C	At the bottom corner

The differences in temperature can be exemplified with the compost above where food waste is composted in two identical 30L boxes where one is insulated with 10cm insulation and the other is not insulated at all. The boxes were placed in room temperature, just above 20 degrees.

When comparing the heat loss from the two boxes it was possible to see a major difference in the heat transfer coefficient, and the heat resistance was 25 times higher in the insulated box.

This can also be exemplified by the difference in temperatures reached in the boxes as the peak temperature, both highest and lowest. The lowest temperature in the corner of the non insulated reactor was very close to the ambient temperature, this indicate that it is important with insulation even in warmer climate as the temperature needed for proper sanitisation is above 50 degrees celcius.

Composts – small scale



These small composts reach high temperatures, thanks to good insulation

This is examples of small compost reactors (volume ca 200L) used for faecal co-composting with food waste that works well, reaching temperatures high enough for sanitisation. The reason to the good function is the large amount of insulation, 10-20cm of cellplastics on all sides and the top minimising the heat loss.

Composts - medium scale



These medium size windrow composts reach high temperatures. For good sanitation they ought to be covered by some insulating material, e.g. straw.

Windrows can be insulated by their own surface, but for this a height of at least 1.2 metres is required, otherwise the loss to the surface is too high compared to the heat production capacity in the windrow.

The insulation can be improved by using straw or plastic/tarpuline sheets that is put on top of the compost.

Mixing is also important assuring as large proportion of the material is treated in high temperature. The material in the surface should be mixed into the middle of the windrow during the high temperature process.

As a rule of thumb should a windrow compost be mixed five times and a reactor three times during the high temperature process for assuring good hygiene of the finished compost.

Composts - large scale



Insulated large scale compost with mechanical aeration

In large scale composts the incoming air can also be pre heated assuring the sanitisation.

Compost and plant nutrients

- N: Protein (org. N) + NH_4^+ \Rightarrow 10-50% loss & of remainder ~90-95% is humus (organic N) + a few % NH_4^+ + a few % NO_3^-
 - Usually 10-50% of N is lost to air
 - Low availability of N left in compost
 - ~10% first year and 20-30% in total over the years.
- K: K^+ , high availability, water soluble and thus large risk for loss with leachate
- **Composting decreases the amount of N, due to losses, and the remaining N has low availability**

Most nutrients remain in the compost during and after the process, potassium can be lost via leachate due to its high water solubility.

The major loss is nitrogen that will be emitted to the air mainly as ammonia. The ammonia is formed during the degradation of proteins and due to the high exchange of air and high temperature most of the formed ammonia will follow the air out of the compost. If latrine is composted, urine + faeces, the nitrogen loss will be considerably higher as the ammonia nitrogen from the urine will be vented off during the process.

In vermicomposting the process is completely different and the nitrogen loss is considerably less.

The remaining nitrogen in the compost is mainly in organic form and for this to be available for the plants it has to be mineralised by soil microorganisms this takes time and only 10% will be available during the first year and then you can assume that in total 30% will be made available.

Composting - disadvantages

- Difficult to get the whole compost hot – usually cold at air intake ⇒ mixing several times needed for sanitation
- Additional energy rich substrates, e.g. kitchen waste, can be needed to reach above 50°C
- A large proportion of the nitrogen is lost (often around 50%, more if urine has not been well diverted)
- Mixing - handling - is needed also before sanitation ⇒ hygiene risk

As parts of the compost often is used for insulation there will be parts not heated enough for sanitisation in the compost, even if the centre is very hot. This needs to be compensated for via mixing of the material.

Composting faeces only can reach high temperatures, but the process will be improved considerably by adding food waste. It is important to reach 50°C and above for sanitisation.

Most nutrients will remain in the compost but nitrogen will be lost during the process.

The composting process requires mixing and initial preparation of the compost. During these processes there is a high risk of contamination of the person performing the labor. Information of these risks is important to give to the workers and also provide protective gear and hand washing facilities.

Summary - Why compost?

- To sanitise \Rightarrow 50°C required \Rightarrow insulation
- To eliminate visual contaminants (toilet paper etc)
- To decrease C/N-ratio - to eliminate risk for N fixing
- To homogenize – simplifies handling
- To produce good humus – high doses can be used
- To decrease the amounts to handle
 - Organic matter is degraded by 30-60%
 - Finished compost has a high dry matter content (50-70%)

The compost is an efficient method for sanitisation of faecal material if proper temperatures (>50C) are reached.

The finalized compost will have an attractive look as it have a pleasant smell and visual contaminant will be removed. It will also be homogenized and thereby easier to handle and distribute.

The composting process will also decrease the C/N ratio which otherwise can decrease the nitrogen availability in the soil as high carbon loads leads to fixation of available nitrogen into the process of degrading carbon.

The process will also decrease the volume of the material as approximately 50% of the organic material is transformed into carbon dioxide and water.

4.4 Biogas – a way to solve sanitation problems

Anaerobic fermentation is a natural and unavoidable process

How much biogas can be produced from excreta and biomass?
How safe is the process and its sludge??



Learning objectives: to know about the fundamental processes in biogas production, and get an overview of biogas generation in the world

Jam-Olof Drangert, Linköping university, Sweden

Energy from the sun drives the **water** (hydrological) **cycle**, lifting water molecules from the surface of the earth to clouds. The resulting rain and snow flows to lowlands and we can harness its potential energy and convert it to hydroelectric power or use it directly via water wheels. The sun also drives **photosynthesis** which makes the building blocks of plants and trees. The stored solar energy can be released again by burning firewood or oil and natural gas. Oil and gas are the result of biomass which was left to putrefy for millions of years.

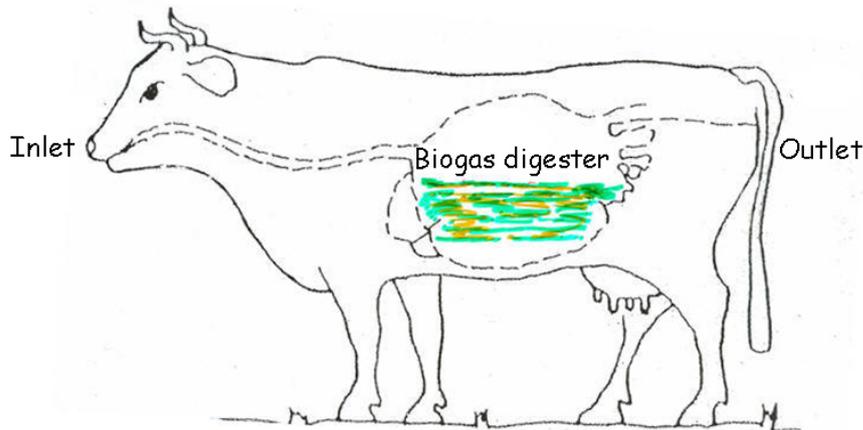
Today, we can shorten the storage time from millions of years to just weeks by managing our organic waste in a more efficient way. At the same time we can solve a serious solid waste problem, since organic waste makes up more than half the volume of solid waste. The simple idea borrowed from nature is to feed organic wastes including excreta and manure into an anaerobic biogas digester. The generated gas is used as an energy source and the digested residue can be used as a fertiliser.

Biogas is gaining in popularity in Asia and parts of Europe. People need energy for cooking where firewood is scarce, and for lighting where there is no electricity and kerosene is expensive. The huge volumes of food waste, animal manure and human excreta, and some of the garden waste can be reduced substantially, while producing the biogas. Also, the slurry is rich in nutrients and can be used as a fertiliser. Thus, biogas should be considered in any discussion about sustainable environmental sanitation. More information is available at www.gc21.org This website “Global Campus 21” is hosted by Borda.

In this chapter we provide basic knowledge about fermentation and technologies to enable the introduction of decentralised biogas digesters. As discussed in the greywater modules 4.5–4.7, treatment and recirculation is safe if households refrain from disposing of hazardous items in the wastewater or organic waste collection unit.

Spying on Nature – What can we learn from cows?

4.4 - 2



Cows convert biodegradable plants and water to milk, cow dung and urine – and gases

Pedro Kraemer, BORDA, Indi

Some characteristics of the cow's digestive tract are: there is no or little oxygen (air), the temperature in their stomachs is high and stable, there is plenty of water, and the material moves through four stomachs and guts in 30–36 hours. A cow may eat some 15–25 kg dry biomass, and excrete 40–60 kg of dung and 30–70 litres of urine per day. In order to survive, and produce meat and milk, the cow also needs nutrients such as iron, sodium, calcium, cobalt and nickel. Most of the nutrients are found in the milk and urine, and therefore free-range cattle distribute the urine nutrients rather evenly, while farmers try to collect and plough in the dung and urine from stall-fed animals. The dung is only partly decomposed biomass and its nutrients are readily available to plants.

The cow is only interested in the energy that is produced when the biomass is broken down in its stomachs, and not the gas. The gases are released mainly from the cow's mouth but also from its anus and from excreted manure. A cow releases some 300 litres of methane gas into the atmosphere every day (<http://www.g-o.de/dossier-detail-163-6.html>) and ideally, we should trap this gas and use it productively. Gas is mainly formed in the rumen, which is the first of the cow's four stomachs. Here, grass and fodder is broken down and fermented by microorganisms into a wide variety of fatty acids (acetic, propionic, lactic, butyric acid etc), hydrogen and carbon dioxide. The fatty acids are assimilated by the cow through the rumen wall and transported by the blood for essential cell functions. More than 30% of the energy supply to a cow comes from the fatty acids generated in the rumen. In the rumen, anaerobic microorganisms multiply during fermentation and these organisms together with remaining fodder are digested in the following three stomachs and absorbed by the cow. The microbial biomass formed in the rumen is essential for the cow's uptake of amino acids and provides 60–90% of the absorbed raw protein together with vitamins such as cyanocobalamin (vitamin B12).

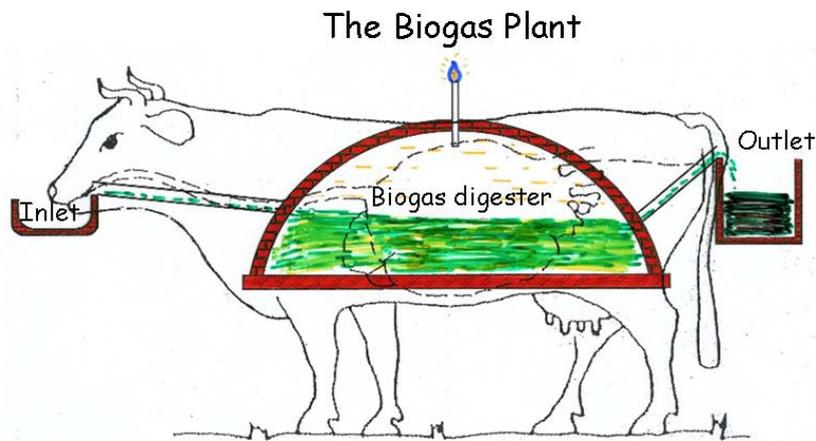
From a biogas perspective the reactions occurring in the rumen are most interesting. Hydrogen serves here together with carbon dioxide as food for methanogenic organisms that convert four moles of hydrogen and one mole of carbon dioxide to one mole of methane and two moles of water. The production of methane in the rumen is very important for the cow since it reduces the volume of gas that would otherwise have to pass out of its mouth. The process can be explained by the following example: Fermentation of 1 kg of sugar (glucose) gives rise to 489 g of butyric acid, 280 litres of hydrogen (22 g) and 280 litres of carbon dioxide (489 g). The formation of methane from the hydrogen and carbon dioxide reduces the total gas volume by 50% from 560 litres (280 litres hydrogen and 280 litres carbon dioxide to 282 litres (70 L methane and 210 L carbon dioxide). However, even though this process is essential for the cow because it reduces the volume of gas that the cow has to deal with, the loss of methane is also a loss of potential energy. Research today has partly been oriented towards letting other microorganisms in the rumen convert hydrogen to something useful for the cow, such as acetic acid from hydrogen and carbon dioxide. A company in the UK is manufacturing a garlic derivative (Mootral) which reduces methane production by 15–20 % and raises milk production by 1.5 litres per day (bbc.worldchallenge.co.uk in 2009).

The volume of biogas created by ruminants (animals with a rumen) is in fact, so great that they contribute a large proportion of the 18% of global greenhouse gas emissions for which the livestock industry is responsible – causing global warming! A Japanese study found that the production of one kilogram of beef involves the production of greenhouse gases with a warming potential equivalent to 36.4 kilograms of carbon dioxide. The production of one kilogram of beef also releases fertilizing compounds equivalent to 340 grams of sulphur dioxide and 59 grams of phosphate, and consumes 169 megajoules of energy (Ogina, 2007). The study did not include emissions from farm infrastructure and transportation of the meat, so the total environmental load is even higher than the study suggests!

Cows also produce some heat in their stomachs, using oxygen that comes with the fodder or is supplied by the cow via its stomach wall. Cows can therefore utilise the reactions in their rumens as a tool to regulate their body temperatures. Also, human bodies release heat and carbon dioxide due to cellular activities and small amounts of methane from microbial digestion processes in the faeces. A dairy cow drinks some 30–200 litres of water every day, and produces 5–40 litres of milk. A bull drinks some 40–100 litres of water, but produces no milk. Since bulls and cows urinate about the same volume, they both need this large amount of water for digestion. We will later discuss why this is so.

A new look at the cow – and bull

4.4 - 3



Pedro Kraemer, BORDA, India

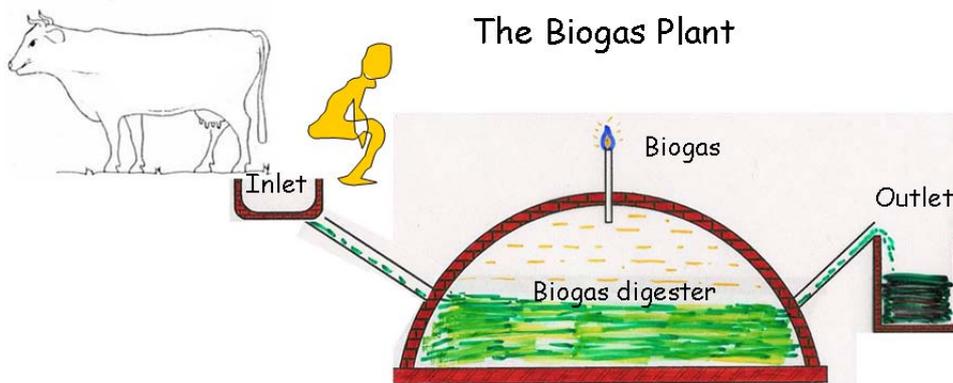
Technology often mimics nature, and by learning under what conditions cows digest grass, we may copy and control a similar process. If we view the stomachs of a cow as a biogas digester we will find several prerequisites for biogas production. In order to function properly, we need to ensure the biogas process has a relatively stable temperature, digestible organic material, and nutrients. The cow is a fantastic fermentation factory (see picture). However, there is an essential difference between a cow and a biogas digester. The fatty acids generated in the rumen are absorbed by the cow but in the biogas digester they are converted into methane and carbon dioxide.

Digestion means that plants and other organic matter are broken down into smaller components. The original Latin word *digere* means scatter, disperse or dissolve. Such a process is called aerobic when it occurs in the presence of air (and molecular oxygen), and anaerobic when digestion occurs without molecular oxygen. The organisms that operate under anaerobic conditions originate from the first life forms on our planet some three billion years ago. Two billion years ago, when cyanobacteria first managed to absorb energy from sunlight and create molecular oxygen by photosynthesis, the environment became aerobic – an environment which was (and still is) poisonous for anaerobic organisms. The anaerobes then had either to adapt (mutate) to be able to survive in the aerobic environment in order to stay in the remaining anaerobic environments or die. That is why these fantastic creatures can still be found in sediments, marshlands and peat bogs but also in termites, ruminants and landfills.

In human beings and other aerobes, organic matter is degraded or transformed to serve as building blocks for cell material and to generate energy. Digestion is an oxidation process that produces carbon dioxide from the organic material and reducing power. In aerobes the reducing power is utilised to generate useful energy for the cell during the reduction of molecular oxygen to water. This digestion process is almost the opposite of photosynthesis in plants in which the energy in the sunlight does two things: 1) it generates energy and 2) it splits water into reducing power and molecular oxygen. The plants use the reducing power and carbon dioxide to form organic molecules and then to synthesize cell material by using generated energy, water and nutrients.

A biogas plant operates through anaerobic digestion of organic material

4.4 - 4



Pedro Kraemer, BORDA, India

We now try to mimic a cow stomach with a structure made of bricks and mortar, which we call a biogas plant. Its central component is the anaerobic biogas digester (see picture).

To replicate four features of a cow's stomach in the digester we need to: i) keep a stable temperature, ii) ensure that enough water is available, iii) ensure an oxygen-free environment and iv) ensure that essential nutrients are available. If the ambient temperature varies a lot over the year or between night and day, the digester must be insulated or just built underground as is done in China.

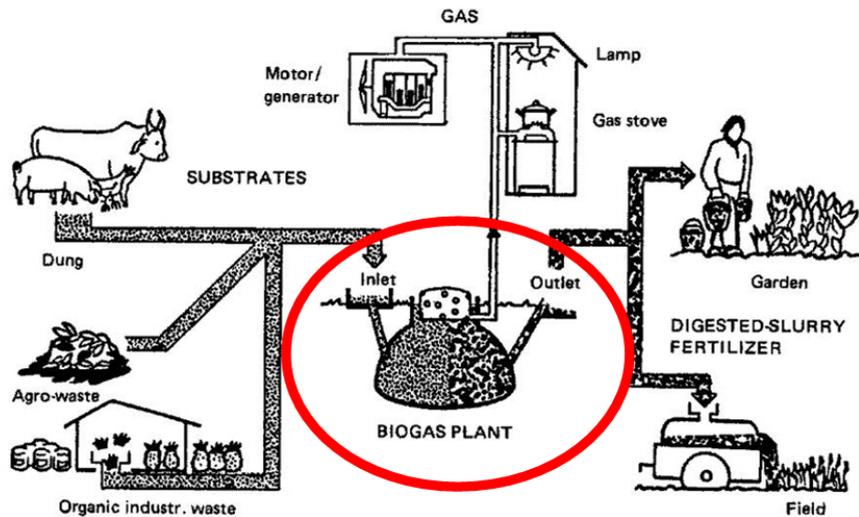
Any biodegradable organic matter is suitable for feeding the digester, except material containing a substantial amount of lignin, e.g. wood. High levels of organic matter are found in organic waste and wastewater from households, communities, and industries, as well as sludge and source-separated solid organic waste from industries, markets and restaurants, human excreta and agriculture. Suitable microorganisms are usually present in the organic mixture especially in sewage sludge and manure and do not need to be added. If industrial waste is toxic, it may be bad for the microorganisms and may prevent the use of sludge as fertiliser.

Ideally, a watery liquid is preferable for the digester with a mixture of organic material and water that contains 10% dry matter. What happens if dry-matter content deviates and how to remedy is discussed later in this module. Human faeces contain about 80% water and 20% organic and inorganic material, while urine contains 94% water and only 6% organic and inorganic material. It is not enough to only feed the digester with human excreta, because it contains too little carbon (energy), and other organic material must be added.

A Chinese rule of thumb is that a small biogas plant requires dung from at least six pigs to produce enough gas for one household. Cattle dung (urine and excreta) contains roughly 12% dry matter and requires another 20% of added water to reach ideal dry matter content. The addition of human excreta and household wastewater is a bonus from a process point of view. There are millions of rural biogas reactors in China, and also a number of advanced biogas plants in Japan processing vast amounts of human excreta.

Integrating biogas in agriculture

4.4 - 5



Pedro Kraemer, BORDA, India

A biogas plant is part of a larger system. It can be fed with substrates from various sources such as manure, agricultural waste, organic waste from households, restaurants etc. (left). The gas can be used to run stoves and lights, electric generators and be upgraded to vehicle fuel wherever needed. The gas has a high ignition temperature and is therefore perfect for combustion engines.

The digestive residue which is left after digestion can be used to fertilise gardens and fields, preferably after some hygienisation. Health risks associated with biogas production are dealt with in Chapter 3.

The digester is therefore an environmentally friendly way to convert a “waste” into useful products. Trapping the gases from the digester reduces emissions of greenhouse gases as well as discharge problems pertaining to meat production, including water acidification and eutrophication, and high energy use. We will perform a systems analysis in the last section of this chapter with an example of a biogas plant in a periurban setting.

Some examples of biogas plants



Pedro Kraemer, BORDA, India

Anaerobic bacteria break down organic matter at suitable, stable temperatures, mainly into CO₂ (carbon dioxide) and CH₄ (methane). A combustible mixture of CH₄ (50–75 %) and CO₂ (25–50%), commonly referred to as biogas, is generated in the air-less digester – leaving behind digested slurry, only partially hygienised, and a reduced volume of organic matter. There is a wide variety of biogas reactors from household versions to large units for communities.

A digester made of plastic for household use (upper left) can convert the waste generated by a four-person family and provide enough gas to cook all meals. The sludge can be used to fertilise the garden. The Indian government recently agreed to subsidise about a third of the cost for this type of family-sized unit.

A German biogas plant (bottom left) comprises a circular concrete insulated digester and a canvas tent to store biogas. The gas is utilised in a gas engine to generate electricity for sale to the electric grid.

The right-hand picture shows an underground biogas plant with a fixed dome-shaped digester. The feeder is in front, and the slurry tank in the rear.

We are now far away from the cow's stomach and the emission of some 300 litres of gas every day. But, the digestion processes are similar.

Where is biogas technology applied?

4.4 - 7

Approximate numbers of biogas units in selected countries:

Country	No of units	Volume >100 m ³
China	12,000,000	x0
India (in 2004)	3,600,000	?
Nepal (in 2007)	200,000	?
Vietnam, Thailand, Tanzania, Bangladesh, Burundi, Brazil	x,000	3,400 (2006) in Germany
Kenya, Mexico, Cuba, Guyana	x00	?
Morocco, Ghana, Zimbabwe, Nicaragua, Jamaica, Bolivia	x0	DK, NL, S, Thailand,

99% of all systems do not use pumps, agitator, and heating

Pedro Kraemer, BORDA, India

In Asia and in developing economies in general, most digesters are for household use and are constructed with appropriate robust technology which is easy to manage. The leading nation is China with more than ten million small biogas reactors in rural areas. Over the decades, the Chinese have built up diverse know-how in the construction and utilisation of digester plants, and they are mainly motivated by the production of gas for energy. Likewise, governments in India and Nepal promote small units in rural areas.

European biogas digester development started in the 1930s as a means of reducing the amount of wastewater sludge. Later on it became politically driven with the aim of reducing emissions and the gas is used to generate heat and electricity as well as for the production of vehicle fuel. The aim is to strengthen the renewable energy sector. The table above shows that most digesters are small units, except in Germany which has thousands of digesters with volumes of more than 100 m³.

A lot of research and technology development takes places, especially in Germany and Denmark where digester technology has reached an advanced stage. For example, egg-shaped thermophilic digesters (see [4.4-7](#) and [4.4-13](#)) with a heating system, agitator and gas purification are constructed to achieve high gas yields. In Europe biogas digesters are expensive and have high capacity and often take the feed from a variety of sources such as restaurants and animal stables.

Available human excreta in India compared to the need of fertiliser

4.4 - 8

**Excreta viewed
as waste:**

Faeces	250,000 tons/day
Urine	1,000,000 m ³ /day

**... or
as a
resource**

Dry org. matter (DS)	90,000 t/day	N-P-K:
Nitrogen (N)	15,000 t/day	X
Phosphorus (P₂O₅)	5,000 t/day	Y
Potassium (K₂O)	3,000 t/day	Z
Carbon (C)	35,000 t/day	
Calcium (CaO)	5,000 t/day	R
Potential biogas	50 mil m ³ day	

Pedro Kraemer, BORDA, India

This example from India shows the amount of human faeces and urine being produced every day. The content of the excreta in terms of various nutrients can be translated into fertiliser values. With a fertiliser mixture of nutrients in the common proportion N:P₂O₅:K₂O = 1:0.5:1, it is possible to use all the 3,000 tons of potassium, the limiting nutrient in the excreta, to produce 7,500 tons of this fertiliser per day. There would be huge amounts of excess N (12,000 tons a day), as well as excess phosphorus (3,500 tons a day) to be used to manufacture additional fertilisers (Sasse, 1999).

The 7,500 t of fertiliser per day would add up to some 2,700,000 t per year of a complete fertiliser. This fertiliser is as effective as commercial fertilisers and much cleaner. We may compare this with the actual daily imports to India of fertilisers (annual import divided by 365 days): (NH₄)₂HPO₄ (diammonium phosphate) 844.000 t; urea 68.000. The amount of nutrient will basically be the same – if you digest a waste and faeces slurry, the organic content will be less (it leaves as gas). Nutrients like N and K will be set free. So if the digested slurry is not dewatered all nutrients remain in the slurry. And they are readily taken up by plants.

At sewage treatment plants the digested slurry is dewatered – thus lots of nutrients are lost via the water phase leaving mainly P in the digested residue.

In a later section (4.4-12) we deal with the biochemical processes involved in gas production. The biochemical reaction is mediated by microbes in the absence of molecular oxygen. As a general rule the biogas process consumes water during the complete conversion of organic matter to methane and carbon dioxide.

Slurry application in agriculture

4.4 - 9



Pedro Kraemer, BORDA, India

The use of slurry or digested residue from the gas production depends on many factors like soil, climate, crop and common agricultural practices. Much of the nutrients in the residue have been mobilised and made plant available without further transformation by soil microorganisms. However, since part of the nitrogen is present as ammonium there is a risk of ammonia evaporation at dry and windy conditions. Depending on the technique used for soil application, the loss of nitrogen and other nutrients in the liquid slurry can be kept to a minimum. The liquid can be taken out of the digester by bucket (see left picture) or with a pump since the dry matter content is only 0.5–1.5%. This combined irrigation and fertilising practice is favourable for permanent plantations, in particular if the wastewater was not mixed with industrial wastewater before digestion (see Module 4.5).

A typical fertiliser requirement is some 80 m³ per hectare, which equals 8 litres of slurry per day per square meter. For instance, fodder grass production yields some 50 tonnes per ha per year depending upon climate and growth period. A cow requires some 18 tonnes of fodder grass per year and therefore a hectare can carry almost three cows. Each cow produces a slurry volume enough to fertilise 1,500 m² and the three cows will provide slurry for half a hectare. Additional fertiliser is needed if nutrients are removed by milk and meat production.

Another solution is to compost the slurry and use it for seasonal crops. Such use entails significant losses of nitrogen, is a labour-intensive process, but a good soil conditioner with long-term fertilising effect. Another positive aspect is that the weight of the composted slurry is small and so it is easy to handle during application. The application of slurry, on the other hand, may cause high losses of nitrogen.

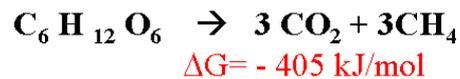
Energy balance – for composting and digestion

4.4 - 10

Aerobic conversion (*composting*):



Anaerobic conversion (*digestion*):



Burning of biogas:



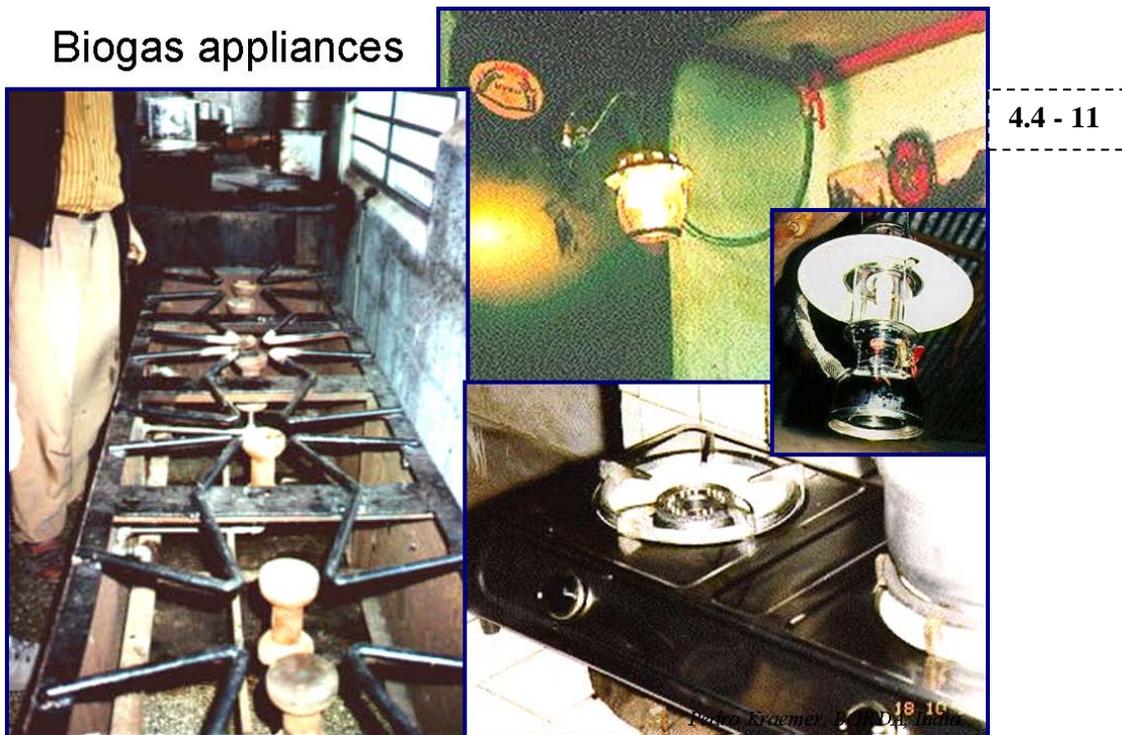
Pedro Kraemer, BORDA, India

Energy cannot disappear; it can only be converted to other forms of energy of higher or lower entropy. The sun provides the energy for photosynthesis which builds sugar molecules from water and carbon dioxide. The sugar molecules are in turn building components for other organic compounds. In this way the sun energy is transformed into chemical energy in the biomass. We now compare how this chemically bound energy is transformed in the two processes of aerobic composting and anaerobic digestion.

In conventional composting **aerobic** bacteria break down organic molecules such as sugar with the help of oxygen (air) to produce water and carbon dioxide (see formulas above). Chemically bound energy is utilised by microbes degrading the biomass. Excess heat is released and heats up the compost heap. This result helps kill pathogenic microorganisms and if the temperature is high enough, the compost heap will become hygienised (see Module 4.3).

In contrast, the **anaerobic** microorganisms in the biogas digester release very little energy (405 kJ/mol) when sugar converts into carbon dioxide and methane. Most of the chemical energy is contained in the methane molecules (CH₄) and is released only when the biogas is burnt. One of the favourable aspects of biogas is that it can be moved easily from the digester to any nearby place where it is needed for heating or lighting.

Biogas appliances



A good thing with the low pressure biogas is that it allows transport of the gas in a plastic pipe to the place where it is to be used. Unfortunately, the low pressure reduces the efficiency of technical appliances in the kitchen, even if they are properly designed. For instance, the efficiency of a biogas lamp is only half of the efficiency of a kerosene lamp due to the low gas pressure. Another example is that a fairly good burner has only just over 50% efficient. The poor efficiency is compounded by abrasion of stoves and lamps.

Parameters affecting the efficiency are: the air-biogas mixture, the design of the burner including the geometry of the mixing chamber, the diameter of the jet, the diameter and number of burner outlets, the distance between outlets, and the distance between the burner head and pot.

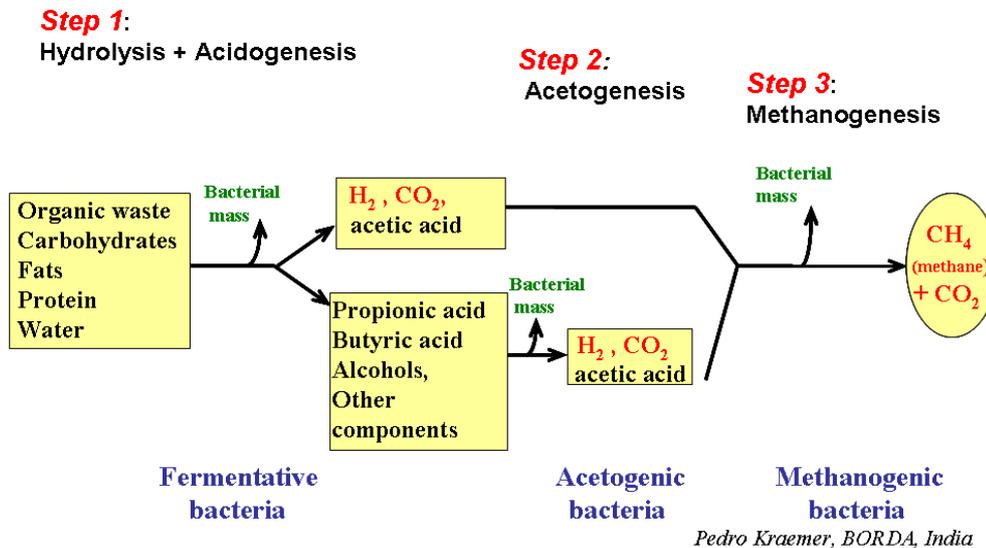
Comparison of efficiency of cooking fuels.

Unit	Fuel	Calor value	Efficiency	Net calor value
Kg	Cattle cake	2.5 KWh/Kg	12% open fire	0.3 KWh/Kg
Kg	Fire wood	5 KWh/Kg	12–16% better stove	0.75 KWh/Kg
Kg	Charcoal	8 KWh/Kg	25%	2.0 KWh/Kg
Kg	Butan (LPG)	13.6 KWh/Kg	60%	8.2 KWh/Kg
m ³	Biogas	6 KWh/ m ³	55%	3.3 KWh/ m ³

Low efficiency is normally accompanied by more emissions of unburned methane. This is a serious problem since the methane is a greenhouse gas that is 25 times more powerful than carbon dioxide ([IPCC, 2007](#)).

Biochemical process of anaerobic fermentation/digestion

4.4 - 12



The biochemical processes in the digester are driven by various specialized anaerobic micro-organisms. These organisms are born, work as chemical engineers, multiply and die. The bacteria have a density just over that of water, and most of them form a sludge layer at the bottom of the digester. But if the material is not properly mixed or if the Upstream Anaerobic Sludge Blanket (UASB) technique is used the sludge does not settle. Most often scum occurs due to poor mixing and it consists of sterols and fat floating up to the surface with the help of gas bubbles.

Organic matter is anaerobically broken down in a sequence of processes called the anaerobic food chain that is divided in three phases: Hydrolysis/acidogenesis, acetogenesis and methanogenesis. In the first phase, the so-called fermentative bacteria attack organic waste such as carbohydrates, fats and proteins and degrade them to simpler organic compounds (hydrolysis) and then into simple monomers such as sugars from carbohydrates, aminoacids from proteins and long chain fatty acids and glycerol from fat. These monomers are then further metabolised to alcohols and volatile organic acids such as butyric and propionic acid. In addition, acetic acid, hydrogen and carbon dioxide may be formed in various amounts.

In the second step, the alcohols and volatile fatty acids can be further digested to hydrogen and acetic acid by highly specialised acetogenic microbes. The biogas process is completed in the third step where a population of methanogens utilises hydrogen and carbon dioxide to form methane and lastly a second, completely different methanogenic population cleaves acetic acid to methane and carbon dioxide. Methanogens are microbes called *archaea* and are not bacteria

In a cow it is basically only the first step (hydrolysis and acidogenesis) and part of the third step (hydrogenotrophic methanogenesis) that occurs since all volatile fatty acids are absorbed by the cow. The cow more or less lacks the step of methane formation from acetic acid. In the biogas digester the reactions are pushed towards complete conversion of the acids to biogas and it is therefore important to stress the importance of the prevailing hydrogen concentration. In the first step (hydrolysis and acidogenesis), the some biochemical reactions involved can generate hydrogen at concentrations up to 50 %. However, in the acetogenic step, other biochemical reactions are involved during the formation of acetic acid and hydrogen and they can for thermodynamic reasons only be performed at hydrogen concentrations below 0,01%. Basically the high concentration of hydrogen formed in the acidogenic step is now inhibiting acetogenesis. By consuming hydrogen to low concentrations, hydrogenotrophic methanogens “push” the acetic acid generating reactions to become thermodynamically possible.

The importance of hydrogen and its effects upon the whole biogas process cannot be stressed enough. The first thing that almost always happens when something goes wrong in a digester is that the levels of hydrogen increase and, this limit or hinders the metabolisation of fatty acids. A biogas process that for some reasons is getting out of balance is characterised by increased levels of fatty acids.

How added organic matter to a digester affects the efficiency of digestion varies quite a lot and for many reasons. Major factors are: colonisation of the substrate by microorganisms, substrate quality, particle size, lignin content and retention time. The first thing that has to occur in a digester is that microorganisms must colonise the substrate. An illustration of this is that a cellulose fibre is about 3–4 mm long and a microbe is 0.003 mm long. To a microbe, eating a cellulose fibre is like chewing on a 1 km size sandwich. Therefore, huge numbers of microbes are required on the same piece of substrate in order to manage proper digestion.

A cow chews its grass food several times. Similarly, in a biogas digester, mechanical pre-treatment enhances the digestion rate and the degree of digestion. Another important factor is the content of lignin in the organic material. Lignin can be found in almost all types of plants to various degree and is resistant to anaerobic digestion. Thus, a high content of lignin, such as the amounts found in wood (25–35%) makes the otherwise degradable cellulose and hemi-cellulose unavailable for digestion. Wheat straw also contains concentrations of lignin (about 10–15%) which decrease the digestability of the straw to about 50%. Therefore, proper mixing with a focus on blending in the substrate into digester liquid is very important. Another major factor affecting digestion efficiency is the average time in the digester – the retention time. Generally a longer retention time increases digestion efficiency. While the process can in theory reduce all organic matter, this would take too long. For economic reasons, most digesters run so long that only some 40–60 % of the organic substrate is degraded. When there is no fast degradable biomass left the substrate is said to have stabilized and is less odorous.

It is important to remember that the symptom indicating that the biogas process is being impaired by toxins is exactly the same as nutrition deficiency – an increase in fatty acid levels and foaming. Such an effect can also be found in cows and this disturbance is called acidosis.

A biogas digester is not meant to hygienise organic matter. Therefore, extra efforts must be made to hygienise the slurry and sludge (see Greywater modules 4.6 and 4.7).

What parameters affect anaerobic digestion?

4.4 - 13

The most important determinants of good living conditions for anaerobic bacteria and therefore efficient gas production, are :

- Temperature
- Retention Time
- pH-level
- Carbon/Nitrogen ratio (C/N ratio)
- Proportion of dry matter in substrate = suitable viscosity
- Agitation (mixing) of the substrate

If any one of these determinants is outside acceptable range, the digestion may be inhibited

Pedro Kraemer, BORDA, India

We mentioned earlier that the cow's stomachs provide a stable temperature, enough water and an oxygen-free environment for efficient digestion. Knowing the weakness of a person with diarrhoea makes it plausible that regular feeding and long retention time is important. Any chemical process is affected by the pH-level and anaerobic digestion of biomass is no different. Less obvious is the importance of the carbon-nitrogen ratio, and we will come back to that issue.

The viscosity of the feeding material is also important. To allow easy flow through the digester, the dry matter content should be around 10%. Studies also show that feedstock particle diameter is important and that the rate of methane gas production is inversely proportional to the diameter (Kayhannian and Hardy, 1994). All organic waste such as garden waste should therefore be chopped into small pieces in order to facilitate the operation of the microorganisms.

Mixing of the substrate in the digester improves digestion, if only because it ensures a uniform material which becomes accessible to the bacteria. The cow manages this mixing by moving around and by transferring the material from one stomach to the next.

We now investigate each of the above parameters, and also identify potential inhibitors.

Substrate temperature in the digester

4.4 - 14

Anaerobic fermentation can work in an ambient temperature between 3°C and 70°C and, if colder, the reactor has to be insulated and/or heated.

Common temperature ranges for bacteria:

- Psychrophilic bacteria below 20°C
- Mesophilic bacteria 20 – 40°C
- Thermophilic bacteria above 40°C

Methane production is very sensitive to **changes in temperature**

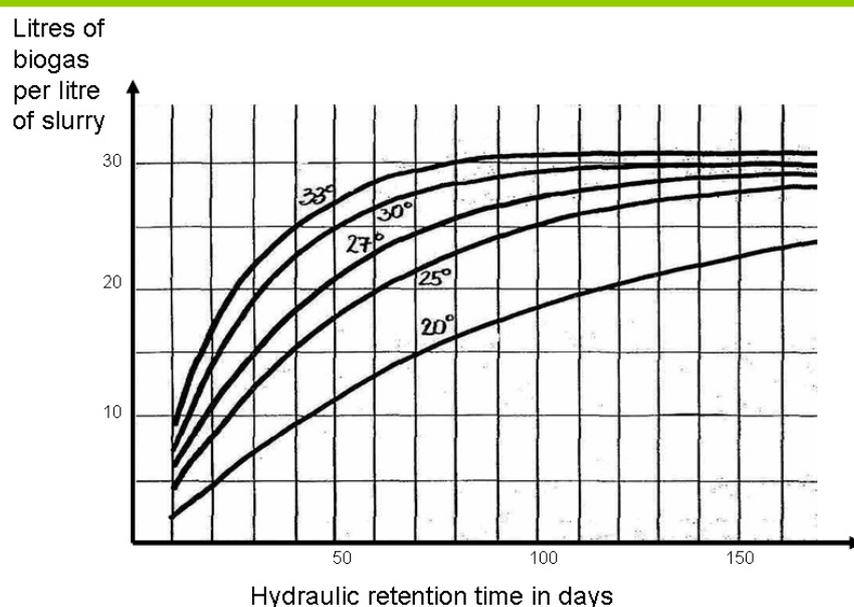
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The temperature in the cow's rumen is stable at around 37°C and therefore mainly mesophilic microorganisms are peacefully at work. It is interesting to note that different species of microorganisms are present in the three temperature ranges, and they can only survive in their specified ranges (see picture above). If the temperature goes above 40°C the mesophilic bacteria will die and be replaced by thermophilic microorganisms. If it goes below 20°C the mesophilic bacteria will die and be replaced by psychrophilic bacteria! However, breeding of the new bacteria population takes time and the digestion will slow down for a period.

If the ambient temperature is below 3°C, the digester should be insulated. Also, if the day and night temperatures differ much, insulation is highly recommended. The small rural biogas plants in China (see [4.4-7](#)) are dug into the ground and are insulated by the soil! This is an example of how operation can be simplified and secured by a good design.

Biogas production with continuous feeding

4.4 - 15



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One kilogram of fully degraded carbohydrates gives 415 litres of methane independently of temperature (asymptotic end). The time it takes could however be affected by temperature since the rate of fermentation and biogas formation increases with temperature.

The diagram above shows how the gas production varies with mesophilic temperatures and retention time. In this case the biogas plant is fed with cattle manure mixed with some water, so that dry matter content is about 10%.

A litre of slurry can provide some 30 litres of gas (graph) in this temperature range after an extended retention time. This amount can be compared with 0.1 kg of carbohydrate giving 41.5 litres of gas (10% dry matter). The graph provides the interesting information that if the substrate temperature is raised a little, say, from 25 °C to 30 °C, the gas production in a period of 50 days goes up 50% from 17 to 25 litres. Also, the same gas production can be attained in 25 days instead of 50 days if the substrate temperature is raised 5 degrees. This, again, confirms that insulation and even heating can be very economical measures since retention times and also the size of the digester can be reduced. The cost of building a big digester is considerable, and typically it is only practical to degrade 40–60 per cent of the organic matter.

The curves may change considerable with addition of urine (+) or lignin (-) to the substrate. The reason is that urine contains large quantities of nutrients that are easily available for the microorganisms, while lignin is not degradable. A substrate with high lignin content is less favoured also because the resistance of lignin to anaerobic digestion. There are ways to increase digestion potential of the substrate including mechanical pre-treatment like chopping and limited composting before being fed to the digester. The resistance to anaerobic digestion of lignin can be exemplified by the build-up of organic matter as lignin in peat bogs. Also brown coal (also called ligno coal) is remains of non-putrified lignin.

How much is 30 litres of biogas? Household consumption of biogas may range from 600 to 2500 litres per day depending on cooking and other habits. For instance, a lamp may use some 500 litres per day, and a 100-litre refrigerator uses 700–1800 litres biogas per day. A comparison with actual gas production shows that a daily addition of 20 litres of slurry is required just to run the lamp (mainly because lamps have a low efficiency shown in [4.4-11](#)).

pH –value is crucial for a good result

4.4 - 16

pH is a central parameter for controlling the anaerobic process

- **Optimal production when pH 7.0 – 7.2**
- **Inhibition** (due to acids) if pH < 6.2
- **Inhibition** (due to ammonia) if pH > 7.6

Deviation from the optimum range results in:

- Lower gas yield
- Inferior gas quality

Pedro Kraemer, BORDA, India

The pH value of a digester is good measure of the prevailing environment for the biogas process. The pH level can change due to several matters of which some are related to temperature and substrate composition and others to disturbances of the microbial community. Such disturbances are typically due to large temperature variations which influence the whole microbial population, or to a lack of nutrition. The acids lower the pH and if the value in the digester drops below 6.2 the acids produced by acetogenic bacteria may become inhibitory. When the environment becomes inhibitory, mainly acetogenic and methanogenic organisms slow down their reactions and finally the whole biogas process can come to a standstill.

Declining temperatures will decrease the pH of the digester due to increased solubility of carbon dioxide in the digester liquid and sludge. Dissolved carbon dioxide is in equilibrium with carbon acid which will decrease pH. Also the composition of added substrates will influence pH: fat and carbohydrates will decrease pH during digestion whereas digestion of proteins will increase pH. Thus, a good balance between the substrates will give a suitable pH in the digester, which can be expressed as C/N ratio (see below).

The pH value can be increased by adding alkaline material such as lime or ash. If no substrate is added, the biogas production will resume and the volatile fatty acids be consumed. Adding lime water is more effective but has to be done in a way that does not increase the pH value too rapidly ([Reith et al., 2005](#)).

After the substrate has stabilized in the digester, the pH value of the slurry is commonly between 7 and 8.5.

C/N ratio is important

4.4 - 17

Microorganisms need N (nitrogen) and C (carbon) for their metabolism

Methanogenic organisms prefer a C/N ratio of between 10:1 and 20:1

N must not be too low, or else
 shortage of nutrient

**Recommendation:
Mix different substrates**

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Carbon and nitrogen are both vital for the digestion processes. Experience has shown that if the carbon to nitrogen ratio is too high or too low, gas production will be slower. A mixture of substances can achieve a convenient substrate ratio. For instance, chicken manure has a C/N ratio of 7–9 and straw has a C/N ratio of 50 to 150. For further reading see Kayhanian and Hardy (1994)

The calculation of the ratio can be done for biodegradable C which is optimal for fermentation. A C/N ratio of 25–30:1 is equivalent to a C/ N ratio of 30 to 40:1 if the values are based on total C and total N (this is the conventional unit).

Nitrogen inhibition

4.4 - 18

If N concentration is **too high** (>1,700 mg/l of $\text{NH}_4\text{-N}$) and pH is high, then

 **growth of bacteria is inhibited** due to toxicity caused by high levels of (uncharged) ammonia

Methanogens, however, are able of adapt to 5,000 - 7,000 mg/l of $\text{NH}_4\text{-N}$ given the pre-requisite that the uncharged ammonia (NH_3 controlled by pH) level does not exceed 200-300 mg/l

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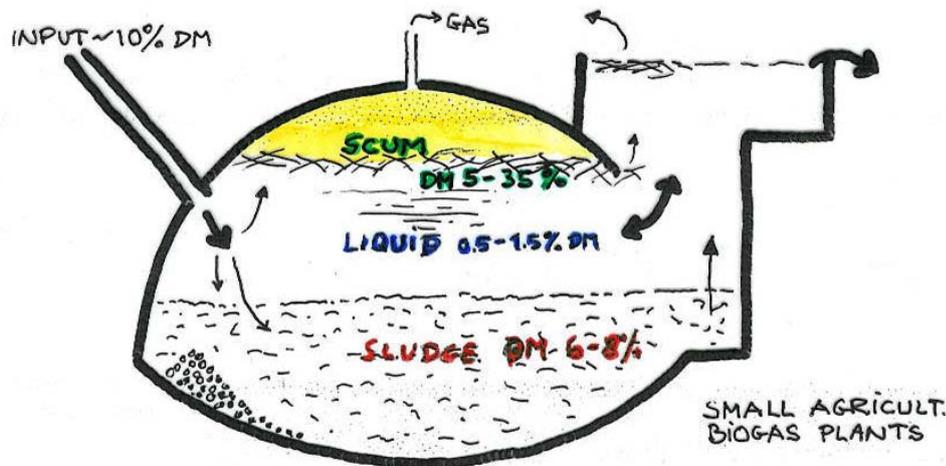
In the digester, nitrogen present in the substrate is released as ammonium (NH_4^+) during digestion. At pH values above 7.6 ammonium is transformed to ammonia (NH_3). If the concentration of ammonia exceeds 20–30 mg/l, the ammonia gas may be toxic to the microbial population and again biogas production will cease. High ammonia concentrations and pH values can be reduced by adding water.

Dissociation of ammonia in water depends on the temperature and pH values of the substrate: the free ammonia concentration increases with higher temperatures and with higher pH levels.

This is an example which inspired scientists to use urea as a hygienization agent for faecal pathogens (Module 4.2).

Changes in dry matter (DM) concentration inside the digester

4.4 - 19



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The recommendation for low-tech digesters is to have a viscosity or dry matter concentration of about 10% in the substrate fed to the digester. We have to strike a balance between the rate of gas production, the dry matter content and the physical operation of the digester. If dry matter is, say 15%, the gas production will increase, but such a substrate is rather solid and it can hardly flow. This leads to mechanical problems. If the dry matter content is 7% instead, the gas production will be lower but the physical operation may be easier with less mechanical problems. The 10% is important when feeding the digester. By mixing different substrates and if necessary adding some water, it is easy to reach the desired dry-matter content. Experience has shown that fresh cattle dung has 19.5 % dry matter content, human faeces 25% and human urine has 7%, while a substrate made up solely of organic waste from markets market has a dry matter content of 35–40%. A cucumber is 3% dry matter and greywater has only 0.5 % dry matter.

