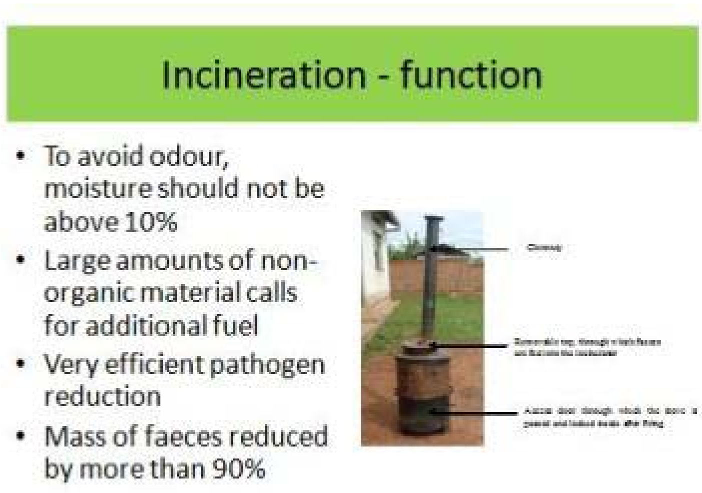
Chapter 4 module 2 Treatment of excreta for safe reuse

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 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.

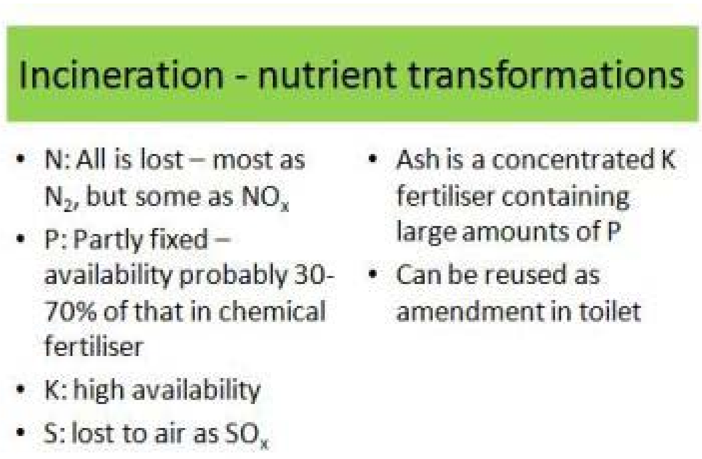


When excreted the faeces hold a moisture content of approximately 80%, for incineration the material required to be dried to 10% moisture only. If the material contain more moisture there is an overlying risk for strong odour during the incineration. In most cases the faeces can be sun dried in a thin 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.



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 whish 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.

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 is 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°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

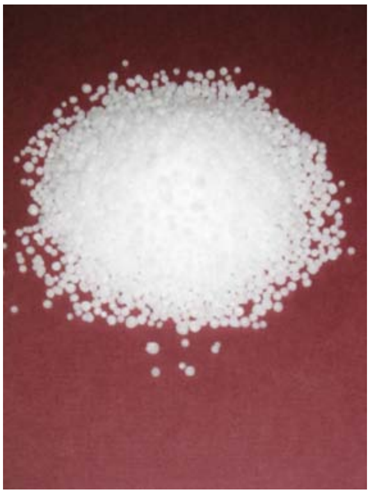
- Uncharged ammonia is toxic to all organisms
  - animals, plants, bacteria, viruses and parasites
- The ammonia distributes by itself through the material
- The ammonia can be added as urea or as ammonia(aq)

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 orgaisms and for the one that have strong survival agains high pH, e.g. *Ascaris* spp., the pH needs to be above 12. Ammoina 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 become 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 orgaisms. 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 watersolved 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.

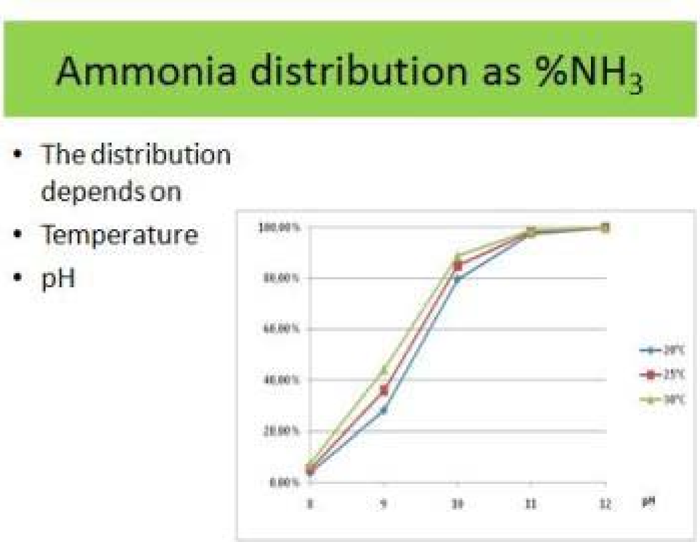
Ammonia treatment

- Urea is enzymatic degraded to ammonia
- $CO(NH_2)_2 + 2\ H_2O \Rightarrow 2NH_3 + H_2CO_3$
- $NH_4^+ + OH^- \Leftrightarrow NH_3(aq) + H_2O$
  - pKa=9.25 at 25°C
- $NH_3(aq) \Rightarrow NH_3(g)$
- Upon addition pH reach 9
  - the higher the pH, the more $NH_3(g)$, the more toxic



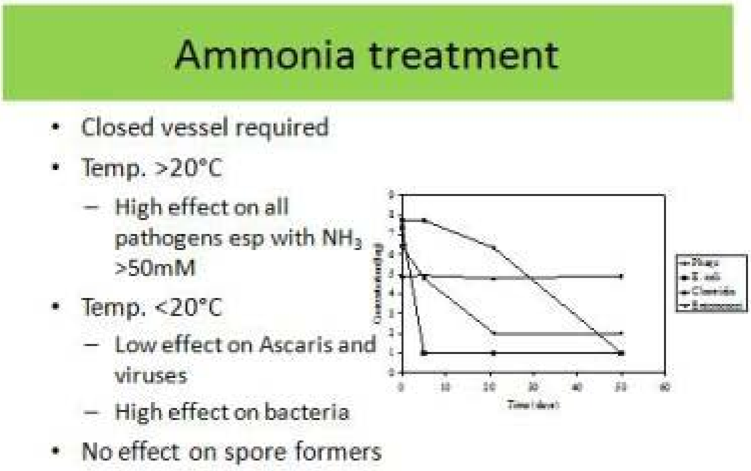
When the urea is added to the faecal matter it will be degraded by naturally occurring enzymes. The enzyme, urease, is a very common enzyme found in bacteria as well as in humans and plants. The degradation of urea produces one carbonate and two ammonia molecules. This degradation will increase the pH 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.



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.

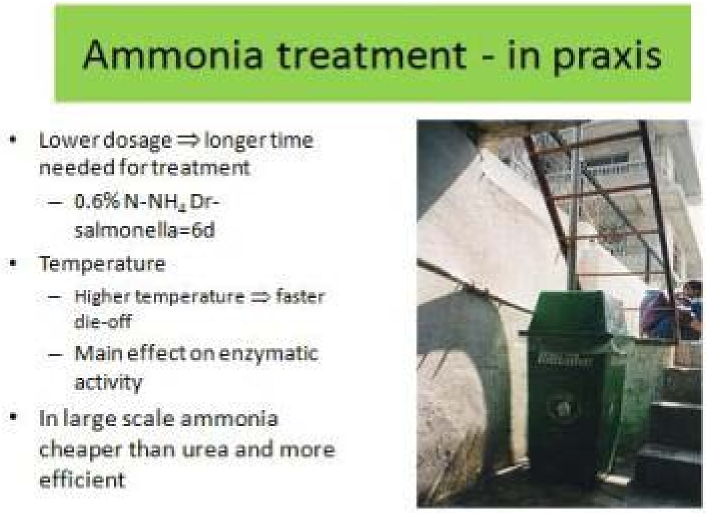


Due to the high volatilisation of ammonia the treatment needs to be performed in closed containers avoiding losses of ammonia.

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.

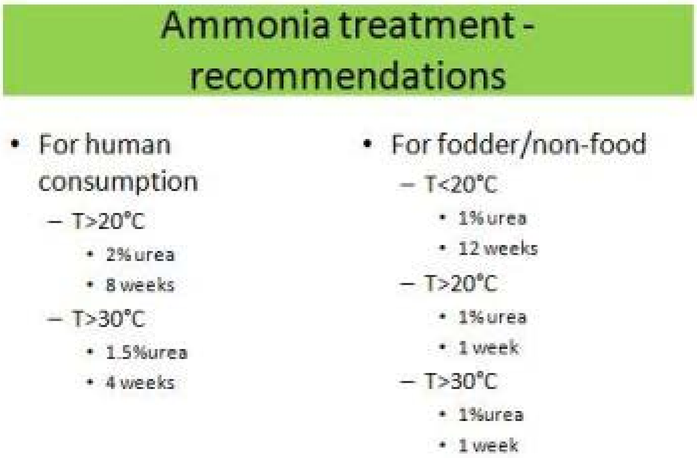
At ammonia levels below approximately 50mM NH_3 the rate of inactivation decreases fast, especially for the non bacterial organisms. At temperatures below 20°C the inactivation of bacteria is still very fast in presence of ammonia while the inactivation of parasites and viruses occurs at a much slower 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. Hepatitus E, Ascaris spp, Cryptosporidia. Read more about other barriers in chapter 3.



To use ammonia for treatment of manure there are several environmental factors that needs 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 are 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.



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 calls 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.

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.

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.