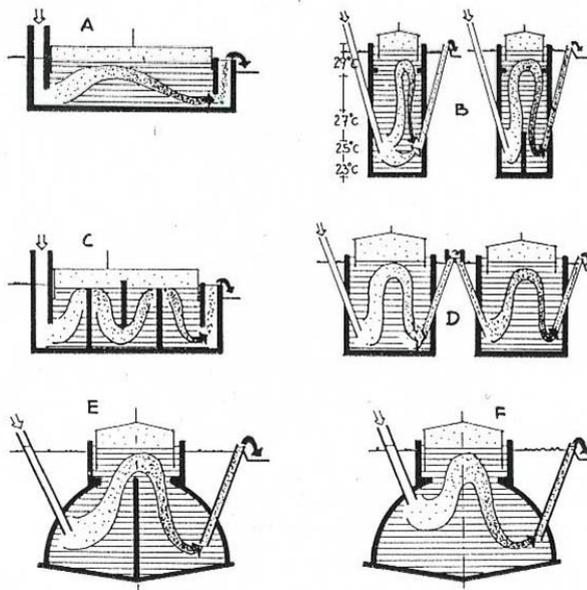
Once the feed has entered the digester the dry matter is relocated as indicated in the picture above, due to the release of biogas and other processes. The rates at which different components of the feed are digested will vary greatly. Carbohydrates in cellulose are easy to decompose (hydrolyse), but cellulose also contains 10–15% non-degradable lignin. Tree wood contains some 25% non-degradable lignin. The decomposition of proteins to methane, carbon dioxide, ammonium and hydrogen sulphide is guided by pH. Fat is decomposed to biogas. What is not emitted as gases will be found in the slurry, and to a lesser extent in the sludge.

The sludge at the bottom has some 6–8 % dry matter, and the liquid slurry leaving the digester has only 0.5–1.5%. The scum layer of organic matter and dead organisms varies between 5 and 35% dry matter content and can become a hard crust.

The operator cannot observe the inside of the digester, so the only way to secure smooth operation and high gas yields is to be careful about the composition of the feed. The feed should also be shredded to ensure it does not block the movement of the substrate in the digester.

Behaviour of the substrate inside the digester

4.4 - 20



Pedro Kraemer, BORDA, India 23

The route of the viscous substrate through the digester can be arranged in several ways, and the objective is to expose it as much as possible to the microbial population. The slide shows some of the most common designs of biogas digesters. A fixed-dome digester is shown in the diagram for Section 4.4-20.

During digestion the substrate will be turned into a liquid and sludge. Sludge will accumulate in the digester but there will also be continuing degradation going on in the sludge. Baffles can be inserted to make sure the substrate flows over as long a distance as possible in the digester, thereby ensuring it gets maximum exposure to bacteria. The routes shown in the pictures are all longer than a straight line and the actual retention time is longer than the theoretical one. If the retention time is one week the movement of the substrate is slow, and the bacteria have easy access to the slowly passing feed. There is no turbulence and so bacterial activity is not disrupted.

Stirring the substrate

4.4 - 21

Stirring improves the efficiency of digestion by:

- Removing metabolites (gas removal)
- Bringing fresh material in contact with bacteria
- Reducing scum formation and sedimentation
- Preventing temperature gradients in the digester
- Avoiding the formation of blind spots (short cuts)

However, *excessive* stirring disturbs the symbiotic relationship between the different bacteria species

Simple biogas units normally do not have mechanical stirring devices

Pedro Kraemer, BORDA, India

Stirring the material in the digester improves gas production for the reasons given on the slide. It can be done mechanically with a rod, or by injecting compressed biogas from the bottom of the digester. The bubbles move the substrate around and give bacteria access to all of it. However, it should be done gently to avoid disturbing the symbiotic relationships between different bacteria species.

Efficiency of a biogas unit

4.4 - 22

Input:

1 kg of dry (95%) cattle dung will produce 2.5 kWh (rule of thumb)

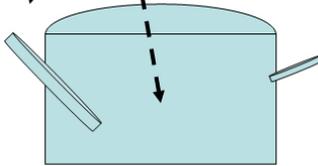
1 kg dry (100%) matter can generate 2.5/0.95 = 2.63 kWh

Slurry contains 10% dry matter, thus 1 litre can generate 0.263 kWh

1 litre slurry (27°C, 90 days retention) releases 27 litre biogas

1 m³ of biogas can generate 6 kWh (rule of thumb)

So, 1 lit of slurry generates 0.027*6 = 0.162 kWh



$$\text{Efficiency} = \frac{\text{Actual kWh}}{\text{Potential kWh}} = \frac{0.162}{0.262} = 0.62$$

62% efficiency and the other 38% energy remains in the slurry

Pedro Kraemer, BORDA, India

The calculations in the above diagram are based on experience in the field:

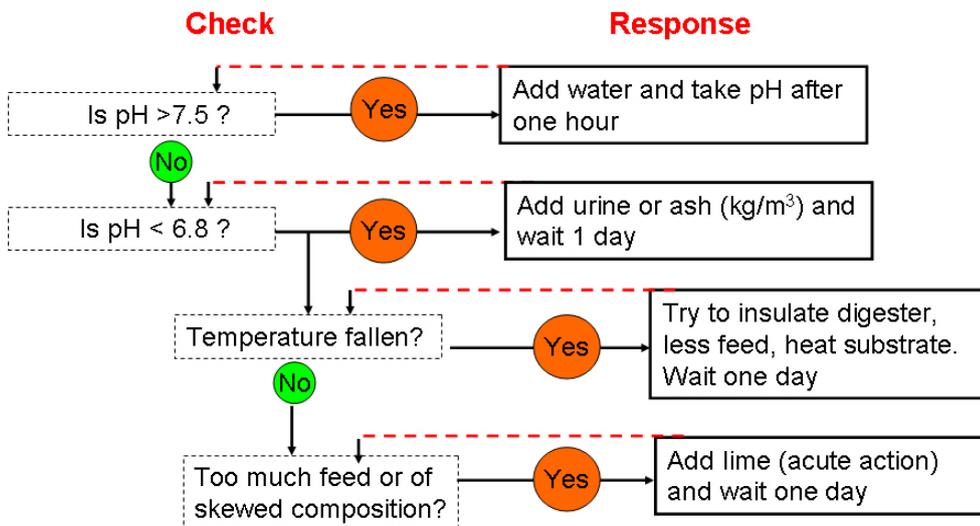
1 kg of dried (95%) cattle dung, release about 2.5 kWh in the field

1 m³ of biogas generates some 6 kWh energy

What the calculations above tells us is that if the retention time is three months, typically about two-thirds of the potential energy is out of the substrate as biogas and one-third remains in the liquid leaving the digester. However, this liquid contains nitrogen and other nutrients and can be used as a fertiliser and so it is not wasted.

Check-list if gas production is lower than expected

4.4 - 23



Drangert & Ejlertsson, Linköping university, Sweden

If gas production is lower than expected, the above parameters have to be assessed. Some of these parameters cannot be measured in a household unit. Therefore the checklist is arranged so that the parameter that is the most common cause of problems, or the parameter which is easiest to check, comes first, followed by the others.

(1) **PH-value:** The pH-value is the most critical parameter during the digestion process and cheap pH sticks are available on the market. Furthermore, pH is easy to measure with a litmus test. If the pH-value exceeds 7.2 water should be added to the digester to dilute the sludge. A low pH-value may be caused by several factors. Methanogenic bacteria are not able to produce enough methane if too much substrate is fed into the digester. Acidification will result, and if the pH-value is below 6.9, no more biomass should be added until pH returns to a value of between 7 and 7.2. If the pH value falls below 6.6 there are two ways to increase pH. The first is dilution with water. The second is to add chemicals like lime water (or urine). As bacteria adapt only slowly to new conditions the chemicals must be added slowly. Note also that temperature effect pH. Decreasing temperature allow more carbon dioxide to dissolve in the digester liquid. Dissolved carbon dioxide forms carbonic acid which decreases pH.

(2) **Temperature:** Low gas production may be caused by a drop in temperature which also chemically will decrease pH (see above) due to a higher proportion of carbon dioxide in the digester liquid. A declining temperature also decreases the rate of digestion, where especially the methanogenic populations loose pace. In low-tech digesters, it is not possible to solve this problem instantly. A long-term solution is to insulate the digester and preheat influent feed. A new heating process should be started slowly (maximum 1 degree Celsius per day).

(3) **Substrate composition:** The composition of the substrate is very important, especially for co-fermentation of various substrates. For example, chicken and swine dung are known to cause problems because both have high values of fat and carbohydrate and so they may cause acidification. Another possible problem is the concentration of sand in dung that accumulate at the bottom of the digester.

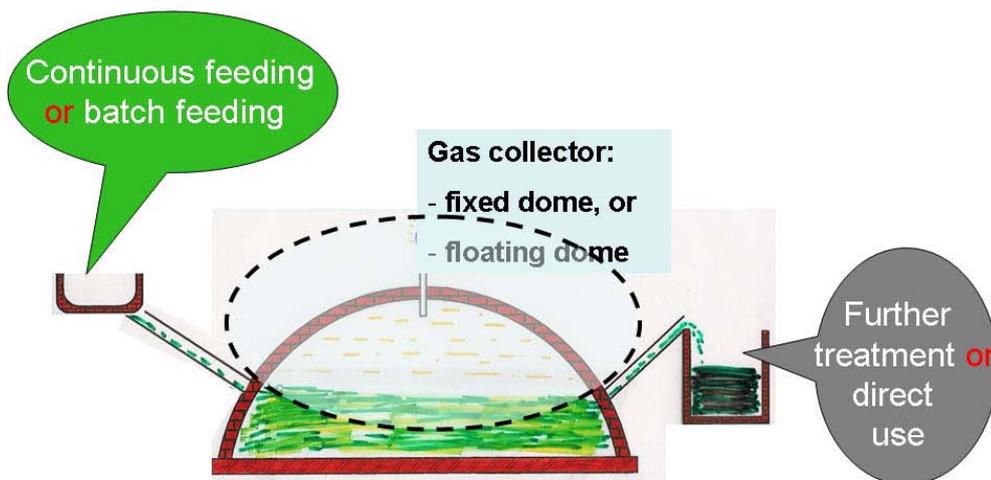
(4) **Toxic material:** Toxic material may inhibit or even kill bacteria and other microorganisms. But it is difficult to analyse samples for toxic materials like heavy metals, medicine residues, solvents or disinfectants, because the concentrations of these toxic substances is very low. The only solution is to encourage the discharge of less polluted wastewater and to avoid mixing organics with other solid or liquid wastes.

(5) **Total Solid (TS):** If the effluent contains a rising TS volume it is possible that the digester is leaking. It is also possible that the composition of the substrate has changed and it has a dry matter content above 10%.

(6) **Agitator:** The agitator extends contact between degradable substances and microorganisms. Less gas production may be caused by improper performance of agitators.

Principles for design and construction

4.4 - 24



Pedro Kraemer, BORDA, India 28

Up to now, we have discussed biochemical and other processes involved in biogas production. As will be shown in this section there are certain principles guiding the design and construction of well-performing digesters.

There are essentially two basic approaches to producing gas. One is to use lots of organic waste as substrate and produce large amount of biogas, while at the same time reducing the problem of waste disposal (biogas digesters). The other approach is to collect gas from the wastewater treatment process, despite its low organic load. The volume of gas is moderate, but the reason for collecting it is to avoid the release of greenhouse gases.

The digester chambers must not have any leakage points where water can seep into the ground or gas escape into the air. If made of bricks and cement the workmanship has to be meticulous. There should be manhole big enough to enable a person to enter the digester.

Biogas digesters:

There should be enough space to store the organic material and to mix it before feeding it into the fixed-dome digester or floating-drum digester. It is recommended that the inlet to the digester has a shape that makes it possible to judge by eye inspection the volumes of added feed and water. Also, the inlet should be such that it is easy to read the height of the material standing in the inlet pipe, to take a pH test, and to measure the temperature of the substrate in the digester.

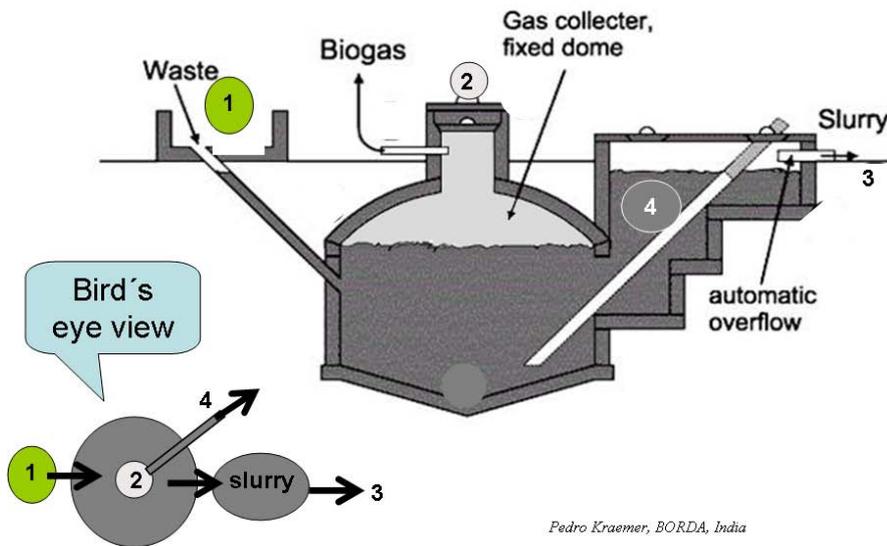
There are different ways of feeding the digester. Continuous feeding is the most commonly used. There are two different types of continuous feed digester: The full mixed and the plug-flow digester.

Anaerobic (baffled) reactors

There are many ways to treat wastewater, for instance in anaerobic filters or the Upstream Anaerobic Sludge Blanket (UASB) digester (see Module 4.7). The degradation of organic material produces some biogas that is collected. The tunnel digester is an example of a plug-flow digester which is more or less a tube the water has to pass through.

Fixed-dome biogas digester

4.4 - 25

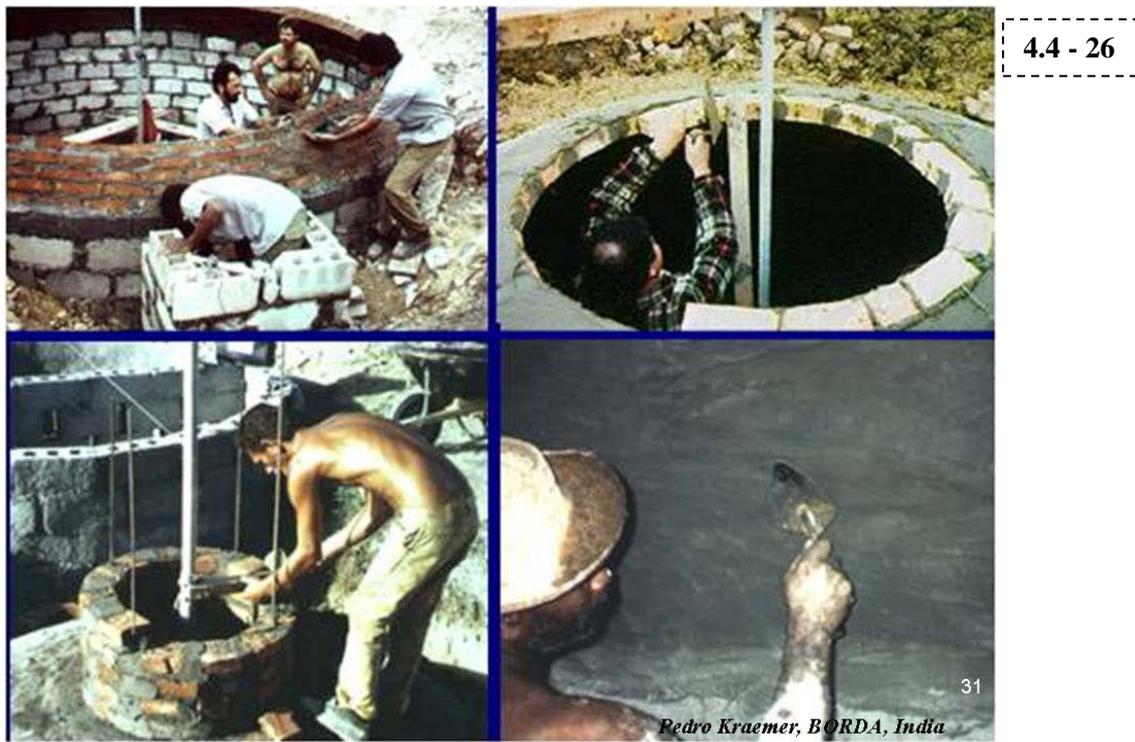


There are several designs of biogas plants, and we first show the Chinese invention of a fixed-dome digester. Its advantages are low initial cost, simple operation since the scum layer breaks automatically and low maintenance. There are no moving or rusting parts so it has a long life. The downside is fluctuating gas pressure. Furthermore, qualified and experienced masons are required to build the gas-tight fixed-dome digester.

Organic solid waste including manure and faeces are mixed with wastewater to a watery mass with a 10% dry matter content (see picture). This is fed to the digester where anaerobic micro-organisms decompose starch and other materials to methane gas and other products (see 4.4–9). The movement of the substrate relies on hydraulic pressure from the added feed.

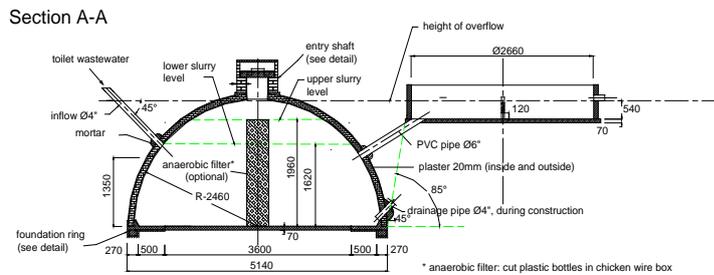
The gas rises through the scum layer to the upper part of the fixed dome. As pressure builds up, the liquid in the digester is pushed down and will escape as slurry (No 3). If the gas is not let out (No 2) it will start seeping out in the slurry chamber, because this exit is the first available when the substrate level sinks. So, it is easy to know from the smell when to empty the gas. When gas is let out (No 2) the liquid substrate rises again and the crusty scum layer on top breaks into pieces since the diameter of the dome is ever smaller. This makes the system very robust and there is no need to enter the reactor or use a mechanical device to crack the scum crust.

The white pipe (No 4) is used for emptying the degraded material (sludge) at the bottom of the reactor. It is not inserted through the slurry opening as it may appear in the diagram; it enters from another direction (as shown in the bird's eye view). The slurry (No 3) is still rich in nutrients (except N) and other compounds that have not been decomposed. Therefore, it is suitable as fertiliser. The digester is not meant for reduction of pathogens, but there is a 1–2 log unit reduction of bacteria. Further treatment, for example in a wetland filter is required to make the effluent safe to irrigate the garden (see Module 4.7).

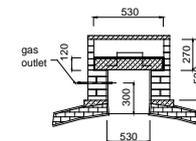


The pictures show the construction of fixed-dome digesters in different Latin American countries. The circular-shaped brick wall (top-left from Cuba) is built on a cement fundament. The dome is built with bricks and cement and a skilful mason does not need a support under the dome (top-right). After the cement has hardened it is possible to add the manhole (bottom-left) and gas pipe on top of the dome. The inside of the dome, the wall and floor are “painted” with water-proof cement 3–4 times in order to ensure that it is airtight (bottom-right).

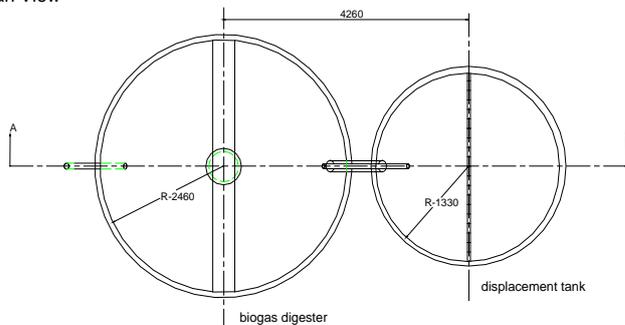
Biogas digester



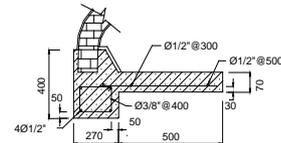
Detail: entry shaft



Plan View



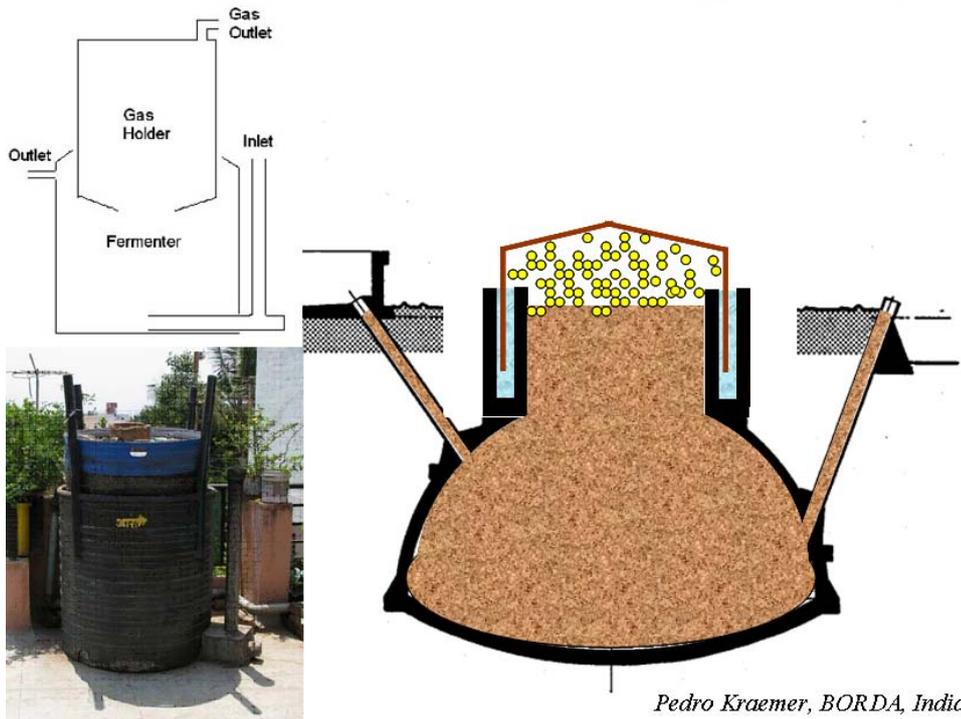
Detail: Foundation



treatment of blackwater from 50 people:
 digester volume - 28.25 m³
 volume of displacement tank - 3.02 m³

Floating-drum unit with water-jacket

4.4 - 27



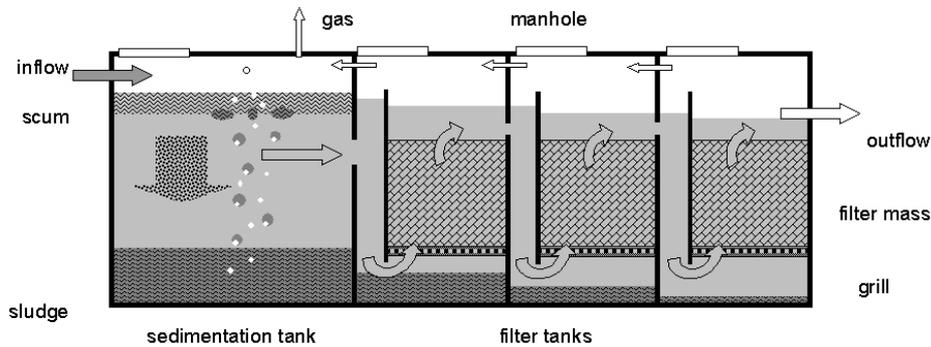
Another design is the floating drum. The reactor can be above ground (left) or in the ground (right). The top of the digester is made airtight by keeping the upside-down drum dipped in a water apron (right-hand picture). The drum is pushed upwards by the gas, while the substrate level is pushed down to a small extent by the drum. The position of the drum shows when it is time to empty the gas. The gas pressure is even and can be adjusted by selecting the weight of the drum. This is an advantage since gas lamps and gas burners work more efficiently with a constant high gas pressure.

This design requires the same kind of operation as the fixed-dome digester, except that it may be necessary to crack the scum layer by lifting off the drum. The downside is that the drum is relatively expensive and requires a lot of maintenance.

The left-hand unit is made of plastic and can be placed in the corner of the garden or on a roof garden.

Anaerobic filter (off-plot system)

4.4 – 28



Pedro Kraemer, BORDA, India

Anaerobic filters are used as part of a wastewater treatment system in order to catch the gas released in the processes. The influent has a low content of dry matter (about 1%), which is very different from biogas digesters which contain 10 % dry matter.

The anaerobic filter, also known as a fixed-bed reactor, comprises a fixed bed of tanks and the wastewater flows through a sequence of filters made of gravel, slag or plastic elements. The wastewater flows continuously and both upstream and downstream flow through the filters are design possibilities. The wastewater is pre-treated in a sedimentation tank to prevent clogging.

Gas is produced in all tanks and collected in a gas storage tank. All the tanks have to be airtight to prevent the gas from escaping. Anaerobic organisms are added to improve degradation of organic matter in the wastewater.

Microorganisms grow on the filter material and make up a so called biofilm. The smaller the pores, the larger is the contact area of microorganisms and wastewater. The downside is that smaller pores may clog or even block totally, so there has to be a balance between pore size and contact area. Clogging means that dissolved and non-settleable solids adhere to the filter material or simply physically block passageways and in both cases they diminish the permeability of the filter. The few small channels still open to water flow compel a high-speed flow which washes away the bacteria. Also, high local speed provides little time for the bacteria to work and poor effluent quality can be observed. Back-flushing of the anaerobic filter has to be done regularly to prevent such operational problems. If operated correctly, the anaerobic filter is reliable and robust.

One anaerobic filter can serve many households, and take care of wastewater from institutions and public conveniences.

Another biogas technology to capture gas from wastewater is one without filters. The Upstream Anaerobic Sludge Blanket (UASB) reactor contains in this case an active sludge blanket at the bottom of the reactor (See 4.7–10). The reactor is designed as an upstream system with the inlet pipe at the bottom of the chamber. Instead of forcing the wastewater through a filter, the upstream flow pushes the sludge upwards but it remains in the lower strata of the reactor. Here, the microorganisms attached to sludge particles attack the substances in the surrounding wastewater. This is what is meant by “activated sludge”



The Anaerobic Baffled Reactor is a combination of a UASB reactor with the principle of a septic tank. This is a technology often used for housing complexes and institutions such as hospitals and schools.

The larger solids in the wastewater settle in the first sedimentation (septic) tank followed by a sequence of connected chambers. Each inlet to a chamber is at the bottom so that the flow of wastewater disturbs the sludge and it whirls up in the water body. Each outlet is at the top, forcing the wastewater to flow upwards and the sludge particles try to settle because of weight. The microorganisms attached to the sludge particles are exposed to the surrounding wastewater and start degrading organics and other solids. The advantage gained is good wastewater exposure to the microorganisms. The drawing shows that the chambers receive less and less settled sludge.

This treatment system is very robust against hydraulic and organic shock loads, and easy to operate. Unlike the UASB, there is no risk of clogging. Even difficult-to-degrade solids are affected, thanks to the very long retention obtained in the settled sludge. Such solids are hydrolysed and fermented by acidogens so that they after some time are transformed into biogas.

Biogas is produced in all the chambers and collected in a storage tank. The construction must therefore be air-tight in order not to lose any gas. The gas pressure fluctuates and is therefore not ideal for household appliances.

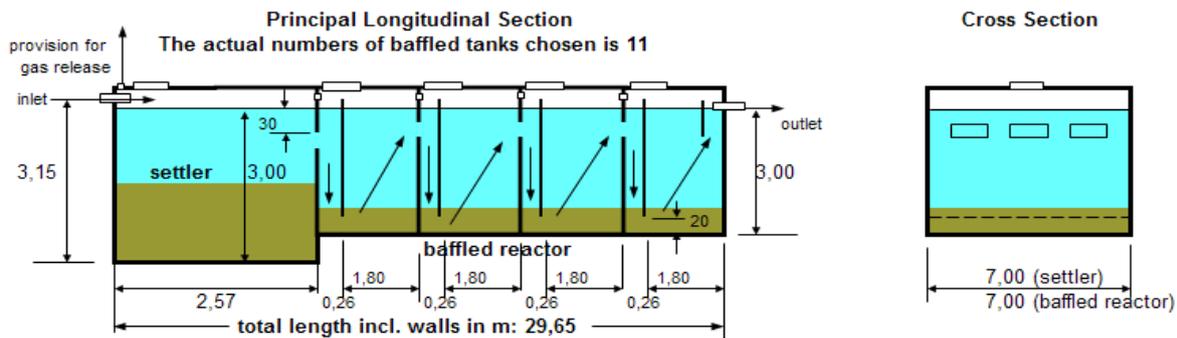
General Spread Sheet for Baffled Reactor with Integrated Settling Tank

daily waste water flow	time of most waste water flow	max peak flow per hour	COD inflow	COD / BOD ratio inflow	Settleable SS / COD ratio	lowest digester temp.	de-sludging interval	HRT in settler	BOD removal rate in settler	COD removal rate in settler	inflow into baffled reactor		org. load limit factor					
avg.	given	max.	given	given	given	given	chosen	chosen	calcul.	calcul.	BOD	COD	calcul.					
m ³ /day	h	m ³ /h	mg/l	mg/l	mg/l / mg/l	°C	months	h	%	%	mg/l	mg/l	factor					
610	12	18,00	1,540	1,47	0,30	30	12	1,50	17%	16%	874	1,296	1,00					
usual values =>													domestic	1,7-2,0	0,5	1,5 h	TIP: set HRT=0 if no settler provided	

Data for Calculation of Baffled Reactor										Dimensions Settler			
factors to calculate BOD removal rate of baffled reactor	BOD rem. 25°, COD 1500	theor. rem rate acc. to factors	BOD rem. rate baffle only	COD rem. rate baffle only	BOD out	COD out	total BOD rem. rate	total COD rem. rate	inner masonry measurements chosen acc. to required volume	length of settler	length of settler		
calcul.	calcul.	calcul.	calcul.	calcul.	calcul.	calcul.	calcul.	calcul.	width	depth	calcul.	chosen	
f-strength	f-temp	f-HRT	%	%	%	mg/l	mg/l	%	%	m	m	m ³	m
0,98	1,10	92%	99%	98%	97%	17	38	99%	98%	7,00	3,00	2,57	2,57
										sludge l/g BODrem. 0,0027			

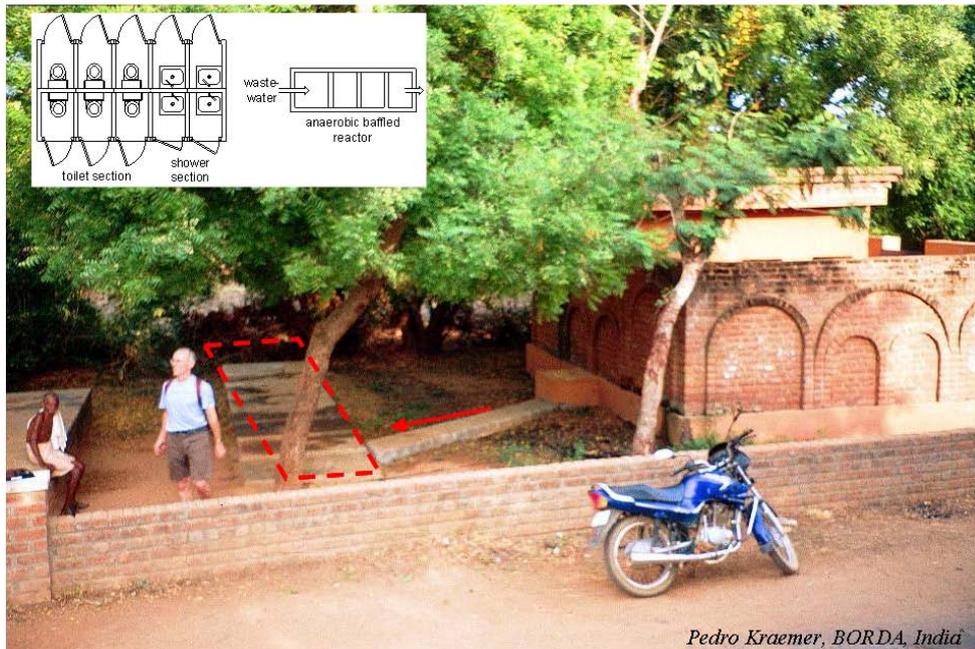
Dimensions Baffled Reactor													
max upflow velocity	number of upflow chambers	depth at outlet	length of chambers should not exceed half depth		area of single upflow chamber	width of chambers		actual upflow velocity	width of downflow shaft	actual volume of baffled reactor	actual total HRT	org. load (BOD)	biogas (ass: CH ₄ 70%; 50% dissolved)
chosen	chosen	chosen	calcul.	chosen	calcul.	calcul.	chosen	calcul.	chosen	calcul.	calcul.	calcul.	calcul.
m/h	No.	m	m	m	m ²	m	m	m/h	m	m ³	h	kg/m ³ *d	m ³ /d
1,65	11	3,00	1,50	1,80	10,91	6,06	7,00	1,43	0,26	475,86	18	0,79	157,10
1,4m/h; max<2.0 m/h										HRT reduced by 5% for sludge			

TIP: If removal rate is insufficient; increase number of upflow chambers. Then, HRT will increase also but upflow velocity remains low.



Public toilet with hidden treatment unit

4.4 - 30



A practical example of an anaerobic baffled reactor is shown in the picture above. This DEcentralized Wastewater Treatment Systems (DEWATS) receives wastewater from a public toilet (to the right). The digester is “hidden” in the ground and does not require any extra space (indicated). It can therefore be readily integrated into public areas like parking lots, parks, foot paths etc. As mentioned earlier, the reactor is tolerant of peak loads and fluctuations in flow. The unit is easy to operate, and a trained gardener can take care of its maintenance including calling a vacuum truck for desludging.

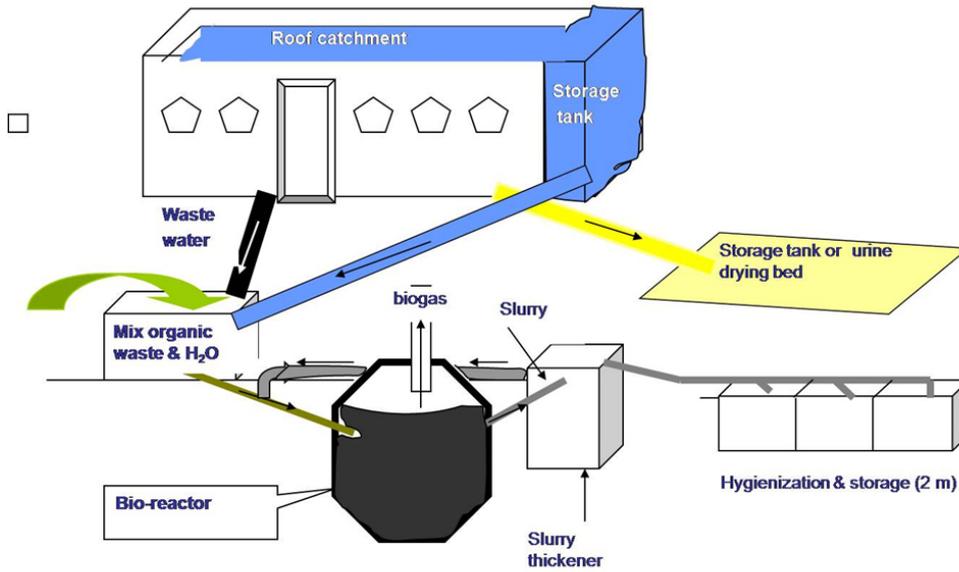
The sludge is composted and ends up as an organic fertiliser which contains very few chemicals, and it is safer to dispose hormones on soil than in water bodies. The biogas is collected in a gas tank from which the gas can be used for lighting, heating or cooking.

The ABR can be built with local materials by a contractor with skilled masons. The capital cost is moderate and can be estimated by any contractor. A design proposal is shown in 4.4–30.

The treated effluent is clear but not safe water, and will need some treatment depending on subsequent use. This effluent water is good for irrigation and fertilisation, although about half of the organic matter has been removed. The sludge in the chambers is removed and after some composting it becomes a safe and good manure since very few chemicals have been added in the public toilet – ideally only biodegradable substances.

A public toilet with a biogas digester

4.4 - 31



Jan-Olof Drangert, Linköping University, Sweden

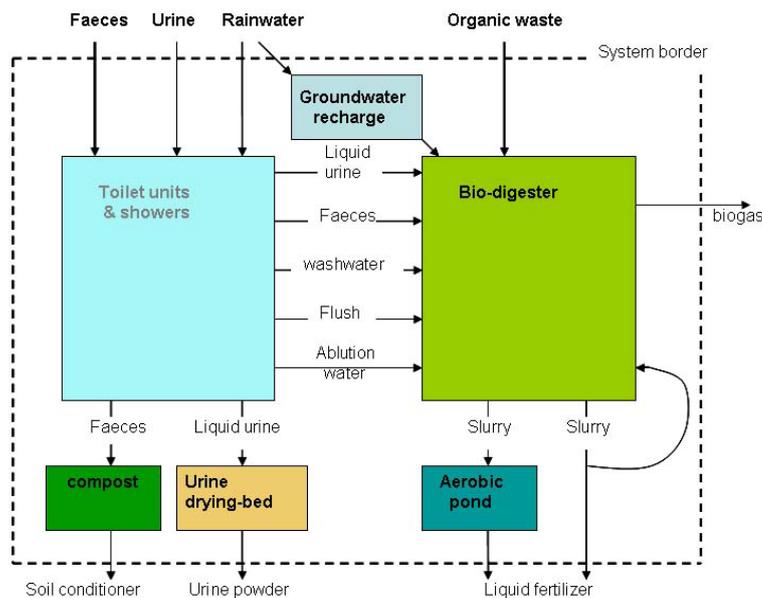
This picture shows an application of a bio-digester in an urban area with no access to tap water or sewerage. The public toilet is adjacent to a market and the municipality wants to solve the dual problems of providing a public toilet service and collection of organic market waste.

Rainwater is collected and during dry season well water is drawn. The water is used for handwashing and to flush pour-flush toilets. Minimal water volumes are required since the inclination of the pipe to the nearby digester is steep. The digester is designed to degrade all the market waste and to treat the wastewater from a public toilet. Urine is diverted and used directly as a fertiliser in agriculture. The remaining blackwater and greywater is treated in the digester. Afterwards the slurry is hygienised and applied in a nearby garden or used to feed the digester.

A calculation exercise follows on the next slide.

Material flows in the toilet complex

4.4 - 32



Jan-Olof Drangert, Linköping University, Sweden

This is a schematic picture of the material flow in the public toilet complex and incoming organic waste from the market described in 4.4–32. It can be used as an exercise to find out what can be produced from the potential waste. The input data has to be gathered from the field or be invented for this purpose.

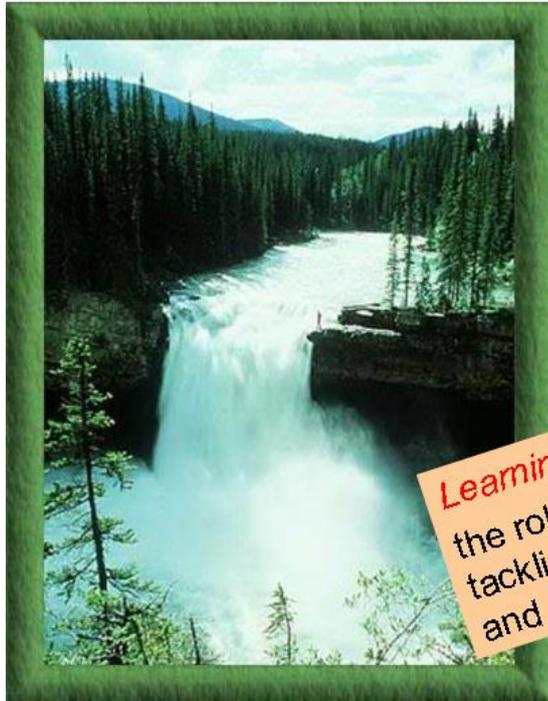
The material flow concept was introduced in Section 1.3 and can be applied here. The rules of thumb for equations, sinks and flows are found in the previous descriptions of bioreactors. A rough first calculation can be done manually, while a scenario or sensitivity analysis will require a mathematical model with an associated computer programme.

References

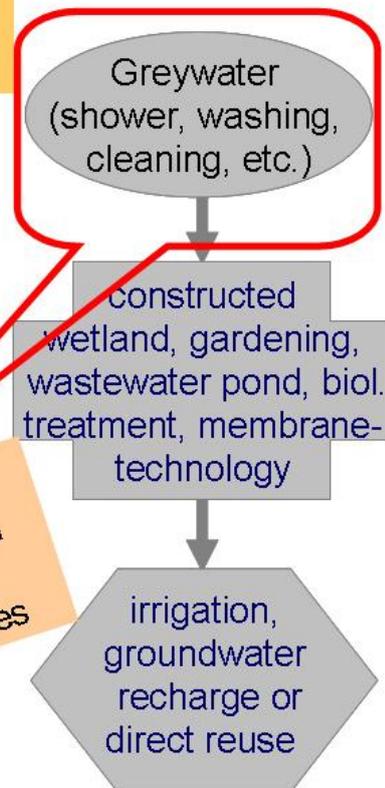
- IPCC 2007. *Climate change 2007 – the physical science basis*. Chapter 2. Changes in atmospheric constituents and in radiative forcing. Table 2.14, pp. 212-13. Working Group I Contribution to the Fourth Assessment Report. Intergovernmental Panel on Climate Change,
- Kayhanian, M and Hardy, S , 1994. The impact of four design parameters on the performance of a high-solids anaerobic digestion of municipal solid waste for fuel gas production. *Environ. Technol.* Vol. 15, no. 6, pp. 557-567.
- Ogina, A. 2007. *Animal Science Journal*, DOI: 10.1111/j.1740-0929.2007.00457.x)
<http://www.animals-angels.de/Umwelt%20-Klima%20-3.-Welt,1073>
- Reith, J.H., Wijffels, R.H., and H. Barten (eds) *Bio-methane and bio-hydrogen. Status and perspectives of biological methane and hydrogen production*. At
<http://gasunie.eldoc.ub.rug.nl/FILES/root/2003/3339875/3339875.pdf>

4.5 Greywater is man-made

– an untapped water and nutrient resource



Learning objective:
the role of households in tackling environmental and resource challenges



We are undergoing a radical shift in our understanding of water pollution. Up to a few decades ago we were mainly concerned with microbial risks to humans from polluted drinking water. These risks have been extensively studied and they can be controlled rather well by improving sanitary conditions and protecting water sources, be they wells or containers in the home. The eutrophication problem is largely understood and heavy investments in P and N reduction in wastewater treatment plants have reduced the problem.

The current threats come largely from chemical pollutants in wastewater originating from production and consumption of goods in our ‘chemical society’. These pollutants affect both the environment and human health. Chemical health threats are more complicated to analyse than those of microorganisms since chemical compounds are ingested in very small amounts and may persist and accumulate in our bodies. Dose-response studies therefore require long time periods and are expensive. Also, the number of artificial substances is very high – about 100,000 compounds – but these are known at least by the manufacturers. This is very different from microorganisms which emerge as part of the evolution and are gradually detected, with some new strains causing diseases within days.

During the last century, the industrial sector was blamed for causing environmental problems. It earned its bad reputation through many bad practices. However, legal action and greater awareness have improved the situation and today many industries are treating their used water on site. They can often recover some of the chemical substances in the water and use these again in their production and also recycle the partially treated wastewater back to the production line.

Today, releases of environmentally hazardous substances are increasingly linked to diffuse consumption-related sources (e.g. individual households) rather than production-related large point sources. Discharges from households may even be more polluted than those from industry

and offices. This is because households buy more and more chemical products such as personal care products, textiles, medicines, plastics, etc. Substances related to these products include plasticizers, brominated flame retardants, endocrine disrupting substances and many others that should not be released into the environment. A generation ago most of these products were not available at all, while the corresponding products were mainly biodegradable and we did not have to worry about them. Today, we have wastewater treatment plants, but they are not built to take care of the tens of thousands chemical compounds in the wastewater we discharge. It is true to say that householders are responsible for their purchase, use and discharge. However, the task of informing millions of inhabitants about the effects of these products, and making sure they take appropriate precautions is daunting.

A major problem to overcome is the perception that transparent water is always clean water. Staff at wastewater treatment plants may proudly show a bottle of clear water after the treatment of dirty water, but the disturbing fact is that this water still contains disease-causing microorganisms, hormones, heavy metals, etc. No WWTP in the world monitors more than a handful of the tens of thousands of compounds in the effluent and sludge. All stakeholders need to be involved in order to improve the quality of used water by not discharging harmful substances.

Population centres are becoming hot spots for pollution. Dealing with diffuse sources raises new challenges since legislation and other available tools are traditionally directed towards point sources. Therefore, there is a need to develop new methods to deal with these diffuse sources. Such methods include source control through, for example, legislation on hazardous compounds, information, green procurement, cooperation with stakeholders and new approaches to supervision.

This chapter focuses on how households can manage their water use so that the used water becomes less polluted and useable again after some treatment, and thus more sustainable. We discuss what potential pollutants can be avoided (source control) and what valuable resources can be recovered and used for crop and energy production. Also, if water and greywater are properly managed, there will be no water shortage in cities, since the water can be used over and over again with little treatment!

There is recommended hierarchy of solid waste management measures:

1. **Minimise waste** volumes by reducing the amount of products and the quantities of toxic components in them to avoid unnecessary problems,
2. **Sort** the various wastes to be able to:
3. **Recycle** particular products several times,
4. **Reuse** products by processing waste materials to a new product,
5. **Incinerate or digest (biogas)** what cannot be recovered in order to take out the energy content
6. **Safe landfill** of toxic and other non-recovered material from the other options.

There is a similar hierarchy for the management of greywater. The first step is source control to minimise the volume and pollutant content of greywater. This involves residents as well as manufacturers of household products, often with the support of government agencies. The second step is to install arrangements that enable the sorting waste streams and may include not mixing flows from stormwater, industrial wastewater, black water, urine and faecal matter. The third and fourth steps are to recycle and reuse the components of the treated flows.

We discuss greywater from households, that is, all used water except toilet water but most conclusions also apply to mixed wastewater. Four aspects of greywater management are presented: consumption and use patterns, source control and content of greywater, treatment processes and arrangements, and recirculation of water and nutrients.

Challenges and possibilities

4.5- 2

Greywater represents environmental challenges:

- **Unpleasant odours**
- **Health hazard (pathogens and toxic compounds)**
- **Soil erosion**
- **Pollution of surface water and groundwater**
- **Mosquito breeding**

Benefits of using treated greywater and sludge:

- + **Reduces water shortage**
- + **Reduces environmental degradation, eutrophication and health hazards**
- + **Reclaims otherwise wasted nutrients**
- + **Alleviates food shortages and poverty**
- + **Protects the quality of groundwater**

Courtesy of Nicola Rodda University of KwaZulu Natal, Durban

Some of the most common challenges and benefits related to greywater are given in the list above. After just a few hours, stored greywater releases an unpleasant odour. It may contain pathogens and chemical compounds detrimental to human and animal health, and if the effluent is released in an uncontrolled manner it may cause soil erosion. Depending on how well the effluent is treated, it can pollute soils and the waterways into which it is discharged. Some species of mosquitoes thrive in standing wastewater and can spread diseases.

The effluent coming out of a treatment process should be put to good use. Examples are irrigation, recharge of groundwater, recirculation as toilet flush water or other non-potable uses. Treated greywater can reduce water shortages in households and industries, and larger volumes from towns can be used to irrigate farmland. Equally important is using the nutrients in greywater and sludge for fertilising crops. Increased yields may in turn help alleviate food shortages and help attain food security. An instant benefit is that environmental degradation such as eutrophication and groundwater pollution is reduced or prevented.

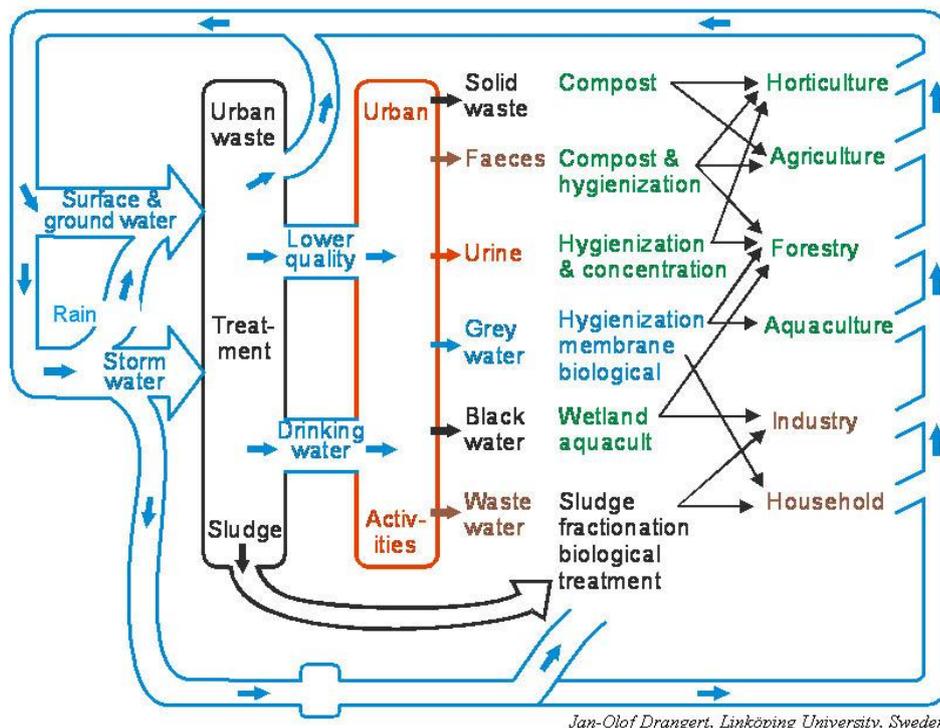
In Singapore, wastewater is treated to a high degree and used for drinking water. Several states in the US and in India allow urban reuse of treated greywater. Applications range from permitting households to use it for irrigation to allowing commercial buildings and housing complexes to use it for toilet flushing (see 2.1–18). It seems as if the growing scarcity of virgin sources of water tends to make legislators more open to allowing the reuse of wastewater. In future, increased scarcity of nutrient sources may also encourage the recycling of wastewater byproducts.

Poor waste management in dense informal settlements often has serious impacts, both on health and the environment. Yet, greywater and stormwater management is generally not a priority in these settlements. In many cases it may be that the social cohesion is too limited for collective action (Module 1.4). It appears that whatever management strategies adopted, their success depends on communities' attitudes and understanding of the issues, as well as a commitment of the authorities.

Legislation and by-laws which allow treatment and reuse of greywater will stimulate innovation in the sector. WHO Guidelines (2006) provide scientific support and advice. Ways to address the above challenges and realise the mentioned benefits will be described below.

Urban *horizontal* water and nutrient flows

4.5- 3



The first step is to acknowledge that wastewater is part of the water cycle. The picture shows the *horizontal* flows of water (and partially nutrients) from nature to urban use and back to nature.

Water is always on the move (see Section 1.2- 4) not only in nature, but also in communities. Surface water and groundwater, and sometimes rain and storm water is collected, treated and used for urban activities in households, offices, and industry, and for street cleaning, fire fighting, etc. A dual delivery system is possible, where lower-quality water is used for washing, and high-quality water is used for drinking, cooking and bathing. Bottled water is another way of distributing high-quality water for drinking.

Residents add artificial compounds to the water (red box) while using it, such as soap for washing hands, detergents for washing dishes and clothes, shampoo for washing hair, and excreta are transported in the wastewater pipes. These activities take away dirt and improve hygiene standards but at the same time they pollute the used water. The extent to which the various waste flows are mixed varies between communities as well as between types of infrastructure. A general rule is, however, that less mixing makes it easier to treat the water and to recover usable resources. The industrial sector is leading the way in the profitable recycling of treated water and of other useful products. The household sector lags behind and only a few countries have started to treat and use the wastewater from households in a controlled way.

Various treatment methods and recycling options are indicated in the above picture (details in Modules 4.6 and 4.7). Potential reusable materials are the treated water itself and – perhaps equally important – the recovered plant nutrients. We do not deal with industrial effluent in this sourcebook, but it may be profitable to recover special components from such wastewater. If more sophisticated treatment methods are introduced (such as nanofiltration and reverse osmosis) the treated greywater may be directly circulated back to household use, as is being done in Singapore and some other water-scarce cities (www.waterhub.org). Sludge generated during treatment of wastewater remains a major management challenge.

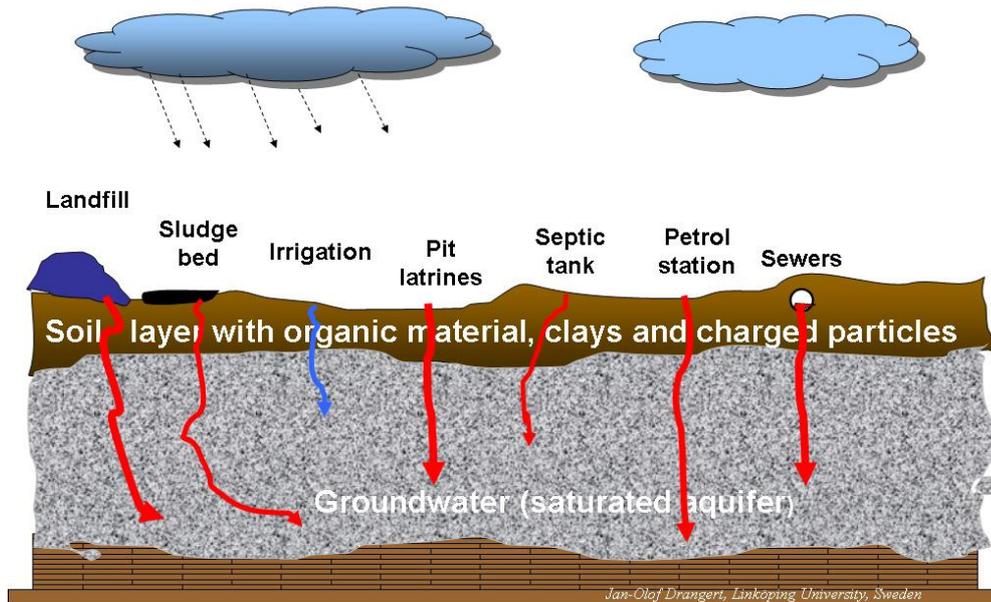
Keeping valuable components separate is often easier than combining them and then separating them in WWTPs (source control). Collected urine from a single household can be used straight away to fertilise plants. In apartment areas, however, it is hygienically safer to collect and store the urine before application on farmland. The same goes for hygienised excreta (Module 4.2). In cases where the blackwater from flush toilets is collected separately, it can be treated in various ways, for example to produce biogas (see Module 4.4), and the treated slurry may be circulated back to farms via a wetland.

Fresh water is becoming increasingly scarce due to higher demand caused by population growth, urbanisation and economic progress. The amount of wastewater will also increase if we do not replace our 'business as usual' approach. In addition, there is an energy aspect attached to each water system. For instance, California uses 19 % of its electricity, 30 % of its natural gas, and 88 billion gallons of diesel fuel annually to pump and treat its water and wastewater! ([California Energy Commission, 2004](#)).

The main easily accessible water and nutrient resources are those involving recirculation such as using wastewater for irrigation. There are obvious benefits from recycling such as better food security for many households and, in turn, improves nutritional status and lessens vulnerability to diseases. On the other hand, poorly managed greywater and sludge are associated with negative impacts on human health. Such health risks can be minimized when good management practices are adhered to. The WHO Guidelines ([2006](#)) for the safe use of wastewater, excreta and greywater provide practical guidance on what to do and what not to do from a health-risk assessment point of view.

Urban *unintended* vertical flows of contamination

4.5 - 4



A water-based system also has a vertical part! The picture shows the mostly unintended vertical flows of water and whatever is mixed into it, which move microbial as well as chemical pollutants from the surface down to the groundwater. Groundwater is a valuable resource which can be polluted via various pathways from sludge, pit latrines, leaking sewers and landfills. Pollution may be made worse by occasional rain that washes various wastes into water bodies or helps infiltrate them into the soil, from where it may reach the groundwater. Simultaneously, valuable nutrients and water are lost.

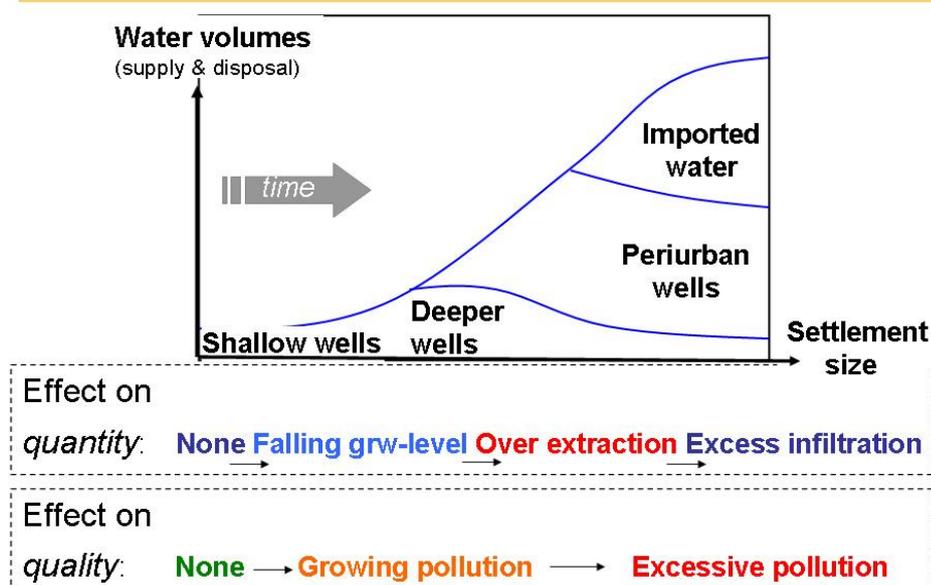
There is a complex interaction between water, soil, and human activities (BGS, 2001). Most soils are vulnerable to being polluted by water from urban infrastructure and human activities. All pipes, septic tanks and pit latrines leak. Also, all groundwater under cities is polluted by pathogens and/or chemical compounds which may make the groundwater unfit for human use. This is particularly serious in areas where groundwater is the only water source, and is drawn from wells and used by households – often untreated. The only secure water supply is thus made into a health hazard for the users, and water utilities are not likely to provide any other water supply. The remedy is to ensure that waste handling is done properly to protect groundwater from all waste flows.

Waste should be treated above ground rather than in the ground where it becomes invisible and very difficult to monitor. The soil contains most of the microorganisms (see Section 4.6- 24) and animals that can help to decompose waste material in its upper layer.

There is also an upward vertical flow of greenhouse gases from landfills, sludge drying beds, septic tanks, and wastewater treatment plants. This will be discussed in connection with the various treatment systems presented in this chapter.

The effects of urbanisation on groundwater utilisation, quantity and quality

4.5 - 5



Courtesy of G. Jacks, Royal Institute of Technology, Stockholm

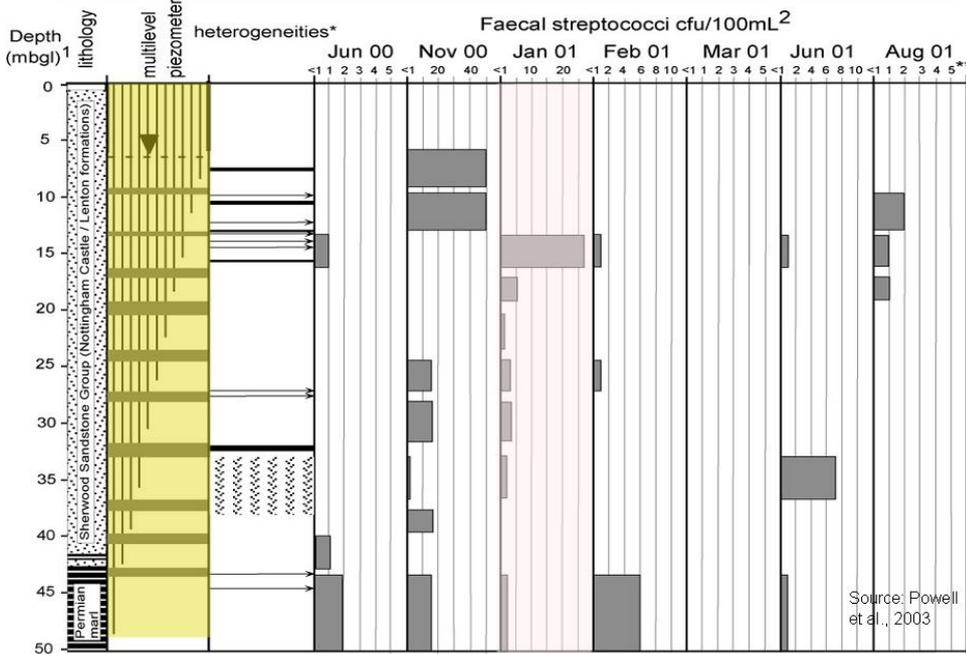
It is useful to observe how water systems change over time. For example, the quality and availability of groundwater can change dramatically when settlements grow into cities. Small settlements may find enough water from local wells, and the groundwater is likely to be of good quality (left-hand side of picture). However, on-site sanitation may threaten groundwater quality. The groundwater level may fall as the settlement grows, and deeper wells are drilled to reach deeper aquifers. The groundwater quality in the upper aquifers deteriorates due to increasing pollution. Unless the geology is particularly favourable, with a clay cover large enough to protect the aquifer, pollution will occur from bacteria, virus, nitrate etc. Even salinity may become excessive. In periurban Dhaka, the geological conditions are very favourable with a 10–15 metre clay layer above a sand aquifer, and no bacterial or nitrate pollution has been detected so far. However, further population growth will result in over-abstraction of groundwater and its level will subside further. In that phase even houses may be destabilised and crack when the soil dries out (e.g. Mexico City 2.2-7).

The so-called water scarcity in cities is addressed by conveying additional water from distant rivers, lakes and well fields. When this happens, the water situation is reversed and the groundwater level rises, since the amount of discharged used water is so huge that infiltration becomes excessive and the quality of groundwater deteriorates because of the infiltration of polluted water. In this phase basements of houses built during the dry period may be inundated by groundwater. In central London during the first half of the 20th century, the groundwater also rose because water-consuming industries were forced to move out from the central city, and today groundwater is constantly being pumped out to secure a low groundwater level! (Drangert and Cronin, 2004). Many cities in the world face similar problems caused by leaking water and sewage pipes which raise the groundwater level to the extent that drainage is needed.

Avoiding pollution and waste of water resources becomes more important as cities grow. In eastern Botswana, thousands of inhabitants used wells in the villages in combination with pit latrines. Unlike in Dhaka in Bangladesh, the soils in Botswana are permeable and excessive bacterial pollution and nitrate levels were detected. Today these so-called “villages” have tens of thousands of inhabitants and their water is now pumped in pipes from new well fields kilometres away.

All groundwater under cities is polluted

4.5 - 6



As shown in the above example of the city of Nottingham, UK, groundwater is vulnerable to polluting land uses and leaking water infrastructures. Nottingham is sited on a sandstone formation which contains an open aquifer of between 65 and 150 metres. Dramatic changes in land use have occurred over time, from farming activities to city infrastructure. The first steam-powered public supply well was installed in 1858. Rapid urban growth commenced in the 1870s. Over-abstraction took place in the early expansion of Nottingham, causing the water table to fall (by 10 m) and some areas to subside. The water supply infrastructure had to be continually refurbished. In the later stages of city development, increased recharge was more common due to reduced abstraction and increased leakages. This may cause flooding of basements and tunnels, infiltration of pollutants into the unsaturated zone and damage to the foundations of buildings.

A research team undertook a study of the history of Nottingham's groundwater recharge, use and quality for the period 1850–1995 (Yang et al., 1999). They developed a groundwater flow model, supplemented by calibrated solute balances (Cl^- , SO_4^{2-} and total N), to identify the origins of recharge fractions from precipitation, water mains and sewers. The validity of their results was checked by a sensitivity analysis to mitigate for the limited availability of early data (Cronin et al., 2003). The studies show (when average flow is expressed in the same units as precipitation) that:

- In the 1850s rainfall (which averaged 700 mm a year) recharge of the groundwater was about 230 mm per year
- Today the city's use of water from external sources is equivalent to 700 mm per year.
- Recharge from water mains leakage has grown significantly and is now the major contributor to recharge with an estimated 93–162 mm/year over various parts of the city.
- Total recharge has varied little over the period (-8%) because increases in leaks from the water supply pipes have compensated for the effects of the increase in the area covered by impermeable surfaces in urban areas.
- Recharge from sewer leakage is estimated to be 6–13 mm/year (+/- 100%) and has changed very little, perhaps reflecting widespread use of foul soakaways in the nineteenth century.

- Sewage-derived bacteria and viruses were detected to depths of 60 m ([Cronin et al., 2003](#))

These results refine our understanding of recharge, abstraction and land use. Groundwater tends to be polluted by wastewater, but generalisations about the overall effect of urbanisation are not possible across all cities due to the variable geologies, climates and infrastructures.

The research team sampled data on microorganisms and inorganic matter from three depth-specific multilevel piezometers installed into purposely drilled open boreholes ([Taylor et al. 2000](#)). The table above (left-hand brownish column) shows findings from one of these boreholes. The depth profiles 0 to 50 mbgl (metres below ground level) and heterogeneities in the soil profile (symbols: fissure , mudstone band , and coarse horizon     ) at one of the sites. The level of the water table (in November 2000) is indicated by the dashed line at 6.5 mbgl. Anthropogenic loading of chlorides, nitrates, and sulphates were found to be rather stable over the year and decreased with depth ([Cronin et al., 2003](#)).

The depth-specific monitoring of microorganisms (thermotolerant coliforms, faecal streptococci and sulphite-reducing clostridia, and enteroviruses, Norwalk-like viruses, and coliphage) showed they were regularly detected to depths of 50mbgl. Data from one of the boreholes on the distribution of faecal streptococci is presented in the table. Note that the seven sampling periods have varying scales.

The team found strong temporal variations in the presence and levels of sewage-derived bacteria and viruses. Enteric viruses were detected during periods of the year when their prevalence in the population was high ([Powell et al., 2003](#)). The rapid penetration of microbial contaminants into sandstone aquifers, presumably through fissures and mudstone bands, not reported in previous studies, highlights the vulnerability to leaking sewers. The results invalidate the assumption that faecal bacteria and viruses are effectively attenuated within the subsurface through filtration, adsorption and inactivation.

Wastewater = clean water + what has been added

<i>Component</i>	<i>Content in different fractions</i>			<i>Impact (potential)</i>	<i>Means of control</i>
	Faeces	Urine	Greywater		
Water lit/person/day flush included	4-10 (WC) 0 (no flush)	20-40 (WC) 0 (no flush)	80-200	- water scarcity - heat loss - investment - water logging	- behaviour - fee structure - water saving equipment
Pathogens (bacteria, viruses, helminths)	high	very low	low	- infections	- 'no' faeces in water - hygienic handling - aerobic treatment - minimize exposure
Organic matter BOD kg/p/year	5.5 Excreta 7.5	2	10	-deplete oxygen -bacteria growth	Physical, aerobic, anaerobic treatment
Phosphorus kg/person/year	0.2	0.4	0.05-0.3	-eutrophication	urine separation, precipitation, etc
Nitrogen kg/person/year	0.5 Mean value 5.0	4	0.5	-eutrophication -consume oxygen	urine separation, aerobic/anaerobic
Heavy metals	present	negligible	present	-toxic to humans	use other products
Organic toxic compounds	negligible	negligible	present	-toxic to humans	Aerobic treatment
Pharmaceutical residue/hormone	present	negligible	negligible	-toxic for aquatic	Degrade in top soil

Courtesy of Peter Ridderstolpe, WRS, Uppsala, Sweden

Wastewater is the sum of clean water and the substances we add while using it. The table above summarizes some information that is useful when considering the contribution from an individual to the wastewater content. The degree of potential impacts of various components and how to avoid ensuing problems are indicated. Module 4.6 gives details of how various treatment methods work.

Today, monitoring of the discharge from wastewater treatment plants only pays attention to a small number of easily measured indicator substances and organisms. This limited scope is understandable since there are 30,000 chemical compounds in household wastewater and hundreds of pathogen species. New strains of bacteria and viruses are found every year, and improved analytical methods allow us to identify chemical compounds at lower and lower concentrations. Yet, we do not take advantage of this and we still know too little about what substances there are in greywater (and wastewater more generally). In small-scale systems, householders may know more about what is in their greywater, simply by knowing what products they purchase and use in the home and whether they are discharged with the wastewater or not!

The health risks and chemical risks arising from effluents and sludge from wastewater treatment plants as well as from small household treatment units are addressed here and in Chapter 3. The toxicity, volume or frequency, persistence or die-off, and bio-accumulation or exposure of each component or compound has to be considered, as well as how vulnerable humans and the environment are to the threats they pose. Such data is available for many pathogens, but only for a small portion of organic compounds and non-organic chemicals as discussed in WHO (2006).

Constituents in wastewater may cause other types of problems as well. Laundry, for instance, presents special challenges due to lint material from washed clothes. Non-biodegradable fibres of nylon, polyester and polyethylene are too small to be trapped in washing machine sieves, but too big to easily pass through a soil or sand filter. Even when lint and other insoluble materials pass through the treatment they may settle in distribution pipes and drip irrigation nozzles. In fact, wash water is responsible for many clogging failures of soil filters and subsurface flow wetlands. There are filters which can be fitted to washing machines to remove fibres. However, clogging may also occur due to other solids in the rinsing water such as solid insoluble grit from dirt and building materials.

What do we put into the water?

4.5 - 8

What is in soap, detergents, shampoos, solvents, disinfectants, paints, medicines, pharmaceuticals, etc ?

Soap contains alkali salts with long-chained fatty acids:

Hard soap usually contains sodium (Na) ☹️

Liquid soap usually contains potassium hydroxide (K) 😊

Detergents can contain (check list of contents on package)

- Phosphorous ☹️ in water and 😊 on soil
- which can be replaced by potassium ☹️ or 😊
- Salts: sodium ☹️ or ☹️
- Bleaches: chlorine ☹️ and peroxide ☹️
- Fluorescent whitening agents ☹️
- Non-degradable substances:
zeolites ☹️ or 😊 and fillers ☹️ or 😊

Courtesy of H. Jönsson, Swedish University of Agricultural Sciences, Sweden

The selection of consumer products in the shop and their use and misuse in the home decides what treatment is required for your wastewater. Wise choices will improve the sustainability of any sanitation system, be it in rural homes or inner-city flats.

The environmental impact of some common household products is indicated in the list above. A positive impact is represented by a smiling face. In the case of detergents the first face relates to the impact on surface water, while the second face relates to the impact on soil.

The long-chain fatty acids in soap can clean hands and clothes by breaking the bond between the surface of skin or cloth/fabrics and dirt particles and microbes. Particles are suspended in the wash water and become part of the wastewater. Hard soap is based on sodium that has a negative effect on vegetation. For instance, sodium can inhibit the transport of water and nutrients in some plants and it can cause hypertension in their cells. Potassium-based soaps, on the other hand, have the same bond-breaking capacity as sodium, but potassium itself is a plant nutrient.

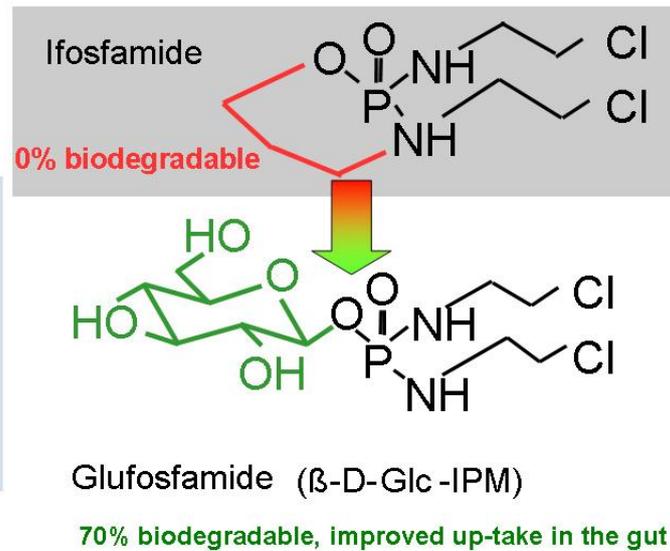
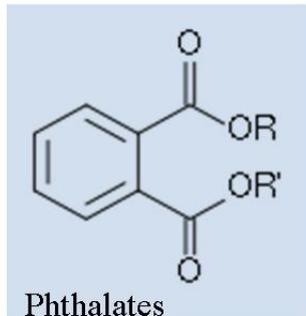
Recently, the European Union banned phosphorus in detergents because it contributes heavily to the eutrophication of water bodies. Instead, manufacturers now add zeolite in conjunction with other chemicals such as polycarboxylates which have the same positive washing effect as the phosphate compounds. Customers do not see the difference in washing results but surely do in eutrophication! Detergents contain not only phosphorus but other chemicals such as bleaches, corrosion inhibitors, fluorescent whitening agents, enzymes, anticoagulation agents, and bulking material. Some of these components are commented on in the picture.

At present, big detergent manufacturers are trying to reduce or abandon altogether the bulking material in detergents, since it contains harmful salts that have no washing effect. Their problem is to convince households that a smaller dosage (since no bulking material has been added) gives the same washing result.

We could easily reduce the use of harmful products, and totally abandon the ones with a red face!

Toxic organic compounds

4.5 - 9



Source: Kümmerer, 2007

As mentioned before, in our daily lives we use numerous organic substances in household chemicals, cosmetics, and pharmaceuticals and also as additives in clothes, mobile phones, computers and other products. Even the food that we eat and drink may contain synthetic chemicals. One example is artificial sweeteners. For example, sucralose is produced from sugar but the saccharose molecule has been chlorinated to become more stable against degradation. This substance has been detected in small quantities in discharges from wastewater treatment plants in countries where this has been investigated. In 2008, an estimated 8 tonnes of this substance was released into surface water in Sweden alone. So far there is NO scientific knowledge of whether this has any effects on ecosystems or human health.

Small quantities of pharmaceuticals such as *psycopharmaca*, hormones and antibiotics are excreted by humans, and end up in greywater. Many of them are fairly resistant to degradation, and are only partially removed in wastewater treatment units. They are some of the persistent and water soluble substances that are discharged to aquatic ecosystems. Some of these substances are known to have a negative impact, but for others we have very limited knowledge. The discharge of antibiotics to the environment may spur the development of resistant bacteria with long-term health impacts for human beings. It is also known that sex hormones such as testosterone and estradiol may have severe negative ecological impacts on processes such as fish reproduction. A source-control measure is to avoid flushing leftover medicines away in water, and return them to the pharmacy as hazardous waste.

Kümmerer (2007) provides an example of an unintended life-cycle improvement of a pharmaceutical product. The cytostatic agent Ifosfamide (top right) had undesirable side-effects. By modifying the chemical structure to Glufosfamid (bottom right) the side-effects were reduced by improving the uptake in the bowel. At the same time, the new medicine proved to be biodegradable to 70% while the previous one was persistent. It is difficult to modify pharmaceutical products since the environment in the human gut is different to the environment in which the product ends up when it is discharged via urine. The diversity and prevalence of bacteria and enzymes is different in the bowels and the outside-body environment for several reasons. The body temperature is high and stable in the body (thermophilic microorganisms), and there is an abundance of nutrients to feed on. The bowels provide essentially anaerobic conditions (mostly anaerobic microbes) and the pH is well below 7 in the stomach, while it is

above 7 in the wastewater. The resulting difference in redox conditions makes for different chemical reactions in the bowel and in the environment. Also, it is dark in the bowel while surface water and topsoil is affected by UV light. These aspects are discussed in Module 4.6.

Phthalates (left picture) belongs to a group of toxic organic substances that are added to plastic products to make them tender. They are commonly also found in roofing materials, flooring and wall coverings. This means that there is a stock of phthalates in buildings which is gradually released. It is not chemically bound to the plastic material and can easily be taken up by fats, oils and solvents used in the household. Phthalates are very toxic for aquatic organisms, but less so for human beings. Studies indicate that between 75 and 97 per cent are degraded in treatment plants or appear in the sludge. Thus, between 3 and 25 per cent remains in the effluent and is discharged to water bodies.

Often there are limits to the amounts of *phthalates* that are allowed in sludge to be used as fertiliser on farms, but no regulations apply to the discharges to water bodies! This is an example where legal approval does not only take human and animal health and nature into consideration as intended, but other aspects possibly claimed by strong lobbyists.

Metals in wastewater & excreta

4.5 - 10

		1.	2.	3.	4.	5.	6.
Element		Daily intake (mgr)	Output in faeces (mgr/kg P)	Found in sludge (mgr/kg P)	Quotient $\frac{3}{2}$	Output in urine (mgr/kg P)	Quotient $\frac{3}{5}$
Copper	Cu	1,400	1,000	14,000	14	68	206
Chromium	Cr	300	214	1,300	6	0.65	2,000
Nickel	Ni	120	88	720	8.3	16	78
Zinc	Zn	11,000	7,200	25,000	3.5	424	69
Lithium	Li	17	12				
Mercury	Hg	5	3,5	40	11	0.64	63
Lead	Pb	23	16	1,500	94	16	94
Cadmium	Cd	14	10	44	4	0.32	137

Courtesy of G. Lindgren, Sweden

Human beings eat and excrete heavy metals and other inorganic micro-elements. Some of these are essential for their metabolism and survival, but excessive doses are hazardous. Studies of the origin of metals in municipal wastewater show that more than half comes from households and, for example, cobalt (Co) and nickel (Ni) are found in residual sediments in treatment plants. Human exposure to heavy metals must thus be controlled. Since this sourcebook recommends the recirculation of nutrients in excreta we need to show that it is beneficial not to mix them with other wastewater before treatment. The table shows how much of various metals an average person ingests daily and how much of these are found in the faeces, urine, and municipal sludge (in micrograms per kg of phosphorus to make a comparison with P in commercial fertiliser possible).

Regulators first became aware of the presence of heavy metals in sludge around 1970 when atomic adsorption spectrophotometry first made sensitive heavy metal analysis possible ([Balmér, 2001](#)). Excreta contain only background levels of heavy metals originating from the eaten food (columns 2 and 5). The values are expressed here in mgr per kg of P (phosphorus) to make it easy to calculate the application of heavy metals to soils in accordance with required P level. A direct comparison with the concentration of heavy metals in wastewater sludge (column 4 and 6) shows that urine and faeces contain only small fractions compared to sludge. For example, the cadmium concentration in sludge is 137 times greater than in urine, and sludge needs to be reduced by more than 2 log units to attain the same quality as urine.

In most countries the permissible concentrations of heavy metals in wastewater sludge are regulated. Since data on environmental and health risks are not available, country-based limits vary considerably. In some countries, it seems that regulations are based on what is believed to be achievable. In other countries, regulations are based on risk analysis and in some countries the approach is that the concentrations of heavy metals in agricultural soils should not increase when wastewater sludge is used as a fertiliser (Balmér, 2001). Over time, set limit values have become more strict, which shows that previous limits were inadequate. Yet they were used to convince residents that it is safe to dispose of the sludge on farmland.

The accumulation of metals worries most authorities and the European Union has established a commission (ECHA) to oversee the production of chemicals and their use. In 2008, the commission established new regulations for industries and manufacturers, and this is viewed as a step towards enforcing source control of what goes into wastewater. The most toxic metals are

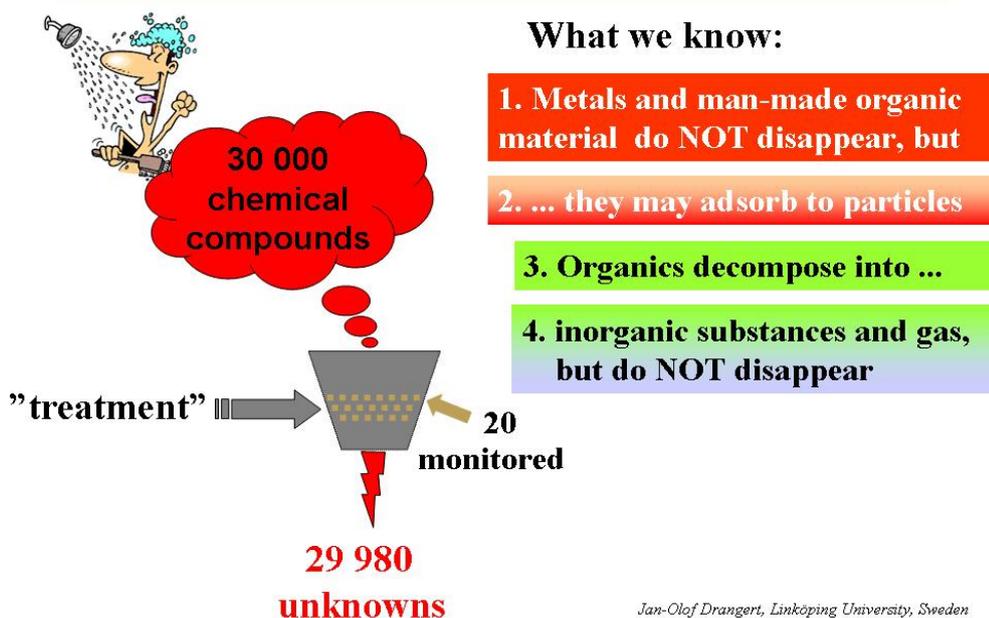
mercury (Hg), lead (Pb) and cadmium (Ca) but these are ingested in very small quantities. However, the products causing contamination have only been on the market for some decades, and increased consumption of such products may, as time passes, reach alarming levels.

Hamilton et al. (2005) classify potentially phytotoxic metals in wastewater into four groups based on their retention time in soils, translocation in plants, phytotoxicity and potential risk to the food chain. They place cadmium (Cd), cobalt (Co), Mo and Se in the group posing the greatest risk to human and animal health even though these elements may appear in wastewater irrigated crops at concentrations that are not generally phytotoxic.

Application of these metals on soils via wastewater irrigation is undesirable because, once accumulated, they are extremely difficult to remove. Qadir and Scott (2010) found that the time it takes for wastewater-irrigated soils (with cation exchange capacity CEC 5-15 cmol_c kg⁻¹) to reach today's loading limits in calcareous, alluvial soils from three locations in Pakistan varied. For Cd the time taken was between 13 and 67 years; for copper it was between 48 and 69 years; for nickel it was between 13 and 120 years, and for lead it was between 96 and 1676 years. The amounts of metals removed by crops are small (< 10 per cent of the added metal) compared with the amounts applied to the soils. If excreta were not mixed with greywater, farmers could apply urine and hygienised faecal matter as fertilizer without the risk of heavy metals accumulating in the soil!

Can we cope with the chemical society ?

4.5 - 11



Artificial chemical products have inundated the whole globe via international trade. Most households use medicines, detergents, shampoos, synthetic clothes, etc. which contain various chemicals. Today many households use some 30 000 different chemical compounds in a year, many every day and others occasionally. Some of these compounds are toxic, others are not degradable and will remain for a long time though their possible impacts are not known. This is very different from fifty years ago when most household products were biodegradable and few contained artificial chemicals.

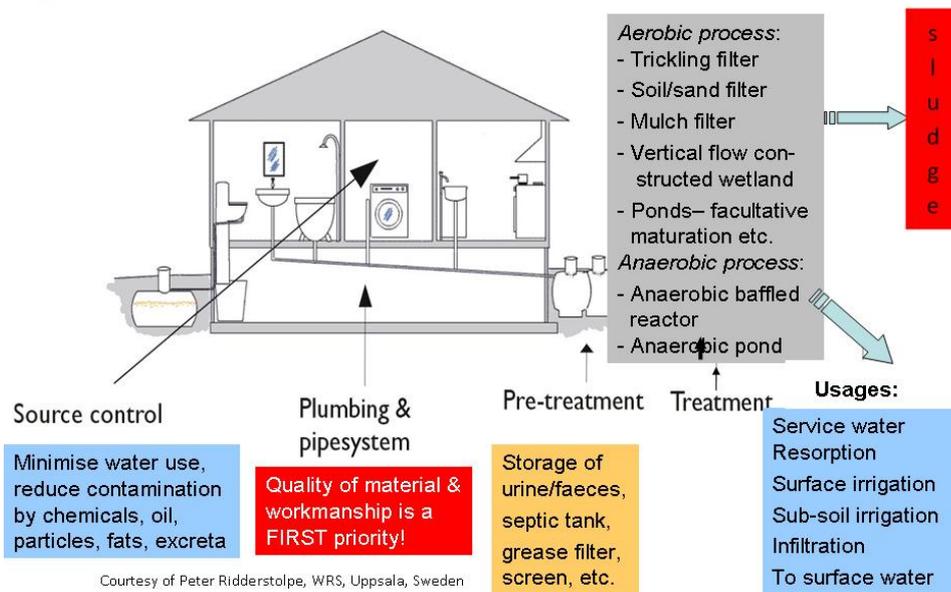
It is common knowledge that most organic chemicals can be decomposed but at very variable rates. They can adsorb to particles and become partly immobilised, thus prolonging the time of potential exposure. Some artificial organic compounds are also very persistent and do not disappear easily. During incineration, some organic compounds in waste may convert to very toxic gases. Other organic materials are rapidly decomposed by microbial activities and the resulting parts are used to build new cells and organisms. In the process, gases are produced e.g. CO₂ in a compost or methane in a biogas digester.

The result is that today's wastewater treatment units receive water mixed with difficult-to-degrade organic matter and inorganic chemicals that are difficult to "treat" i.e. to disentangle into non-hazardous recyclable compounds. Typically, the staff in treatment plants measure some indicators such as BOD and COD levels for organic matter, total phosphorus and nitrogen, and occasionally some specific chemical substances. This is to say that the focus (which is actually what most wastewater treatment plants have been designed for) is on organic matter and the nutrients that cause eutrophication, algal blooms and dead zones on lake bottoms. The other chemical residues are rarely measured and perhaps 29 980 substances are not accounted for. This is a mammoth challenge for our societies.

Our collective failure to address the challenges posed by the present chemical society is the starting point for this chapter on greywater management. The main remedy is to control the source of pollution i.e. by being careful with what we buy and use in the household.

A: Source control comes first

4.5 -12



This section deals with water flows through homes and communities. A home may contain a number of water installations, and the purpose of the above picture is to illustrate various installations and conventional measures to deal with flows through the home.

The better the quality of workmanship and materials of sanitation systems, the easier they are to manage. Some examples: a leaking pipe requires regular mopping, that could have been avoided. A rough floor surface makes cleaning more difficult. A urine pipe leaning backward will cause crystallization and eventually a blockage. An overburdened treatment unit will stop working properly. Therefore, proper design and installation are crucial for easy operation and maintenance (see Module 2.7).

Source control of what is added to the water while using it is essential for attaining ecological sustainability and residents become indispensable partners in managing the flows. The basic recommendations made in this section apply to ALL houses. Poor homes are more vulnerable to polluted surface and groundwater in their crowded areas, and they need to be protected against pollution. Rich districts may import virgin water from afar and dispose of it in sewers which make residents less aware of their polluting activities.

We buy and use washing agents, solvents, lotions, paints, antibiotics and other chemical products and mix them with water and discharge them in sinks, wash basins, toilets and drains. The discharged wastewater therefore contains everything we have put into the water while using it. Buying environmentally friendly products, and using less of them, will therefore enhance wastewater quality.

Pharmaceuticals and endocrine disruptors are a challenge for conventional wastewater treatment methods, since these chemicals pass through all treatment steps together with the effluent. Since these chemicals remain in the water, they can have severe impacts on aquatic animals. The story of fishes changing their sex is a telling one. Research indicates that applying such effluent water on soils is less harmful than discharging in into waterways since soil microorganisms will in due time decompose most of these compounds. In this connection it may be said that the dung from cows, which are given antibiotics everyday to stay healthy (*sic*), is applied to farmland with no restriction! This is an example of an unresolved conflict between health and other considerations.

Households can contribute – NOW!

4.5 - 13

Use as little water as possible by mimicking the use of water in buckets (do not wash under running tap, take quick showers, mend leaking taps, put full loads in washing machines,)

Do NOT add solid matter to water (put food scraps from plates and utensils in the waste bin, do not flush tooth picks etc. down the toilet, do not put cigarette butts in urinal,)

Do NOT add chemicals and oils to the water while using it (put fat from frying pan in the solid waste bin, use biodegradable soap and detergent, do not flush paint, medicines or other chemicals down the toilet,)

Buy and use environmentally friendly products for your home

Then you can use greywater in your garden, and you avoid blockages

Jan-Olof Drangert, Linköping university, Sweden

There is no excuse for waiting – each one of us can contribute to a safer and more sustainable environment by modifying our routines in the kitchen and bathroom – and when shopping. If we all do so, the global pollution load can be substantially reduced (see 2.4-2).

If we follow the above recommendations our greywater will have a much improved quality. Sewer pipes will not clog as easily and the smell from the water will be reduced. There will be less clogging of sand filters and other filters from oil, fat and food scraps. Filters will not need not to be cleaned or backwashed so often, and the amount of sludge will be less.

Water-saving installations will reduce the amount of discharged greywater and, at the same time increase the concentration of pollutants. This is no problem but rather an advantage from a treatment point of view. Water demand management has been quite successful in reducing the demand for water. Measures include progressive and high water tariffs, low-flush toilets, waterless urinals, dry toilets, etc. (see Module 2.1).

It is best to use toilet tissue that is made from wood or recycled paper. Turning a tree to paper requires more water than turning paper back into fibre. One eucalyptus tree can produce as many as 1,000 rolls of toilet paper and one person may use 20 rolls per year, or one tree per lifetime! Chlorine-based bleaches are used for whitening toilet paper, but so is peroxide which is environmentally friendly and good for the soil. Ask for this next time you buy toilet paper.

If a household uses only biodegradable products for washing, its greywater can be used to water the garden without causing the accumulation of heavy metals, salts and other pollutants. From a society viewpoint, there is a need to develop strategies to support and promote sustainable household routines. Also, authorities can support users by regulating the compounds that manufacturers are allowed to put in household products to be sold in shops. The European Union REACH programme is working towards this end and monitors the introduction of chemical compounds in products sold in shops, so that consumers do not have to be experts in selecting environmentally friendly products (http://echa.europa.eu/news/press_en.asp). The responsibility for the quality of the greywater lies with all parties in our society including the manufacturing industry.

Households can invest: install proper devices in your kitchen and bathroom

4.5 - 14

When you build or retrofit your home:

- *Buy water- and energy-saving devices* e.g. water-efficient shower heads, taps, washing machines and low-flush toilets
- *Install a dry or low-flush urine-diverting toilet* to recover nutrients and to save water
- *Avoid leaking taps and keep a record of the amount of water used* every now and then to monitor your usage

Example: A new suburb in Stockholm, Sweden with proper saving devices achieved (www.stockholmwater.se):

- a 40 % reduction in water use
- a 25% reduction in hot water use (= energy saving)
- a 50% reduction in eutrophying substances to the lake

Jan-Olof Drangert, Linköping university, Sweden

The previous picture suggested changes in household *routines* that we adopt to sustain nature. There are also many installations that contribute to improved sustainability without changes to routines. Worldwide in the next 50 years, we will need to double the number of urban buildings! If we build and equip these houses with sustainable installations, they will require less resources than the present stock of houses. The cost is not higher for such buildings, and they need no retrofit after some years because we did think ahead! Here are a few examples:

Flush toilets: About 1/3 of the total household water is used to flush the toilet. A conventional WC uses 6–9 litres per flush. You can save a few litres per flush by placing a brick or two into the water cistern. So-called low-flush toilets only use some four litres per flush which cannot be reduced further without compromising the ability to flush away all excreta and paper. With less than three litres you may have to flush twice! A dual-flush toilet uses only 0.5 litres of water to flush away urine while a waterless urinal uses none at all, and it does not smell and allows for easy use of the nutrients in the urine.

Dry toilets: A composting waterless toilet is easy to install when retrofitting. No flush water means no excreta in the wastewater. The dry toilet system does a better treatment job than septic tanks can do with black water, and it is often enough to treat the greywater in a sandfilter to reduce its solids.

Washing machines: A normal washing machine requires 50 or more litres of water per wash, irrespective of the amount of clothes. If you only fill a 4 kg machine with 2 kg of clothes, you waste 25 litres of water. New machines adjust the amount of water to the weight of the clothes. Of late, washing machines without water are being developed in Japan!

Shower heads and water taps: You can reduce the amount of water per minute by half, without losing the feeling that the shower gushes enough, if you install a mesh in the shower head. Electronic faucets only use one-quarter of what an ordinary tap uses for the same purpose.

Leakages: If water drops every second from your tap it adds up to 15 litres per day, and if the drops come one after the other the wastage is 60 litres per day. With a water price of US\$1 per m³, you lose more than US\$20 per year and you can buy a new tap every year if you replace the leaking one.

"Benign by design" - manufacturers need not make products with problematic content

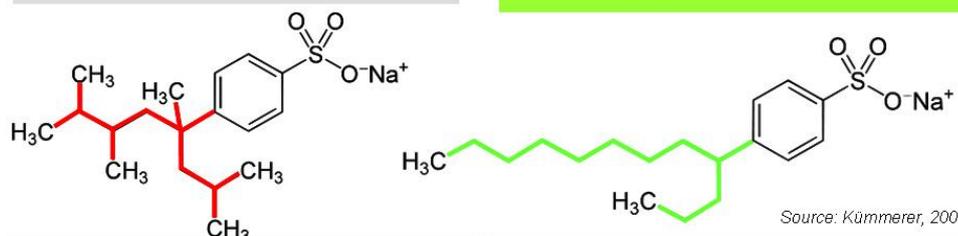
4.5 - 15

Classical view on functionality of chemical products:

- + stable (persistent)
- + effective
- + efficient
- + affordable

New view:

- + complete and fast degradation
- + no risk of harmful effects
- + effective
- + efficient
- + affordable



TPS non-biodegradable for washing powder

LAS readily biodegradable replacement of TPS

The last half-century can be characterised as the period in which the chemical society emerged. Almost all products in the shops today were not available fifty years ago. Scientific and technical development in combination with international trade is the basis for the saturation of every corner of the world with consumer products that challenge sustainable sanitation. Manufacturers therefore play a central role in facilitating the task of treating greywater and wastewater through improved chemical design (picture).

In some cases manufacturers have changed their products more or less voluntarily. A good example was when manufacturers of toilet paper replaced chlorine with peroxide to bleach the paper. The biodegradable peroxide results in equally white paper and has no harmful side-effects, whereas chlorinated paper enters wastewater and harms water bodies and living organisms.

On other occasions manufacturers refuse to swap hazardous compounds for biodegradable ones for commercial or other reasons. A continuous negotiation is going on between companies and government authorities on what should be allowed. Since it is costly and difficult to assess health and environmental impacts of chemical compounds, there is a serious lack of solid information to build decisions on. Despite such problems, the EU Parliament adopted a policy in 2002 aiming for "... within a generation chemicals should be produced and applied that do not have any impact on the environment." ([EU Parliament, 2002](#)).

Chemicals become problematic because some are persistent, and may accumulate in biological tissue and also be toxic. These risks are difficult to assess due to the long time-scale and large geographical areas involved which often makes evidence from lab trials inadequate. The EU REACH programme found that of 3000 tested chemicals, 30% are readily biodegradable and so are 27% of pharmaceuticals. The vast majority are more or less persistent. This was not a problem earlier when an important functionality criterion was that the compound should be stable. The new criterion is that products should be composed of chemicals that degrade rapidly and cause no harm to humans or the environment. This criterion can be fulfilled by clever chemical design.

New washing powders were introduced in the late 1950s, containing the persistent compound tetra-propylene sulfonate (TPS). It caused lots of foam and the manufacturers had to design a more substitute. They chose LAS (linear alkylbenzenesulfonates), derived from naturally occurring lipids (bottom picture). Despite LAS being more toxic to aquatic organisms than TPS, it conquered the market due to its rapid biodegradability in the WWTP ([Kümmerer, 2007](#)). Recently, LAS molecules have been found in sludge in concentrations of 100–2000 mg/kg dry matter. There is room for further chemical design engineering to improve washing powders (Yu et al., 2008).

In case insufficient evidence is available to assess whether a compound is harmful or not, the precautionary principle (2.3-5) should apply. This means that a product cannot be introduced until more supporting data are available. However, this principle is likely to be under stress from strong economic interests prepared to introduce a product containing untested compounds.

One straightforward example is the introduction of diapers that small children could manage themselves. Procter and Gamble initiated a big promotion campaign in Sweden in 2008. Shortly afterwards, some WWTPs faced problems with thin plastic that choked moving parts in the treatment processes. They identified the plastic and traced its origin to the diapers. The company claimed that it was biodegradable within twelve hours, but tests by the Stockholm water utility showed much longer degradation times. They contacted the manufacturer which responded that their product could not possibly cause this problem. As the use of diapers spread, more WWTPs faced similar problems. Utility managers called a meeting with the company and threatened to go public if they did not change the product or withdraw it from the market. The company must have rated the potential loss of credibility as high, since they decided to withdraw the product and end the costly promotion campaign.

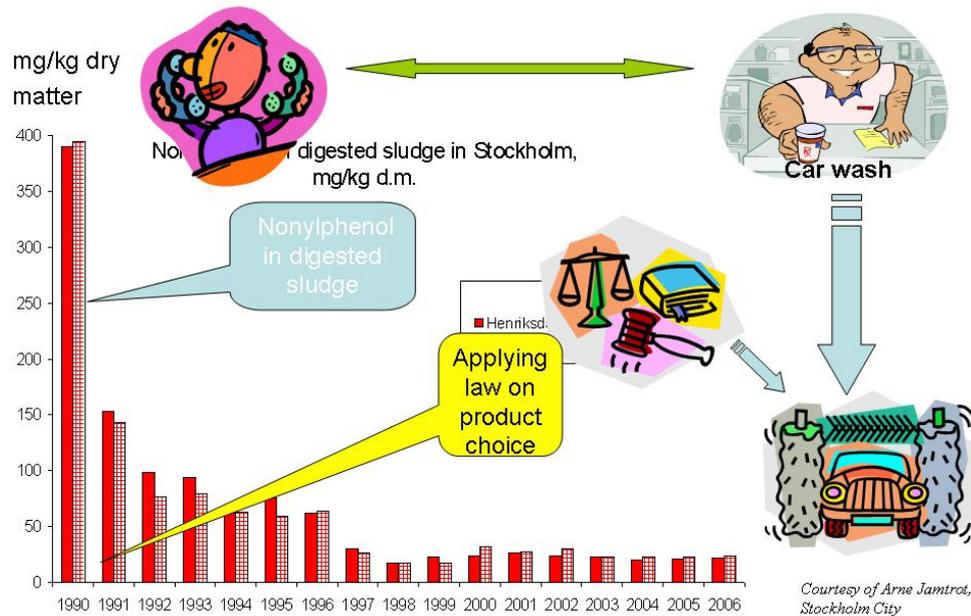
Another example is the use of sludge in agricultural production. One study ([VMK, 2009](#)) examined almost a thousand chemical compounds and found that octylphenol, nonylphenol and LAS were the only contaminants for which the PEC (Predicted Environmental Concentration in the water environment based on calculations or sample readings) exceeded the PNEC (Predicted no effect concentration). A PEC/PNEC ratio higher than one means a high risk of a biological impact on the aquatic environment. However, the authors argued that these compounds degrade rapidly ($t_{1/2}$ in soil = 8–10 days) and the highest concentrations were found immediately after the application of sewage sludge followed by a rapid decrease. The report found octylphenol, nonylphenol and LAS ‘to be of low concern’ when taking into account the uncertainties related to the occurrence levels, and the rapid degradation in the soil. The precautionary principle was not applied; rather, the authors struggled to get around it.

The study also argued that only a few PAHs and PCBs were expected to accumulate with repeated applications of sewage sludge (every 10th year) on fields in a 100-year period and still their model indicates that the concentrations of these substances will be well below the PNEC-value even at the end of the 100-year period.

The pressure to return contaminated sewage sludge to farmland is massive because the sludge volumes are huge and alternatives few. The only safe method to access the valuable nutrients P, K and N in the sludge is perhaps to apply a source control system on what goes into the wastewater.

Supervision: nonylphenol in car care products

4.5 - 16



With the active participation of various stakeholders, a wide range of improvements can be made to source control. Two previous sections (4.5-12 and 4.5-13) illustrate how individuals can contribute in the short term as well as with long-term investments in sustainable houses. Manufacturers carry a major responsibility because they choose what products enter the market. With some 30,000 compounds on the market, there is no silver bullet that will solve contamination problems, unless we want to return to the lifestyle of a few centuries ago. The task comprises a myriad of small contributions which together will make a difference globally.

The City of Stockholm has several activities to reduce toxic materials in consumer products:

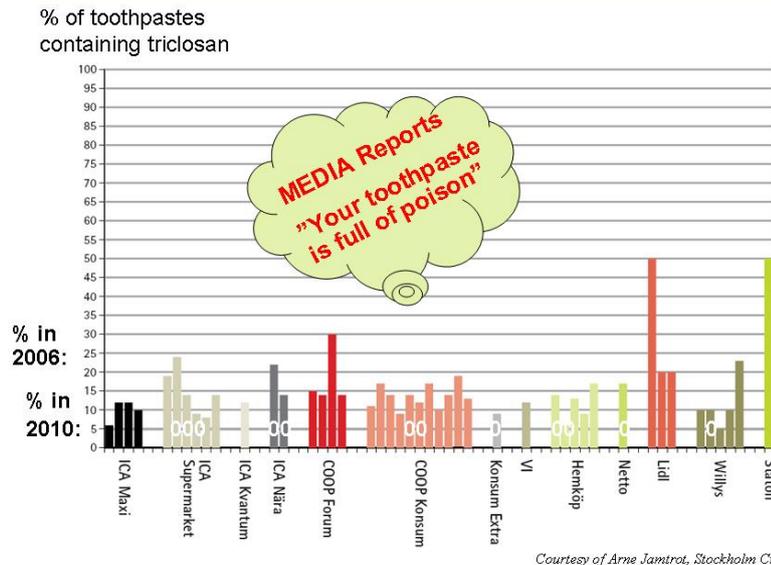
1. professional staff supervise various activities according to the environmental legislation
2. influencing the choice of construction materials
3. providing information about the content of products
4. having a green public procurement policy
5. engaging in dialogue with trade and customer organisations

The selection of substances is based on risk, prevalence and emissions, knowledge about sources, and prospect of effective actions ([Bergbäck and Jonsson, 2008](#)). The picture above shows an example of car wash facilities in Stockholm that used a common detergent containing the toxic compound nonylphenol which is harmful to the environment (4.5-14). The chemical was discharged into wastewater which went to a WWTP but they could not deal with it. Had the carwash facility not been connected to a sewer the nonylphenol may have damaged living organisms in a nearby stream or creek. Nonylphenol-free detergents were introduced on the market and the city's Environmental and Health Administration launched a campaign in 1990 to inform all car wash facilities in the city that they were obliged by the product-selection act to switch to nonylphenol-free detergents. The owners gradually substituted to these the new alternative products and the diagram above shows decreasing amounts of nonylphenol in sludge. The concentration dropped from about 400 mg/kg dry sludge to 30 mg/kg over a ten-year period.

It is likely that the manufacturers of detergents containing nonylphenol have adjusted the chemical formula in order to stay in the market. The city took this precautionary step despite the then ongoing discussion about how toxic nonylphenol is (previous picture).

Media attention: Triclosan in toothpaste

4.5 - 17



Toxic organic substances are rather common in household products. For instance, the bactericide triclosan is a common ingredient in toothpastes, deodorants and sports garments. Triclosan is classified as highly toxic to water-living organisms and can cause long-term harm in water environments. Triclosan is not acutely toxic for mammals, but *in vitro* studies on rats and humans indicate that it can disturb biological systems by affecting metabolism and the hormone balance. There has been no health risk assessment of long-term exposure of humans (Bergbäck & Jonsson, 2008). Incineration of sludge can create, unintentionally, chlorinated dioxins from the removed triclosan. So, if not caught as sludge it will be toxic to fish, and if caught the resulting dioxin will be toxic to humans.

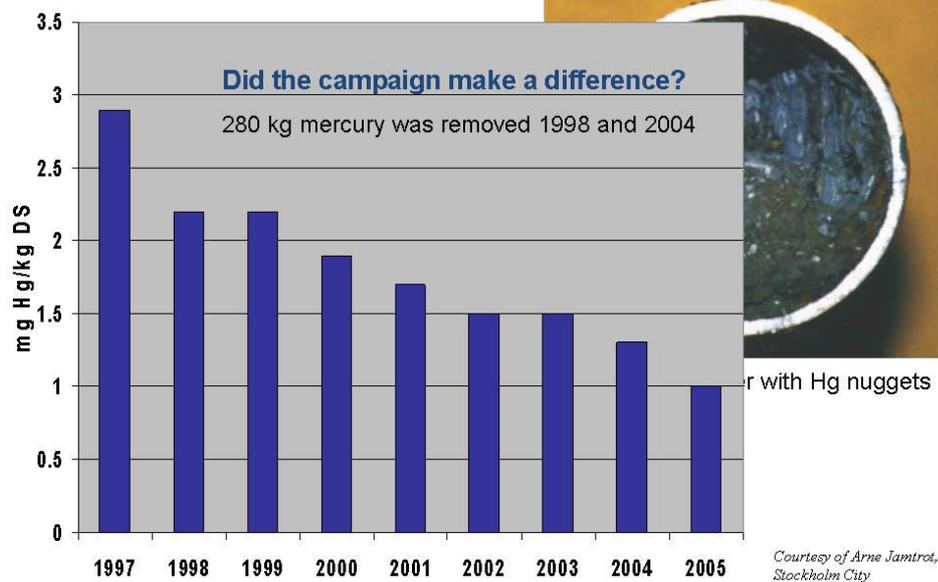
The City of Stockholm wanted to remove triclosan from the market because it was found in the treated wastewater (330 ng/l) and in fish (0.56 µg/kg fat weight). The first step to solving the problem was to identify the sources of triclosan. A survey showed that a total of about 4 tonnes of triclosan was used annually in Sweden, half of which was in toothpastes since it kills bacteria.

In 2006, an NGO, the Swedish Nature Protection Association, surveyed forty-five retail outlets from supermarkets to small shops to find the proportion of toothpaste brands that contained triclosan (diagram above). Newspapers and TV reported several times about the environmental problems with triclosan. The “dialogue” with manufacturers did not help and they refused to change this component in the toothpaste with the argument that current labelling on triclosan toothpaste informs the consumer that a dentist should be consulted before use! The Swedish Dental Association has not found any odontological justification for the widespread use of triclosan in toothpaste. A survey in 2010 by the city’s Environmental and Health department found that, major retailers had withdrawn triclosan-containing brands from their shelves as indicated by an “0” in the diagram. This is rated as a success story for reducing triclosan.

For other toxic components in consumer products the City of Stockholm applies a Green Procurement Policy when they sign large contracts for school and office products. Suppliers who cannot, or do not wish to, comply are not considered. Since the city purchases goods and services worth billions of dollars every year the policy has an effect on what the market supplies. At the same time it is a challenge for the city council to identify products which contain a certain harmful toxic compound. In this, the central government agency for chemicals and the environmental protection agency have important roles to play.

Subsidies: Hg in sewers at dental clinics

4.5 - 18



For generations, mercury has been known for its toxicity. Today, mercury has a very restricted use and the leakage of mercury to the environment essentially comes from forest soils and old sediments. In 1988 the city council of Stockholm decided to launch a campaign to reduce the sources of mercury pollution. The first step was to locate the known sites for leaking Hg – dentist clinics and hospitals, since mercury has for a long time been used for filling teeth.

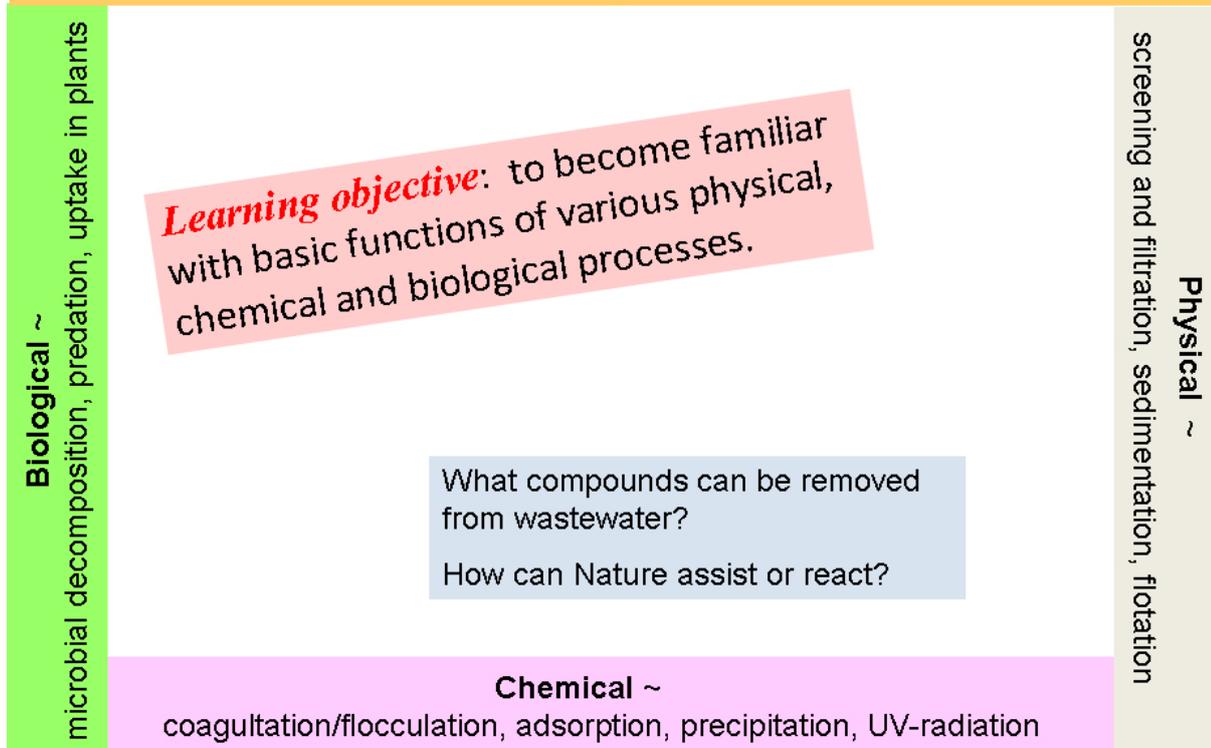
Investigations were launched to locate u-bends in sewers (right picture) which are likely to trap and contain Hg due to its high density. Owners, landlords, enterprises and institutions were contacted and offered a 60% subsidy towards the cost of removing the Hg-containing sediments in the pipes. The response was good and the government contributed € 1.3 million to the campaign and the property owners contributed almost as much.

Altogether 280 kg of mercury was removed from sewers in this campaign. The monitoring program at the wastewater treatment plant recorded a gradual decrease in Hg concentrations in its dry sludge (graph). The concentration of Hg in dry sludge went down from 3 mg per kg to 1 mg per kg during the eight-year project period and this is a permanent improvement since the source has been removed. Today all dentist clinics are equipped with traps for Hg to prevent further releases.

References:

- Balmér, P. 2001. Possibilities to improve the quality of wastewater sludges. *Water Science and Technology*. Vol 44 No 10, pp 19-26. IWA Publishing.
- Barrett MH, Hiscock KM, Pedley S, Lerner DN, Tellam JH, French MJ (1999) Marker species for identifying urban groundwater recharge sources—a review and case study in Nottingham, UK. *Water Res* 33(14):3083–3097
- Bergbäck, B. and A. Jonsson (eds.), 2008. Stockholm – Towards a non-toxic environment. Stockholm City Environmental dept and Stockholm Water Company. At: http://www.stockholm.se/Global/Stads%c3%b6vergripande%20%c3%a4mnen/Klimat%20%26%20Milj%c3%b6/Kemikalier%20och%20miljogifter/Nya%20gifter%20-%20nya%20verktyg/0906_towards_nontoxic_environment.pdf
- BGS 2001. Guidelines for assessing the risk to groundwater from on-site sanitation. British Geological Survey. Commissioned Rep CR/01/142:97.
- California Energy Commission, 2004. In Steinfeld, C. and Del Proto, D. 2008. Reusing the resource: Adventures in ecological wastewater recycling. Ecowaters Books. USA.
- Cronin A.A, Taylor, RG, Powell KL, Barrett MH, Trowsdale SA, Lerner DN 2003. Temporal variations in the depth-specific hydrochemistry and sewage-related microbiology of an urban sandstone aquifer – Nottingham, UK. *Hydrogeol. J* 11(2):205-216.
- Drangert, J-O. and A. Cronin. 2004. Use and abuse of the urban groundwater resource: implications for a new management strategy. *Hydrogeology Journal*, 12:94-102.
- Hamilton, A.J., Boland, A.M, Stevens, D., Kelly, J., Radcliffe, J., Ziehl, A., Dillon, P.J. and Pailon, R. 2005. Position of the Australian horticultural industry with respect to the use of reclaimed water. *Agricultural Water Management*, vol 71, pp. 181-209.
- Jönsson, H., Richert Stintzing, A., Vinnerås, B., and Salomon, E., (2004). Guidelines on use of urine and faeces in crop production. Report 2004-2, Ecosanres, Stockholm Environment Institute. Stockholm, Sweden. Available at: www.ecosanres.org.
- Kümmerer, K. 2007. Sustainable from the very beginning: rational design of molecules by life-cycle engineering as an important approach for green pharmacy and green chemistry. *Green Chem.*, 2007, 9, 899-907.
- Powell KL, Taylor RG, Cronin AA, Barrett MH, Pedley S, Sellwood J, Trowsdale S, Lerner DN 2003. Microbial contamination of two urban sandstone aquifers in the UK. *Water Res* 37(2):339–352
- Qadir, M., and Scott, C.A. 2010. Non-pathogenic trade-offs of wastewater irrigation. In Drechsel, P. et al. (eds). *Wastewater irrigation and health. Assessing and mitigating risk in low-income countries*. Earthscan. London.
- Taylor, R.G., Barrett, M.H., Baines, O.P., Trowsdale, S.A., Lerner, D.N., and Thornton, S.F. 2000. Depth variations in aquifer hydrochemistry using a low-cost multilevel piezometer. In Sililo, O. et al. (eds.) *Groundwater : past achievements and future challenges*. AA Balkema, Rotterdam, pp561-654
- VMK 2009. Risk assessment of contaminants in sewage sludge applied on Norwegian soils. Norwegian Scientific Committee for Food Safety. 2009.
- Yang, Y., Lerner, D., Barrett, M. and Tellam, J. 1999. Quantification of groundwater recharge in the city of Nottingham, UK. *Environmental Geology* 38(3): 183-198.
- Yu, Y., Zhao, J., and A.E., Bayly. 2008. Development of surfactants and builders in detergent formulation. *Chinese Journal of Chemical Engineering*. 16(4) 517-527.
- WHO (2006) *Guidelines for the safe use of wastewater, excreta and greywater*. Volume IV. Excreta and greywater use in agriculture. Geneva, 2006. http://www.who.int/water_sanitation_health/wastewater/gsuww/en/index.html

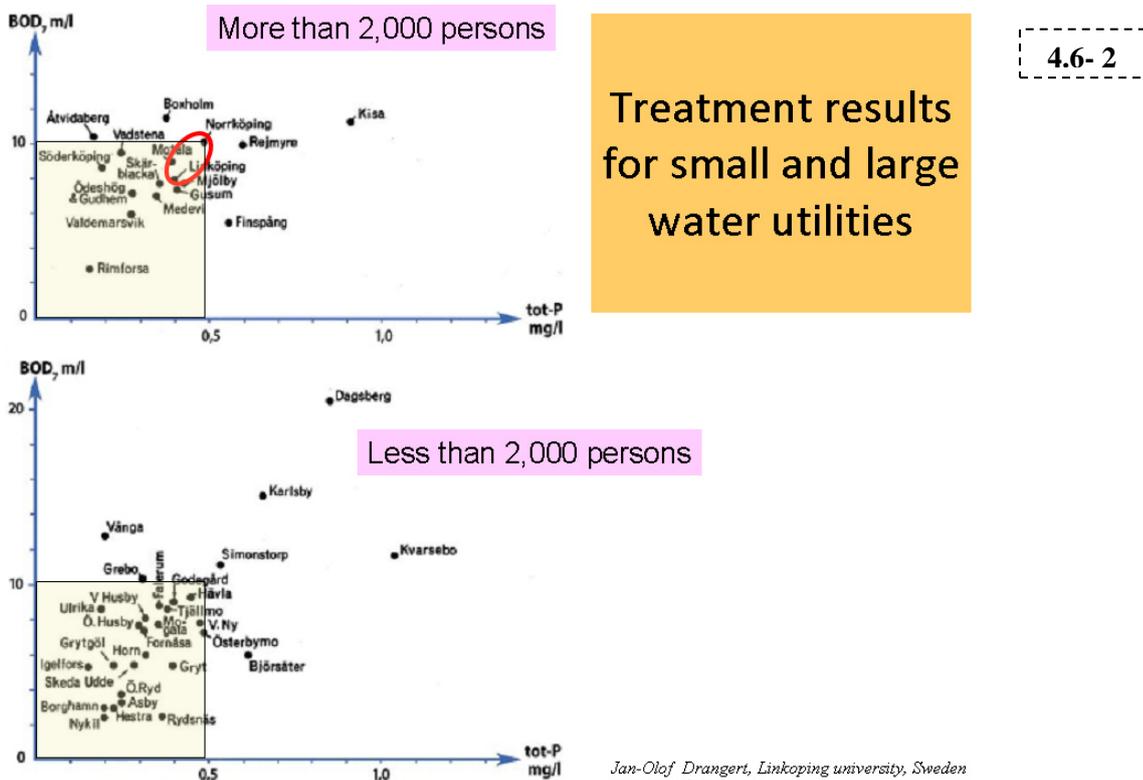
4.6 Physical, biological and chemical treatment processes



A focus in this sourcebook is on managing greywater from households. In Module 4.5 the focus is on reducing wastewater volumes and the concentration of unwanted components through source control measures. In this module the focus is on potential processes to reduce the amounts of undesirable ingredients in the wastewater that reaches the final water body or soil. We describe each basic physical, chemical and biological process and why they can reduce undesirable components in wastewater and sludge. The aim is to deliver an effluent and sludge of a quality that does not endanger the receiving environment.

In the following Module 4.7 we combine different basic processes to treat a large spectrum of pollutants. Examples of treatment technologies and management systems are discussed.

The objective is to provide information on the treatment of greywater and wastewater from individual households as well as from smaller communities and towns. The basic processes are the same in both situations but the sophistication of the application may differ, and so may the combinations of processes. The good news is that small systems can be as effective or more effective than large-scale ones when it comes to effluent and sludge quality. We begin this module with an illustrative example.



A powerful standard argument in favour of centralised networks is that a large-scale utility will use the latest technology, have better trained staff to operate and maintain the system, and can provide cheaper services for its customers. Research and development of wastewater treatment has focussed on large units, and household options such as septic tanks attract almost no R&D. Yet, there is evidence that the large units cannot provide better effluent quality than small systems.

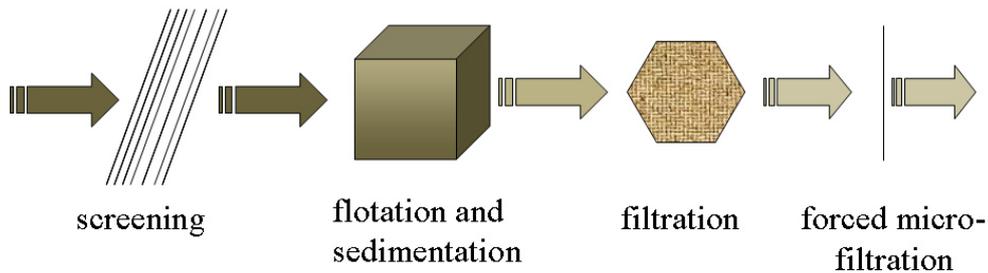
In 1987 a county board compared treatment results for small and large wastewater treatment units in Sweden ([Drangert and Löwgren, 2005](#)). Two important indicators of effluent quality were selected. BOD (measure of organic content) and total phosphorus (TP) levels were measured and the findings are presented in the above graphs for communities with more than 2,000 persons and for those with less than 2,000 person equivalents (picture). The only two cities in the study, Linköping and Norrköping, each had BOD levels in their effluent of 10 mg/l, and total P levels of 0.4 and 0.5 mg/l respectively (red oval). Only three small communities in the county had higher values, while ten had clearly better results than the cities (inside the coloured rectangle).

The communities with less than 2,000 inhabitants also exhibit better treatment results than the two cities with three exceptions (far outside the rectangle). The good performance of small and middle-sized communities is not because all industries are located in the two cities. That could have been the case for other compounds but not for BOD concentrations and amounts of P. The conclusion is that bigger treatment plants do not guarantee better treatment results. Since then, more research has gone into small treatment units down to the household level and today, treatment quality is not an argument in favour of centralised solutions.

In the future, when households are acknowledged partners in managing the waste flows, it will still be easier for residents to make meaningful contributions in a small system than in a large one. This contribution is likely to have a crucial bearing on reuse management.

B: Physical processes

4.6- 3



Possible combinations of physical processes

Jan-Olof Drangert, Linköping university, Sweden

Physical treatment processes use particle size or relative density to sort out certain components from the wastewater. A treatment unit may contain all the physical processes shown in the picture above, or only a few of them. The sequencing of processes may vary, but the one above is common. Debris and larger items are trapped in a screen. However, small particles and suspended material such as non-biodegradable fibres from clothing, powdered detergents, soaps and grease go through the screen and may be trapped by sedimentation, flotation, or media filtration and manufactured-membrane filtration. Physical processes reduce the amounts microorganisms and chemical compounds to varying degrees. The trapped material always has to be removed regularly in order for the physical treatment process to function at full capacity.

Generally, it is easier and less expensive to sort items at the source and not discharge them in the wastewater. This is obvious for a household arrangement or a small group of households with a joint system. The household members can easily wipe food remains and fat from plates and cooking utensils, and they know that the more they allow into the water, the messier the job of emptying their grease trap will be. However, in a city sewerage the householder does not see the connection, and they do not know that cleaning grease crusts from pipes is one of the tasks they pay for through their water bills.

Screening of debris and other solid items

4.6- 4



Solids trapped by a screen in a city wastewater treatment plant



Organics from kitchen pipe sorted out in a plastic screen

Jan-Olof Drangert, Linköping university, Sweden

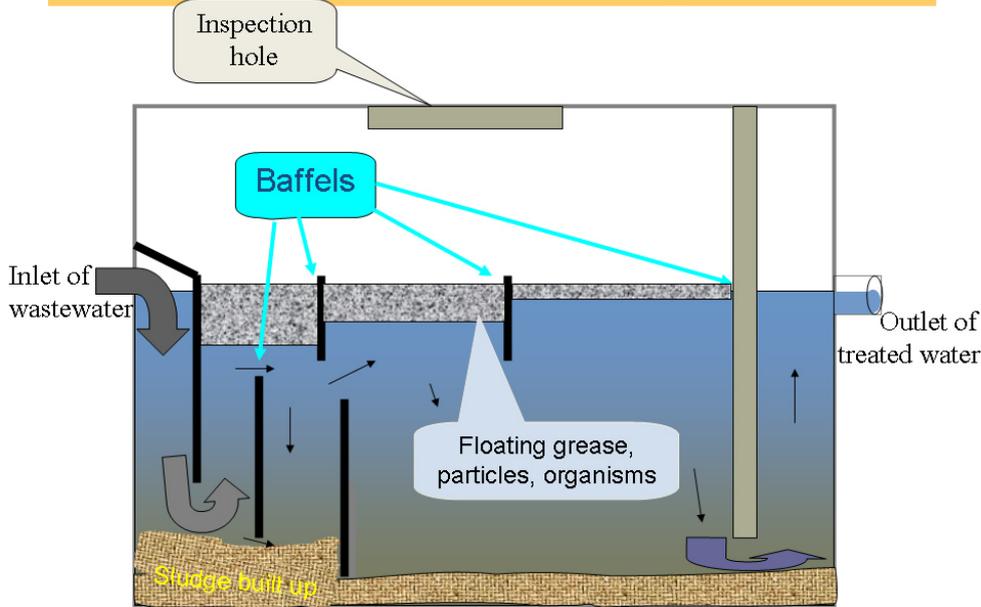
Debris and large particles are removed from the wastewater through screening. The finer the screen is, the smaller the items are that can be trapped. The main purpose is to avoid clogging in subsequent treatment stages, e.g. sand filters. A screen is not intended to remove pathogenic microorganisms or dissolved matter in wastewater. The size of the screen unit takes into account the requirements of subsequent treatment steps, the content of influent water, the available space, and the rate of water flow. If the screen is very fine and the wastewater contains a lot of debris, only a moderate water flow can be managed. To treat a high flow with a fine screen, the unit itself needs to be bigger than if a coarser screen is used. The trapped material has to be removed regularly to prevent blockages of the screen.

The left-hand picture shows debris and other solid items trapped by a screen in a wastewater treatment plant. This waste is taken away for incineration or disposal by other means. At one wastewater treatment plant in Stockholm serving half a million residents, 35 tons of such solids are trapped in the screen each week; everything from paper, plastic bottles to carpets and dead cats. In towns where stormwater also enters the WWTP, the amount of debris is significantly larger (see Section 1.1- 4).

Typically, the kitchen sink, washbasins, and outlets from showers are fitted with a grate to catch objects and particles which are collected and thrown in the solid waste bin. The right-hand picture shows solids in kitchen wastewater being trapped in a plastic screen before it enters a simple grease trap. At the household level a screen removes, for instance, left-over food, potato peels, and paper coming through the kitchen sink, or hair, nails and tooth picks from the shower which may clog subsequent treatment screens.

Flotation and sedimentation processes

4.6- 5



Jan-Olof Drangert, Linköping university, Sweden

Sedimentation and flotation are cheap methods for removing particles and suspended material which has managed to pass through the screen, and they will facilitate subsequent filtration and/or biological and chemical processes. Sedimentation works on the principle of specific weight that causes heavier material to sink to the bottom. The process can be enhanced by intentional flocculation (see 4.6-11) of solid matter into larger and heavier particles. Flotation works both on the principle of lighter material floating to the surface of the water body and suspended material interacting with highly dispersed air bubbles that can lift the material to the surface. Baffles can be used to force the flowing wastewater to deposit heavy material at the bottom, and the upward flow helps the light material to reach the surface (picture). Flotation may also be enhanced by aeration of the tank from the bottom.

Simple **flotation** occurs in a so-called grease trap where, for example, fat, oil and grease (FOG) cool down and form a light solid agglomerate that floats up to the water surface. Grease traps are placed under kitchen sinks, or any other drain that collects grease, fat and oil. Removal of FOG enhances the visual appearance of the wastewater and, more importantly, facilitates subsequent treatment steps and reuse. The same benefits apply to FOG from restaurants, hospitals, hotels, convention centers, sports arenas and prisons where huge amounts of FOG is generated each year. If allowed to enter wastewater pipes, this material readily adheres to the inner surface of the piping material. Such layers harden into a crust as tough as baked clay, becoming a primary cause of clogs, backups, overflows and equipment failure, ultimately requiring replacement of the affected pipes. The U.S. Environmental Protection Agency estimates that there are over 40,000 sanitary sewer overflows each year in the USA, the majority caused by grease buildup. Maintaining sewers is expensive and costs more than US\$25 billion per year in the US – a situation often exacerbated by attendant cleanup fines levied by the EPA or the authority that has jurisdiction (Building Safety Journal, 2008).

The optimal size of the suspended particles that float to the surface is 10^{-5} to 10^{-3} m. The scum layer may form a crust so hard that the process in the chamber becomes anaerobic. Thus, the scum or crust should be removed regularly. The removed material can be used in biogas production and also as compost material. The objective, however, is not the generation of energy or compost but to improve the efficiency of further treatment steps by reducing clogging.

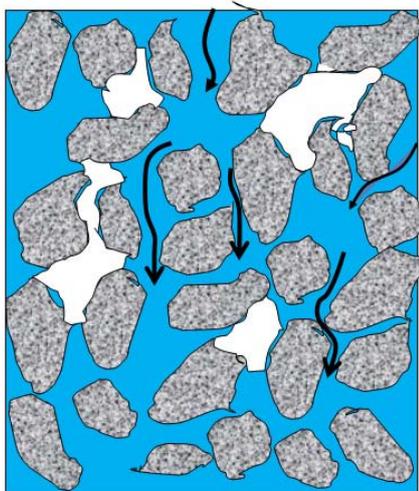
Sedimentation takes some time to occur and becomes quicker if the wastewater moves slowly. Almost all the settleable solids in the wastewater sink to the bottom within 2–6 hours. However, bacteria, viruses and metals are only removed if they are adsorbed to or trapped within a matrix of settleable solids.

If the organic content in the wastewater is low, an open pond can be used, where mainly aerobic microorganisms will decompose some of the organic matter. If the wastewater contains a lot of organic material, the aerobic bacteria will use up all available oxygen in the water, and anaerobic bacteria will continue the decomposition in the pond and sediment, causing potential smell problems. Therefore, the sedimentation unit is often covered, as in the case of the common septic tank for sedimentation of wastewater content from single households. In any system, the accumulated sludge has to be removed regularly, otherwise the treatment efficiency will decrease.

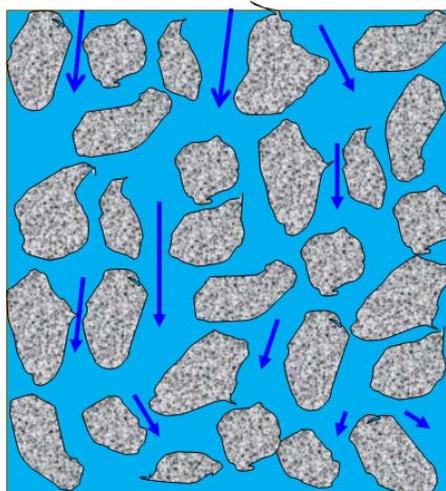
After desludging a sedimentation unit, the sludge can be immediately incorporated into agricultural fields, or stabilised in different ways – e.g. anaerobic fermentation or liming – to reduce the nuisance of smell before putting it on soil. A prerequisite for reuse is that the levels of contaminants in the sludge are acceptable, and this can be achieved through proper source control, as discussed in Module 4.5.

Filtration – mainly by gravity

4.6- 6



Partially unsaturated flow



Saturated flow of wastewater

Jan-Olof Drangert, Linköping university, Sweden

A wastewater flow through porous natural material such as sand, peat, and plant fibres, or manufactured microfilters is called filtration. This involves the deposition of suspended matter from the wastewater on the surface of granulated filling (film filtration), or the deposition of suspended matter in the pores of the filtration media, or a combination of the two. Filtration differs from screening in that it also includes physico-chemical and biological processes. Pollutants may be retained by sieving, adsorption (see 4.6–8), straining, interception and sedimentation (see 4.6–5). Pathogens can be trapped in the filter if its pore size is small enough, or if the adsorbing capacity is high enough, or by predation.

The right-hand picture shows a *saturated medium* (all pores filled with water), allowing the wastewater to flow freely through the large pores, while solid particles may be trapped in the smaller passages. If the trapped material is not entirely decomposed by bacteria the filter has to be backwashed regularly to remove such clogs and open up the pores again.

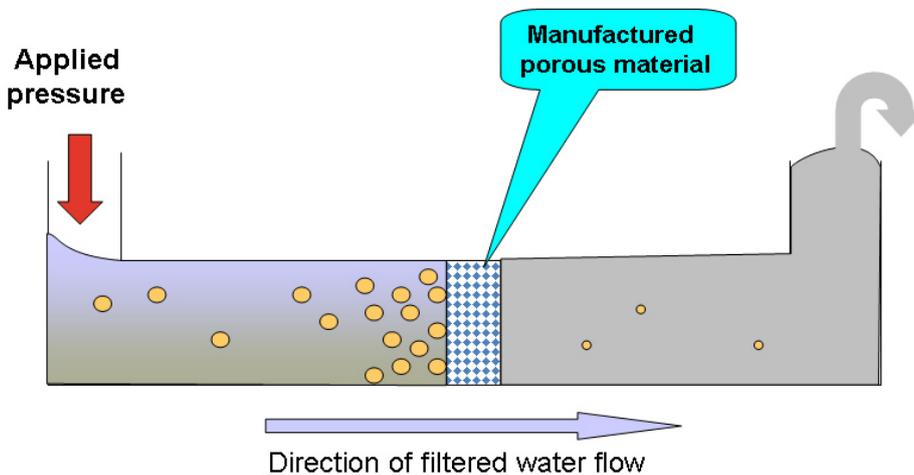
The same medium in the left-hand picture is *unsaturated* with some of the pores filled with air (white). The air obstructs the flow but air promotes the presence of aerobic microorganisms in the medium. Aerobic bacteria (breathing the air) are mostly attached to the surfaces of sand grains and an unsaturated flow allows them to feed on the passing organic matter transported with the wastewater. They are more efficient than anaerobic bacteria at decomposing organic matter – and removing disease-causing bacteria and helminths.

Wastewater tends to pass through small pores in an unsaturated medium while in saturated media the main water mass flows through the large pores as the latter have less hydraulic resistance. Unsaturated flows therefore provide better filtering but that the passage will be slower than for saturated flows. In saturated media only modest chemical and biological activity takes place because there is less contact between the sand grains and the bulk of the suspended material.

An unsaturated flow can be achieved through a proper loading of wastewater using design dimensions that account for the hydraulic conductivity of the media material (soil). A constant wastewater flow should be avoided. A simple tipping device is helpful to apportion pulses of wastewater to the filter media (see left picture). The top layer of the filter medium may have to be replaced from time to time due to a reduced permeability as a result of gradual clogging.

Forced micro-filtration

4.6-7



Jan-Olof Drangert, Linköping university, Sweden

Microfiltration is a filtration process that works by pressing wastewater through a manufactured porous material with thin micron-sized pores. Microfilters are produced mostly in the form of a quite thick porous partition (e.g. cartridge filter) or thin-film membrane filters. Microfiltration is used to remove fine suspended particles from water.

Nowadays, membrane filters can be so fine that almost any dissolved matter can be caught in them. Depending on the pore size of the semi-permeable membrane, ions (in reverse osmosis or nanofiltration processes) and organic molecules (in nanofiltration or ultrafiltration processes) can be caught. Colloid or thin suspended matter can be filtered out by ultra- or microfiltration. With a membrane pore size of 20–500 nm all pathogens, including viruses, can be filtered away.

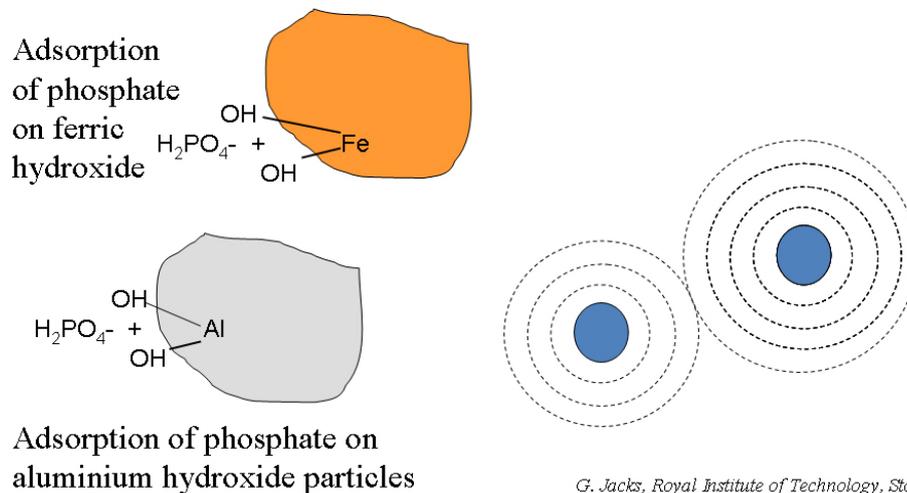
Membrane technology was firstly developed to treat drinking water and is now also used to turn treated wastewater to drinking water standard. In Singapore, all treated wastewater is put through a reverse osmosis filter before it is delivered as tap water to households.

The cost of membrane filters has gone down, but the process (especially reverse osmosis) is quite energy intensive as it requires the application of pressure and circulation of feed water. The energy for these processes is normally generated by electricity. The membrane filtration processes require constant care and maintenance, are complicated by the problem of concentrate formation. Membrane filtration is feasible only where management and economic resources are available – and where high quality water is required.

C: Chemical processes

4.6- 8

Adsorption of charged particles



The physical treatment processes discussed in the previous section depend upon particle size and specific weight. However, many substances are dissolved in wastewater or are too small to catch in this way. Instead we need to employ chemical or biological methods to catch them. The chemical processes include adsorption, precipitation, coagulation, UV-radiation, ozonation and chlorination.

Adsorption is widely used in water treatment processes. It is based on an interaction between a solute in the water (organic molecules, charged solutes) and the surface of a solid sorbent (adsorbent). This process requires special mass exchange apparatus and various sorbents with porous surfaces, such as activated carbon, synthetic polymer sorbents, or natural mineral sorbents (zeolites, clausm etc.).

The interaction between dissolved substances in the wastewater and the medium they pass through is often governed by electrical charges of their surfaces. The medium and the dissolved substances may bond and this is called adsorption – an electrostatic phenomenon. This phenomenon is utilised to remove unwanted particles from the wastewater. Most of the dissolved substances in wastewater can bond with solid adsorbents. This occurs as a result of a set of complex processes.

Commonly, electrons on the surface of a substance determine how it behaves in relation to other substances. At the level of protons/neutrons and electrons (right picture) what happens is determined by whether the shell of electrons is “filled” or not. MORE eller mindre? If the outer shell of the substance has negatively charged ions (*anions*), the substance will be attracted to a positively charged ion (*cation*). Two types of adsorption can be distinguished: inner and outer sphere adsorption. When ions bind directly to the surface with no intervening water molecules, an inner sphere complex is formed. These types of surface complexes are restricted to ions that have a high affinity for surface sites and include specifically adsorbed ions that can bind to the surface through covalent bonding. Outer sphere adsorption is less strong since water molecules which are dipoles may hinder the adsorbed specie to be closely attached to the adsorbant ([Keiluweit & Kleber, 2009](#)).

If a filter medium is positively charged it will attract particles with negative charges and vice versa. Filter media may have a permanent charge. For example, many silicates and clay minerals which are negatively charged. These may therefore adsorb positively charged particles or cations like heavy metals e.g. Cu^{2+} and Pb^{2+} . Other filter media may have a pH-dependent charge (pH is a negative logarithmic measure of the concentration of hydrogen ions H^+).

Filter media attract microorganisms such as bacteria and fungi, and some of these are charged and can attract cations. Filter media can also be modified. For example, *zeolites* are silicates with a large surface area which is normally negatively charged but by covering it with ferric iron (Fe^{3+}) it may be made to adsorb negative particles.

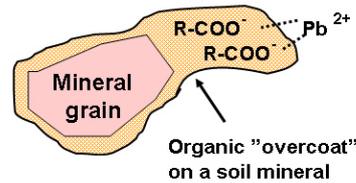
Adsorption of charged particles to soil medium

4.6-9

The three important kinds of charged soil particles are:

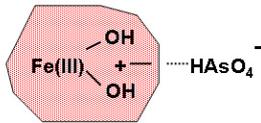
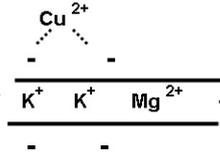
1. Organic matter

$\text{RCOOH} \leftrightarrow \text{RCOO}^- + \text{H}^+$
 (a **negative** pH-dependent charge)
 R is phenolic ring derived from lignite in residues of plants

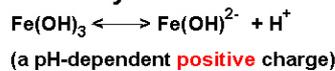


2. Clay minerals

Clay mineral consist of Al-Si-sheets with different cations (Na^+ , K^+ etc.) in between the sheets. There is a **negative** charge on sides and edges:



3. Ferric hydroxides



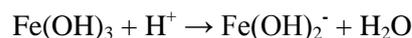
Gunnar Jacks, Royal Institute of Technology, Stockholm

Charged soil particles serve as filters or catchers of dissolved substances when wastewater percolates through the soil profile. Three types of charged particles, all of which are common in most soils, are especially important: 1) organic matter; 2) clay minerals and; 3) ferric hydroxides.

Organic matter in soils consists to a large extent of humic matter from degraded plants and animals and their phenolic rings are bonded to abundant carboxylic groups (R-COO^- in picture). This means that organic matter is a weak acid which reacts, for example, like oxalic acid. Also, the higher the pH the more the carboxylic groups are dissociated (i.e. R-COOH releases H^+ ions to water resulting in the negatively charged R-COO^-) and the negative charge increases as well as the cation adsorption capacity. The phenolic rings are inherited from lignin which covers plant cells, particularly the woody parts. They are only slowly degraded (the time varies from years to centuries depending on the complexity of molecules).

Clay minerals consist of sheets of Al-Si tetrahedra (aluminium and silicate). Sandwiched between these sheets are cations of hydrogen, sodium, potassium, magnesium or calcium. There is usually a deficit of positively charged cations which means that there is a net negative charge on the sheet surfaces and at the edges of the clay particles. The charge is more or less constant throughout the pH scale. Therefore cations such as Cu^{2+} , Pb^{2+} , and Zn^{2+} adsorb to the clay and are immobilized.

Ferric hydroxides Fe(OH)_3 often cover silicate mineral grains and at low pH there is a deficit of hydroxyl-ions and so the hydroxides have a positive charge which decreases with increasing pH. Many hydroxides (with an OH group) have a positive charge at lower pH, meaning a higher concentration of H^+ . For instance, sand coated with Fe(OH)_3 may adsorb negatively charged ions as part of the OH-groups' reaction with abundant H^+ at low pH:



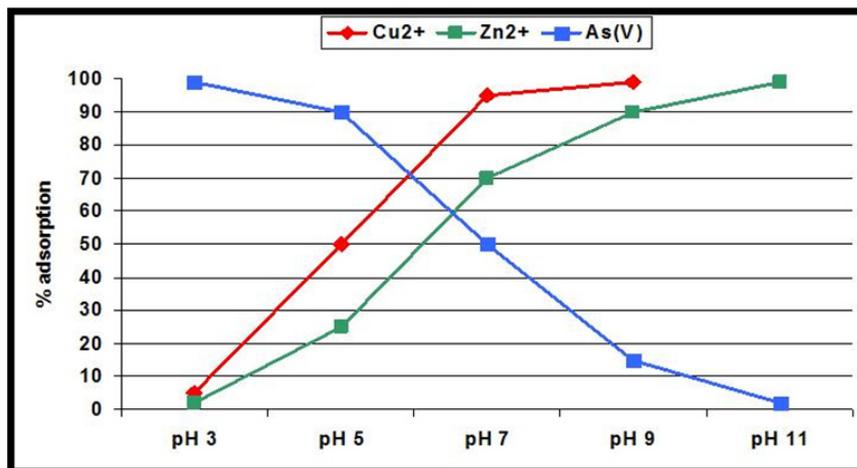
Any anion can adsorb to ferric hydroxides. Arsenic is an example of this but its adsorption depends partly on the charge of the ferric hydroxides and also on the dissociation of the arsenic acid:



The equilibrium constant for the dissociation is 7, which means that at pH 7 the two forms are present in equal concentrations. If the pH is below 7, the HAsO_4^{2-} dominates and due to the higher negative charge it is more efficiently adsorbed.

Adsorption of chemical compounds differ

4.6- 10



Copper (Cu) and Zinc (Zn) are positively charged, and adsorb easily on organic matter and clays when the pH > 7

Arsenic (As) is negatively charged and adsorbs easily on ferric hydroxides when pH < 7

Gunnar Jacks, Royal Institute of Technology, Stockholm

Cations like Pb^{2+} , Cu^{2+} and Zn^{2+} are adsorbed onto the negatively charged organic matter and clay minerals. More cations can be adsorbed as the abundant carboxyl groups on the organic matter are dissociated (R-COOH becomes $\text{R-COO}^- + \text{H}^+$, see [4.6-9](#)). Anions like As^- are adsorbed onto the positively charged ferric hydroxides.

The graph shows that the propensity to adsorb is highly dependent on the pH of the environment (although Pb^{2+} and Cu^{2+} are strongly adsorbed even below pH 7). Half of Cu^{2+} is adsorbed at pH 6, and almost all at pH 7. Zn^{2+} and Cd^{2+} are less strongly adsorbed. Arsenate (H_2AsO_4^- and HAsO_4^{2-}) has an opposite dependence, and adsorption decreases with rising pH as the OH^- ions fill up the positions around the ferric iron. At pH 6 almost all the arsenate is adsorbed while adsorption is nil when pH is 11.

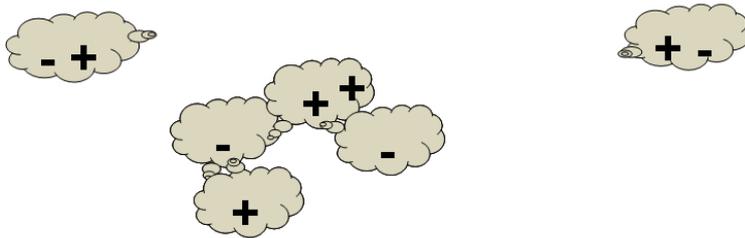
It is desirable to remove metals from the wastewater before the effluent is discharged to water bodies or is recirculated for human use. The dependence on pH complicates treatment, not least because soils can have naturally different pH levels. Human activities produce acid rain which makes soils acid (low pH), and so previously adsorbed Cu and Zn are being mobilised. Soils in Bangladesh have pH levels of about 7, while soils in Argentina have pH levels of 8.5. Therefore, copper and zinc are essentially immobilised in Bangladesh and are not found in its water bodies, while arsenic is mobile in Argentina and water bodies can contain high levels of arsenate.

In a treatment unit the pH level can be raised by adding calcium. Lowering the pH of a soil profile or in a filter is not a common practice. However it might be done if there is a question of removing arsenic for instance. Ferrous chloride is then added, which oxidizes to ferric hydroxide, releasing hydrogen ions and precipitating as ferric hydroxide. The ferric hydroxide is a good adsorbent for arsenic and can be filtered away.

Precipitation and flocculation

4.6- 11

- Precipitation – a chemical reaction between dissolved compounds to form solids
- Flocculation - an aggregation process (or processes) leading to the formation of larger particles from smaller particles



G. Jacks, Royal Institute of Technology, Stockholm

The word precipitation originates from hydrology and describes the process when cooled air moisture condenses from vapour to form drops which precipitate or deposit e.g. rain and dew. In the context of wastewater treatment, precipitation is a chemical reaction where ions or molecules in dissolved form react with other chemicals (added to water) and form an insoluble compound that can sediment.

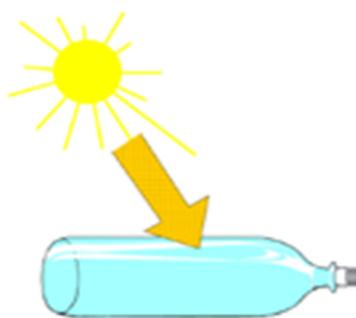
Flocculation is an aggregation of smaller particles to a bigger one, usually with the help of polymers as flocculants. In wastewater treatment this process is often preceded by coagulation. This is an aggregation of highly dispersed particles (colloids) in wastewater by addition of coagulants (hydrolysed salts) such as ferric chloride (FeCl_3), aluminium sulphate ($\text{Al}_2(\text{SO}_4)_3$) and chloride (AlCl_3) and others. The positively charged (cations) coagulants reduce the negative charges of the colloids, and thus neutralize the forces that keep them apart. As a result, the dispersed particles collide to form larger particles (flocs). The size of the flocs ranges from a few micrometers to a few millimetres. Further flocculation by polymers is an electrostatic process in which the polymer has numerous “arms” which collect small particles and form larger ones that are of high density and can be separated from the water by sedimentation. The aggregating particles in greywater are heterogeneous and are composed of dissolved, colloidal (gluey), and particulate materials of varying size and composition.

The processes of flocculation and precipitation can be speeded up by forcing the wastewater to flow through lamellar baffles in a settling tank. The retention time may be reduced from four to six hours in an ordinary settler down to less than one hour in the lamellar settler. The design has to strike a balance between building a more complicated lamellar settler and the cheaper settler that requires more space. In both cases helminth eggs will settle, while part of the organic matter and nutrient content remain in the effluent which makes effluents more valuable to agricultural use. However, bacteria and viruses remain in the effluent and have to be inactivated for some uses. As discussed before, metals and organic substances that tend to adsorb to inorganic and organic particles will settle with the particles that are removed.

By adding different types of chemicals, precipitation can be combined with flocculation to increase the removal of certain compounds. This is commonly done in conventional wastewater treatment plants, where iron- or aluminium-containing chemicals are added to precipitate phosphorus. In the process, a substantial amount of organic matter is also flocculated and removed by sedimentation. However, flocs are fragile and can easily break, and therefore the water velocity to the settling tank should be gentle to maximise sedimentation.

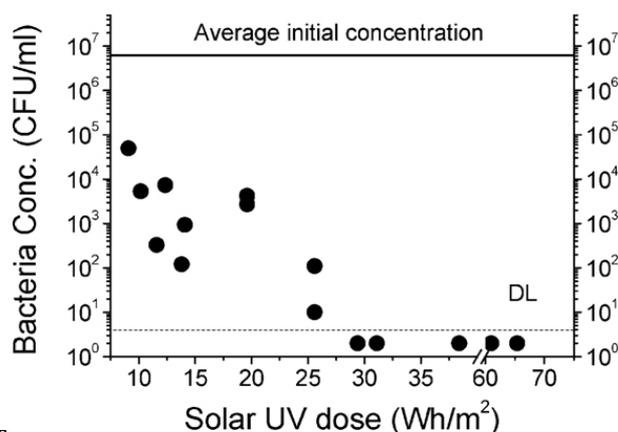
UV-radiation by sunlight

4.6- 12



Inactivation of micro-organisms by UVA-radiation and increased temperature

<http://www.sodis.ch/Text2002/T-TheMethod.htm>



Source: Ubomba-Jaswa et al. 2009

Exposure to UV light is an effective disinfection method which kills microorganisms. However, it is costly to use if the UV light has to be generated by lamps. Solar UV light disinfection, on the other hand, can be both practical and inexpensive.

The main ultraviolet component of sunlight is UV-A, and this can inactivate pathogenic organisms through photooxidation, where the energy-rich light causes the loss of one or more electrons from a chemical compound as a result of photoexcitation. The energy contained in the UV-light may also cause the formation of reactive forms of oxygen in the water that are damaging proteins, bacterial membranes and DNA.

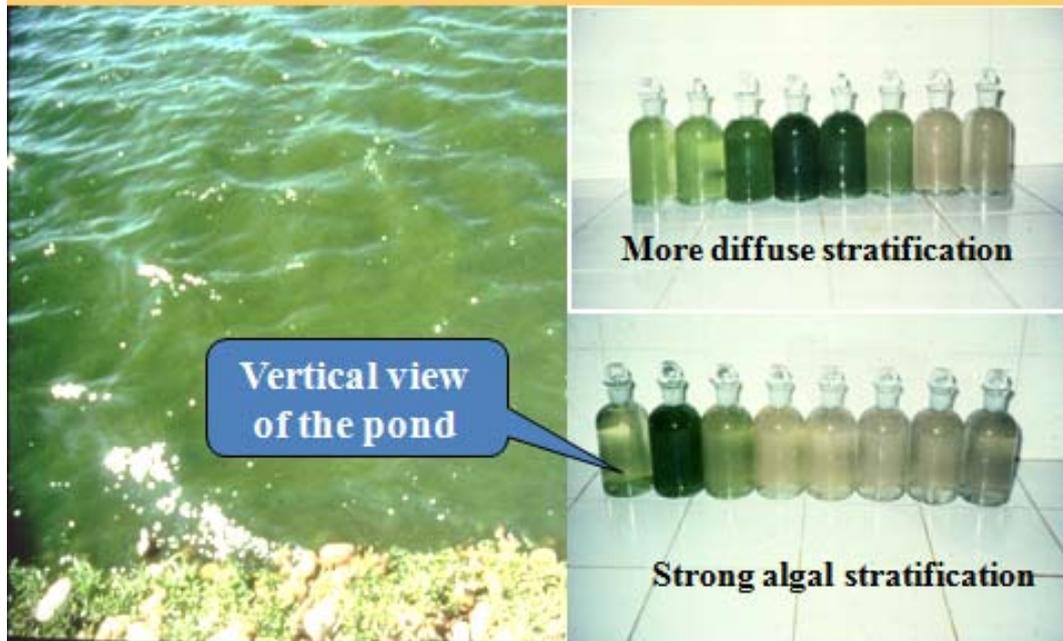
Our understanding of the disinfection process is incomplete, but it seems that its efficiency depends on the uninterrupted total dose of UV light received by the bacteria (see graph above).

There are examples of microbial pathogens in drinking water being inactivated after 6 hours exposure to intense sunlight. A common method is to keep the water in a half-full transparent PET bottle exposed to the sun (Sodis method). A number of factors affect the time required for an efficient disinfection process. A high turbidity of the water will annul the process, since viruses and bacteria can hide behind particles. The intensity of the sunlight and the way the sunlight reaches the water also impact the time required. A general recommendation is to keep the bottle in the sun for two days assuming that the water is clear and not turbid.

Treated greywater is usually more turbid and contains more particles than drinking water and therefore the required dose of UV to obtain a safe level of bacteria inactivation is higher. There is still not enough scientific evidence of the die-off of viruses in the process. However, UV radiation reduces many pathogens and is a cheap method to reduce health risks.

Shallow ponds with a dense population of algae

4.6- 13



Karin Tonderski, Linköping University Sweden

Courtesy of Duncan Mara, University of Leeds, UK

We often view eutrophication as a serious problem when it occurs in lakes. The argument is that the decomposition of large numbers of dead organisms depletes oxygen and results in bottoms devoid of higher life forms. The oxygen-free environment gives rise to anaerobic bacteria which survive and produce methane gas and other residues.

However, in a controlled situation with a shallow pond, eutrophication can be used productively. The difference between shallow ponds and lakes is that the photosynthesis is active in the whole water body down to the bottom (see right picture). The released oxygen from the photosynthesis is used by aerobic bacteria to break down decaying organic material (dead algae, plants, etc.) without producing methane.

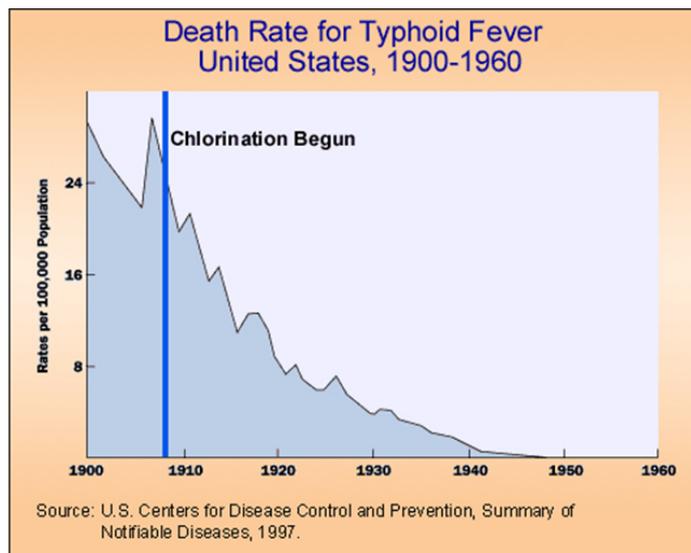
The water in a pond may contain a strong algal stratification or it may be more diffuse as indicated in the pictures.

Experiences from sewage stabilization ponds show that in shallow ponds with high populations of algae the concentrations of bacteria known to be potentially pathogenic drop rapidly. This is thought to be due to a combination of UV from sunlight, a high pH caused by intensive photosynthesis by the algae, and possibly the high oxygen concentration resulting from photosynthesis.

Hence, adding a shallow pond for greywater polishing after the main treatment can be a low-cost method to reduce its pathogen content. The effluent leaving the pond also has low levels of algae and has a near-neutral pH if the discharge point is placed a bit below the pond surface, where the algae population and photosynthetic activity is highest.

Ozonation and chlorination

4.6- 14



Ozone and chlorine (Cl_2 , chlorine gas or sodiumhypochlorite) are very strong oxidants that can degrade organic matter and damage cell membranes, thereby killing bacteria and viruses. Chlorine can also combine with organic matter in the water to form chlorinated compounds. A common name used for such compounds formed as by-products of the chlorination of water is Trihalomethanes (THMs). Chloroform is one example. Such chlorinated compounds are potentially carcinogenic, and hence this is a non-desirable side-effect of chlorination. However, the risk to humans from those byproducts is small in comparison to the risks associated with inadequate disinfection ([WHO Guidelines, 2006](#)).

Ozone is an alternative to chlorine for killing bacteria and viruses as it is very reactive and a strong oxidant. It is effective over a larger pH range and needs a shorter reaction time. No other chemicals are added. In addition, the ozone also oxidizes (= covers with a layer of oxygen) hydrogen sulphide, manganese and iron into sulphur or sulphate, and insoluble iron and manganese oxides that can be filtered away. The disadvantage with ozone is that it is more expensive and the regrowth of bacteria cannot be controlled. The risk posed by possible toxic byproducts is not well known. Another disadvantage with ozone is that – unlike chlorine products – it does not have any residual disinfectant effect after its immediate action. This means that regrowth of microorganisms may occur in the network of distribution pipes. Possible formation of toxic by-products is less evident than for chlorination, but cannot be excluded as a possibility.

The graph above gives a tentative relationship between the water-borne disease typhoid and chlorination of drinking water in the USA. There are also other factors that have promoted the decline of typhoid in USA, and discussions about how to interpret epidemiological data are relevant in this case (Chapter 3).

D: Biological processes

4.6- 15



Karin Tonderski, Linköping university, Sweden

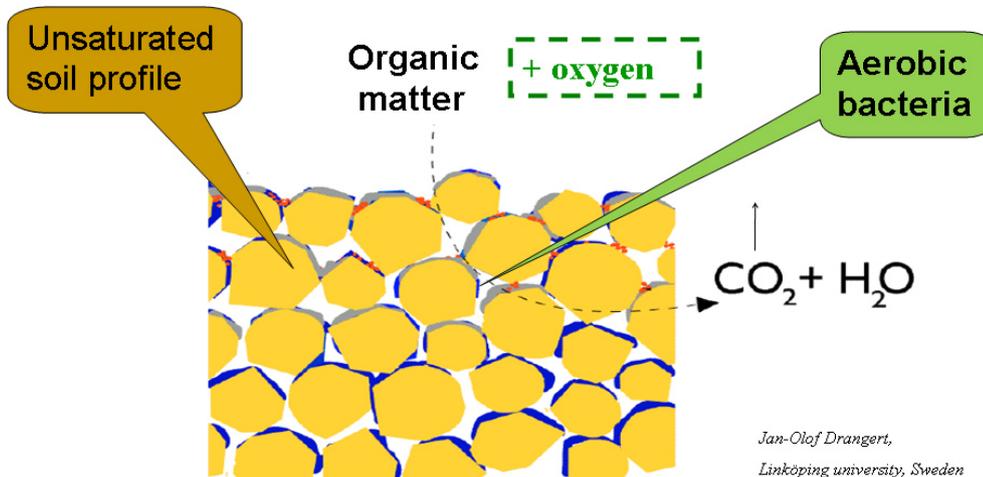
A number of wastewater treatment systems are based primarily on biological processes, where microorganisms decompose energy-rich organic substances, such as proteins, fats, starches and cellulose to support their growth. Biological treatment relies mainly on microbiological processes that take place in the water, sediment and on plant tissue (stems, leaves and roots) in ponds and wetlands, or on the surfaces of sand and soil grains in sand filters with or without plants (see photographs above). In both ponds and wetlands, plant and algal uptake of nutrients may periodically be important for nutrient removal, particularly if the plant biomass is harvested, while the interactions between wetland plants and microorganisms are significant for all water treatment processes. The oxygen supply to biological treatment systems is of crucial importance for their functioning and for determining what the end products of the decomposition processes will be. If the biological treatment systems are supplied with sufficient oxygen, the major end products from organic molecules will be carbon dioxide (CO₂), water and new microbial cells.

The effluent from biological systems can be used for irrigation under certain restrictions (WHO, 2006). If the treated effluent is just discharged it may pollute the groundwater. Therefore, planning of biological systems should consider potential impacts on shallow groundwater and leakage of the effluent into receiving surface waters.

Biological processes - with air

4.6- 16

Oxygen is vital for most living organisms, including bacteria and viruses. When oxygen is present, organic matter (measured as BOD) is efficiently decomposed by organisms into $\text{CO}_2 + \text{water}$:



Microorganisms are adapted to live in aerobic (with oxygen) environments or in anaerobic (without oxygen) environments. Some can live in both. Aerobic microorganisms decompose organic matter into new cell material, carbon dioxide and water. The most complete and rapid decomposition of organic matter takes place when oxygen is available.

The picture above shows the profile of an unsaturated soil or sand filter with voids or pores of air/oxygen (white colour). In practice, the best way to maintain aerobic conditions in a treatment system based on filtration through sand is to apply the wastewater at intervals. By doing using a device such as a pump or siphon (see 4.7-13), the flushing wastewater is distributed over the whole surface. Also, the sand profile can dry up and passive aeration of the pores occurs in between the wastewater applications.

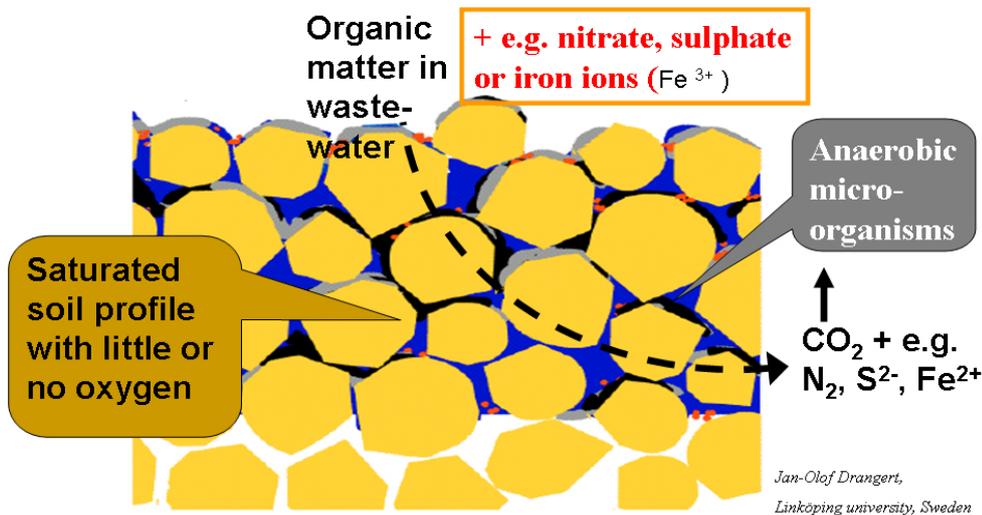
Aerobic microorganisms can live and grow on the filter particles and form a thin layer or biofilm around the soil particles (blue on the picture). They come into close contact with the organic matter in the wastewater which (intermittently) flows past the particles. They decompose the organic matter and the by-product is carbon dioxide which dissipates into the air, and the newly formed cells are small and do not clog the pores when they move along with the wastewater flow. If the application rate of wastewater is reasonably low, the filter will remain unsaturated and aerobic.

Sand filters do more than just reduce organic matter – as mentioned in the previous section about chemical treatment. Ions of metals may adsorb to the microorganisms and sand particles. Some potentially pathogenic organisms will also be removed by adsorption, decomposition and predation by the micro-fauna (small animals).

Biological processes - without air

4.6- 17

Many microorganisms can survive in environments with no oxygen and they use other compounds for their survival:



If the loads of wastewater entering a soil or sand filter are too high, if they contain too much organic matter, or if the filter is operated with a continuous load of effluent, the soil profile will become saturated – that is, all pores will become filled with wastewater (blue section). Typically, a thick biofilm develops consisting of live and dead cells and a “gel” of exudated organic molecules between the cells (black layers). The hydraulic conductivity of the soil decreases as a result of the accumulated organic matter in the soil pores. We say that the filter has clogged and anaerobic conditions develop in the soil filter.

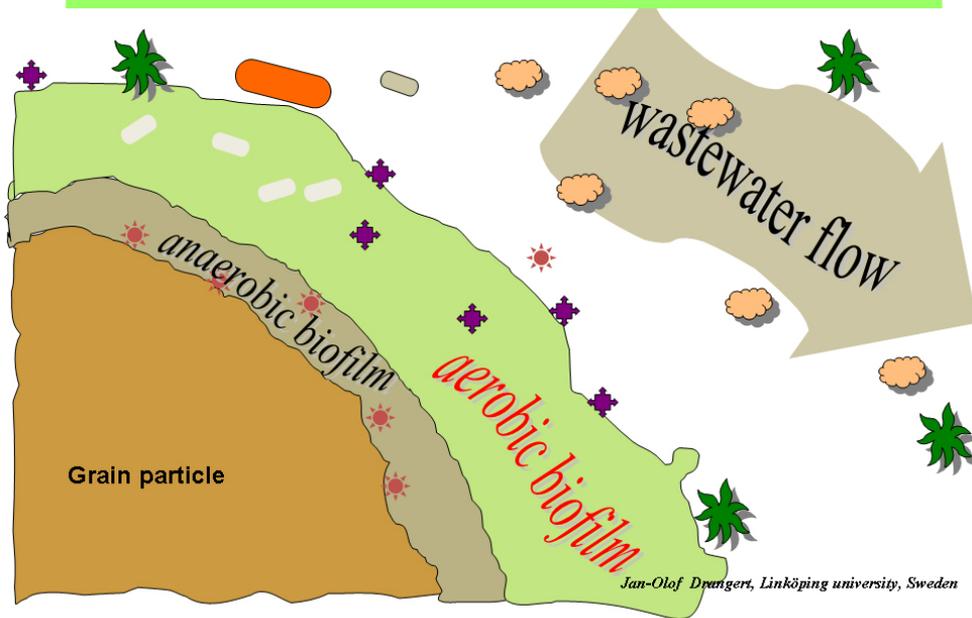
Anaerobic microorganisms can survive in this harsh anaerobic environment. Instead of oxygen they can use other chemical components to extract energy from the organic matter for their growth (details in 4.6-17). For example, the sulphate-reducing bacteria transform sulphate (SO₄²⁻) in the wastewater into sulphide (S²⁻) in order to make use of the energy contained in the organic matter. In turn, this sulphide ion will efficiently attract positively charged metal ions in the wastewater and the resulting solid substance precipitates and settles at the bottom of a pond or in a soil filter. The smell of sulphide is an indicator of anaerobic conditions.

Anaerobic microorganisms are less efficient than aerobic ones in decomposing organic matter, and if saturated conditions prevail for a prolonged period the treatment efficiency drops due to the lack of oxygen. Even in an unsaturated profile (previous slide), the microorganisms may consume all oxygen locally if the treatment system lacks artificial aeration, and anaerobic zones are interspersed with aerobic ones. A more detailed discussion of the change that occurs in the microbial community and metabolism when systems turn from aerobic to anaerobic is given on page 4.6-21.

Enteric bacteria are essentially anaerobic bacteria (excreted from our anaerobic intestines) and will therefore survive better in an anaerobic sand or soil filter. Survival of pathogens is dealt with in Chapter 3

Microorganisms attached to surfaces are more stable than those suspended in water

4-6- 18



In a wastewater treatment system with a solid medium such as a sand filter, the microorganisms become attached to the surfaces of the medium. This contrasts to activated sludge systems or open ponds where microorganisms remain suspended in the water. The active bacteria form a biofilm on the grain particles and they decompose substances in the flowing wastewater. Bacteria multiply by building new cells out of the decomposed material. Organic matter, nutrients and oxygen diffuse into the film and are absorbed by the (growing) microorganisms, resulting in a gradually thickening microbial film (green layer in picture). Eventually, the film is so thick that oxygen-free conditions develop in the inner (grey) layer, where organic matter from the wastewater and dead microorganisms are decomposed anaerobically. In high-loaded systems the thickest part of the outer layer is gradually sloughed off, and must be removed in a settling unit beneath or beside the filter (page [4.6-17](#)).

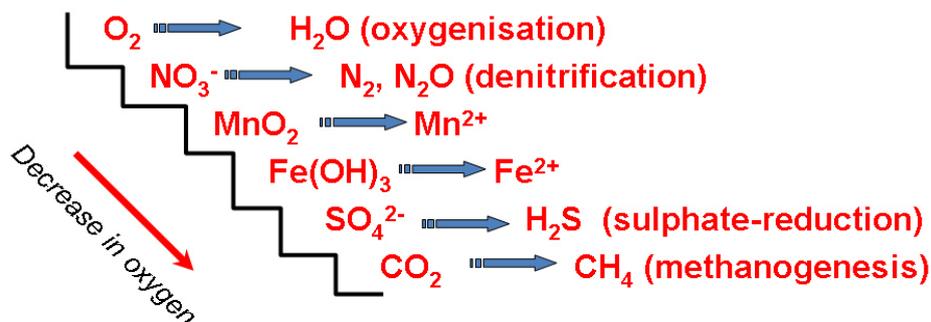
Such attached growth allows a much higher cell density than is possible in a system with suspended growth (e.g. activated sludge). This permits the use of smaller reactor volumes with a lower specific growth rate of microorganisms. As a result, the amount of biological sludge (i.e. dead microorganisms) that is formed and needs to be removed in a settler is less than in a suspended growth treatment system ([Pandey, 2004](#)).

Microbial studies have also shown that microorganisms growing attached to surfaces are less susceptible to different kinds of potentially harmful chemicals, e.g. antibiotics. A microbial community growing attached to surfaces, for example sand or soil grains, is also more tolerant to large flow variations that might wash away microorganisms growing in a suspension.

“Redox-ladder”

4.6- 19

When microorganisms descend the redox-ladder they first use O_2 as an electron acceptor, then nitrate NO_3^- , and further down other compounds as electron acceptors. The blue arrow indicates a reaction with energy-rich organic substances (electron donors) in the wastewater



Gunnar Jacks, Royal Institute of Technology, Stockholm

In the photosynthesis *autotrophic* organisms use energy from the sun to form new cells from carbohydrates, carbon and water. The new cells consist of carbohydrates, proteins and or fats, in which energy from the sun has been converted into chemical energy. Most living organisms (both humans and bacteria) want to use this chemically bound energy for their own growth and survival. To do that, they decompose such carbon-containing molecules back into carbon dioxide, water and nutrients, to free the energy for their own metabolism. Humans and other mammals, earthworms, many fungi and bacteria use oxygen for this decomposition in a so-called *oxidation* reaction.

The microorganisms can initiate two types of *chemical* reactions that are instrumental in wastewater treatment; acid-base reactions and redox-reactions. Acid-base reactions involve transferring hydrogen ions (H^+) from one molecule to another. The redox-reactions (REDuction and OXidation reactions) involve transferring electrons (e^-) where one molecule is an *electron donor* and another is an *electron acceptor*. These reactions occur in most treatment processes. In this section we discuss the reactions in environments with a lot of oxygen, small amounts of oxygen or no available oxygen.

The organic matter contained in the morning sandwich for a human being, or the carbohydrates and grease in greywater for the microorganisms in a treatment system, are examples of *electron donors*. The amount of energy that an organism can retrieve from electron donor molecule depends on which molecules are available as *electron acceptors*. Oxygen is the best and enables the organism to make use of much of the energy contained in the carbohydrates. The less favorable ones follow as we go down the so called *redox ladder*.

Aerobic bacteria, as well as humans, have enzymes in their cells that can use oxygen (O_2) molecules as electron acceptors to form water molecules (H_2O). In the process, each oxygen atom receives two electrons from the organic matter that is being decomposed and the now negatively charged oxygen attaches to available hydrogen ions (H^+) and forms a non-charged water molecule. In this process, energy from the electron donor molecule is released. This is described in the highest rung of the redox-ladder where oxygen meets with any molecule which is an electron acceptor.

There are many organisms that can grow both with and without oxygen, for example by using the second best (from an energy recovery point of view) electron acceptor molecule one step down in the ladder, nitrate NO_3^- , when oxygen has been depleted. The denitrifying bacteria use energy from an organic substrate and to release that energy, they transfer electrons to the nitrate ion, which changes into nitrogen gas or dinitrogen oxide. As nitrate is depleted and less and less favorable electron acceptor molecules are the only ones available down the ladder, other anaerobic microorganisms can use other molecules to get energy from organic matter. Such environments with no oxygen are found in certain wet soils, and in wetland and lake sediments.

The next electron acceptor to step in if the nitrate is not there or depleted are manganese oxides which can be three- or four-valent. There exists a large number of different manganese oxides formed under different conditions. When manganese oxides are used as electron acceptors the manganese is transformed into Mn^{2+} which is fairly soluble and is a common problem in groundwater.

The next type of organic matter degrading bacteria use ferric iron in iron hydroxides (see page [4.6-9](#)) as electron acceptors forming ferrous iron (Fe^{2+}) which is quite soluble and is a common problem in groundwater.

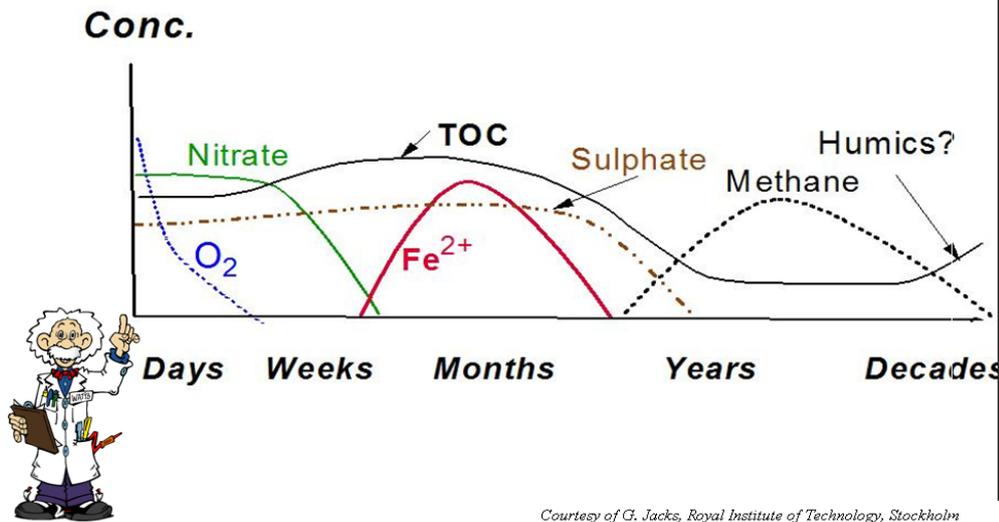
We mentioned before that sulphate-reducing bacteria use sulphate (SO_4^{2-}) in the wastewater as electron acceptors, and transform it into ion sulphide (S^{2-}). Sulphide has a distinctive smell which is therefore an indicator of anaerobic conditions. In turn, this sulphide ion will efficiently attract positively charged metal ions in the wastewater and the resulting solid substance precipitates and settles on the bottom the pond or in the soil filter.

The methanogenesis reaction is important for biogas production. This is the last step in the “ladder” and is quite “uneconomical” for the microorganism since it forms an energy-rich compound, methane. The methane fermenters are a unique group of microorganisms, Archaea, that can operate in a very reducing environment where all other oxidants like oxygen, nitrate, manganese, ferric iron and sulphate have been consumed (see biogas Module 4.4-11).

In a landfill with organic matter, all the processes in the aerobic-anaerobic “ladder” take place simultaneously but in different parts of the landfill. The initial oxygen in the waste is consumed soon after it is dumped and more and more reducing conditions develop in the deposited organic matter. Eventually, we reach the bottom step of the ladder in an environment where methane-producing organisms are favoured. The same gradient also develops as we move down through sediments of treatment wetlands or ponds, or even in septic tanks, with methane production occurring a bit below the sediment surface.

Changes in concentration of electron acceptors when organic matter (TOC) decomposes

4.6- 20



A solid waste deposit is a good example of a redox-sequence. When the waste is fresh, oxygen in the air in the pores is consumed in the degradation of the organic matter. The organic matter is quite reactive and the oxygen is fast consumed, within days (blue curve). Then nitrate is used as an oxidant (green curve) and further on in the process manganese oxides and ferric oxides are used. These oxides can be present in the waste itself but also in soil used to cover the waste. The next step is sulphate reduction (brown curve) and finally methane fermentation.

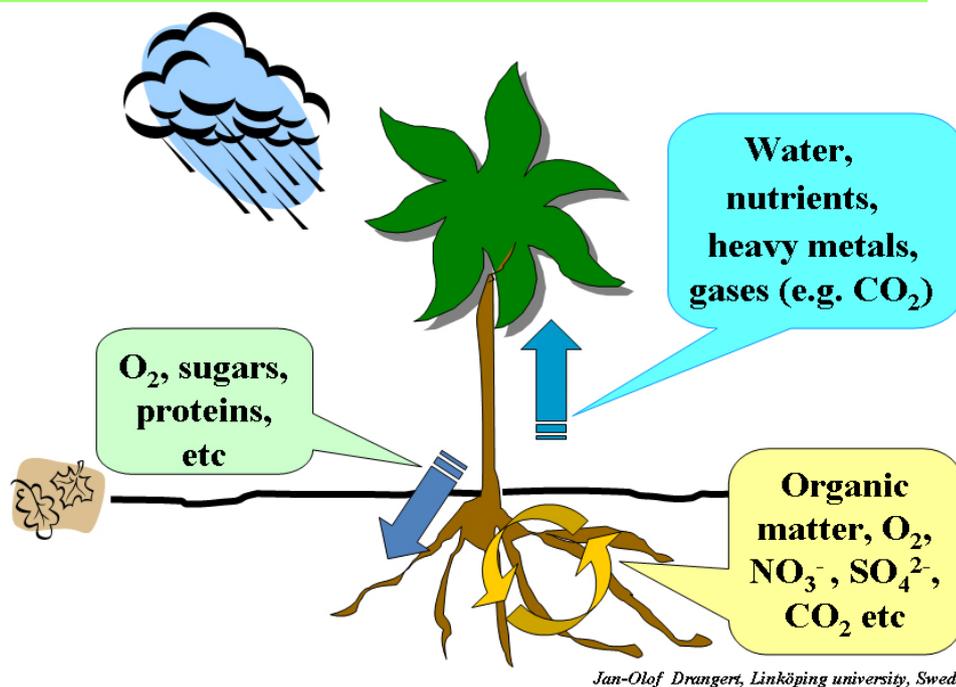
The redox sequence has a practical implication as the first steps produce high concentrations of total organic matter (TOC) in the leachate which consumes oxygen in water courses receiving the effluents from the waste deposit.

The methane step produces a leachate with lower TOC and in addition, for a period of about ten years it produces methane which can be used commercially as a fuel. Thus the deposition of waste involves compaction of the waste to squeeze out air/oxygen from the waste, usually by using a bulldozers and covering “pillows” of waste very soon with soil.

A similar sequence of redox reactions can also be observed as we move down through sediments of treatment wetlands or ponds, or even in septic tanks, with methane production occurring a bit below the sediment surface.

What happens in the root zone?

4.6- 21



Many wetland plants are able to transport oxygen from the leaves down to their root systems to help the root cells survive in the anaerobic sediment. Some of this oxygen leaks out to the surroundings, and usually creates a very thin film around the roots and underground stem (rhizome) in which more oxygenated conditions prevail – the so-called *rhizosphere*. The oxygen sustains aerobic microorganisms and they oxidate and precipitate ferrous ions as reddish ferric oxides and hydroxides around the roots in treatment wetlands. It is still debated whether this oxygen leakage is large enough to play a significant role for the microbial community in decomposing the fats and carbohydrates in a wastewater treatment system.

Whatever the answer to this question, both plants and microorganisms contribute to partially remove organics, pathogens, nutrients, heavy metals and toxins in wetlands and planted soil filters. The total environment in the vicinity of the roots (*rhizosphere*), represents a complex biogeochemical entity comprising both aerobic and anaerobic zones, and the corresponding processes are in operation. When the greywater enters the rhizosphere some of its components are digested by microorganisms. Enzymes produced by bacteria and fungi help break down greywater components and transform these to energy and building blocks for the microorganisms. Rest products are excreted and other microorganisms and plants can use these products, along with dead microbial and root cells.

Plants take up nutrients through their roots to use for their growth and fruit and seed production. Ions are at lower concentrations outside the plant in the rhizosphere than inside the root cells and they move into the plant cells by a process called “active transport”. Active transport is catalyzed by enzymes and consumes energy. Ions which are at higher concentrations outside the plant than inside can be transported by diffusion ([Del Porto, 1998](#)). However, too high a level of salt in the water is detrimental to the plants, which is also worth remembering when applying urine in the garden, as urine is rich in salts ([Jönsson et al., 2004](#)). For example the common sodium Na^+ and chloride Cl^- ions may provoke specific ion toxicity if high concentrations build up in the soil, and they may interfere with plants’ uptake of nutrients such as nitrate and potassium. If the proportion sodium to the sum of calcium and magnesium is too high, the soil structure is negatively affected leading to clogging of soil pores. Hence, in arid and semi-arid regions, where excess salt is not washed away with rainfall, it is important to follow guidelines when using greywater for irrigation (WHO, 2006). If the dosage of urine is based on the N demand of the crop, detrimental effects of the salt concentrations will be avoided ([Jönsson et al., 2004](#)).

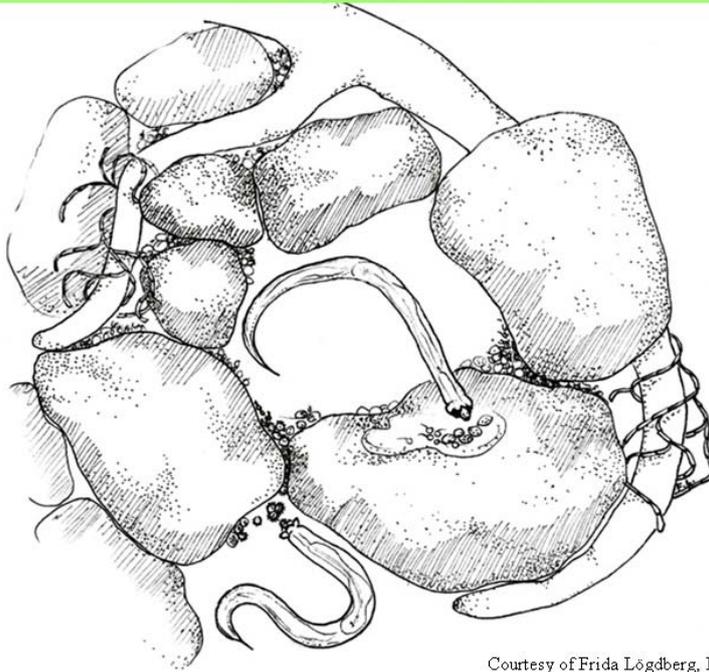
The plants also need water to replenish the water that is lost in evapotranspiration from the leaves’ open stoma during photosynthesis. In small planted greywater treatment systems, a significant amount of water is lost to the atmosphere due to evapotranspiration, particularly in hot climates.

A first step in the retention of heavy metals in wetlands is the adsorption on the organic matter that accumulates in wetlands due to the slow degradation in the absence of oxygen. These metals may then be transformed into sulphides when the sediments accumulate and the organic matter is buried deeper and the environment becomes sulphide reducing. Clays deposited in estuaries with abundant growth of algae and organic production often contain black iron sulphide (FeS). When aging, the monosulphide may slowly be transformed into pyrite (FeS_2). Other sulphides are co-precipitated. When a black clay soil is drained for agriculture the sulphides may oxidize producing sulphuric acid. Thus they are often called “acid sulphate soils” and are common in many coastal areas.

Another fate of heavy metals is that they get co-precipitated in the ferric hydroxides formed around the roots of wetland plants. Also, negatively charged substances like arsenic can get trapped by adsorption onto the ferric hydroxides.

Predation on microorganisms stimulates decomposition

4.6- 22



Courtesy of Frida Lögberg, Linköping university

In a soil ecosystem, the microbial biomass formed when microorganisms decompose organic compounds in the soil, such as dead plant parts and organic matter in wastewater, becomes food for small animals. Protozoa, small worms called nematodes, and earthworms can all feed on fungi and bacteria in the biofilm around soil particles (picture). It has been shown that this predation stimulates decomposition of organic matter and other biological processes, probably because the microbial population is kept in an exponential growth phase. It is also possible that the predation helps control the thickness of the biofilm thereby preventing clogging of sand filters.

Potentially pathogenic microorganisms like *Salmonella* and *Campylobacter*, which cause human enteric diseases, can be present in wastewater. Bacteria-eating animals consume them, thereby helping in the disinfection of wastewater during treatment.

Soil organisms vary tremendously in size and numbers

4.6- 23

A teaspoon soil ~ one gram

Microbial group	Example	Size (µm)	Numbers (per gram soil)	Biomass (g wet mass per m ² soil)
Bacteria	Pseudomonas	0.5 – 1.5	10 ⁸ - 10 ⁹	30 – 300
Fungi	Mucor	8 (hyphae diameter)	10 ⁵ – 10 ⁶	50 - 500
Protozoa	Euglena	15 * 50	10 ³ - 10 ⁵	0.5 – 20
Nematodes	Pratylenchus	1000	10 – 10 ²	0.1 – 10
Earthworms	Lumbricus	100 000		1 - 100

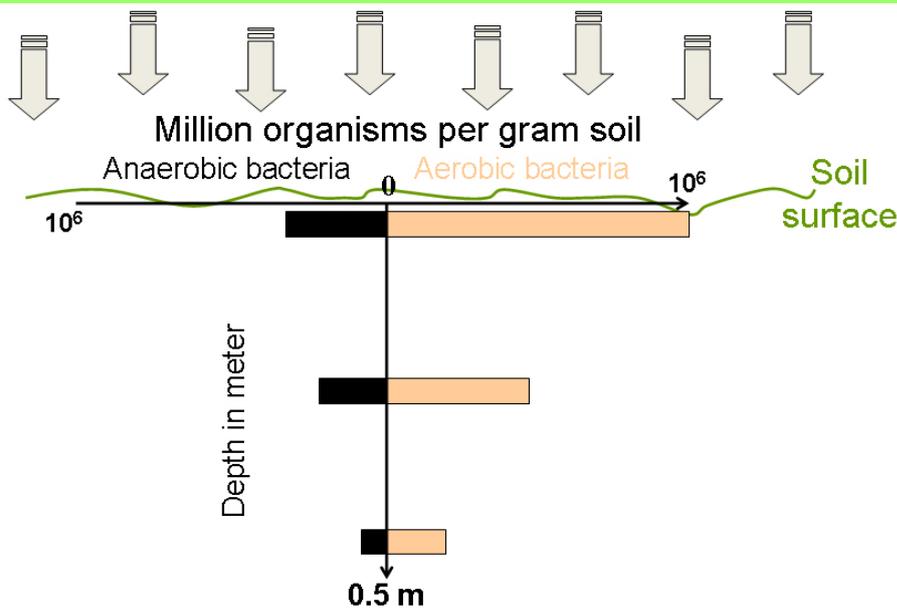
Modified from Sylvia, D. *et al.* 2004. Principles and applications of soil microbiology

Despite their minuscule size (one µm is 10⁻⁶ meter), bacteria and fungi make up the major part of the total biomass in an aerated soil profile. It is worth remembering that a teaspoon of soil is the home for a billion invisible organisms, most of which contribute to the treatment wastewater if we use the soil/sand for that purpose.

The table above shows that other, larger, microorganisms are fewer but they are nevertheless important in soil ecosystems. It has been shown that predation by soil animals promotes decomposition, which releases the available nutrients and thus enables the growth of plants. One mechanism is that the animals constantly feed on the bacteria and fungi populations and thus maintain them at a high growth rate. In addition, when earthworms feed on nutrient-rich bacteria or fungi, they excrete nutrients that become available to plant roots and stimulate plant growth. Hence, we should view a soil or sand filter as a complex ecological community in which the interactions between organisms are vital for the efficient decomposition of organic matter contained in the wastewater we want to treat. As the animals are dependent on oxygen for their survival, when using filters to treat wastewater it is important to keep the soil unsaturated for this ecological community to function the way we want it to.

Organic matter is decomposed most efficiently in the top soil

4.6- 24



Courtesy of G. Jacks, Royal Institute of Technology, Stockholm

Now we view the soil profile and the number of microorganisms living there in order to understand how to get the best treatment results for wastewater.

The largest source of energy for soil ecosystems is normally organic matter from dead plants, with the highest amounts, consisting of leaf litter and dead fine roots, in the top layer. In addition, oxygen availability is highest closest to the soil surface and therefore many aerobic microorganisms dwell here (10^6 per gram of soil). As explained before, there are always small spaces with no oxygen, even at the top layer of the soil profile, where completely anaerobic bacteria can survive, for example inside aggregates formed by clay and organic matter. As a consequence, the number of both aerobic and anaerobic soil organisms is highest closest to the soil surface (picture). Hence the activity of the microorganisms is also highest in the upper layer of the topsoil. This must be considered when using soils for wastewater treatment, and also when treating drinking water.

As the size of the microbial community drops rapidly with depth, a good distribution of water over the surface intended for wastewater treatment is essential for a good treatment result. It also helps to avoid overloading a particular section, thus preventing saturated water flow and the formation of zones with completely anaerobic conditions.

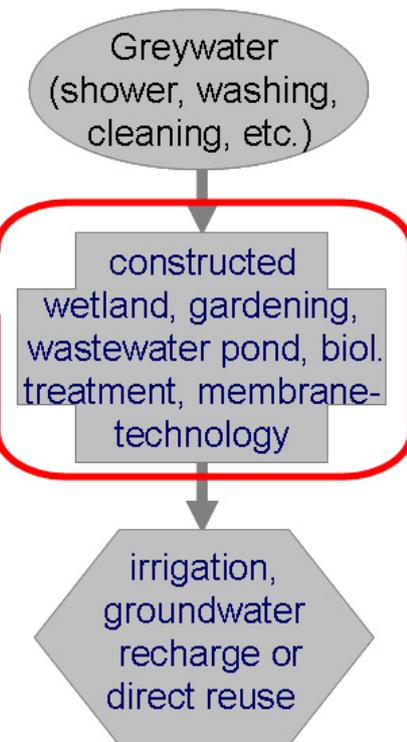
References:

- Bergbäck, B. and A. Jonsson (eds.), 2008. Stockholm – Towards a non-toxic environment. Stockholm City Environmental dept and Stockholm Water Company. At: http://www.stockholm.se/Global/Stads%20b6vergripande%20c3%a4mnen/Klimat%20%26%20Milj%20och%20miljogifter/Nya%20gifter%20-%20nya%20verktyg/0906_towards_nontoxic_environment.pdf
- BGS 2001. Guidelines for assessing the risk to groundwater from on-site sanitation. British Geological Survey. Commissioned Rep CR/01/142:97.
- Del Porto, D. and Steinfeld, C. 1998. *The Composting Toilet System book. A practical guide to choosing, planning and maintaining composting toilet systems and alternative sewer and septic systems*. Center for Ecological Pollution Prevention, Concord, Massachusetts
- Drangert, J-O. och M. Löwgren. 2005. *Förändring eller kontinuitet. Faktorer som påverkar va-systemens utveckling under perioden 1960-90* (Change or Continuity. Factors affecting the evolution of water supply and sanitary systems). Rapport 2005:1. Forskningsprogrammet Urban Water, Chalmers Tekniska Högskola. Sweden.
- IVL, 2007. *Results from the Swedish screening 2006*. By Woldegiorgis, A., Green, J., Remberger, M., Kaj, L., Brorström-Lundén, E., Dye, C. & Schlabach, M. 2007. Subreport 4: Pharmaceuticals. IVL Report B1751. Swedish Environmental Research Institute Ltd, Stockholm.
- Jönsson, H., Richert Stintzing, A., Vinnerås, B., and Salomon, E. 2004. Guidelines on use of urine and faeces in crop production. Report 2004-2, Ecosanres, Stockholm Environment Institute. Stockholm, Sweden. Available at: www.ecosanres.org.
- Keiluweit, M. & Kleber, M. 2009. Molecular-level interactions in soils and sediments. *Environ. Sci & Techn.* **43**(10): 3421-3429.
- Pandey, A (ed.) 2004. Concise encyclopedia of bioresource technology. The Haworth Press Inc. Benhampton, NY. http://www.amazon.com/gp/product/1560229802/ref=cm_rdp_product
- Sylvia, D., Fukrman, J., Hartel, P.&D. 2004. *Principles and applications of soil microbiology*. 2nd edition, Librairie Lavoisier, Paris. 640 pp.
- Sylvia, D., Fuhrmann, J., Hartel, P., Zuberer, D. 1999. Principles and application of soil microbiology. Prentice Hall, Upper Saddle River, NJ. 520 pp.
- Ubomba-Jaswa, E., Navntoft, C., Polo-López, M.I., Fernandez-Ibáñez, P., McGuigan, K.G. 2009. Solar disinfection of drinking water (SODIS): An investigation of the effect of UV-A dose on inactivation efficiency. *Photochemical & Photobiological Sciences*, 8:587-599.
- WHO (2006) *Guidelines for the safe use of wastewater, excreta and greywater*. Volume IV. Excreta and greywater use in agriculture. Geneva, 2006. http://www.who.int/water_sanitation_health/wastewater/gsuww/en/index.html

4.7 Greywater treatment

Learning objectives: Get familiar with various treatment options and with the application of various processes

Can we remove all the pathogens and heavy metals?
What is in the sludge?

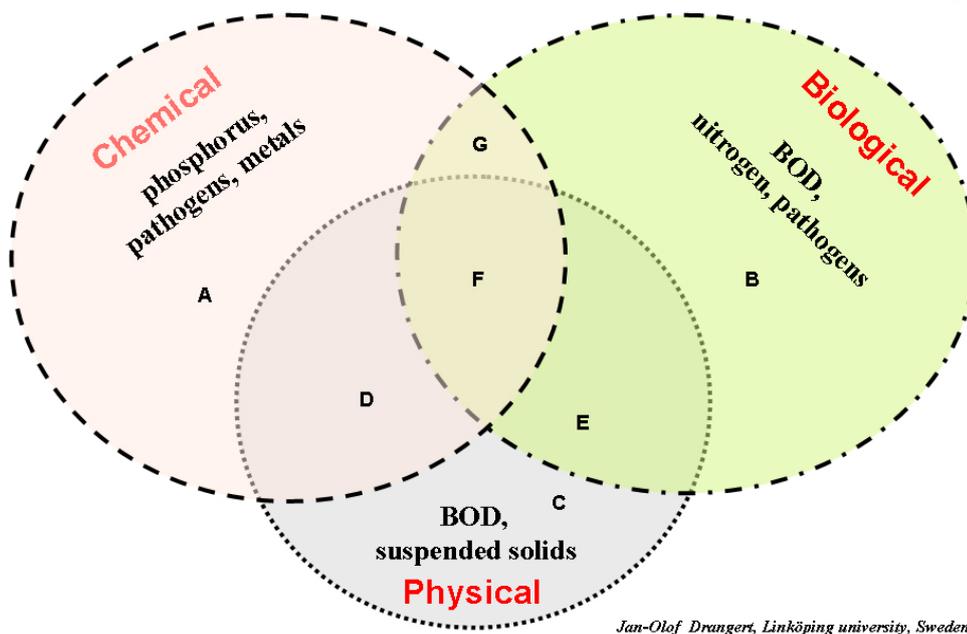


An outcome-based strategy initially outlines what levels of pollutants – after treatment – are acceptable for the intended use. The next step is to find out the origin of any pollutants that are present at excessive levels. Is it possible to reduce or prevent these pollutants from entering the water flow? How can unnecessary pollution of the water be avoided? There is a host of source-control measures that can be used (see Module 4.5). If source control measures cannot solve the problem, the pollutant has to be captured in a treatment process. A range of processes are explained in Module 4.6. This “start from the end” approach is helpful in developing a treatment strategy.

Before selecting technology or method to treat the wastewater to the desired standard, a lot of issues have to be thought through. Is the solution intended for a single household or a small community? The management options stretch from own-key to turn-key arrangements (see Section 2.3- 5). The local physical conditions also play a role and a holistic sanitation selection algorithm can be helpful to decide what technology may be appropriate (see Section 2.5-11).

Application of processes

4.7- 2



The picture shows how various treatment processes, i.e. physical, chemical and biological, can be combined. The first example is a combination of measures to prevent eutrophication of a water body. The amounts of nitrogen and phosphorus (N and P) in the effluent need to be reduced. It is well known that most P and N originate from excreta (mainly urine) and an effective source-control measure would be to introduce urine-diverting toilets and use the urine to fertilise farmland. If this long-term solution is not possible, the wastewater has to be stripped of N and P in a treatment process. There are a number of possible ways to do that at the end-of-pipe by combining physical, chemical and biological processes (F in the picture):

- Some N and P are found in larger organic particles, fat and grease. These can be caught in a grease trap through screening and flotation (C). The collected scum can be composted and returned to the soil.
- A further reduction of nutrient-rich particles can be obtained through settling in a septic tank or baffled anaerobic reactor where anaerobic decomposition also takes place (E).
- N and P from urine are dissolved in the wastewater. N can be partly reduced by biological processes such as microbiological nitrification-denitrification in a wetland or pond (B). P can be reduced by treating the water in filters made up of reactive materials rich in iron, aluminium and/or calcium compounds to which P is adsorbed (A and D).
- Reduction of both N and P can be attained by using the pre-treated, particle-free, greywater for irrigation, where the crops will absorb nutrients and some P will be adsorbed to the soil particles (G).

The second example demonstrates that a treatment process for drinking water may act on two or more metals simultaneously. Assume that the groundwater contains iron and arsenic. When the groundwater is aerated (D), the iron is precipitated as Fe(III) hydroxide. It is positively charged and a good adsorbent for the negatively charged arsenate ions. The flocs that are formed have a high density and sink to the sediment at the bottom. The single process of aeration solves both problems.

The above example indicates how effluent and sludge can be made useful.

Overview of possible technical options

4.7- 3

Treatment:	Possible technical solutions for greywater:
Physical <i>(SS and BOD-levels)</i>	Screen, grease trap, septic tank, sedimentation pond
Biological I <i>(BOD-level reduction)</i>	ABR, anaerobic filter, UASB, soil filters, reactive filters, trickling/bio-filter, stabilisation pond, sub-surface wetlands, irrigation
Biological II <i>(N & pathogen reduction)</i>	Nitrification-denitrification in wetland or sandfilter, maturation pond, crop production, mulch beds, overland flow
Chemical <i>(P, pathogen, metal removal)</i>	soil filters, reactive filters, precipitation pond, irrigation
Sludge management	Thickeners, centrifuge, sieve, fermentation, lime, drainage bed, reed beds, composting, lime stabilisation

Karin Tonderski, Linköping university, Sweden

The table above lists how the different processes shown in the preceding diagram translate into a number of different technical solutions available for treatment of wastewater in general. All wastewater treatment methods generate sludge to varying extents, and hence we have also included methods to manage the sludge in a safe way. This is a crucial component of the entire wastewater management system.

In the first column, we list in italics the prime purpose of the respective treatment process in terms of which substance in the wastewater it is primarily designed to reduce. SS (Suspended Solids) refers to particles in the wastewater. BOD (Biological Oxygen Demand), COD (Chemical Oxygen Demand) and TOC (Total Organic Carbon) are three different analytical methods for measuring the concentrations of organic matter in wastewater.

In this module, we present in more detail the techniques that are most relevant for greywater treatment and their pros and cons. As will be seen, it is common to combine two or more of the techniques to achieve a certain treatment goal. The desired maximum levels of pollutants should preferably be determined based on the intended use of the treated water and related sludge. This requires knowledge about the content of the greywater.

The second column lists both high-tech techniques (such as UASB and centrifuges) requiring a lot of operational skills and electrical energy input, and more low-tech techniques such as stabilization ponds, wetlands and sandfilters. It is thought to be implicit that high-tech techniques are more suitable for larger, centralized systems where the management costs can be shared among many connected households, whereas for small villages or individual households, robust simple easily managed techniques are more suitable. However, there are low-tech solutions fit for large system (e.g. polishing effluent in wetlands) and recent technical developments have produced advanced technical solutions for individual households. The various techniques are therefore rather neutral as for the number of users.

Screens and grease traps

4.7- 4



Jan-Olof Drangert, Linköping university, Sweden

Fat, oil and grease (FOG) are usually rinsed with hot water and/or detergent in the sink. However, when the greywater cools down, the FOG becomes solid again and separates itself from the liquid. The left-hand picture shows a simple grease trap serving a single household. The warm greasy water passes a plastic sieve or screen where larger particles are trapped. The greywater collects in the compartment underneath, and slowly cools and overflows to the bigger compartment in front. The grease floats to the surface and has to be removed. A pipe next to the bottom leads the effluent to a soil filter or other treatment. The grease trap must be large enough to provide a long enough retention time for the FOG to solidify and float up to the surface. Information about designs and dimensions of grease traps can be found in Crites and Tchobanoglous (1998), Sasse (1998), and Tchobanoglous (1991).

If allowed to enter wastewater pipes, FOG readily adheres to the inner surface of the piping material. Many states in the US therefore require grease traps for kitchens in institutions and restaurants to control the solidification where it can be taken care of before it reaches the sewers and eventually the treatment plant.

Similarly, an individual household benefits from having a grease trap to reduce the amount of FOG before treating and reusing the greywater. Householders can also wipe off and dispose of organics on cooking utensils and plates together with other organic waste instead of flushing them away in the sink. Such a source-control measure is easier than emptying the sieve. The picture on the right shows an ordinary plastic colander (red colour) being used to catch solid particles before the greywater flushes down through a kind of a trickling filter which contains material such as coconut fibres with lots of microorganisms and worms that feed on FOG and other organic matter (Section 2.7- 4). The floating FOG is regularly removed and can be put on a compost heap, in a biogas reactor or in an incinerator.

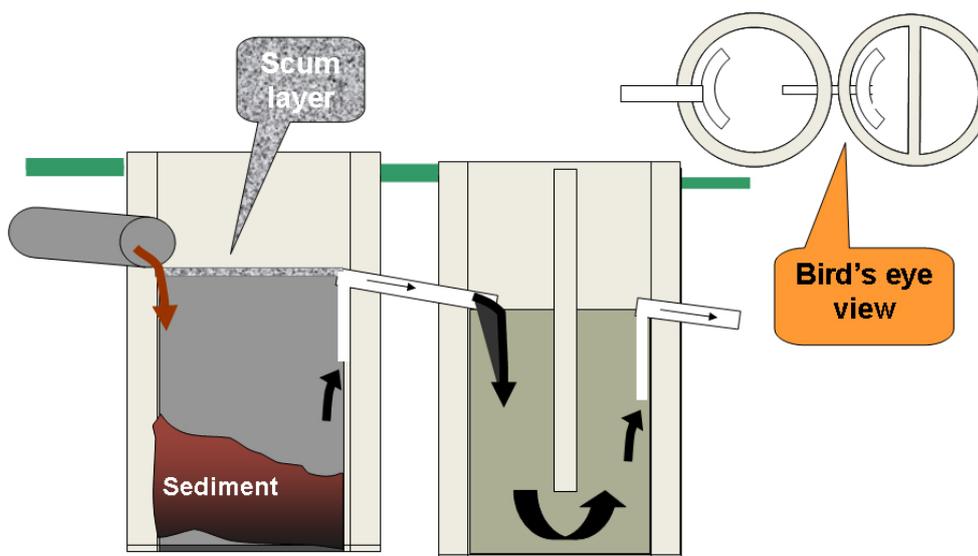


Sedimentation of particles and flotation of grease in greywater can also be achieved in a pond. In warm climates, so-called stabilisation ponds for wastewater treatment are commonly used as a cheap method to treat mixed wastewater (e.g. [Mara, 2004](#)). Typically, a series of ponds ranging from anaerobic, facultative, and maturation ponds (shallow ponds densely populated with algae, see Section 4.6–13) ensures a considerable reduction in the levels of pathogenic organisms and solids (due to sedimentation), organic matter (decomposition) and chemicals (adsorption and precipitation). Heavy metals, if present, may be precipitated as sulphides in the first anaerobic pond (see Section 4.6–19). Organic chemicals are to a large extent decomposed as the retention time in a pond system is quite long (5–20 days in each pond); however more persistent organic chemicals will most likely remain a problem. Stabilisation ponds can also achieve significant removal of microorganisms, and cyst and helminth eggs ([Jimenez et al., 2010](#)). These remain in the pond sediment and may be viable for several years in the sludge. Viruses are removed through adsorption onto solids, including algae, and remain in the pond sludge as these solids settle. Bacteria are removed in the same way and in addition they can be inactivated by several mechanisms including UV light (see Section 4.6- 12) and a pH value above 9.4.

If a pond is used as the first step in greywater treatment without first going through a grease trap and screen, it may develop into an aesthetic problem with an unpleasant smell and appearance. An alternative is a covered sedimentation unit, i.e. a septic tank.

Simple septic tank

4.7- 6



Jan-Olof Drangert, Linköping university, Sweden

A septic tank is an anaerobic system consisting of one or two interlinked watertight tanks of concrete, plastic or fibreglass buried in the ground. The greywater should ideally flow with as little turbulence as possible, since this can disturb both the settling and the flotation of suspended solid material. Perforated wide inlet pipes (see bird's eye view) entering just below the water surface (main picture) reduce turbulence and prevent flocs and scum from entering the drainage or subsequent stages in the treatment. Many countries provide national standards for septic tank design and dimensions. The permeability of soil and the groundwater level are important restrictions for siting septic tanks ([British Geological Survey, 2003](#)).

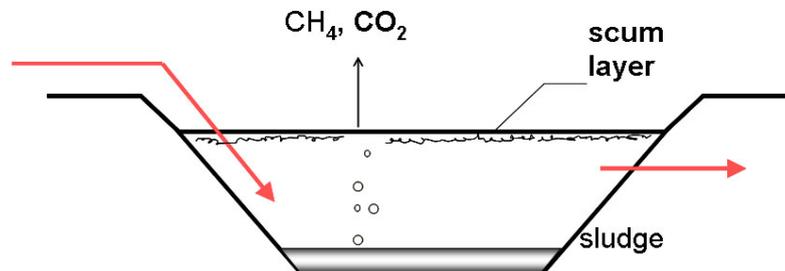
A properly designed and maintained septic tank is odour-free and has a long life. It removes FOG and solids, which either float to the surface or sink to the bottom. It removes 30–75 % of the biodegradable solids from the greywater and thus 25–70 % remains in the effluent. The efficiency is higher when the flow rate is low, and the designed retention time should be at least 24 hours. If the tank is divided into 2–3 chambers, or if a second tank is added, the fluid will be forced to move down and up an extra time and the treatment will further improve (see the tank to the right in the picture). Pathogen removal in septic tanks is always poor and, like metal removal, depends on the efficiency of particle removal ([WHO, 2006](#)). Thus, both effluent and sludge need further treatment.

A person contributes the equivalent of about 70 kg of dewatered sludge annually to the wastewater. Removal of sludge (desludging) is vital for a well-functioning septic tank, and should be done every year depending on the dimensions. If the sediment is allowed to fill a large section of the tank the raw greywater will simply pass over the surface of the sludge directly to the exit pipe, so quickly that no or very little sedimentation, flotation and decomposition takes place. There is no reason not to empty the sludge since the anaerobic process rapidly re-starts – provided some sludge is left in the tank.

Septic tank effluent is the most frequently reported cause of groundwater contamination ([USEPA, 1977](#)) and it is estimated that in the USA only 40% of existing septic tank systems function correctly. Since every part of the tank is buried in the ground, owners are less likely to worry about the functioning unless there is a blockage pushing the effluent back to the bathroom or up through the inspection hole. Therefore, municipalities often stipulate annual compulsory emptying of tanks.

Anaerobic pond

4.6-7



Karin Tonderski, Linköping university, Sweden

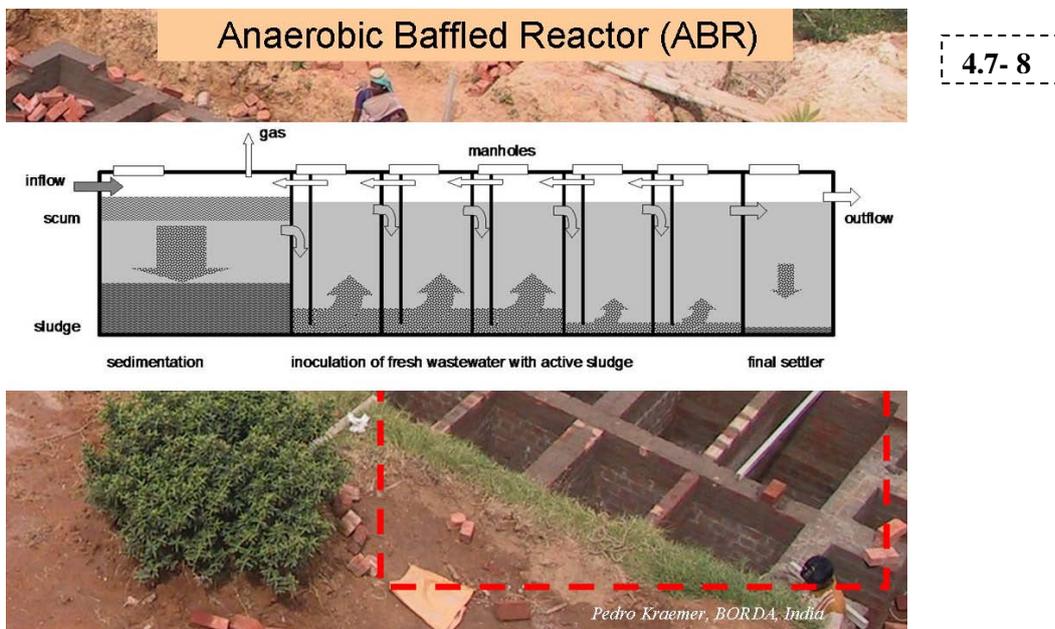
If the wastewater is rich in organic matter (high BOD concentration), an anaerobic pond can be used for pre-treatment (picture above). Such a pond is usually 2–4 m deep depending on the local soil and groundwater conditions. The dominant treatment processes are sedimentation of particles and decomposition of organic matter with a copious production of ‘biogas’ (CO₂ and CH₄ bubbles in the picture). An anaerobic pond functions much like an open septic tank, with the same groups of bacteria involved. This means that the required environmental conditions for successful treatment are the same. However, an open pond will be more sensitive to cold temperatures than a buried septic tank, and the decomposition rate will decrease as the temperature drops below zero. Another important parameter is the pH of the wastewater, which should preferably be > 6.5. A high pH also minimises the risk of releasing the strongly smelling gas H₂S, since this gas is in equilibrium with the dissolved ions H⁺ and S²⁻ and the proportion of H₂S gas decreases with an increasing pH. If the pond emits a bad odour, lime or soda ash can be added to raise the pH and get rid of the smell. However, experience has shown that odour problems are rare if the sulphate (SO₄²⁻) concentration of the household water supply is below 500 mg/l. The sulphate concentration is one factor that limits how much S²⁻ can be formed (since one molecule of SO₄²⁻ yields one S²⁻ ion), and therefore the risk for smell drops at lower sulphate concentrations. Sulphate is part of naturally occurring minerals in some soils and rocks, and hence the sulphate concentration in ground water depends on the local geological conditions.

The organic loading, λ_v , of a pond is measured in g per m³ per day, i.e. the BOD concentration (mg/l) multiplied by the retention time [daily wastewater flow (m³/day) divided by the volume of the pond in m³]. Typically, the load measured as BOD₅ in g/(m³ day) should be in the range

$$100 \leq \lambda_v \leq 400$$

If the loading is less than 100, the pond cannot be anaerobic, and if it is higher than 400 there is a risk of odour problems.

A properly designed and maintained anaerobic pond can remove around 70 % of the organic matter and suspended particles in the wastewater. However, for small-scale wastewater treatment, a septic tank is a preferred solution, since the risks of smell and fly breeding in the scum layer are lower in a covered septic tank than in an open anaerobic pond.



4.7- 8

The Anaerobic Baffled Reactor (ABR) combines a septic tank with a series of baffled compartments. A baffle forces the wastewater to flow from the bottom upwards to the surface without additional energy being applied. This is a technology often used for housing complexes and institutions such as hospitals and schools where a competent operator is available (see Module 4.4).

ABRs remove organic and settleable matter from the greywater more efficiently than a conventional septic tank. The suspended solids settle primarily in the first sedimentation (septic) tank and less in the following compartments (drawing above). Each inlet is at the bottom so that the flow of wastewater disturbs the settled sludge and it whirls up in the water body (activated sludge). The greywater flow and gas bubbles bring the sludge particles towards the outlet at the top, while they try to settle because of their higher density. The flow velocity must be regulated so that the anaerobic sludge does not leave the reactor with the effluent (max upflow velocity is 0.6 m/h). According to the design the particles should stay as a floating blanket, where the bacteria attached to the particles have easy access to the surrounding wastewater and can degrade its organic content. As in other treatment systems involving sedimentation, the sludge has to be removed annually.

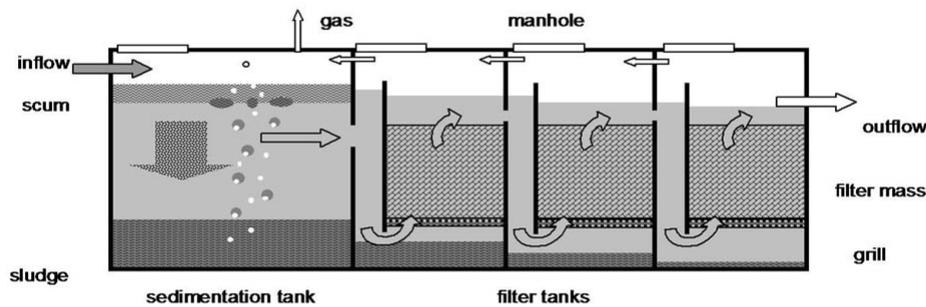
This treatment system is very resistant to hydraulic and organic shock loads, and is easy to operate. Unlike treatments based on filtering processes, ABRs are not at risk of clogging. Even difficult-to-degrade organic matter is affected, thanks to the long retention time (48–72 hrs). Such organic matter may be hydrolysed after some time and then further degraded (4.4-12). The result is that 50–90% of the organic matter is removed. Gases are generated in the ABR, including carbon dioxide, methane, hydrogen sulphide and nitrogenous gases, and they dissipate into the atmosphere unless collected.

The treated effluent is clear but not hygienically safe. The reactor is not designed to reduce pathogens or metals and chemicals in the wastewater, although there is some reduction since ions and microorganisms may be attached to the settled sludge particles. Hence, the operator is exposed to health risks when desludging, but they can protect themselves easily.

If only greywater is treated, the effluent is not rich in plant nutrients and may be connected to a sewer or drain. If the wastewater also contains human urine and faeces, a large proportion of the nutrients remain in solution and will be in the effluent when it leaves the ABR. In any case, the effluent water may be good for irrigation and some fertilisation, with more health precautions required when the greywater is mixed with blackwater ([WHO, 2006](#)).

Anaerobic Filter (off-plot biogas system)

4.7- 9



Courtesy of Pedro Kraemer, BORDA, India

Anaerobic filters consist of a sedimentation tank followed by one or a series of tanks with fixed filters made of gravel, slag or plastic elements. One system may serve a single or many households, as well as treat wastewater from institutions and public conveniences. The aim is to trap particles, reduce BOD levels and catch the gases released from the tanks. The influent must contain enough organic matter in dissolved form to produce gas, but too high concentrations of suspended particles will cause clogging of the filters. In practice a volumetric load (measured as COD) varying between 1 and 3 kg/(m³ day) is used (Henze et al., 2002: pp. 311–317). This is different from a biogas digester which requires a dry matter content of 10%.

The filters require a continuous flow. Both upstream and downstream flow modes are possible. However, an upstream flow (picture above) is preferable since it reduces the risk of fixed biomass being washed out from the tank. The efficiency in reducing the BOD level is influenced by retention time, and up to 80 or 90 per cent reductions can be achieved if the water is processed for 1–1.5 days.

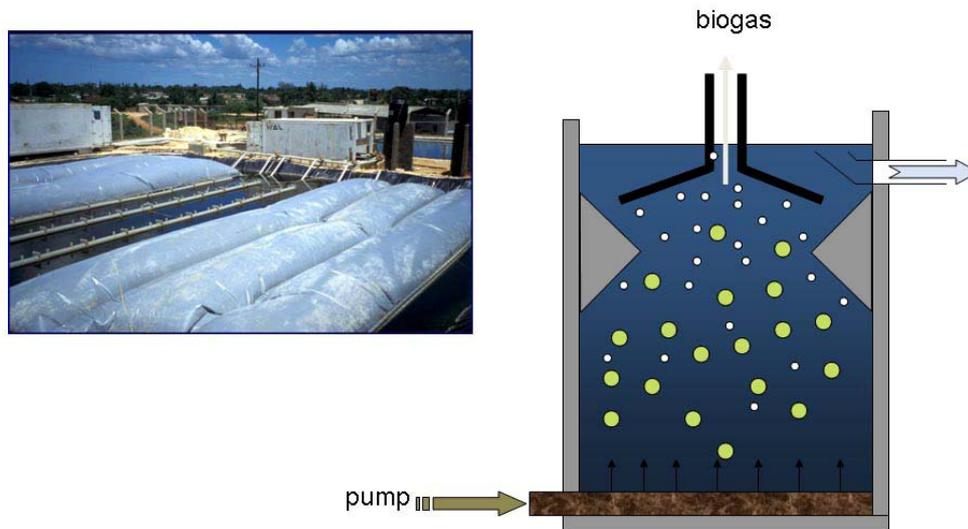
Microorganisms grow on the filter material and make up a so-called biofilm. The surface area of the filter material may be 90–300 m² per m³ of filter material. The smaller the pores, the larger the area of contact with microorganisms and wastewater. However, there has to be a balance between filter material size (typically 12 to 55 mm) and organic load since small pores have a tendency to clog when receiving high loads of organic matter. Clogging means that dissolved and non-settleable solids adhere to the filter material or simply physically block passage ways. Both situations diminish the permeability of the filter. The water flow in the remaining open pores increases and tends to wash away the bacteria. Also, high local speeds provide little time for the bacteria to degrade organics and poor effluent quality may result.

The filter material has to be washed regularly to keep the pores open. This can be done by back-flushing or by physically removing the sand/gravel/plastic, washing it and putting it back. If operated correctly, anaerobic filters are reliable and robust. However, the start-up time is more than half a year because that is how long it takes for the biofilm to develop fully. It has been suggested that anaerobic microorganisms can be added to improve the decomposition of organic matter in the filter.

‘Biogas’ (mainly CO₂, CH₄, H₂O and H₂S) is produced in all tanks and collected in a gas storage tank. Therefore, all the tanks have to be airtight to prevent gas from escaping. However, the gas pressure fluctuates and therefore it is not ideal for household appliances. An alternative is to have a flame burning to prevent the methane from reaching the atmosphere.

UASB Reactor

4.7- 10



Jan-Olof Drangert, Linköping university

The upflow anaerobic sludge blanket (UASB) reactor is an advanced treatment method invented in the 1980s. It comprises a single tank (right picture) into which wastewater is pumped from the bottom and flows through an anaerobic sludge bed where the microorganisms degrade the organic material and release biogas (methane and carbon dioxide; white spots). The sludge bed is composed of microorganisms that form small granules (yellow spots) with a high sedimentation velocity, which makes them resist wash-out from the tank. The upward motion of the gas bubbles provides a self-sustained mixing mechanism.

The process works on the assumption that the speed of the upstream flow is high enough to prevent sludge from settling but low enough to keep the sludge granules in the reactor. The tank has deflectors in the upper part (see right-hand picture) which prevent granules and flocs from escaping. The operator controls the electric pump to maintain a flow velocity of 0.6 to 0.9 m/h to optimise the contact with microorganisms. This is a delicate task that requires the support of monitoring equipment. The UASB technology is therefore developed and used in industrial and communal wastewater treatment plants (left-hand picture).

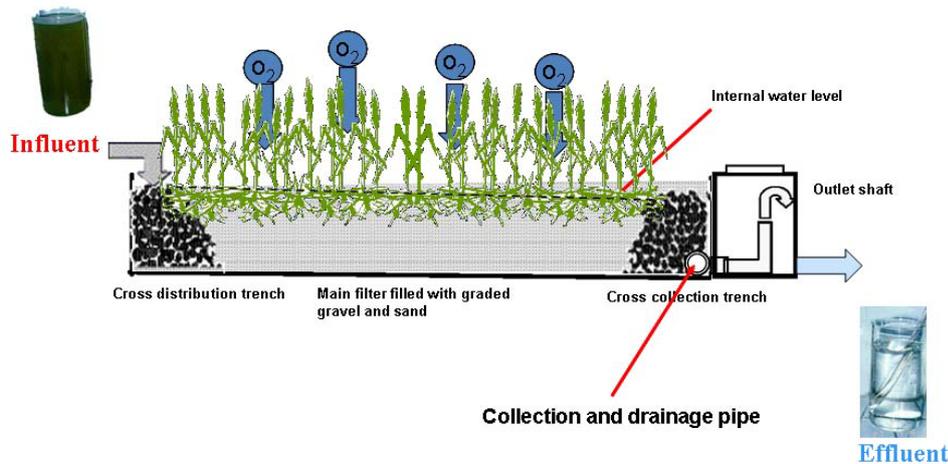
The reactor can produce a better effluent than a septic tank despite a smaller reactor volume, and can remove 85 to 90 per cent of the organic matter measured as chemical oxygen demand (COD).

Biogas is generated and collected in a storage tank, and hence the construction must be airtight. The gas pressure fluctuates and is therefore not ideal for household appliances.

At the start-up phase anaerobic granules of floating organic matter must be formed. When in operation, the UASB is stable because the granules grow heavier and their settling speed increases. The aim is to retain the maximum possible amount of sludge in the reactor to affirm a high Solid Retention Time (SRT) of about 50 to 100 days or more, while at the same time having a short Hydraulic Retention Time (HRT). Basic design principles are given by [Ghangrekar](http://www.waterandwastewater.com/www_services/ask_tom_archive/design_of_an_uasb_reactor.htm), at: www.waterandwastewater.com/www_services/ask_tom_archive/design_of_an_uasb_reactor.htm

Horizontal subsurface flow wetland

4.7- 11



Courtesy of Roshan Shrestha, UN-Habitat, Nepal

Another predominantly anaerobic treatment system is the subsurface horizontal flow wetland shown in the picture above. Subsurface flow wetlands are low-maintenance systems suitable for treatment of small flows of wastewater, and the simplest type to operate is the horizontal flow wetland with gravity flow. The pre-treated wastewater (grease and particle reduced) is spread evenly with a perforated cross-distribution pipe along one edge of the wetland bed. Depending on the local soil and groundwater conditions, the bed may be sealed with clay, concrete or a rubber sheet to prevent seepage. The effluent flows horizontally through the bed composed of gravel and/or sand and planted with a wetland plant species tolerant of anaerobic conditions. Microorganisms grow on the gravel/sand grains and feed on organic matter in the wastewater. Plants modify the physiochemical environment in the rhizosphere in different ways that stimulate the microbial communities (see Section 4.6–21). One example is that some oxygen is transported from the leaves to the roots and leaches out to the surrounding bed material, thus stimulating some aerobic decomposition of organic matter in the otherwise mainly anaerobic bed. The plants also take up some of the nutrients in the wastewater, though this process is usually of minor importance for the overall nutrient removal. Plants also increase the water losses, particularly in warm climates where the plant evapotranspiration rate may sometimes be higher than the inflow rates, resulting in zero effluent discharge.

Another advantage with a subsurface flow wetland, in contrast to ponds and open-water wetlands, is that mosquito breeding is not an issue, since no flooding of the sand/gravel occurs in a well functioning system. A reliable performance also in harsh winter conditions has been demonstrated as long as freezing of the distribution system is prevented, though cold weather may cause the nitrogen removal efficiency to drop. One of the most important design aspects is that the hydraulic load must be adapted to the hydraulic conductivity of the bed material.

Experience shows that such systems effectively reduce concentrations of organic matter (BOD/COD) and particles (80–90%), but the N removal is lower due to the predominantly anaerobic conditions that prevent nitrification ([Vymazal, 2005a](#)). Generally, a better treatment is achieved with a finer grain size, but there is a trade-off between grain size and the amount of water that can flow through the bed. Hence, the size of the bed depends on the grain size of the material versus the amount of water that needs to be treated per day.

If the bed is filled with a material with a high P sorption capacity, phosphorus can also be removed. However, eventually the material will be saturated with P and will need to be replaced to maintain the removal capacity. Such P saturated material may be a good source of phosphorus for fertiliser, provided that no toxic compounds are discharged from the household. If toxic metals are discharged into the wastewater, they may be adsorbed to the material and hence make it less suitable for use in agriculture.

Although the effluent from such treatment systems is clear, it may still contain potentially pathogenic organisms. The reduction of common indicator bacteria is relatively low, around 1–2 log units ([Vymazal, 2005a](#) and [b](#)).

The advantage of a horizontal subsurface flow constructed wetland is that it provides a high treatment level (of organic matter and suspended particles) of effluents compared to a septic tank alone, and can do so with minimal management. Increasingly, such wetlands are also used for treating stormwater prior to discharge into groundwater or surface waters. However, the very variable water flow may become a problem as each subsurface flow wetland has a definite upper limit to how much water that can pass through the bed per hour, depending on the permeability of the material.

Some guidance how to design and construct a subsurface wetland is given in [4.7-12](#).

Construction of horizontal flow wetlands

4.7- 12



Karin Tonderski, Linköping university, Sweden



The left-hand picture above shows a horizontal flow wetland where the unit is constructed from concrete with a sealed bottom. A common alternative is to use a rubber sheet to protect the groundwater from any infiltrating wastewater. The inflow part (top right) is filled with coarse gravel or stones followed by a finer sand as the main treatment material in which wetland plants are planted. Planting is usually done manually by digging up pieces of roots and rhizomes with intact shoots from natural wetlands and transferring these to the upper layer of the constructed wetland. It is important to keep the upper bed layer wet without flooding the new shoots completely during the first weeks after planting. This is done by regulating the level of the outflow pipe. *Diluted* wastewater from the source to be treated can be discharged into the wetlands immediately after planting, but it is important to maintain relatively aerobic conditions in the bed material until the plants are successfully established.

Useful information on the design of horizontal flow, vertical flow and surface flow (see Sections [4.7- 15](#) and [4.7- 21](#)) for constructed wetlands is available from the US EPA at:

http://www.epa.gov/owow/wetlands/pdf/Design_Manual2000.pdf

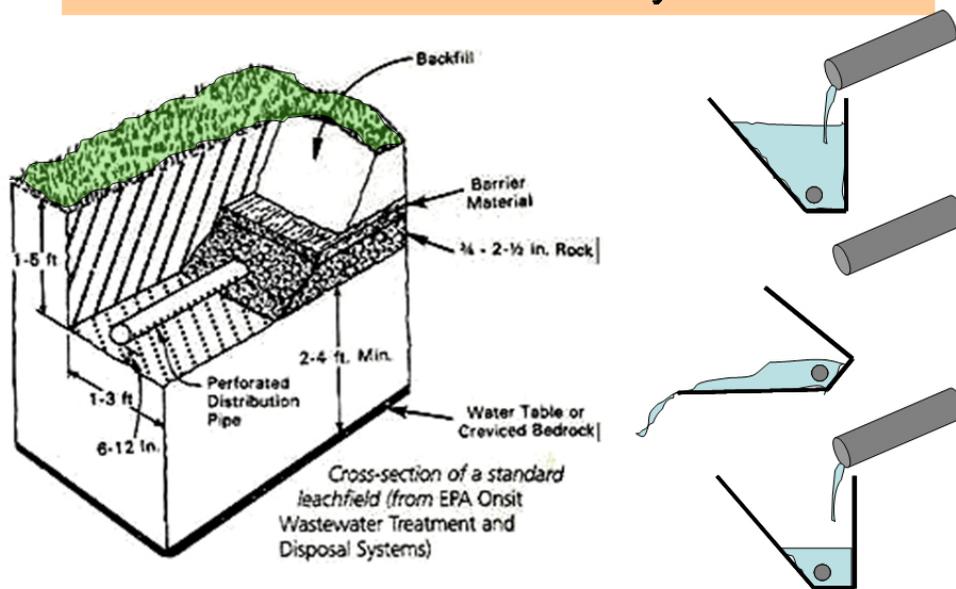
The UNEP Division on Technology, Industry and Economics also provides a design manual for subsurface flow wetlands and stabilisation ponds based on experiences from East Africa at:

http://www.unep.or.jp/ietc/Publications/Water_Sanitation/ponds_and_wetlands/index.asp

This site also contains a mathematical design model.

Soil filters – leachfield or mound systems

4.7- 13



Jan-Olof Drangert, Linköping university, Sweden

Soil filters, or leach fields, are common in many parts of the world. They are similar to the subsurface horizontal flow wetlands presented earlier. However, unlike horizontal flow wetlands they are aerobic treatment systems as the wastewater is applied on top of the soil (or filter sand) via a perforated distribution pipe. The water then percolates vertically to a deep groundwater table. A well functioning soil filter depends on a good distribution of the water to maintain the soil in an unsaturated state. That is, the load of water should be low enough to ensure that the distribution pipe and soil layer are not completely flooded.

The cross-section of a leachfield (left picture), shows a perforated distribution pipe (with a slight downward slope) embedded in a layer of coarse gravel or stones. The 40–60 cm deep trench is backfilled with soil on which grass can grow. The gravel layer is covered with a barrier material such as geotextile that keeps the backfilled soil separated from the gravel and also prevents infiltration of stormwater to some extent. The pipe distributes the pre-treated greywater evenly over a subsoil surface (bottom of the trench), which allows the greywater to infiltrate and percolate further down in the soil profile. If the greywater is not pre-treated in a septic tank or other system, the leachfield will soon clog. Should the local soil be unsuitable for wastewater treatment (e.g. if the grain size is too small), a sand filter can be constructed with a collector pipe at the bottom. In many countries, percolation to groundwater is not allowed, and instead the treated effluent is collected in a perforated pipe deeper down in the soil and discharged to a ditch or other surface water body (the appropriate method depends on the topography).

Several treatment processes are at work in a leachfield. The greywater enters in batches, preferably by gravity, from a septic tank or other treatment process. This allows for some drying and aeration between the batches. The vertical flow of the water allows for some aeration of the gravel layer and a rich microbial flora and fauna zone develops in the subsoil layer just below the pipe. Here, micro-organisms feed on the organic matter in the greywater and decompose it into carbon dioxide, water and inorganic ions of nutrients and metals (aerobic decomposition). Due to the predominantly aerobic conditions, the treatment of suspended solids and reduction rates of organic matter (BOD/COD) are very high, and oxidation of some ammonium to nitrate is also commonly observed. As in all wet soils, anaerobic micro-sites will also develop, where the decomposition may result in some production of hydrogen sulphide gas and even methane (anaerobic decomposition).

A tipping device can supply the wastewater in intervals. It is made of an open “bucket” with a rod fixed onto it from both sides (round grey in the right picture). The position of the rod is such that when water reaches a certain height, the bucket becomes heavier on the left-hand side and flips over and empty into the leachfield. A spring turn the bucket back to the original position, and water fills again.

If the dimensions of the leachfield are appropriate, the subsoil beneath the distribution pipe and gravel layer does not clog. If the application rate of wastewater and/or organic matter content is too high, the soil infiltration capacity may decrease due to the growth of microorganisms and the accumulation of organic matter in the soil pores. Hence, the life expectancy of the leachfield depends on the greywater composition and the load. A rule of thumb is that sieved subsoils can manage a daily load of about 30–60 litres per m² depending on the sand content, whereas lower loads have to be applied in finer soils. Similarly, the recommended hydraulic load on a sand filter depends on the grain size of the sand (see [US EPA 2002](#), pp. 4–12) and on the concentration of organic matter in the wastewater. Leachfields for greywater only (without excreta) are usually 35–40 % smaller than fields for ordinary wastewater. The money saved by installing a wastewater-only leachfield can pay for the installation of a compost toilet.

The removal of phosphorus depends on the physical and chemical composition of the material in the bed (e.g. local soil, a filter sand or a material designed for high P removal). If a soil or sand layer with high P sorption capacity is used, the phosphorus concentration in the effluent can initially be less than 1 mg per litre, but will increase as the soil gets saturated with phosphorus. Metals will also largely be adsorbed to the soil particles in the filter, as discussed in Sections 4.6–9 and 4.6–10.

For information about the siting and design, the reader is referred to Siegrist, Tyler and Jenssen ([2000](#)) and USEPA (2002). Information can also be found in Chapter 5 of the WHO guidelines.

Trickling filter

4.7- 14



Jan-Olof Drangert, Linköping university, Sweden

A trickling filter comprises a medium of rocks, gravel or shredded PVC bottles on which microorganisms can attach. The pre-treated wastewater is sprayed over the medium. A trickling filter is often part of the treatment processes in a wastewater treatment plant, typically with a rotating distribution pipe (left-hand picture). The jet can be directed a bit sideways so that the pipe moves around without other energy input. A household unit which requires no electricity can be constructed in which the water is spread over the media with a perforated immobile pipe (right-hand picture).

The upper part of the medium is wetted and wastewater percolates through the aerobic lower part. Thus, aerobic microorganisms are active in decomposing organic matter into water and carbon dioxide (see Section 4.6–16). The microbial biofilm on the medium gradually grows thicker until the outer part eventually sloughs off and flows away in the treated effluent. Typically, a trickling filter is followed by a clarifier or sedimentation tank to separate and remove this microbial biomass, i.e. sludge. Further treatment and use of the sludge is discussed in Section 4.7

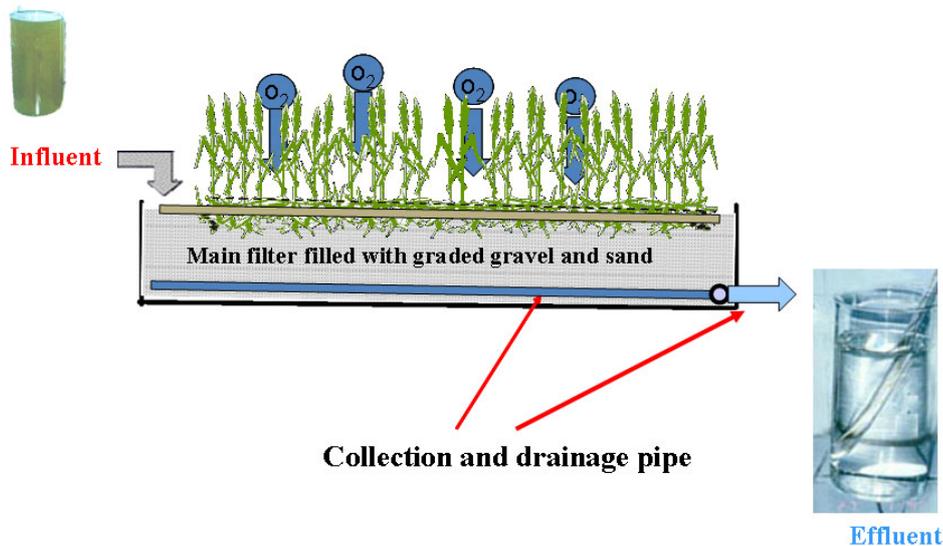
The capacity to reduce the level of organic matter (BOD, COD) is good, and with an even distribution of the wastewater on the media, some nitrification of ammonium to nitrate can also be achieved. With respect to reduction of pathogens, the US EPA states that there is a 1–2 log unit reduction of faecal coliforms, and that the reduction is lower than with activated sludge treatment. Studies of parasite removal suggest 75–90 % removal of protozoa. In general the removal increases at lower filtration rates (i.e. lower loads).

Trickling filters are not designed to trap heavy metals but they are partly adsorbed on particles and microbial biomass and may settle in the clarifier.

Large trickling filters require trained staff to monitor the distribution pipe and the accumulation of sludge and check the growth of filter flies (alternatively drain flies).

Vertical flow subsurface wetland

4.7-15



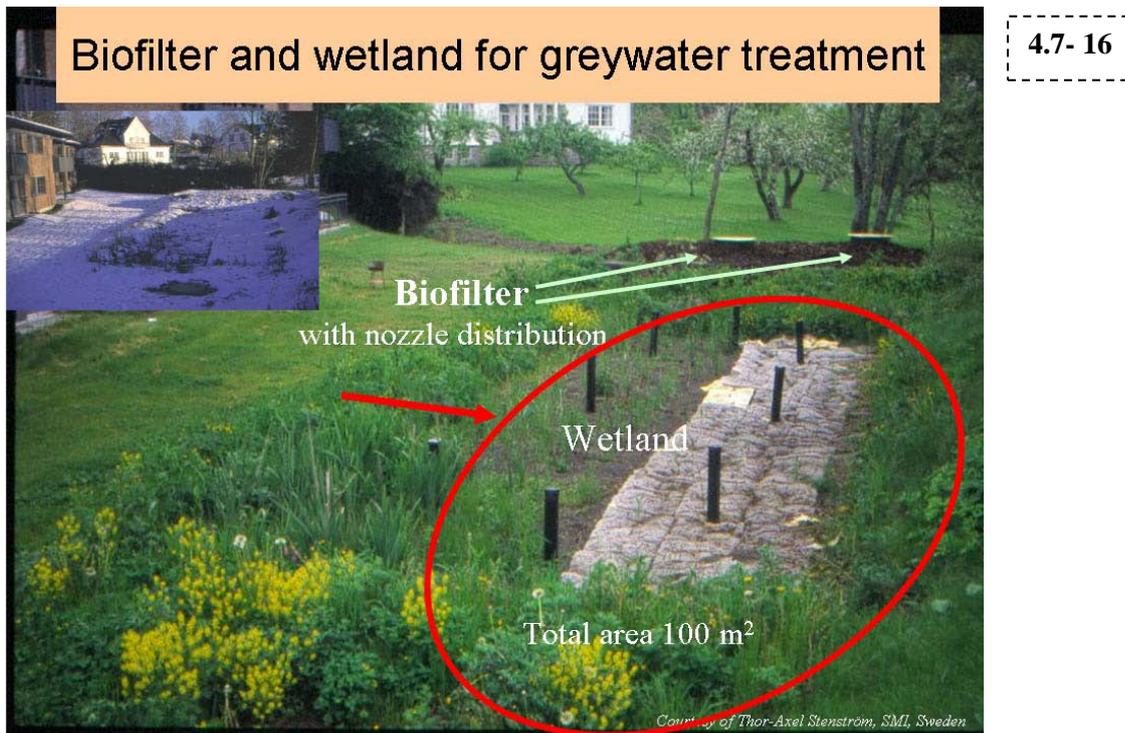
Courtesy of Roshan Shrestha, UN-Habitat, Nepal (revised)

Vertical flow subsurface wetlands might be viewed as a soil filter planted with wetland plants. Pre-treated greywater (e.g. in a pond or septic tank) is evenly distributed on, or just below, the coarse sand at the top of the filter (upper brown pipe in picture above). The greywater percolates by gravity down through the sand and gravel filter material, where aerobic and anaerobic microorganisms feed on its organic content. Usually, the unit is sealed with clay, concrete or a rubber sheet at the bottom, and the treated effluent is collected in a perforated drainage pipe (blue pipe).

The processes in operation are the same as in soil filters (see Section [4.7-13](#)), but in addition the root zone of the plants contributes to the treatment. The evapotranspiration by plants may be quite high in warm climates, and this turns the system into a low or zero discharge unit. In colder climates, the dead plant biomass serves as an insulating layer during the cold months of the year. Also, some plants have an efficient gas transfer system, and leach some oxygen to the microorganisms in the root zone.

The treatment results are similar to those of a sand filter, with very high removal of particles and organic matter, and with some oxidation of ammonium to nitrate. The log reduction of bacteria is usually 2–3 units, which means that the treated effluent is not hygienically safe and some care is needed when reusing it. With a proper sizing, the filter will not clog, but as for soil filters, a high load of wastewater or organic matter may result in flooding of the filter. If this happens, a resting period needs to be observed, or even an exchange of the upper layer of sand that has clogged. There is no need to remove sludge, but as the functioning of the wetland depends on the removal of particles and grease in a pretreatment unit such as a septic tank, regular maintenance of the sedimentation unit is an integrated part of its operation.

The rule of thumb for a sieved soil is that about 30–60 litres of wastewater can be applied per m² per day. With a suitable sand, even higher application rates have been used without problems. To achieve a high nitrogen removal, sand filters, trickling filters and vertical flow constructed wetlands need to be combined with a more anaerobic unit. This could be a horizontal flow wetland (see Sections [4.7-11](#) and [4.7-12](#)) or a surface flow wetland with a lot of plant biomass ([4.7-22](#)). In such combined systems, a very high removal (3–6 log units) of indicator bacteria has also been recorded, ([Vymazal, 2005a, b](#)).



Student dormitories at an agricultural university outside Oslo, Norway are connected to a greywater treatment wetland serving 48 students. The system consists of a pre-treatment and pump unit, a so-called biofilter for further pre-treatment and a subsurface horizontal wetland with an area of 100 m². The treated water finally percolates down to the deep groundwater..

The biofilter consists of two domes with nozzles spreading untreated greywater uniformly over a filter surface area of 6 m² (like the trickling filter described in Section 4.7–15). The filter material is grains of lightweight aggregate 2–10 mm in size, but other materials such as shredded plastic bottles, or crushed coconut shell could be used to house the (aerobic) microorganisms. If there is a favourable topographical gradient, the pump and nozzles could be replaced by a siphon or a tipping bucket (4.7-13). This part of the treatment system is designed for aeration, decomposition of organic matter and bacteria. Loading rates up to 1 m per day on a biofilter can achieve treatment results of more than 70% reduction of the BOD level and a 5-log reduction of indicator bacteria – that is, a 99.999 % reduction (Jenssen & Vråle, 2004).

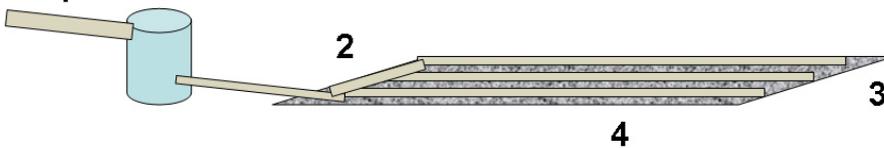
The resulting low concentration of BOD allows a higher load to be injected in the subsequent wetland or infiltration system. Here, the breakdown of contaminants in the pre-treated water is done mainly by aerobic bacteria and fungi that receive oxygen through the black aeration pipes (see picture). Nitrate formed in the biofilter is denitrified to nitrogen gas. The final effluent has very low counts of bacteria (WHO, 2006), and the level of nitrogen is of drinking water quality. If a material with a high P sorption capacity is used in the wetland bed, the phosphorus concentrations in the effluent can be <1 mg/l, but the concentrations will gradually increase as the sorption capacity of the bed is exhausted. When that happens it has to be replaced with new material. Any metal contained in the wastewater is also subject to adsorption to the bed materials.

The treatment unit works in the wintertime with temperatures well below zero degrees (small picture, top left). However, the biological treatment of nitrogen compounds is less efficient in winter time.

Common problems in soil filters

4.7- 17

1. **Overloading** (suspended solids, high BOD, water)
2. **Uneven distribution** (over surface, over clay)
3. **Failure in drainage** (waterlogging, roots)
4. **Wrong choice of sand and gravel** (texture, mineral particle shape)



Jan-Olof Drangert, Linköping university, Sweden

The picture above indicates where problems commonly occur in soil filters and subsurface flow wetlands. By overloading the system (1) with wastewater and/or suspended material and/or organic matter the subsequent treatment steps become less efficient or non-functional. The system design must therefore be correct, or else the application rates must be lowered or the pre-treatment improved.

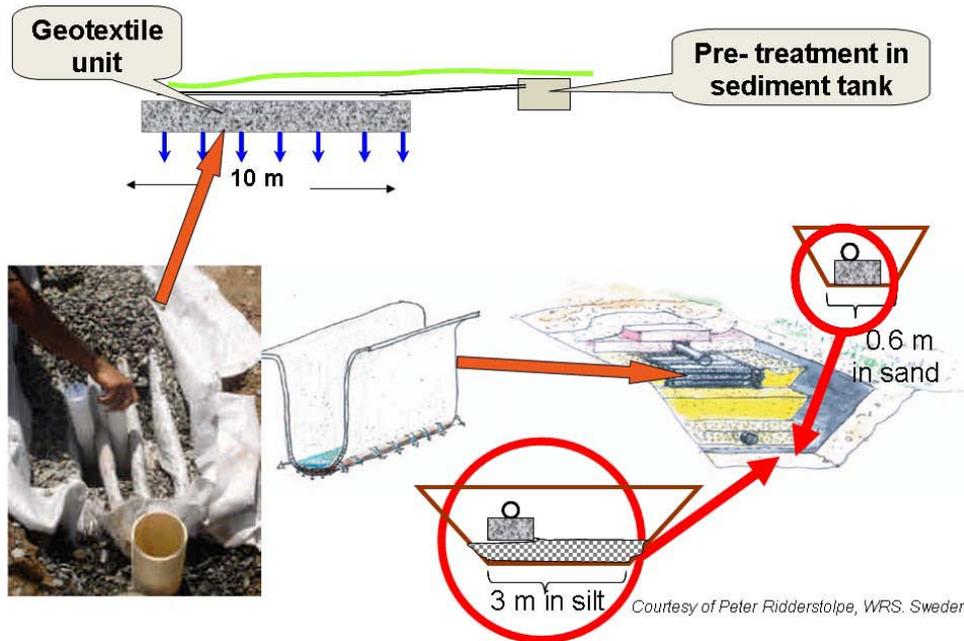
In order to make use of the whole treatment unit, the greywater should be evenly distributed over the soil or filter bed (2). If not, it is likely that the active parts will be overloaded and clogged and/or anaerobic conditions will develop, thus reducing the treatment capacity.

Even if the first two steps function well, problems may arise due to drainage failure (3). Such failure can be caused by waterlogging from below or due to very heavy rains, which prevent a continuous flow of wastewater. Another common problem is that roots grow into the pipes and eventually block them. In such cases, the pipes have to be taken up and cleaned or replaced.

The fourth common problem arises from rapid clogging due to an inappropriate choice of sand and gravel in the filter bed (4). The remedy is to change the sand or to extend the pre-treatment and the size of the bed.

Improved distribution using controlled clogging

4.7- 18



It is possible to control the clogging problem common to filter systems by introducing an artificial geotextile filter. The left part of the picture shows the principle of this technique using a folded geotextile to create a structure containing ‘valleys’ and ‘ridges’. As the bottom of a ‘valley’ becomes clogged with biofilm, the pre-treated wastewater level increases. Infiltration continues along the sides of the ‘valleys’ and the filtered water percolates through the underlying filter media. In addition, this distribution system helps buffering against large flow variations, and a rising water level during high flows will not negatively impact the infiltration of water into the underlying soil/sand.

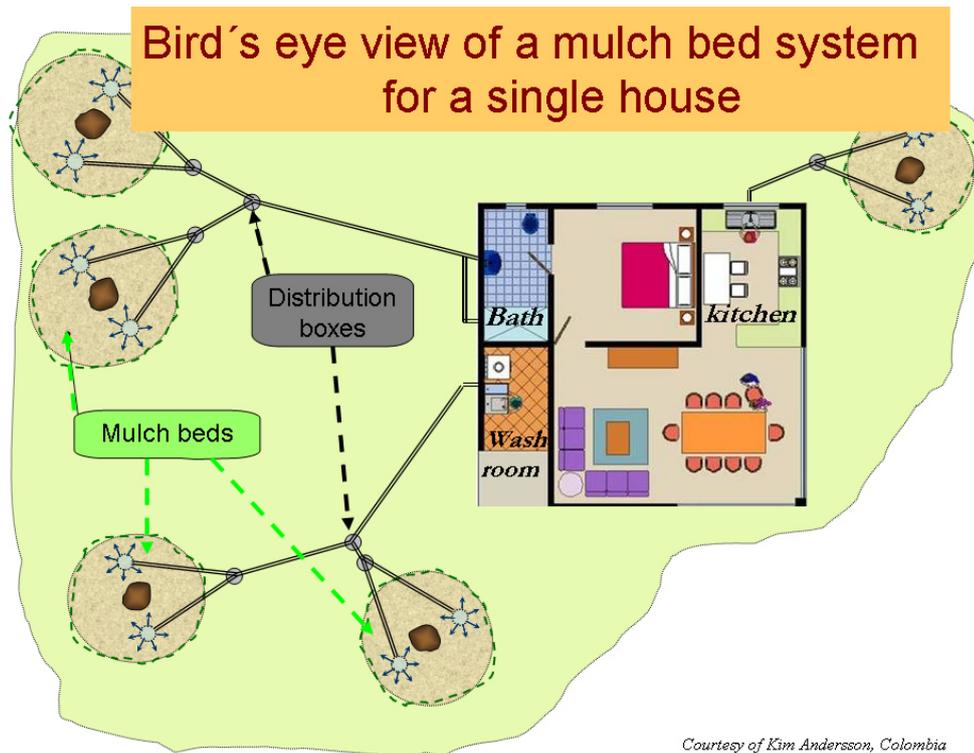
The active, predominantly aerobic, microflora and fauna on the geotextile and in the upper soil/sand layer decompose the organic matter in the pre-treated wastewater.

A perforated pipe on top of the geotextile filter unit distributes the pre-treated water (top picture). A prefab geotextile unit with a typical dimension of 0.2m x 0.6 m x 1.25 m has a capacity of about 125 litres per 24 hours (e.g. EKOTREAT Compact Filter; [Ridderstolpe, 2004](#)). Eight units in a row can form a 10 metre-long filter with a total capacity of 1 m³ per day. This is what a household of some 10 persons will need. Evaluation results for treatment of greywater in Sweden show that the removal of organic matter (measured as BOD) and suspended solids was > 97% and >73%, respectively (Table 1 in [Gustafsson, 2005](#)). The concentrations of indicator bacteria were below the limits for swimming water quality (< 1000/100 ml for faecal coliforms, and < 300/100 ml for faecal streptococci) at most of the sampling occasions.

The wastewater percolates through the geotextile down to the bottom of the trench. The infiltration capacity of the underlying natural soil determines how large the trench area must be. In sandy soils (right-hand picture) a 0.6 m wide trench is enough to infiltrate the percolating water. In all other soil types one has to add a 0.3 m gravel bed between the geotextile unit and the bottom of the trench to help spread the effluent and simultaneously treat it a bit more. For instance, in a silty soil the trench needs to be 3 m wide, and in clayey soils 5 m wide to have enough capacity to infiltrate all effluent from the geotextile. The infiltrated soil pores will not become clogged since the wastewater contains very little solid material after leaving the geotextile. Also, the water is evenly distributed over the soil which is very beneficial for the infiltration. Compared to a gravel bed the infiltration area can be reduced by a factor 2 to 5!

Bird's eye view of a mulch bed system for a single house

4.7- 19



Courtesy of Kim Andersson, Colombia

A garden can be used as a treatment unit for greywater in a system which irrigates and fertilises at the same time. Small mulch beds around trees and bushes serve as the treatment units (see next section). A grid of plastic pipes distributes the greywater to the mulch beds (picture above). A mulch bed system is flexible in the sense that one can add or reduce the number of beds fed by the distribution boxes according to the greywater flow rate and available space. For instance, if the household has a clothes washing day, they can open the pipes to all the mulch beds to manage the extra load of greywater efficiently.

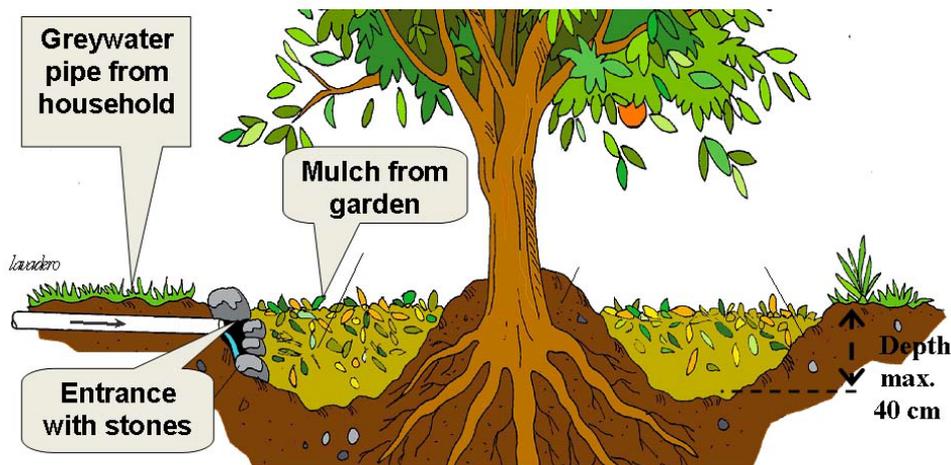
With such a system, there is no need to pre-treat greywater from bathrooms and washing rooms. However, if a lot of fat or oil is used for cooking, the risk of clogging can be avoided with a small grease trap attached to the kitchen pipe. The source-control alternative for the homeowner is to be careful and throw FOG in the solid waste bin. Residents are likely to be careful with what they add to the greywater simply because they know that certain substances will clog or harm their garden or cause extra work.

The plant roots may act as an efficient barrier against the uptake of non-essential metals. However, one important exception is cadmium, which is a non-essential metal that can pass through the root barrier due to its resemblance to zinc. Cadmium is toxic to humans and needs to be limited in wastewater going onto agricultural land (WHO, 2006).

Most other metals will not be taken up by plants unless they have reached a threshold concentration in the soil and the metal is in a mobile form – that is, dissolved in the soil solution and not adsorbed to soil particles. The interaction between heavy metals and crops is complex due to antagonistic interactions that affect their uptake by plants (Drakator et al., 2002). Typically, metals are bound to soil at pH levels above 6.5 and/or if the soil has a high organic matter content (see Section 4.6–10). If the pH is below this value, and all organic matter in soil is saturated with ions, metals become mobile and can be absorbed by crops and can also contaminate water bodies.

Mulch bed filter

4.7- 20



3-10 litres of greywater per m² per day

Courtesy of Kim Andersson, Colombia

A mulch bed consists of mulch from garden refuse (twigs, leaves and woodchips) which is placed in a shallow (< 40 cm) dug trench around a tree (see picture) or berry bush. The untreated greywater enters through a filter of stones to prevent larger particles from entering the mulch bed. Greywater usually enters intermittently because of the use pattern of household water and is spread around the circular trench. This means that both aerobic and anaerobic conditions are present in the bed and this provides environments suitable for different species of bacteria, fungi and worms. The surface area of leaves and other organic material is very large and can host huge numbers of microorganisms (see Section 4.6–24). They oxidise the organic matter into water and carbon dioxide which dissipates to the air, and some of the CO₂ is taken up by the tree leaves (see Section 4.6–21). When a gush of greywater enters the bed, the oxygen is rapidly depleted due to the intensive decomposition, turning part of the bed into an anaerobic system where even nitrogen gas and hydrogen sulphide may be formed. Such reduced chemical compounds are likely to be oxidized when oxygen diffuses into the bed during the resting periods between inputs of greywater, thus minimizing the risk of bad smells.

The effluent infiltrates down to the root zone where additional decomposition takes place. Much of the water, nutrients and other particles are taken up by the plants. The system can be designed in such a way that the amount of effluent which infiltrates further down into the soil is minimal.

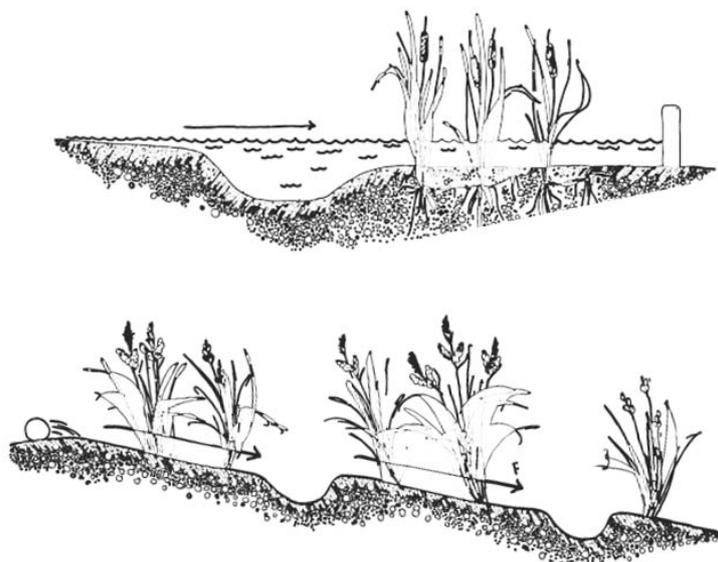
The problem of clogging is managed by adding or replacing the mulch regularly when it has decomposed enough. If necessary, rainwater can be diverted by a circular mound around the mulch bed to make sure aeration is sufficient in the mulch bed material.

The capacity of a mulch bed around a tree ranges from 3–10 litres of greywater per m² per day depending on the tree's water demand and the porosity of the soil. As in all other soil and sand systems discussed, organic chemicals will be degraded in the soil, if they are degradable, and most metals and phosphorus will be retained in the soil through adsorption until the sorption capacity is exhausted. The reduction of potentially pathogenic organisms in the wastewater is comparable to the levels achieved in the soil infiltration systems discussed above (see Section 4.7-13), or better if the amount of water distributed per surface area is kept low.

The removed mulch is composted before being applied as a soil conditioner in the garden.

Wetland irrigation and overland flow

4.7- 21



Karin Tonderski, Linköping university, Sweden

In some cases, a surface flow wetland can be a suitable system for the treatment of greywater. A surface flow wetland consists of a shallow pond with wetland plants, commonly with a variable depth profile (0.2–1 m deep) to support both submerged and emergent plants (top picture). Submerged plants contribute oxygen to the water because photosynthesis takes place in the water. This also promotes colonization by invertebrates (e.g. water insects) that act as predators on mosquito larvae, and thus help to control a potential problem. In tropical areas where malaria is a problem, care must be taken not to create a breeding ground for mosquitoes by using improperly designed ponds or surface flow wetlands for greywater treatment. A suitable pre-treatment is sedimentation and grease removal. If not removed, grease may form a film on the water surface that prevents oxygen diffusion.

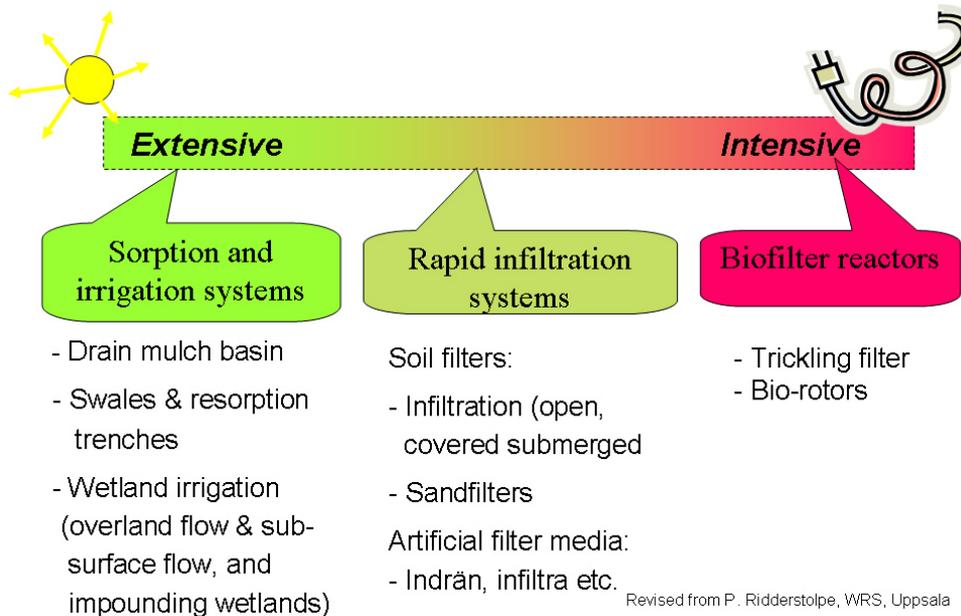
The advantages of a surface flow wetland are that it is easy to construct, can be constructed in areas with heavy soils unsuitable for infiltration, there is no need to purchase filter sand, there is no risk of clogging, and it requires little maintenance. A disadvantage is that a large surface area is needed. A typical load is 20–70 litres per m² per day in wetlands used for polishing wastewater from conventional treatment works. Loads in the lower range are suggested for greywater treatment to create a longer retention time. The main challenge is to ensure that the water flows over the entire wetland area to prevent short-circuiting and a drop in the water retention time. It has been observed that the removal of indicator bacteria increases with higher retention times, and removal of 1–2 log units for faecal coliforms and streptococci has been observed with retention times of 5–10 days ([Vymazal 2005b](#)).

In some areas of the world, a paddy field could serve to treat greywater and at the same time reuse both the water and nutrient resources. However, as mentioned above, proper pre-treatment involving sedimentation and a grease trap is a prerequisite, as is awareness that the effluent is not hygienically safe.

Sometimes, an overland flow system is used as part of a system to treat wastewater (bottom picture). This is a lightly sloping vegetated field where the water flows as a shallow “film”. The effluent is applied along the entire width of the field, for example through perforated pipes or a ditch, and is collected beneath the field for further treatment or reuse. Particles are filtered out in the dense vegetation. As the water flows relatively quickly over the soil surface, intensive oxygenation takes place and this promotes decomposition of organic matter and nitrification of ammonium, as well as some removal of bacteria. Overland flow systems have commonly been used to promote oxygenation and in combination with other methods, such as surface flow wetlands. In such cases, the loads have varied between 100 and 200 litres per m² per day.

Aerobic biofilters and energy

4.7- 22



This picture is a summary of the treatment systems that have been discussed so far, illustrating their dependence on energy input other than the sun. Mulch basins and surface flow wetlands are usually constructed without any external energy input, with gravity distribution of the effluent. At the other end, bio-rotors and rotating trickling filters require electrical energy to circulate the water and the rotors. It is also implicit in this picture that the land area requirement to treat a certain volume of wastewater increases as we move to the left in the figure.

Removal rate of microorganisms in various wastewater treatments (log units)

4.7- 23

Process	Bacteria	Helminths	Viruses	Cysts
Primary sedimentation:				
Plain	0-1	0-2	0-1	0-1
Chemically assisted	1-2	1-3	0-1	0-1
UASB		1-2		
Activated sludge	0-2	0-2	0-1	0-1
Sub-surface flow wetland	1-2	2-6	2-3	0-2
Aerated lagoon	1-2	1-3	1-2	0-1
Slow sand filtration/infiltration	2-3	3-6	2-3	3-6
Disinfection	2-6	0-1	0-4	0-3
Waste stabilization pond	3-6	1-3	2-4	1-4

Large variations in practice due to quality of management

Sources: WHO, 2006 and Jimenez et al., 2010

A long-standing aim of treatment of wastewater is to get rid of pathogens which can cause health problems for staff, farmers, and families reusing greywater. The table above shows the ranges of expected reductions of various microorganisms in different wastewater treatment units. If the treatments units are in a sequence the corresponding reductions add up to the total reduction. From a groundwater quality perspective, it may be mentioned that the eventual soil infiltration also has a high efficiency and bacteria and viruses are reduced by more than 2 logs and parasitic protozoa more than 3 logs, which is similar to the reduction in a traditional wastewater treatment plant ([Siegrist, Tyler, Jenssen, 2000](#)).

The various treatment processes reduce the number of microorganisms in the wastewater in a variety of ways: die-off, photooxidation, predation, suffocation, and poisoning. A 1-log reduction means a 90% reduction and a 6-log reduction is 99.9999% reduction. This may look impressive, but if there are millions of pathogens and a species is infectious to humans in very small doses, not even 6-log reduction may be enough to prevent disease from occurring (see Chapter 3).

A tolerable additional disease burden of $<10^6$ disability-adjusted life year (DALY) per person per year applies to drinking water quality (see Section 3.1). The same risk level is set for wastewater use in agriculture. This translates into the following reduction levels of excessive risks of viral, bacterial and protozoan infections:

- a 3–4 log unit pathogen reduction by the wastewater treatment system is required to protect the health of those working in wastewater-irrigated fields
- a 6–7 log unit pathogen reduction is required to protect the health of those consuming wastewater-irrigated food crops.

These levels can be achieved by a combination of 3–4 log unit reductions by wastewater treatment and an additional 2–4 log unit pathogen reduction by post-treatment health protection control measures such as those listed in Section [4.7–25](#) (crop washing, peeling, and cooking). Furthermore, the treated wastewater should contain < 1 human intestinal nematode egg per litre to protect workers, farmers and consumers from helminth infections ([Mara and Bos, 2010](#)).

E: Treatment of sludge

4.7- 24

Limits	Cd	Cr	Cu	Hg	Ni	Pb	Zn
Old	20-40	-	1,100- 1,750	16-25	300-400	750- 1,200	2,500- 4,000
New	5	150	400	5	50	250	600

New limits on organics proposed under Option 3 from EU (2008)

PAH	6 mg/kg dry matter
PCB	0.8 mg/kg dry matter
PCDD/F	100 ng ITEQ/kg dry matter
LAS	5 g/kg dry matter
NPE	450 mg/kg dry matter

- All treatment processes produce sludge, be it much or little

-Choice of treatment according to kind of reuse

- We need to de-toxify our chemical society

Source: EU, 2008

All wastewater treatment processes produce sludge and the amount depends on the treatment process employed. Sludge is composed of organic matter (i.e. dead and living microorganisms) and any non-decomposed solids that were in the wastewater to begin with and, if flocculent have been used as part of the treatment process they will appear in the sludge. A large proportion of any metals and potentially harmful organic molecules that have been discharged into household wastewater end up in the sludge either because they are adsorbed to the organic particles or are precipitated with the sulphides formed in an anaerobic sedimentation unit.

In large treatment units, some of the sludge composition is known but most is not, simply because the authorities and utilities only monitor a few substances. It is typical in today's chemical society that the focus is on production of goods that are saleable, while little attention is paid to what happens to these products after use. The number of professional chemists employed by industry to develop new chemical products exceeds by a thousand times the number of chemists in environmental agencies and water utilities. The battle against polluting chemicals is therefore lost before it starts, but improvements can be achieved when industries produce non-toxic, rapidly degrading compounds (see Section 4.5–15).

So far, it is Nature which has rung the alarm bell in the form of dead birds or dolphins, or dying sea beds, coral reefs and fish. Only when confronted by such warnings is society motivated to make radical changes. With 9 billion rather well-off people expected to inhabit the globe by 2050, pollution problems will escalate. Nature will hit back more often and more fiercely at the output of the chemical society. This new situation requires tough new measures in order to implement the already existing good framework documents on zero emissions, the precautionary principle, the polluter pays principle, and outcome-based regulations (see 2.3–5).

The huge volume of sludge from cities and towns, where the wastewater is mixed from numerous different sources, makes it tempting for utilities and decision-makers to spread the sludge on farmland. It is well known that it is better to return it to the soil than to water bodies where it does not belong. However, even if the sludge is "certified" to be spread on soil, it may still contain too many unknowns that will accumulate in the soils. If nothing else, the precautionary principle should be applied to prohibit chemically polluted sludge to be used in agriculture. Incineration of sludge from large wastewater treatment utilities is becoming a more common solution but this requires very well designed and operated incineration plants with advanced systems for cleaning the exhaust fumes.

Today, “new” substances are regularly discovered in the sludge, but the manufacturers of the products which contain them are certainly aware of them. For instance, nano-particles from diesel engines and from wear and tear of linings of car breaks can be detected today with measuring instruments. Nano-particles of silver originating from stockings and other clothes are found in sludge. The silver has been added to kill off bacteria and reduce bad odours. Silver particles easily spread through the environment, and are accumulated in the soil and water bodies.

The main remedy has to come from improved source-control measures which reduce the chemical content of **all** household products. Manufacturers should be obliged to prove that their new products are not harmful but easy to handle after use. Furthermore, separating different horizontal water flows (see Section 4.5–3) from each other also facilitates source control. In the long term there are options for source-separating systems which enable the recovery of valuable compounds at the source (urine-diverting toilets etc.). Households must sort hazardous waste and not discharge it in their greywater.

The European Union is engaged in lowering the permissible levels of various compounds (see top table above). This is a complex task due to a genuine lack of knowledge, and the fundamentally different priorities of governments and industry. For example, a background report to the EU on the use of sludge in agriculture states that it is:

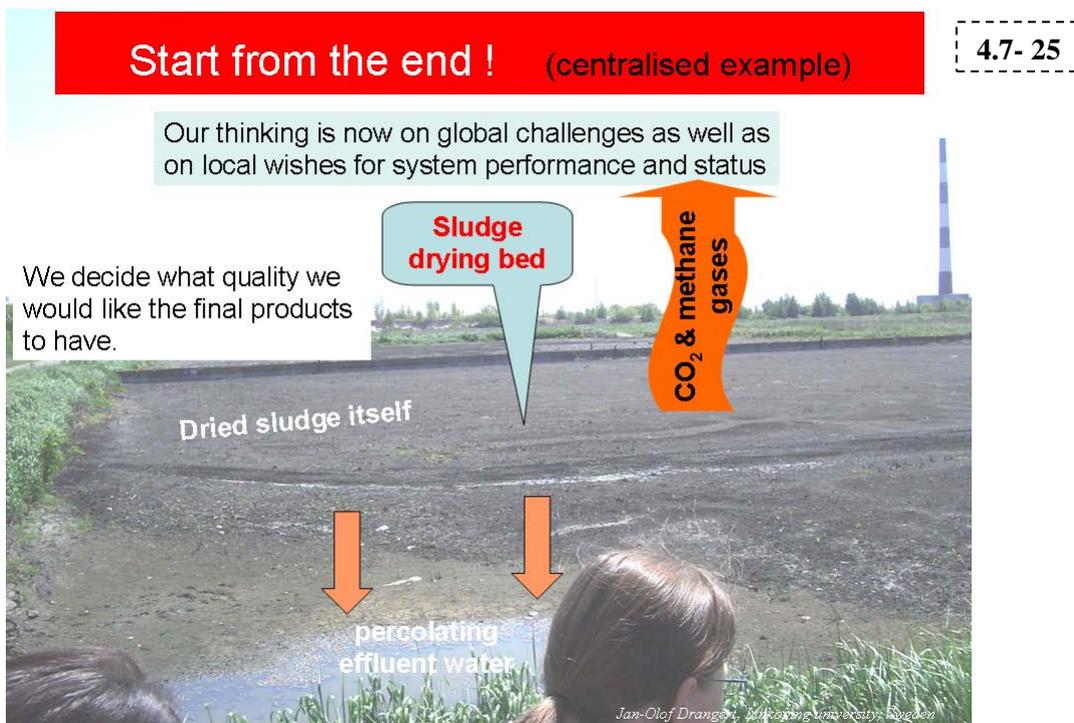
important to recognise that the potential environmental and health benefits resulting from more stringent sludge standards in Options 2 and 3 (as well as the total ban of land use in Option 4) are not quantified here, nor will they be in the final CBA unless respondents can provide relevant data ([EU, 2008](#)).

This demonstrates the limitation of basic data on which decisions are based. The precautionary principle could fill this gap by prohibiting the production or sale of products (see 2.3-5). However, the report states – without supporting evidence – that “the Sewage Sludge Directive (1986/278/EEC) could be said to have stood the test of time in that sludge recycling has expanded since its adoption **without** environmental problems.” This sweeping statement is made at a time when many new hazardous compounds are being developed and put in consumer products. Most chemical compounds are new and it may take a generation or two to reach concentrations where human health and the environment will be affected ([Qadir and Scott, 2010](#)). The rapid expansion of our chemical society will aggravate the problem of lack of data and the regulatory system is likely to slip out of public control.

If the new lower limits for **heavy metals** are enforced (see upper table above), all EU member states except Denmark will have to lower their legislative limits. The case of Denmark shows that the new limits are achievable, though they may not be adhered to in reality. No limits were imposed on **organics** in the 1986 legislation, and the proposed limits in the table (lower table) include PCBs (sum of the polychlorinated biphenyls component numbers 28, 52, 101, 118, 138, 153, 180), PAHs (sum of polycyclic aromatic hydrocarbons: acenaphthene, phenanthrene, fluorene, fluoranthene, pyrene, benzo(b+j+k)fluoranthene, benzo(a)pyrene, benzo(ghi)perylene, indeno(1, 2, 3-c, d)pyrene), PCDD/F (Polychlorinated dibenzodioxins/ dibenzofuranes), LAS (Linear alkylbenzene sulphonates) and NPE (comprises the substances nonylphenol and nonylphenoethoxylates with 1 or 2 ethoxy groups). About 50% of the present sludge is expected to be unacceptable under the new limits ([EU, 2008](#)).

Another new limit concerns methane emissions. Measures will require that sludge shall be stabilised (or pseudo-stabilised) to reduce degradability during field-site storage or after land spreading to reduce methane emissions, and to reduce odours.

The global society needs to de-toxify in order deal with the problem of toxic sludge.



This picture shows one of the end-products from a wastewater treatment plant – a drying bed for dewatering sludge. The purpose is to save on energy by this natural drying before the sludge is incinerated or transported elsewhere. What happens in the sludge bed? Aerobic and anaerobic processes are active and the former creates a lot of carbon dioxide which is emitted into the air and taken up by plants during the photosynthesis. Anaerobic digestion in the bottom part of the sludge layer produces methane gas which is an aggressive greenhouse gas. A productive way to take care of the methane would be to collect it in one way or another (see Module 4.4).

The damp sludge is not only evaporating water but also percolating leachate into the ground. The remedy is to place an impermeable sheet at the bottom of the excavation just as is done in well managed landfills. This will protect the groundwater, but the leachate has to be treated further to avoid the discharge of excess nutrients and other chemicals into the environment.

The dried sludge itself contains the remaining organic material and any number of chemicals including heavy metals and persistent organic compounds that were contained in the wastewater and not decomposed in the treatment. The presence of each of these tens of thousands of compounds should be at low levels before the sludge is returned to farmland. To ensure that no net accumulation of such compounds occurs in the soil, it is also important to control the *amount* of sludge used on each field.

Small decentralised sludge treatment units also release gases and leachate water. The sediment or sludge in a septic tank releases carbon dioxide and methane gases to the atmosphere as part of the degradation of organic material. If the greywater is not very polluted by potentially harmful substances, the sludge can be applied to farmland where microorganisms will degrade it mostly aerobically and less methane will be emitted.

A sustainable society must focus its actions on the sources of sludge and gas emissions. By not mixing urine, faeces and greywater, cross-contamination by metals and other hazardous substances can be avoided. Urine and faeces can be treated with negligible losses of nitrogen and methane (see Module 4.4), and the nutrients can be applied on farmland without causing health problems. With proper source control, the greywater can also be kept relatively free from unwanted and potentially toxic chemicals, thereby allowing reuse of a valuable water resource.

Pathogen reductions achieved by selected health-protection measures

4.7-26

Control measure	Reduction (log units)	Comments
Wastewater treatment	1-4	Usually achieved reduction but depends on type and functionality of the treatment system
Drip irrigation: - low-growing - high-growing	2 4	Root crops and crops such as lettuce that grow just above but partially in contact with soil. Crops such as tomatoes and fruit trees not in contact.
Pathogen die-off	0.5-2 per day	Die-off on crop surfaces between last irrigation and consumption, depends on sunshine, crop type etc.
Crop-washing: - with water - disinfection	1 2-3	Washing salad crops, vegetables and fruit with: clean water. Weak disinfectant and rinsing in clean water.
Produce peeling	1-2	Fruits, cabbage, root crops.
Produce cooking	6-7	Immersion in boiling or close-to-boiling water.

Source: Bos, R., Carr, R. and Keraita, B. 2010.

A major concern for backyard irrigation is the possible spread of pathogens from greywater to humans. Such health risks from pathogens should be considered before, during and after wastewater application. There is no need for advanced measuring of greywater quality; practising some basic safety measures is sufficient (WHO, 2006:41). For instance, if a household washes diapers in the sink or washing machine, the greywater will have a high load of pathogens, and if possible such water should be discharged in the ground in a secluded part of the garden.

There has to be a trade-off between the advantages and disadvantages of greywater use and the best solution for each situation should be sought. The WHO guidelines suggest a multiple-barrier approach for achieving the health-based targets. These include combinations of several measures such as safe irrigation practices and washing food as part of its preparation.

As mentioned in Section 4.7-23 various treatment processes reduce the number of microorganisms in the greywater in a variety of ways. These include die-off, predation, suffocation and poisoning. The table above shows reduction rates of bacteria, viruses, helminths, and cysts in irrigation systems and during food-handling activities. Remember, a 1-log unit reduction means a 90% reduction and a 6-log reduction means a 99,9999% reduction. The WHO guidelines use a pathogen reduction of 6-7 log units as the performance target for unrestricted irrigation to achieve the tolerable disease burden of <math><10^6</math> DALYs per person per year (see Module 3.1). The table demonstrates that combining minimal wastewater treatment, drip irrigation and washing vegetables after harvesting can easily achieve a 6 log unit reduction (Bos, Carr and Keraita, 2010). The ability to select different combinations also allows people living under varying conditions to choose the combination that suits their time, pocket and lifestyle.

Short fact sheets and policy briefs for different stakeholder groups can be found at: www.who.int/water_sanitation_health/wastewater/usinghumanwaste/en/index.html

Environmental and Human health hazards

4.7- 27

	Pathogenic microorganisms	Chemical compounds
Numbers	A few hundreds: handful unknown added each year	100,000 man-made; Hundreds new man-made added each year
Exposure	In food, by skin penetration, insect bites, in aerosols. -	In food, by skin penetration, on skin, in aerosols. Water bodies, soil accumulation
Dose-response	One up to millions; a few to millions needed for infection	Nano- to microgrammes; small amounts that may accumulate.
Vulnerable	Humans but not environment. Mainly children & elderly	Both humans and environment. All, but particularly babies
Barriers	Wash hands & veggies, no finger in mouth, heat food, etc	Only biodegradable, caution with medicines, effluents to soil

Jan-Olof Drangert, Linköping university, Sweden

The picture summarises and compares the hazards that pathogens and chemical compounds pose to human health and the environment. It follows WHO's risk-assessment approach based on numbers or concentrations of each hazardous item, exposure, dose-response relationship, vulnerability, and barriers ([WHO, 2006](#)). A first observation is that pathogens are present in nature, while chemical compounds are manufactured and supplied by companies. Thus, chemical compounds become more sensitive to discuss, and a lot of lobbying is involved.

The health hazards caused by pathogenic organisms (viruses, bacteria, helminth and protozoa) and chemical compounds (heavy metals, persistent organic compounds, nutrients etc.) have different features. Microorganisms are present in nature and perhaps a handful of new strains or species are detected every year. Chemicals are present in nature, but almost all the ones that humans are exposed to are made by humans. Altogether there are some 100,000 compounds in our chemical society, out of which 30,000 are used by households. Industries add hundreds of new compounds to products every year. These new ones are known, but their harmful effects not necessarily known.

Human exposure to pathogens is mainly through ingested food and water, skin penetration (snails), bites (mosquitoes), and inhalation of aerosols. Humans are exposed to chemical compounds in the same way, and also on the skin (from chemicals in clothes, etc.). Chemical compounds can have negative impacts on the environment such as pollution of water bodies, and accumulation in the soil and in plants. Chemical compounds can enter the food chain and move upwards to humans.

The exposure varies widely from hundreds of viruses or helminths to hundreds of millions of bacteria. The infectious dose, however, varies from a few *Ascaris* eggs to millions of enteric coliform bacteria and the effect is seen within a short period of time. Not all pathogens can multiply, and they may predate and die off. Chemical compounds are usually available in small doses, but some of them can accumulate in the human body and in the environment and eventually reach hazardous concentrations. The effects are only seen after long exposure. Some heavy metals (cadmium, lead etc.) can affect the human body functions and can persistent organic matter such as PCBs and some pesticides. The symptoms can be difficult to diagnose, however.

Pathogens cause disease and death among humans and other animals, but have little direct impact on the environment. Children, the elderly and the undernourished are the most vulnerable people. Chemical compounds, on the other hand, can have a negative impact on both animals and the environment. Babies are most vulnerable to acute or short-term toxic exposures (e.g. blue baby syndrome from excess nitrate) while carcinogenic and other disease-causing chemicals affect other age groups. Water bodies are sensitive in the short-term and the atmosphere and soils are affected over longer periods.

Protection against health hazards can be described as barriers, and they include washing hands and vegetables before eating, boiling food and water if necessary, heating left-over food before eating, no fingers in the nose or mouth, and using ORT to cure diarrhoea. Barriers against chemical hazards include being restrictive with medicines, avoiding breathing polluted air, washing new clothes before wearing them etc. However, most barriers against chemicals are long-term remedies which involve protecting the environment, such as only using biodegradable body care products and detergents, collecting and destroying expired medicine and left-over hazardous chemicals, and disposing of wastewater on soil rather than water bodies.

A stark difference between pathogens and chemicals emerges from this. The barriers for pathogens are controlled by the individual and the barriers do not require consumers to stop buying any products. Barriers to chemical compounds, on the other hand, require collective action to ban certain compounds and replace them with safe products to protect both our health and the environment. However, all of us also have an individual responsibility to change our consumption patterns. This involves decreasing our general consumption of status symbols, and restricting the purchase of products containing substances with unknown or negative health and environmental impacts.

The contrasting features of pathogens and chemical hazards call for radically different approaches to remedy the threats they pose.

Summary of strategies to improve wastewater treatment and nutrient use in agriculture

4.7- 28

Principle: *mix as few flows as possible*

- Organic ≠ other solid waste
- Stormwater ≠ sewage
- Industrial ≠ household wastewater
- Black toilet water ≠ greywater
- Faeces ≠ urine

J-O Drangert, Linköping University, Sweden

The best practice is to recirculate treated or untreated greywater. As an environmentalist put it: *'grow it away, don't throw it away!'* The new approach to wastewater treatment is to optimise the nutrient content in the effluent and outsource the treatment task to farmers and gardeners. A strong argument, apart from resource conservation, is that householders will only dispose of items in the sink which they know are beneficial to their garden and, more importantly, they will prefer to dispose of undesirable matter in the solid waste stream.

There are many ways to 'grow away' greywater and sludge. Sludge can be reduced and ideally avoided if water is mixed with environmentally friendly products only. Organic matter and oil, grease and fat should be disposed of as solid organic matter and composted. The microbial content of wastewater will decrease drastically if human faeces are not added to the water, and the die-off of microorganisms is quick if faecal matter is treated by storing it. The hygienised faecal matter is a good soil conditioner that improves soil properties and it contains plant-available nutrient ingredients. Irrigation with recycled greywater has to consider flow rates, soil conditions, and greywater characteristics (see Module 4.5). There are barriers and precautions to take to minimise the health hazards posed by recycled water. Stormwater typically contains large water volumes with low concentrations of heavy metals and should not be mixed with the greywater.

The strategy is simple – to treat each flow separately and return the hygienised products to the soil as a fertiliser and soil conditioner.

References/sources:

- Bos, R., Carr, R. and B. Keraita, 2010. Assessing and mitigating wastewater-related health risks in low-income countries: An introduction. In Drechsel, P. et al. (eds). *Wastewater irrigation and health. Assessing and mitigating risk in low-income countries*. Earthscan with International Development Research Centre (IDRC) and the International Water Management Institute (IWMI). London.
- British Geological Survey, 2003. Guidelines for assessing the risk to groundwater from on-site sanitation. British Geological Survey. Commissioned Rep CR/01/142:97.
- Building Safety Journal, Jan-Feb 2008.
- Carden, K., Armitage¹, N., Sichone, O., Winter, K., and U. Rivett ‘*Management options for the safe use and disposal of greywater in the non-sewered areas of South Africa.*’ Project K5/1524. WRC (Water Research Commission), Pretoria, South Africa.
- Crites, R.W. and Tchobanoglous, G., 1998. *Small and decentralized wastewater management systems*. Water Resources and Environmental Engineering, 1. WCB/McGraw-Hill, Boston, 1084 pp.
- Drechsel, P., Scott, C., Rashid-Sally, L., Redwood, M., and Bahri, A. 2010. *Wastewater irrigation and health. Assessing and mitigating risk in low-income countries*. Earthscan with International Development Research Centre (IDRC) and the International Water Management Institute (IWMI). London.
- DWAF 2001. “Managing the water quality effects of settlements: Planning to avoid pollution problems.” Department of Water Affairs and Forestry. *Government Printer*, Pretoria, South Africa (October 2001).
- EU 2008. Environmental, economic and social impacts of the use of sewage sludge on land. Consultation Report on Options and Impacts. Report prepared by RPA, Milieu Ltd and WRC for the European Commission, DG Environment under Study Contract DG ENV.G.4/ETU/2008/0076r
- Ghangrekar, M. M. at:
www.waterandwastewater.com/www_services/ask_tom_archive/design_of_an_uasb_reactor.htm
- Gustafsson, K. 2005. INFILTRA compact filter for treatment of wastewater - experiences during 1993 – 2004. Report, Water Revival Systems Uppsala Ltd, Uppsala. In Swedish. Available at http://www.ekotreat.se/Pdf/Kompaktfilter_rapport.pdf
- Henze, M., Harremoës, P., Arvin, E. and J. la Cour Jansen. 2002. *Wastewater treatment. Biological and chemical processes*. 3rd ed. Springer-Verlag, Berlin. 428 pp.
- Jimenez, B., Mara, D., Carr, R., and K. Brissau 2010. Wastewater treatment for pathogen removal and nutrient conservation: Suitable systems for use in Developing countries. In Drechsel, P. et al. (eds). *Wastewater irrigation and health. Assessing and mitigating risk in low-income countries*. Earthscan with International Development Research Centre (IDRC) and the International Water Management Institute (IWMI). London.
- Mara, D, 2004. *Domestic Wastewater Treatment in Developing Countries*. 310 pages, Earthscan Publications, Limited
- Mara, D. and Bos, R. 2010. Risk analysis and Epidemiology: The 2006 WHO Guidelines for the Safe Use of Wastewater in Agriculture. In Drechsel et al (eds). *Wastewater irrigation and health. Assessing and mitigating risk in low-income countries*. Earthscan with International Development Research Centre (IDRC) and the International Water Management Institute (IWMI). London.
- Qadir, M. and C. A. Scott 2010. Non-pathogenic trade-offs of wastewater irrigation. In Drechsel, P. et al. *Wastewater irrigation and health. Assessing and mitigating risk in low-income countries*. Earthscan with International Development Research Centre (IDRC) and the International Water Management Institute (IWMI). London.

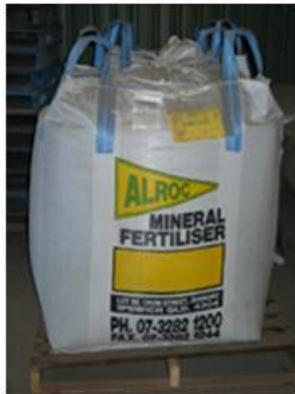
- Ridderstolpe, P. 2004. Introduction to greywater management. Report 2004-4, EcoSanRes Publication Series. Stockholm, Environment Institute, Stockholm. www.ecosanres.org
- Sasse, L. 1998. Decentralised wastewater treatment in developing countries. BORDA, Bremen, 160 pp
- Siegrist, RL, Tyler, EJ, Jenssen, PD (2000). Design and performance of onsite wastewater soil absorption systems. Prepared for National Research Needs Conference, Risk-Based Decision Making for Onsite Wastewater Treatment. St. Louise, Missouri, 19-20 May, Sponsored by United States Environmental Protection Agency, Electric Power Research Institutes Community.
- Tchobanoglous, G. 1991. Wastewater Engineering, Treatment, Disposal, and Reuse, Irwin/McGraw-Hill, 1334 pp.
- US. EPA on http://www.epa.gov/owow/wetlands/pdf/Design_Manual2000.pdf
- US EPA, 2002. On-site wastewater treatment systems manual. EPA/625/R-00/008, US Environmental Protection Agency, Washington, USA. Available at http://www.epa.gov/owm/septic/pubs/septic_2002_osdm_all.pdf
- US EPA 1977. Report to Congress: *Waste disposal practices and their effect on groundwater*. Report No. EPA 570/9-77-001, Washington, USA.
- VMK 2009. Risk assessment of contaminants in sewage sludge applied on Norwegian soils. Norwegian Scientific Committee for Food Safety. 2009.
- WHO 2006. *WHO Guidelines for safe use of wastewater, excreta and greywater*. Volume 1. Policy and Regulation Aspects. WHO. Geneva, Switzerland.
- Vinnerås, B., Palmquist, H., Balmér, P., and Jönsson, H. 2006. The characteristics of household wastewater and biodegradable solid waste – A proposal for new Swedish design values. *Urban Water Journal*, Vol. 3, No. 1, March 2006, 3-11.
- Vymazal, J. 2005a. Horizontal sub-surface flow and hybrid constructed wetlands systems for wastewater treatment. *Ecol. Eng.* 25: 478–490
- Vymazal, J. 2005b. Removal of enteric bacteria in constructed treatment wetlands with emergent macrophytes: A review. *Journal of Environmental Science and Health*, 40:1355–1367)

Module 4.8
**Excreta fertilisers in
Agriculture**

How can ecological fertilisers from
excreta best be used?

What is the farmer applying to the field?

- Mineral Fertiliser
- Animal Manure
 - Slurry
 - Solids
- Water
- Energy



When a farmer is producing food he start with an investment in the soil with the application of seeds. To improve the productivity of the applied seeds will he try to give the plants the best surrounding as possible. This is to 30% of all food production performed by application of mineral fertilisers, normally nitrogen, phosphorus and potassium, in some cases even other macro nutrients such as sulphur and calcium. The mineral fertilisers are focusing on improving the proportion of available macro nutrients, the nutrients that plants have the highest requirement of, these nutrients are most often the ones that limits the growth of the plants. However, there can also be other factors that limits the growth, e.g. temperature, sun light, water etc, and are these conditions not fulfilled the applied nutrients will not have any effect on the growth of the plants.

Animal manure is most often used in agriculture as fertiliser in agriculture. In some cases the manure is just dumped and not utilised but it is a good fertiliser and soil conditioner. In comparison to mineral fertilisers does the animal manure not contain as much readily plant available nutrients as the mineral fertilisers. On the other hand, the manure contain organic matter that will improve the soil quality, as it increases the organic content etc., this will among other things improve both the buffering capacity (better pH) and the water containing capacity.

Except from the nutrients, in some cases will the farmer need to apply water to improve the growth.

In all cases this work to improve the plant growth will need energy, it can be man power, animal power or from machines. Still, all this effort will require input of energy for producing a crop to be harvested.

How is the fertiliser applied?

- Mineral fertiliser
 - Spreader
 - By hand
- Solid manure
 - Spreader for solids TS>20%
 - Manually
 - Trolley + shovel
- Liquid manure
 - Spreader for liquids TS<12%
 - Overflowing
 - Included in watering water
 - Applied bucket/tank wise



Mineral fertilisers can be applied by hand, or by machine. The machine application can either be broad spreading onto the field close to sowing or simultaneously with sowing. Additional nutrients (mainly nitrogen) will also be applied some period into the growth to optimise the harvest. Mineral fertilisers are mainly applied as pellets with a diameter of a few mm.

Solid manure is either spread by machine or by hand using a trolley and a shovel. The manure need to be dry enough for spreading, this means that the minimal dry matter content need to be above 20%, i.e. maximum water content of 80%. If it is too dry there is major risk for dust during spreading, which can be seen as a threat to the health of the workers. Per hectare can between 10 and 50 tonnes of material be applied. The major factor regulating the application rate is the nutrient content as too much nutrients can harm both the crop and the environment.

Liquid manure should be possible to pump, as a rule of thumb will this require at least 88% water, i.e. maximum dry matter content of 12%. The liquid manure can be spread with a spraying machine, preferably close to the ground to avoid aerosols and ammonia losses. Other techniques for application is overflowing of the fields, incorporation in regular watering water, or application by hand tank wise or bucket wise.

When is the fertiliser applied?

- Before plantation
- Until 2/3 of season
- Until Ear setting
- Until one month before harvest
- 2-3 times per cropping
- Every day?



The fertilisation is mainly performed in close relation to plantation of seeds. This is the case when applying fertilisers that require incorporation into the soil, e.g. compost and solid manure. If fertilisation is planned to be performed only once, the optimal time is close to the plantation. When distributing the fertilisation over the growth season phosphorus and potassium are of most importance early in the growth of the plants while nitrogen is mainly required when the plants have started to grow and are visible over ground. SO if the fertilisation should be distributed, looking at excreta based fertilisers, faecal compost etc should be applied prior to sowing and urine should be applied after the plants have started to grow.

The plants will not utilise the nutrients all through the growth season if you are planting cereals. As a rule of thumb is that the plants will take up nutrients during the first two thirds of the growing season or until they are setting ears. If you plant leafy crops, e.g. lettuce, nutrients will be taken up all through growth. However, nutrients applied later than one month prior to the harvest will only be utilised to a very small extent.

If distributing the nutrient application over the season the nutrient losses will decrease and the plant utilisation will be improved. However, if the nutrients are applied more than 2-3 times during the growth season no significant increase in yield will be noted compared to application 2-3 times per season.

Application of water

- When is it needed?
 - Increased water, except during flooding
- How?
 - Spraying
 - Surface overflow
 - Surface application
 - Drip irrigation



Application of water will almost always have a positive effect on the growth. Still, there is not always economical to apply extra water if the existing water distribution to the plants does not significantly decrease the growth as water application also comes with a cost of infrastructure, energy and labour.

The application can be performed via spraying, either as single point or multiple points at one field, depending on systems available. Surface over flow is often used and with proper pre structure with canals etc. the effort for application is minimal.

Surface application and drip irrigation minimises the risk of aerosol formation and thereby spreading of diseases in the environment. Irrigation in systems with small holes, e.g. drip irrigation, tend to risk blockages if dirty water is applied as either the content of the water will block the holes or it will be blocked by growth in the pipes. The choice of system is mainly dependent of what is locally available and affordable.

Group question

- How can we produce these fertilisers from households
 - What materials do we get?
 - Do they need extra treatment?
 - Why?
 - What are the fertilising value of the fractions?

This is a general question for discussion, the aim with this is to get the student to apply a reverse engineering approach, not looking at the conventional systems that we have in our houses today but rather try to look at the different waste fractions from a farming perspective. When doing so, the conventional waste and wastewater system can look a bit odd as the products here is not for farm use but rather pollution prevention out of a societal perspective.

If the students discuss this for 5-10 minutes in group of 2-3 people they can get interesting discussions around both existing systems but also about what do the farmer need for his food production.

This can either be further discussed in the full group or that the students present this material by shortly summarise what they talked about. This gives the teacher an opportunity to reflect back during the further lecture to what the students were discussing.

Nutrient content in wastewater

- Faeces
 - 100-400g/pd 40-100kg/year
 - 0.3kg N/py
 - 0.1kg P/py
 - 0.2kg K/py
 - Most organically bound



The following nutrient fraction is the faecal matter. The volume of the faeces varies and depends on the diet. A general food consumption in the western world contain low amounts of fibres that result in smaller faecal volumes compared to a traditional African and Asian diet that contain more fibres which result in larger volumes. Still, the total faecal volume is small and vary between 40 and 100 kg per person and year of which the water content are approximately 80% and thereby the excreted solids are between 8 and 20 kg per person and year.

The nutrients in the faeces are mainly organically bounded and thereby not as plant available as the nutrients in the urine. The content in the faeces are mainly material and substances that is not metabolised by the body and the faeces can be more seen as a soil conditioner than a fertiliser.

In the faeces will the main part of the disease causing microorganisms, pathogens, be found that end up in the different streams of wastewater. How much you can find is described more closely in chapter 3 and how to manage the pathogens in the faeces to produce safe fertilisers are presented in Chapter 4 module 2.

Nutrient content in wastewater

- Urine
 - 1-1.5L /pd 3-500L /year
 - 0.3-0.7L per urination
 - 3-3.5kg N/py
 - 0.3kg P/py
 - 0.3kg K/py
 - All direct plant available



In human urine will you find the majority of the plant nutrients coming out of one household. It is, in comparison to mixed wastewater, a small volume as the average person urinate between 1 and 1.5 litre per day. This urination is distributed on approximately seven occasions. In the urine you will find 3-3.5 kg nitrogen per year 0.3 kg of phosphorus and potassium. Additionally you find all micronutrients needed for biological activity, such as iron, copper, zink etc. All of these substances are highly plant available and the urine can be compared to a mineral fertiliser. While the levels of non-essential metals, such as mercury and cadmium are extremely low, often as low as they are impossible to detect in the urine. The substances we find in the urine reflects what is metabolised by the body, therefore is the pollution levels low.

The exception is hormones and pharmaceuticals that are excreted in the urine to a relatively high concentration as they are metabolised by the body, most often are these substances excreted in their active form. However, the organic substances from hormones and pharmaceuticals do less harm in the soil compared to the harm they can do if they end up in the water streams.

The exact content of the urine collected from one person vary a lot depending on the diet, as the nutrient content are reflected in the urine by the diet as well as the volume will be dependent of the water consumption together with the transpiration.

Treatment of urine

- Storage
 - 2 Month $>20^{\circ}\text{C}$
 - 1 Month $>30^{\circ}\text{C}$
 - Not according to WHO!
- Urine to own garden direct use
- Urine from urinals only – less treatment required
- Selected use less storage needed



The most common treatment of urine is storage. At storage above 20°C it is enough with 2 month of storage for unrestricted use of the urine as fertiliser, if the storage temperature is even higher, above 30°C only one month of storage is needed. This is not in line with the recommendations presented by WHO but based on later research further detailed studies have shown that this is enough.

The main source of pathogens in the urine is from faecal contamination and if the urine only is collected from urinals the risk for faecal contamination does not exist and lesser restrictions on the time of storage can be used.

When using the urine collected in one household in the own garden no restrictions are applied on the use of the urine as the risks for other routes of transmission for diseases are consider to overshadow the risk of disease transmission via the urine.

If other barriers are applied in the use of urine, explained further in chapter 3, such as restrictions in where the urine is applied, e.g. processed crops, non food crop.

Further description on how to treat urine and what functions that regulate the inactivation of pathogens can be find in chapter 4 module 2.

Treatment of faeces

- Composting
 - $>50^{\circ}\text{C}$ $>1\text{week}$ + turning
 - Low temp composting
- Biogas
 - Long HRT and MRT
 - Additional hygiene treatment preferable
- Chemical treatment
 - Ammonia
 - Lime
 - Ash
- Selected use



As the risk of pathogen content in the faeces are high a more advanced treatment is required for decreasing the risk of disease transmission upon fertilisation.

Composting is the most common treatment of faeces, the composting itself will not inactivate all pathogens present but if the process reaches a temperature above 50°C the potential pathogenic content will be inactivated. The WHO recommendation is composting above 50°C for at least one week. To be sure of enough inactivation of potential pathogens all material needs to be treated at this temperature. Easiest to do this is to mix all material during the high temperature process, as a rule of thumb, reactors should be mixed 3 times and piles/windrows should be mixed 5 times.

Another treatment alternative is anaerobic treatment (biogas process), neither this process will inactivate the pathogens in the material. Here you will not get the process to heat up by itself, the reduction of pathogens are improved by long residence times, both the minimal time in the reactor as well as the average residence time. One alternative could be post process treatment that for example could be performed with chemical treatment.

The traditional chemical treatment is by application of lime or ash. These processes will increase the pH to inactivate pathogens. To inactivate all potential pathogens a pH above 12 will be required. Another alternative is ammonia treatment, mainly performed by addition of urea, this treatment will be performed at pH 9 and have good effect on potential pathogens. The nitrogen can after performed treatment follow the faecal matter to the field as fertiliser and there improve the fertilising value for the faeces as the nitrogen will be direct plant available.

How to apply the urine fertiliser

- Large Medium scale
 - Drip irrigation
 - Hose spreader
 - Watering
- Small scale
 - Drip irrigation
 - Watering can
 - Watering (with GW)
- Application
 - Before planting
 - During growth



The urine can be applied from small scale to large farm scale. In all scales it is important to avoid ammonia losses. This is easiest performed with application close to the ground and incorporation into the soil close after application. In large scale the application should not be performed with sprayers or splash plates that produce large amounts of aerosols but rather with hose spreaders, drip irrigation etc followed either by secondary tillage for incorporation or application of water that transports the urine into the soil. In small/garden scale this can be performed by application into furrows that are covered after application or by watering after application.

In large scale the application can be performed by using conventional farm equipment for liquid manure application. In small scale the application can be done by pumps and hoses or by simple watering cans.

The time to apply the fertiliser is before planting and during the growth. The application rate will be limited by the nitrogen content, and a good application rate is to apply 100kg nitrogen per hectare of soil (10g nitrogen per square metre), this will give an application of 10-50m³ of urine to apply per hectare depending of the nitrogen content of the urine. As a rule of thumb is that the urine collected from one person during one day can be applied to one square metre per growing season. Still up to the urine from five persons collected during one day will have good effect on the soil and not lead to over-fertilisation, but the optimal fertilisation levels are less.

How to apply the faecal fertiliser

- Compost
 - Solid manure
 - Shovel
 - Application
 - Before planting
- Biogas slurry
 - Hose spreader
 - Land overflow
 - Incorporation into soil
 - Application
 - Before planting
 - During growth



When using treated faeces as fertiliser, the treatment method will affect the choice of application method.

Compost will be applied as solid manure, either with a solid manure spreader, or by hand. The compost should be incorporated into the soil after application so the optimal fertilisation is prior to planting.

The biogas slurry can be applied as a liquid manure, using hose spreader or other local suitable application techniques. For optimised use and less smell the material should be incorporated into the soil as soon as possible after application, e.g. by secondary tillage. The biogas slurry contain higher concentrations of plant available nitrogen that are easily utilised by the plants. Therefore, the slurry can be applied during growth.

How to apply the greywater

- Direct application
 - At trees
 - Mulch bed
 - Grass land
 - Avoid storage (smell)
- Treated GW
 - Irrigation
 - Spray
 - Drip
 - Overflow



The greywater contain large amounts of easily degradable carbons that are degraded rapidly after collection, and if no further treatment are planned but field application, storage should be avoided as the greywater start to smell fast. Short piping systems allow for direct use in the own garden, open water surfaces should be avoided, so the water should either be infiltrated directly in a mulch bed or similar.

Treated greywater (Chapter 4 module 5-7) can be stored and applied using conventional watering equipments.

To what can I use the fertilisers?

- Treated urine / at home application
 - Unrestricted use
 - Salt content
 - High ammonia content
- Untreated urine
 - Fodder crop
 - Crop above ground
 - Processed
 - Fruits
 - Ornamental purposes



Urine, either if treated correctly or used in own garden can be used without restrictions. The user should be aware that the urine contain salts and in situations where there is no downward movement of water in the soil over the years, e.g. monsoon rain or rainy seasons etc, there is a risk for salt build up. However this is only in extremely dry areas, where all cropping is performed by irrigation. The urine contains high concentrations of ammonia and should not be applied on the leaves of the plants as the foils of the leaf are destroyed and the plant is killed. Additionally the ammonia will be lost as air emission.

For untreated urine in large systems restriction are needed for usage and how to apply to avoid disease transmission. This urine should not be applied to crops to be consume raw but to other crops that have other barriers for the disease transmission, more about this in Chapter 3.

To what can I use the faecal fertiliser?

- Level of treatment
 - High level unrestricted use
 - Low level restricted use
 - Crops with long growth period
 - Pineapple
 - Banana
 - Coconut
 - Non food crops
 - Fodder
 - Ornamental



The fertiliser usage of faecal based fertiliser will have a close connection to the level of treatment performed on the raw faeces. If the treatment is of high quality regarding the removal of pathogens the usage can be without restrictions. However, if the treatment level is uncertain restriction in the use should be applied, as well as in the application, assuring that workers health will not be affected.

Choices of restricted use can be application of the fertiliser to crops with long growth period, where the application of fertiliser and the harvest can be differentiated by years, examples of such crops are pineapple, banana coconut etc. Another alternative is to use the fertiliser for non food crops, if assurance of no zoonotic diseases can be made the fertiliser can be used for fodder. It can also be used for energy crops and ornamental crops assuring that no one will consume the produce.

To what can I use the greywater?

- Untreated GW
 - At home
 - Direct use (minimise piping)
 - Applied treatment
 - Mulch bed
 - At trees
- Treated GW
 - Can be stored
 - Watering purposes



The hygienic risks with greywater are less compared to faeces and urine. The application of untreated greywater is mainly restricted to that it is not possible to store or transport long distances due to the large bacterial growth and the following smelling problems. Untreated greywater can be used in the own garden. If the system is performed with minimised piping no grease trap is needed as the water will hold such temperatures that there will be no coagulation in the system. The greywater can then be directly applied to trees etc. and also to grass, if particles such as food scrapes are removed prior to the application.

Treated greywater can easily be stored and used for watering purposes.

Selection of use

- Practicality
- Hygiene
 - Barriers
 - Treatment
 - Selection of use
 - Food crop
 - Fodder
 - Other
- Composition
- Acceptance
 - User
 - Farmer (end user)
 - Consumer



When, where and how to use the different fraction are limited to mainly local factors. Is the system practical for all involved persons?

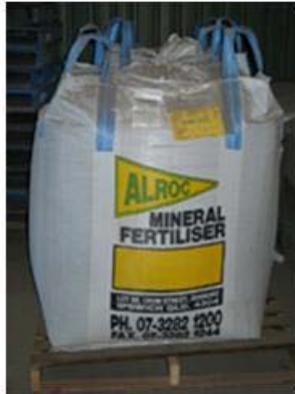
Is the hygienic quality assured? Here it is important to involve all parts of the system, such as workers, inhabitants in the area, animals in the area, consumers of the produce etc. The different barriers for disease transmission need to be assessed and evaluated regarding the treatment, the distribution system and the use of the fertiliser.

Additionally the composition of the fertiliser need to be evaluated, will the farmer understand how and when to apply and will he/she have the proper equipment for application. Substrates that do not full fill the standard of existing fertilisers and fertilisation equipment will be hard to find a receiver/market for as no-one will be able to apply the fraction into the cropping system.

For a successful recycling scheme of excreta based fertilisers the acceptance of the different products need to be evaluated. This involves the user of the system, the farmer and the consumer of the fertilised produce. If the system fails in any of these steps it will be tuff to get it to succeed.

What is the farmer applying to the field?

- Mineral Fertiliser
- Animal Manure
 - Slurry
 - Solids
- Water
- Energy



When a farmer is producing food he start with an investment in the soil with the application of seeds. To improve the productivity of the applied seeds will he try to give the plants the best surrounding as possible. This is to 30% of all food production performed by application of mineral fertilisers, normally nitrogen, phosphorus and potassium, in some cases even other macro nutrients such as sulphur and calcium. The mineral fertilisers are focusing on improving the proportion of available macro nutrients, the nutrients that plants have the highest requirement of, these nutrients are most often the ones that limits the growth of the plants. However, there can also be other factors that limits the growth, e.g. temperature, sun light, water etc, and are these conditions not fulfilled the applied nutrients will not have any effect on the growth of the plants.

Animal manure is most often used in agriculture as fertiliser in agriculture. In some cases the manure is just dumped and not utilised but it is a good fertiliser and soil conditioner. In comparison to mineral fertilisers does the animal manure not contain as much readily plant available nutrients as the mineral fertilisers. On the other hand, the manure contain organic matter that will improve the soil quality, as it increases the organic content etc., this will among other things improve both the buffering capacity (better pH) and the water containing capacity.

Except from the nutrients, in some cases will the farmer need to apply water to improve the growth.

In all cases this work to improve the plant growth will need energy, it can be man power, animal power or from machines. Still, all this effort will require input of energy for producing a crop to be harvested.

How is the fertiliser applied?

- Mineral fertiliser
 - Spreader
 - By hand
- Solid manure
 - Spreader for solids TS>20%
 - Manually
 - Trolley + shovel
- Liquid manure
 - Spreader for liquids TS<12%
 - Overflowing
 - Included in watering water
 - Applied bucket/tank wise



Mineral fertilisers can be applied by hand, or by machine. The machine application can either be broad spreading onto the field close to sowing or simultaneously with sowing. Additional nutrients (mainly nitrogen) will also be applied some period into the growth to optimise the harvest. Mineral fertilisers are mainly applied as pellets with a diameter of a few mm.

Solid manure is either spread by machine or by hand using a trolley and a shovel. The manure need to be dry enough for spreading, this means that the minimal dry matter content need to be above 20%, i.e. maximum water content of 80%. If it is too dry there is major risk for dust during spreading, which can be seen as a threat to the health of the workers. Per hectare can between 10 and 50 tonnes of material be applied. The major factor regulating the application rate is the nutrient content as too much nutrients can harm both the crop and the environment.

Liquid manure should be possible to pump, as a rule of thumb will this require at least 88% water, i.e. maximum dry matter content of 12%. The liquid manure can be spread with a spraying machine, preferably close to the ground to avoid aerosols and ammonia losses. Other techniques for application is overflowing of the fields, incorporation in regular watering water, or application by hand tank wise or bucket wise.

When is the fertiliser applied?

- Before plantation
- Until 2/3 of season
- Until Ear setting
- Until one month before harvest
- 2-3 times per cropping
- Every day?



The fertilisation is mainly performed in close relation to plantation of seeds. This is the case when applying fertilisers that require incorporation into the soil, e.g. compost and solid manure. If fertilisation is planned to be performed only once, the optimal time is close to the plantation. When distributing the fertilisation over the growth season phosphorus and potassium are of most importance early in the growth of the plants while nitrogen is mainly required when the plants have started to grow and are visible over ground. SO if the fertilisation should be distributed, looking at excreta based fertilisers, faecal compost etc should be applied prior to sowing and urine should be applied after the plants have started to grow.

The plants will not utilise the nutrients all through the growth season if you are planting cereals. As a rule of thumb is that the plants will take up nutrients during the first two thirds of the growing season or until they are setting ears. If you plant leafy crops, e.g. lettuce, nutrients will be taken up all through growth. However, nutrients applied later than one month prior to the harvest will only be utilised to a very small extent.

If distributing the nutrient application over the season the nutrient losses will decrease and the plant utilisation will be improved. However, if the nutrients are applied more than 2-3 times during the growth season no significant increase in yield will be noted compared to application 2-3 times per season.

Application of water

- When is it needed?
 - Increased water, except during flooding
- How?
 - Spraying
 - Surface overflow
 - Surface application
 - Drip irrigation



Application of water will almost always have a positive effect on the growth. Still, there is not always economical to apply extra water if the existing water distribution to the plants does not significantly decrease the growth as water application also comes with a cost of infrastructure, energy and labour.

The application can be performed via spraying, either as single point or multiple points at one field, depending on systems available. Surface over flow is often used and with proper pre structure with canals etc. the effort for application is minimal.

Surface application and drip irrigation minimises the risk of aerosol formation and thereby spreading of diseases in the environment. Irrigation in systems with small holes, e.g. drip irrigation, tend to risk blockages if dirty water is applied as either the content of the water will block the holes or it will be blocked by growth in the pipes. The choice of system is mainly dependent of what is locally available and affordable.

Group question

- How can we produce these fertilisers from households
 - What materials do we get?
 - Do they need extra treatment?
 - Why?
 - What are the fertilising value of the fractions?

This is a general question for discussion, the aim with this is to get the student to apply a reverse engineering approach, not looking at the conventional systems that we have in our houses today but rather try to look at the different waste fractions from a farming perspective. When doing so, the conventional waste and wastewater system can look a bit odd as the products here is not for farm use but rather pollution prevention out of a societal perspective.

If the students discuss this for 5-10 minutes in group of 2-3 people they can get interesting discussions around both existing systems but also about what do the farmer need for his food production.

This can either be further discussed in the full group or that the students present this material by shortly summarise what they talked about. This gives the teacher an opportunity to reflect back during the further lecture to what the students were discussing.

Nutrient content in wastewater

- Urine
 - 1-1.5L /pd 3-500L /year
 - 0.3-0.7L per urination
 - 3-3.5kg N/py
 - 0.3kg P/py
 - 0.3kg K/py
 - All direct plant available



In human urine will you find the majority of the plant nutrients coming out of one household. It is, in comparison to mixed wastewater, a small volume as the average person urinate between 1 and 1.5 litre per day. This urination is distributed on approximately seven occasions. In the urine you will find 3-3.5 kg nitrogen per year 0.3 kg of phosphorus and potassium. Additionally you find all micronutrients needed for biological activity, such as iron, copper, zink etc. All of these substances are highly plant available and the urine can be compared to a mineral fertiliser. While the levels of non-essential metals, such as mercury and cadmium are extremely low, often as low as they are impossible to detect in the urine. The substances we find in the urine reflects what is metabolised by the body, therefore is the pollution levels low.

The exception is hormones and pharmaceuticals that are excreted in the urine to a relatively high concentration as they are metabolised by the body, most often are these substances excreted in their active form. However, the organic substances from hormones and pharmaceuticals do less harm in the soil compared to the harm they can do if they end up in the water streams.

The exact content of the urine collected from one person vary a lot depending on the diet, as the nutrient content are reflected in the urine by the diet as well as the volume will be dependent of the water consumption together with the transpiration.

Nutrient content in wastewater

- Faeces
 - 100-400g/pd 40-100kg/year
 - 0.3kg N/py
 - 0.1kg P/py
 - 0.2kg K/py
 - Most organically bound



The following nutrient fraction is the faecal matter. The volume of the faeces varies and depends on the diet. A general food consumption in the western world contain low amounts of fibres that result in smaller faecal volumes compared to a traditional African and Asian diet that contain more fibres which result in larger volumes. Still, the total faecal volume is small and vary between 40 and 100 kg per person and year of which the water content are approximately 80% and thereby the excreted solids are between 8 and 20 kg per person and year.

The nutrients in the faeces are mainly organically bounded and thereby not as plant available as the nutrients in the urine. The content in the faeces are mainly material and substances that is not metabolised by the body and the faeces can be more seen as a soil conditioner than a fertiliser.

In the faeces will the main part of the disease causing microorganisms, pathogens, be found that end up in the different streams of wastewater. How much you can find is described more closely in chapter 3 and how to manage the pathogens in the faeces to produce safe fertilisers are presented in Chapter 4 module 2.

Treatment of urine

- Storage
 - 2 Month $>20^{\circ}\text{C}$
 - 1 Month $>30^{\circ}\text{C}$
 - Not according to WHO!
- Urine to own garden direct use
- Urine from urinals only – less treatment required
- Selected use less storage needed



The most common treatment of urine is storage. At storage above 20°C it is enough with 2 month of storage for unrestricted use of the urine as fertiliser, if the storage temperature is even higher, above 30°C only one month of storage is needed. This is not in line with the recommendations presented by WHO but based on later research further detailed studies have shown that this is enough.

The main source of pathogens in the urine is from faecal contamination and if the urine only is collected from urinals the risk for faecal contamination does not exist and lesser restrictions on the time of storage can be used.

When using the urine collected in one household in the own garden no restrictions are applied on the use of the urine as the risks for other routes of transmission for diseases are consider to overshadow the risk of disease transmission via the urine.

If other barriers are applied in the use of urine, explained further in chapter 3, such as restrictions in where the urine is applied, e.g. processed crops, non food crop.

Further description on how to treat urine and what functions that regulate the inactivation of pathogens can be find in chapter 4 module 2.

Treatment of faeces

- Composting
 - $>50^{\circ}\text{C}$ $>1\text{week}$ + turning
 - Low temp composting
- Biogas
 - Long HRT and MRT
 - Additional hygiene treatment preferable
- Chemical treatment
 - Ammonia
 - Lime
 - Ash
- Selected use



As the risk of pathogen content in the faeces are high a more advanced treatment is required for decreasing the risk of disease transmission upon fertilisation.

Composting is the most common treatment of faeces, the composting itself will not inactivate all pathogens present but if the process reaches a temperature above 50°C the potential pathogenic content will be inactivated. The WHO recommendation is composting above 50°C for at least one week. To be sure of enough inactivation of potential pathogens all material needs to be treated at this temperature. Easiest to do this is to mix all material during the high temperature process, as a rule of thumb, reactors should be mixed 3 times and piles/windrows should be mixed 5 times.

Another treatment alternative is anaerobic treatment (biogas process), neither this process will inactivate the pathogens in the material. Here you will not get the process to heat up by itself, the reduction of pathogens are improved by long residence times, both the minimal time in the reactor as well as the average residence time. One alternative could be post process treatment that for example could be performed with chemical treatment.

The traditional chemical treatment is by application of lime or ash. These processes will increase the pH to inactivate pathogens. To inactivate all potential pathogens a pH above 12 will be required. Another alternative is ammonia treatment, mainly performed by addition of urea, this treatment will be performed at pH 9 and have good effect on potential pathogens. The nitrogen can after performed treatment follow the faecal matter to the field as fertiliser and there improve the fertilising value for the faeces as the nitrogen will be direct plant available.

How to apply the urine fertiliser

- Large Medium scale
 - Drip irrigation
 - Hose spreader
 - Watering
- Small scale
 - Drip irrigation
 - Watering can
 - Watering (with GW)
- Application
 - Before planting
 - During growth



The urine can be applied from small scale to large farm scale. In all scales it is important to avoid ammonia losses. This is easiest performed with application close to the ground and incorporation into the soil close after application. In large scale the application should not be performed with sprayers or splash plates that produce large amounts of aerosols but rather with hose spreaders, drip irrigation etc followed either by secondary tillage for incorporation or application of water that transports the urine into the soil. In small/garden scale this can be performed by application into furrows that are covered after application or by watering after application.

In large scale the application can be performed by using conventional farm equipment for liquid manure application. In small scale the application can be done by pumps and hoses or by simple watering cans.

The time to apply the fertiliser is before planting and during the growth. The application rate will be limited by the nitrogen content, and a good application rate is to apply 100kg nitrogen per hectare of soil (10g nitrogen per square metre), this will give an application of 10-50m³ of urine to apply per hectare depending of the nitrogen content of the urine. As a rule of thumb is that the urine collected from one person during one day can be applied to one square metre per growing season. Still up to the urine from five persons collected during one day will have good effect on the soil and not lead to over-fertilisation, but the optimal fertilisation levels are less.

How to apply the faecal fertiliser

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 - Application
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- Biogas slurry
 - Hose spreader
 - Land overflow
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 - Application
 - Before planting
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When using treated faeces as fertiliser, the treatment method will affect the choice of application method.

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How to apply the greywater

- Direct application
 - At trees
 - Mulch bed
 - Grass land
 - Avoid storage (smell)
- Treated GW
 - Irrigation
 - Spray
 - Drip
 - Overflow



The greywater contain large amounts of easily degradable carbons that are degraded rapidly after collection, and if no further treatment are planned but field application, storage should be avoided as the greywater start to smell fast. Short piping systems allow for direct use in the own garden, open water surfaces should be avoided, so the water should either be infiltrated directly in a mulch bed or similar.

Treated greywater (Chapter 4 module 5-7) can be stored and applied using conventional watering equipments.

To what can I use the fertilisers?

- Treated urine / at home application
 - Unrestricted use
 - Salt content
 - High ammonia content
- Untreated urine
 - Fodder crop
 - Crop above ground
 - Processed
 - Fruits
 - Ornamental purposes



Urine, either if treated correctly or used in own garden can be used without restrictions. The user should be aware that the urine contain salts and in situations where there is no downward movement of water in the soil over the years, e.g. monsoon rain or rainy seasons etc, there is a risk for salt build up. However this is only in extremely dry areas, where all cropping is performed by irrigation. The urine contains high concentrations of ammonia and should not be applied on the leaves of the plants as the foils of the leaf are destroyed and the plant is killed. Additionally the ammonia will be lost as air emission.

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- Level of treatment
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 - Fodder
 - Ornamental



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To what can I use the greywater?

- Untreated GW
 - At home
 - Direct use (minimise piping)
 - Applied treatment
 - Mulch bed
 - At trees
- Treated GW
 - Can be stored
 - Watering purposes



The hygienic risks with greywater are less compared to faeces and urine. The application of untreated greywater is mainly restricted to that it is not possible to store or transport long distances due to the large bacterial growth and the following smelling problems. Untreated greywater can be used in the own garden. If the system is performed with minimised piping no grease trap is needed as the water will hold such temperatures that there will be no coagulation in the system. The greywater can then be directly applied to trees etc. and also to grass, if particles such as food scrapes are removed prior to the application.

Treated greywater can easily be stored and used for watering purposes.

Selection of use

- Practicality
- Hygiene
 - Barriers
 - Treatment
 - Selection of use
 - Food crop
 - Fodder
 - Other
- Composition
- Acceptance
 - User
 - Farmer (end user)
 - Consumer



When, where and how to use the different fraction are limited to mainly local factors. Is the system practical for all involved persons?

Is the hygienic quality assured? Here it is important to involve all parts of the system, such as workers, inhabitants in the area, animals in the area, consumers of the produce etc. The different barriers for disease transmission need to be assessed and evaluated regarding the treatment, the distribution system and the use of the fertiliser.

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For a successful recycling scheme of excreta based fertilisers the acceptance of the different products need to be evaluated. This involves the user of the system, the farmer and the consumer of the fertilised produce. If the system fails in any of these steps it will be tuff to get it to succeed.

Chapter 4 Module 9

Environmental systems analysis methodology

Can totally different sanitation systems be fairly compared?
How are environmental impacts measured?

After this module should the student be able to understand the concepts of:

System definition and boundaries.

Quantification of environmental effects and resource use.

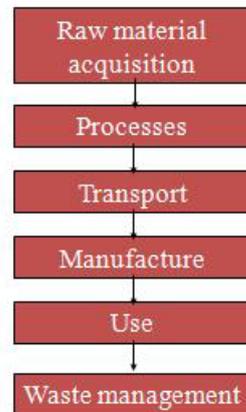
Indexes and weighing.

Acknowledgements:

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Life cycle assessment (LCA)

- Aim
 - Evaluate environmental burdens of a product or service
 - Using a cradle-to-grave perspective
 - from raw material extraction to waste management and final disposal.



LCA is a standardised tool for evaluation of the environmental burdens that a product or service is associated with.

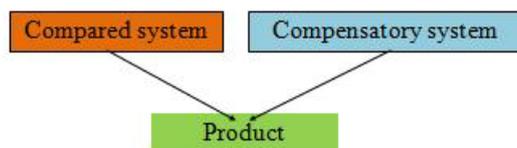
The perspective of the evaluation is from cradle to grave. This means that all parts of the life cycle of the product is included into the system. In the cradle perspective is the collection of raw material included, e.g. if virgin phosphorus is used the effects of the mining should be included in the evaluation. After that should all processing and transportation steps and their environmental impact be incorporated into the evaluation.

The use is then evaluated, this includes effects the material have on the environment or activities associated with the material, e.g. to continue with phosphorus, the effects from the field application such as fuel consumption for the tractor performing the fertilisation.

In the category connected to the grave perspective with the final disposal of the material be included. To continue with the phosphorus example the grave perspective includes several factors such as losses from the field of applied fertiliser, and the emissions from consumed food that is excreted. If the excreta will not be collected and reused as fertiliser the effects from the P that is ending up in the environment need to be considered.

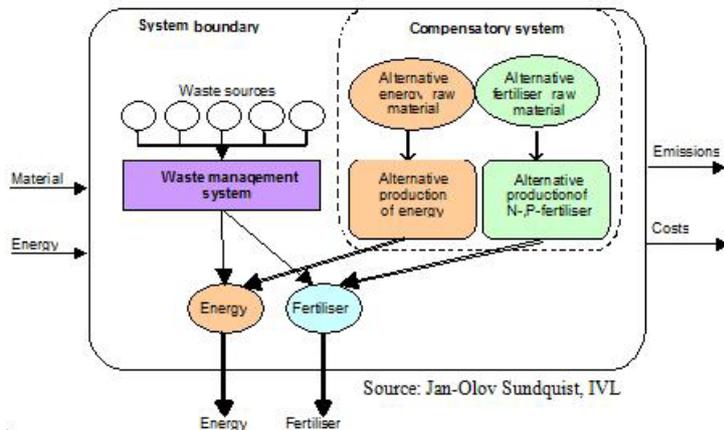
LCA work with an expanded system

- Comparison require delivery of similar product
 - **That leave you with compared system**
 - **And compensatory system** (external system)



To be able to compare two different systems, e.g. sustainable sanitation and conventional water based sanitation, they need to deliver the same products. The products in the case of sanitation could be fertiliser, biogas etc. To be able to perform this comparison you start with your systems to compare and evaluate the delivered products you have out of the system. Then you put up an extended/compensatory system assuring that all compared systems deliver the same amount of products. E.g. if a dry urine diverting system is compared with a conventional wastewater treatment system, the dry sanitation system delivers fertilisers such as nitrogen, phosphorus and potassium. Then the conventional sewage system needs to be compensated with these products, i.e. the conventional system will be included with the environmental effects from mineral fertiliser production to the same extent as the dry sanitation system delivers.

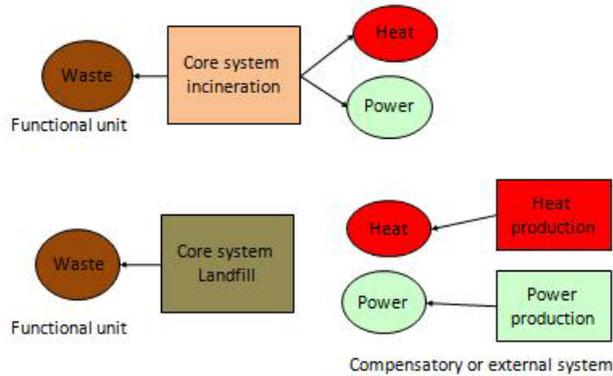
Example of a system comparison



In this example different treatment systems are compared regarding their consumption of material and energy and the emissions and costs associated to the system.

The different systems alternatives produce different amounts of energy and fertilisers. To be able to compare the alternatives a compensatory system is included compensating all systems up to delivering the same amount of fertiliser and energy. This is then included in both the consumption, the emissions and the costs. This makes it possible to compare totally different treatment alternatives that deliver completely different products as the sum of products from waste system and compensatory system is equal in all scenarios.

Functional unit, valued products



This is an example of the system for waste management comparing incineration and land filling. The core system of incineration is based on Swedish systems where the heat from the incineration is collected and used for production of electricity and of heat, used in a central heating system. When comparing this with the land fill system the land fill need to be compensated with production of heat and of power. How these compensations are selected will have a major effect upon the final results, e.g. the electricity can be either chosen as the electrical mix of Sweden where approximately 45% is hydro power and 45% nuclear power and the remaining is biowaste incineration and other systems such as coal power plant. This can be compared to when Sweden is importing electricity that is mainly coal based electricity. Depending on the selection here, the effect on the environment and production of fossil CO₂ differs a lot, so the selection of the compensatory system always need to be motivated.

Impact categories to be considered in an LCA

- Resources - Energy and materials
- Resources – Water
- Resources – Land
- Impacts on human health (toxicological and non-toxicological impacts, excluding and including work environment)
- Global warming
- Depletion of stratospheric ozone
- Acidification
- Eutrophication
- Photo-oxidant formation
- Eco-toxicological impacts
- Habitat alterations and impacts on biological diversity

Upon performing the comparison between the systems what factors to be compared need to be considered.

There are a set of groups to be compared, first it is the usage of resources, this includes use of energy and material (especially virgin material that needs to be newly produced) and water. The final resource is the use of land.

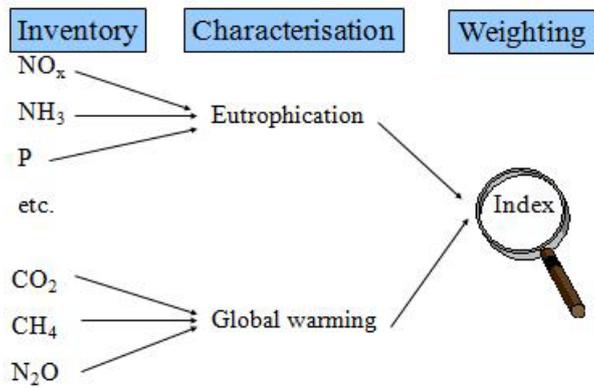
The next category is the impact on human health, both toxic effects and other effects and where the effects are related to if it is the work space or other spaces.

Then it is global effects such as global warming and depletion of stratospheric ozone.

This is followed by more local environmental effects such as acidification, eutrophication, photo oxidant formation, eco-toxicological impacts. All these effects are from emission of chemical substances.

The final effect included is habitat alterations and impact on biological diversity, this can be from chemical, physical as well as biological origin.

Collection and aggregation of data



When the data has been collected, in this case emissions from a system it has to be aggregated into groups where the different substances are grouped together and calculated as one emission. After this grouping the groups are weight to be able to compare the different impact factors.

Which environmental effect is most important?

- Global vs local
- Long-term vs short-term

- Importance of the impact
 - Compare the system impact with total national emissions

When comparing the different impact factors there are several things to have in mind during the comparison, several weighing factors will be presented later in this module. Statements had to be made regarding local and global effects, this will also have political implications for a system as the local effects are more visible for the people nearby, while the global effects are less noticeable for that group. The same is for comparison of long term and short term effects where the short term can be seen here and now while the long term effect will not appear until later.

One good way of evaluating the effect from a system is to relate/normalise that special effect to the same effect, either on national level or on global level. Hereby it is possible to have an objective weighting factor of each specific impact as you get that impacts contribution compared to the same impact on national or global level. When comparing effects it will be possible to estimate the percentage of the effect in the environment.

Weighting of global warming

Global Warming Potentials (GWP) as CO₂-equivalents for different trace gases and time-frames (IPCC, 2001)

Trace gas	GWP, 20 years	GWP, 100 years	GWP, 500 years
Carbon dioxide, CO ₂	1	1	1
Methane, CH ₄	62	23	7
Nitrous oxide, N ₂ O	275	296	156

The global warming is given as CO₂ equivalents with different time spans. The carbon dioxide of fossil origin result in one equivalent in all age categories. For methane and nitrous oxide the impact will be considerably higher as the effect of the gas on global warming is considerably higher. Over time will the effect decrease as some of the gas is degraded and thereby less gas will be available causing global warming.

Weighing of acidification

Weighting factors for acidification for two scenarios, min and max (Lindfors et al., 1995).

Substance	Min [mol H+/g]	Max [mol H+/g]
SO ₂	0.031	0.031
HCl	0.027	0.027
NO _x	0	0.022
NH ₃	0	0.059

For acidification is the effect not varied over time but rather connected to how the substances are utilized. Sulphate and hydrochloric acid will always have the same potential while ammonium and nitrates will vary in their effect depending on if the nitrogen is ending up as an acidifier in the environment or if it is taken up by plants, then the effect is less. Upon uptake by plants of the nitrate it will be ion exchanged into hydroxide and thereby will the pH remain. When doing an estimation of the acidification these min and max scenarios needs to be taken into account.

- $2 \text{NH}_3 + 4 \text{O}_2 \qquad \qquad \qquad 2 \text{NO}_3^- + 2 \text{H}_2\text{O} + 2\text{H}^+$
- $2 \text{NO}_2 + \frac{1}{2} \text{O}_2 + \text{H}_2\text{O} \qquad \qquad \qquad 2 \text{NO}_3^- + 2\text{H}^+$
- $2 \text{SO}_2 + \frac{1}{2} \text{O}_2 + \text{H}_2\text{O} \qquad \qquad \qquad 2 \text{SO}_4^{2-} + 2\text{H}^+$

NH₃ and NO_x are not acidifying if they are taken up by plants instead of being oxidized to NO₃⁻ or if the NO₃⁻ is taken up, because when taken up by the root it is exchanged for OH⁻

Weighting of eutrophication

Substance	Maximum (g O ₂ per g)	Minimum (g O ₂ per g)
N to air	20	
NO _x to air	6	
NH ₃ to air	19.8	3.8
N to water	20	
NO ₃ to water	4.4	
NH ₄ to water	18.6	3.6
P to water	140	140
PO ₄ ³⁻	46	46
COD	1	1

Eutrophication (overfertilisation) is measured as di-oxygen equivalents. This is measured as COD (Chemical oxygen demand) and the effect from other eutrophying substances will be measured as the amount of organic material they can support the growth of leading to a secondary measurement as COD. Here as well as for the acidification the effect of nitrogen depends upon how the substance is utilized. If the nitrogen is taken up by biological growth then it will increase the eutrophication while if it is just oxidized and degraded it will result in acidification. The difference in the emission to water or air depends upon that in water nitrogen is seldom the limiting substance for biological growth. Then the nitrogen emitted will not have eutrophying effects but rather be an acidifier as the nitrogen will not be utilized.

Remember...

It is a **great difference between potential and actual environmental impacts.**

When doing an environmental systems analysis or an LCA you have a good tool for comparing several different systems. The actual numbers that the analysis comes up with will not be possible to utilize in other evaluations as all analysis are very place and situation specific.

The impact proven by a system is the potential impact and this is a large difference to the actual impact. One good example is that ammonia can in the impact be calculated in a max scenario to have both acidifying and eutrophying effects while in reality it can only have one of them and if the nitrogen are taken up by growing plants, e.g. from air emission to a plant there is neither any acidification nor eutrophication.

However, the evaluation is a very good tool to understand and compare what are the potential environmental effects from a system.

Module 4.10

Ecosan versus conventional sanitation

How can dry UD ecosan system be compared with a conventional systems (open defecation, latrine pit, water-borne)?

This module will give a comparison of different sanitation systems using a systems analysis approach. For further understanding of environmental systems analysis the reader is recommended to look at chapter 4 module 9 where the description of the systems analysis and different factors for comparison are included.

After studying the module the student should be able to understand the effects on eutrophication, global warming, water resource use, non-renewable resource use, renewable resource use.

Acknowledgment; Professor Håkan Jönsson have supported this presentation with material regarding the systems analysis comparing different sanitation systems.

4 Swedish systems with nutrient recovery compared

1. **Reference.** Conventional system. N & P removal in WWTP. Effluent: 8 mg N & 0.24 mg P/l. Sludge incinerated, ash landfilled.
2. **Urine.** 80% of urine diverted & recycled as fertiliser. Rest = reference
3. **Blackwater.** Vacuum toilets. Collected blackwater anaerobically digested, sanitised & recycled as fertiliser. Rest = reference
4. **Sludge.** Sludge recycled as fertiliser. Rest = reference

To start with we look upon the comparison of four different systems that is fairly advanced.

The first system is a reference system to which all other systems are compared with. It is important to have a reference system to start the comparison with as the numbers given by an environmental systems analysis will not be exact numbers of the impact from the system but rather a evaluation of one system compared to another. The reason to this is that in all analysis some estimations and assumptions are needed to get the full comparison. Without this, there will never be possible to perform a full comparison, but it also lead to that the study is very specific regarding the numbers. However, the order between the systems in the evaluation is possible to use in other comparisons.

The reference system is a conventional system such as the one found in Sweden, an Active sludge system including nitrogen and phosphorus removal. The effluent is fairly low in N and P and the sludge is incinerated and the ash is land filled.

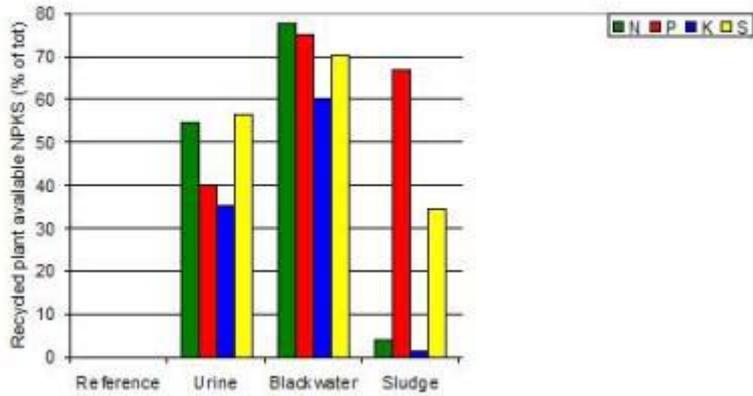
System number two is a similar system as the reference, the difference is that the urine is collected to a rate of 80%, and then recycled as fertiliser. The remaining system is the same as the conventional system.

System number three is still using the wastewater treatment plant for the greywater while the toilet water (blackwater) is collected anaerobically digested, sanitised by heat 70°C for one hour and then recycled as fertiliser.

The fourth system is a mixed wastewater system treated as the reference with the difference that the sludge is collected and recycled as fertiliser.

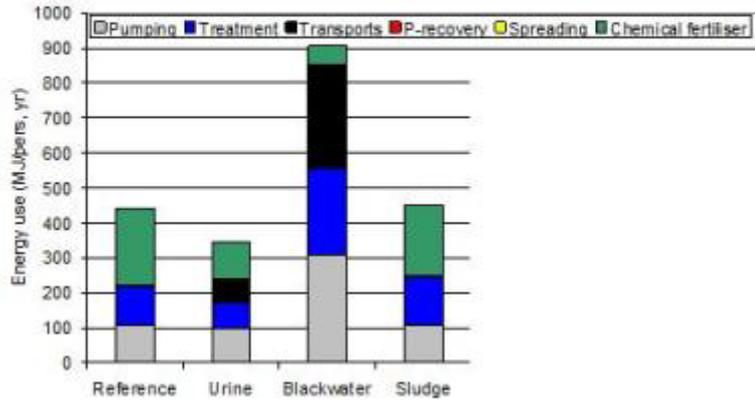
The compensatory systems here will be systems for producing, heat and electricity from the incineration and the anaerobic processes. System for producing compensation for the fertiliser production will also be included, i.e. mineral fertiliser to compensate for the fertilisers recycled in the sludge, the urine and the treated blackwater.

Recycled plant available NPKS



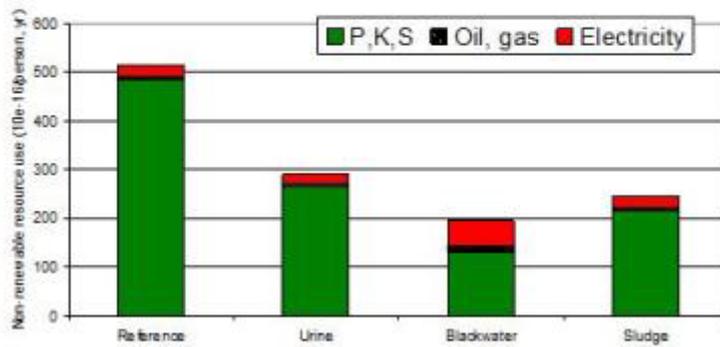
Looking at the plant nutrients recycled, the blackwater system is the one producing the most fertiliser, followed by the urine systems. This is presented as percentage of the total flow of nutrients from the household. The flow is based on assumptions and the flows will be affected by the habits of the people living there, e.g. the P in the greywater would increase if P based detergents are used in the household.

Energy use



When we look at the energy case the table will turn as the blackwater system is the one that will be the major user. The large volumes of blackwater and the advanced treatment will lead to larger energy consumption due to the pumping and treatment and transport. For the non-sorting systems the major energy consumption will be for producing compensatory fertilisers that are recycled with the other systems. The compensatory consumption of mineral fertiliser in the urine and blackwater system is from higher recycling of phosphorus in the system that recycle sewage sludge, the systems of urine and faeces sorting are the sewage sludge incinerated and no nutrients recycled.

Total use non-renewable



When we add these two parts together and compare it as total non-renewable resources the major resource consumption is from mineral fertilisers while the oil and gas and electricity is considerably less, even in the blackwater system that consumed the largest amount of energy.

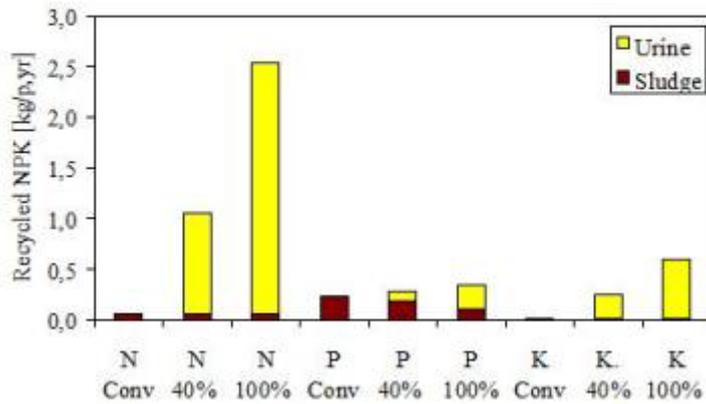
Other studies of sorting systems

- Many systems analysis have found same results:
- Urine diversion
 - decreases water emissions
 - gives lots of useful fertiliser
 - saves chemical fertiliser
 - saves energy

There has been a large number of systems analysis, both in Sweden and international, that have looked upon the environmental effects when comparing conventional wastewater and sorting wastewater systems, all these have shown similar results that the sorting system have major environmental and resource consumption gains compared to the conventional system.

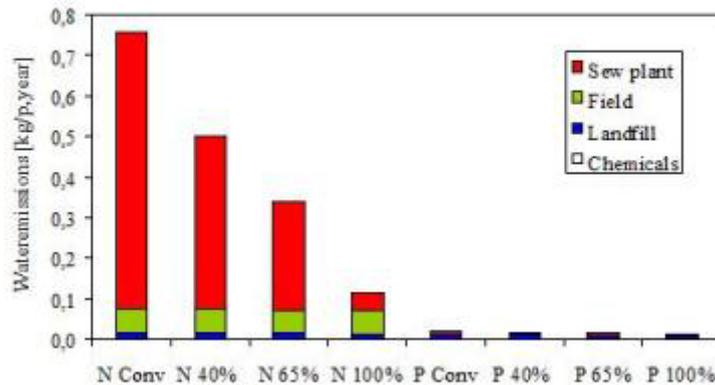
The urine diversion system mainly gain in the fact that the water emissions of nutrients decreases, especially if the wastewater is not treated at all. There is produced a large amount of fertiliser in the sorting system, that compared with increased energy consumption in the sorting system is a larger consumer of resources.

Recycled NPK vs degree of diversion



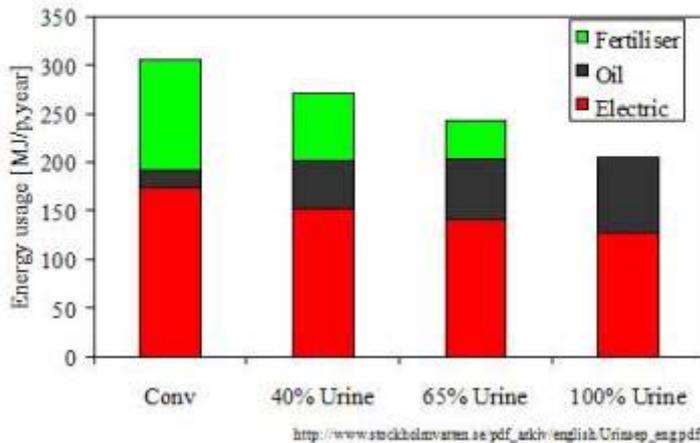
When comparing the proportion of NPK that is recycled in comparison with degree of diversion of urine. When 100% is source separated recycled plant available N increases to 42 times conventional P to 1.5 times conventional K to 35 times conventional. So the recycling effects is very large when including sorting systems. The major effects is in the nitrogen and the potassium as the wastewater treatment plant do not sort these into the sludge at all. Additionally there are several trace elements that are included in the recycling and improving the quality of the soil that is not included in this comparison.

Water emissions vs degree of diversion



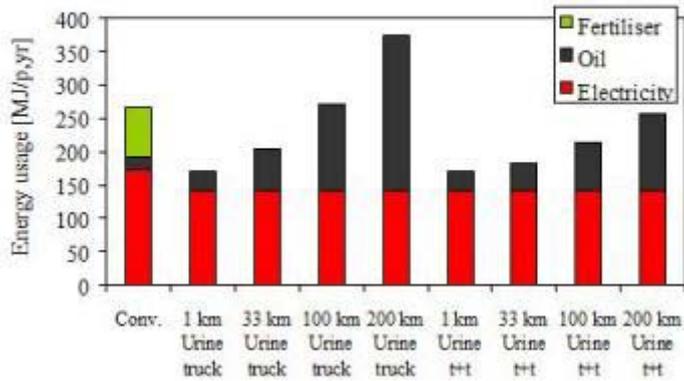
When 65% of the urine is sorted the total N-emissions decreases 55%, sewage plant emissions decreases 60% and Total P-emissions decreases 25%. The effect of nitrogen and phosphorus are different considering that the sludge is recycled. For nitrogen the main effect is that the sorted urine carries the nitrogen so less enters the wastewater and follows the treated wastewater as emission. For the phosphorus the main difference is that the decrease is mainly based upon less water into the treatment plant and as the treatment is a percentage removal there will be less P emitted to the environment

Energy usage vs degree of diversion



Comparing the energy usage, the sorting system will decrease energy for wastewater treatment and pumping as well as for production of mineral fertilizer while the transportation, oil consumption, will increase. Here it is important to have in mind that the environmental effect on local level will increase, with increased sorting, due to larger number of local transports but the global effects will decrease.

Energy usage vs transport distance



One of the major issues discussed with sorting system is that they will increase the cost, and energy consumption, for local transports. When adding the electricity, oil and fertilizer consumption. The conventional system consume fertilizer compared to the sorting system and there is less electricity consumption in the sorting system. When adding these factors it is possible to transport and spread the urine 100km when using a truck and over 200 km using truck and trailer, without consuming larger quantities of energy compared to the conventional system.

System borders

- What to include and what to exclude?
- UDD
 - Solid organic waste
 - Energy production
 - Fertiliser production
 - Food production
 - Delivered sanitational function
 - Greywater
 - Drinking water
 - Other waste

When doing the comparison of two different systems it is important to decide what should be included in the comparison.

For the example of dry urine diversion toilet. Should the management of solid organic waste be included? In the case of co-composting of faeces and solid organic waste it should be included but if the material is not co-composted there is no need of including the solid organic waste in the comparison.

Energy production, should be included if any of the systems compared is generating energy, the best example here would be if the faeces and organic waste is anaerobically digested. The compensation for the energy gain of the biogas needs to be included. If the material is composted, there will as well be energy production in the form of heat, but as long as the heat is not recovered in the system there will be no need to include the heat in the comparison.

Fertiliser production need to be included when the excreta nutrients are recycled, either should the same amount of nutrients be included or the same amount food produced. The later comparison factor is mainly based upon that the systems compared cannot include mineral fertilizers, e.g. mineral nutrients are not available/affordable or not an alternative to consider.

The final comparison factor is the delivered sanitation function, here will other factors such as greywater treatment, drinkingwater production and management of other waste.

Productive Sanitation



The productive sanitation is based on that the nutrients coming out from the households. The concentrations of nutrients differs between regions and in the western high income world the food consumption is higher and thereby also the excreta based fertilizer production. The example here is based on the data for excretion in India that can be considered to be mid income country and for low income countries the food consumption and the fertilizer production is less.

Value of fertiliser - urine

- 2.8kg N = 6kg Urea 0.5€/kg = 3€
- 0.4 kg P = 2kg TPS ~0.4€/kg = 0.8€
- 0.5 kg K = 1kg KCl ~0.4€/kg = 0.4€
- Total value 4.2€ per person and year = 0.012€ per person day
- Value per jerry can 20L ~ 0.23€
- Can at least pay for transport and spreading
- Non-subsidised



When we look at the fertilizer production for one person based on excreta and compare this to the price of the same amount of mineral fertilizer. The price will differ over the year and between years due to differences in production, consumption and price of the substances that is used for production, e.g. the price of fossil gas have a direct effect of the price of urea.

The total value for the fertilizer from one person collected during one year corresponds to just over €4. And if this is distributed into what the fertilizer price of the urine collected in one 20L jerry can will it correspond to 0,23€ Even if the farmer is not interested in paying with money for the product it can at least pay for the transport of the material from the toilet to the field.

Important to have in mind here is that this calculation is based upon a non-subsidised fertilizer. Many countries are though subsidizing the fertilizer making it hard to compare the prices of organic and mineral fertilizers as the organic fertilizer will not carry the same subsidies.

Cost for ecosan

- Pour flush toilet 1900 INR (35€)
- EcoSan toilet 4200 INR (77€)



To compare the price of producing Ecosan, we use an example first presented by Professor Dunkan Mara. The price of the Ecosan toilet is almost the double compared to the conventional system.

Fertiliser per family

	Nutrients	Fertiliser	Amount, kg	Difference
	4 persons	NPK 10-5-20	160	kg
N	18,2	10,0%	16,0	2,2
P	2,32	2,2%	3,6	-1,2

- NPK 10-5-20 Indian, price 5.5 INR/kg (0.1€)
- Value 880 INR/year (16€)
- Present value years 2-10: 5070 INR! (93€)

The organic fertilizer is compared to similar concentration mineral fertilizer and the price of that fertilizer.

Conclusion

- Pour flush toilet cost: 1900 R
- EcoSan toilet cost: 4200 R
 - Income from fertiliser: 5080 R
- Fertiliser can pay for toilet in 10 years, not just additional cost!

Additionally

- Less hazard to ground & surface water
 - Saves on drinking water
 - Protects health

When comparing the produce fertilizer from one family and the non—subsidised fertilizer it shows that during a life span of ten years, the value of the fertilizer is higher compared to the cost of production.

In addition to the gain in decreased cost the toilet system will decrease the use of water for flushing the toilet, and lead to less pollution of the water recipients and thereby increased health.

Cost sharing

- Having no toilet has lowest investment & direct running costs!
- Only type of toilet where the investment can directly pay off
- The cost of Ecosan is competitive compared with any other ecological solution
- The cost is largely paid by household when building – no risk for corruption at municipal level – higher cost acceptance
- More private enterprise – more competition – saves taxes

To conclude this example, the cheapest solution is always not to have a toilet at all, just using the bush/curb/field-toilet.

It is only toilet system that sort the excreta from the total wastewater volume that result in a pay off from the investment.

The cost is in most cases covered by the single household. This leads to decreased risk for corruption and the cost acceptance is higher.

This will also give more private enterprises leading to more competition and thereby decreasing the prices and thereby both increasing the local employment and decreasing the cost for taxes.