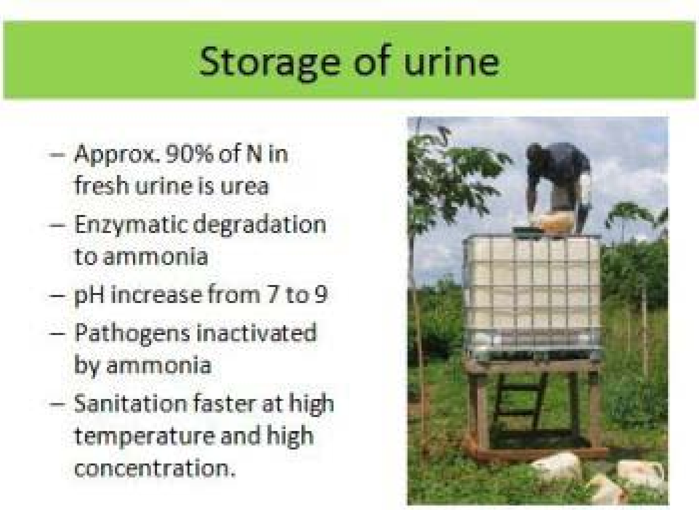
As the ammonia will remain in the material during the treatment there is no risk for regrowth as the repressive effects will continue to be present as long as the ammonia remains. If the ammonia is ventilated off, there will be a risk for contamination and regrowth, depending on how long the treatment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

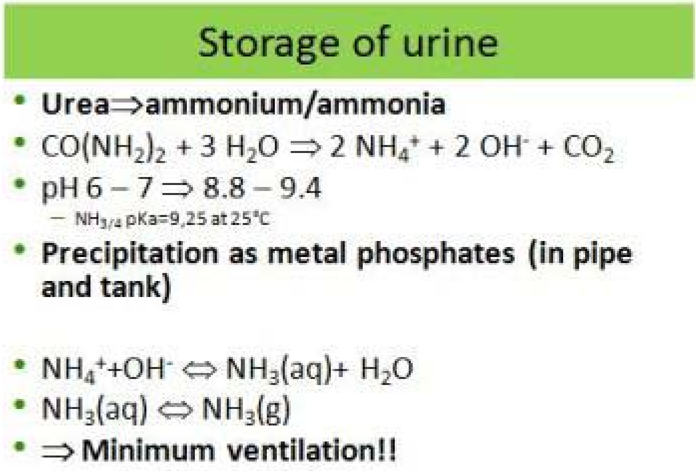
The ammonia is corrosive and metal containers will corrode during the treatment and the recommendation is to use plastic materials for this kind of treatment.

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 abag, 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.



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 naturallyexisting 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.



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 $Ca_X(PO_4)_Z$, 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 ammonina will be found in equilibrium between ammonium ions, watersolved ammonia and gasous ammonia. If the gasous ammonia are ventilated off new NH_3(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.

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.

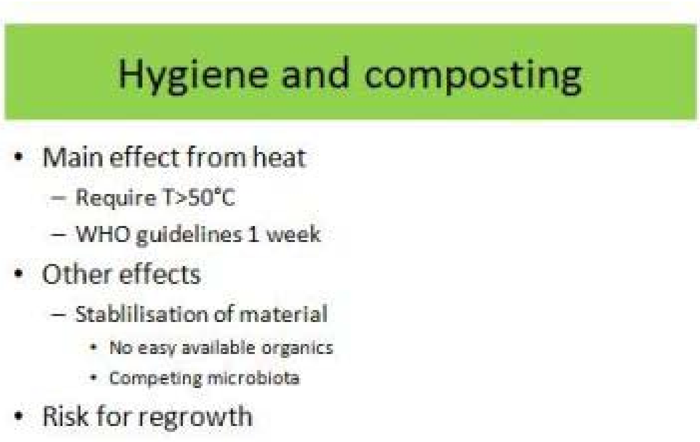
Urine storage - nutrient transformations

- 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.



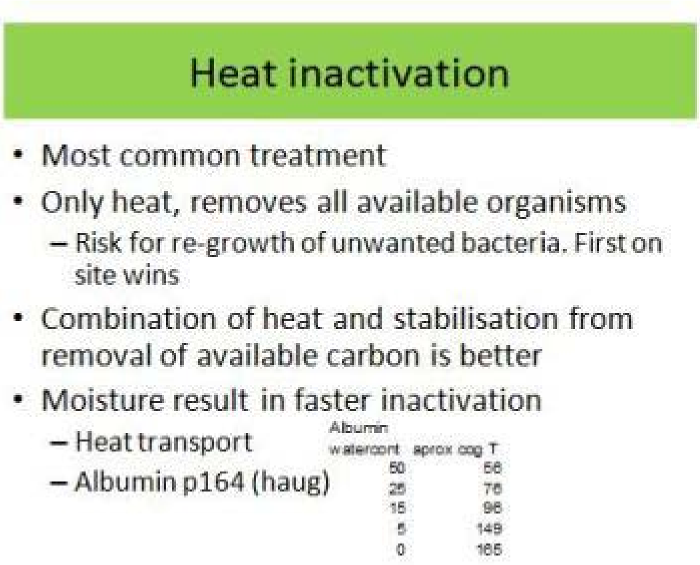
Composting is the most common treatment method for faecal treatment. The composting itself is not any guarantee for proper sanitisation. During the process the organic material are degraded into a humus soil like material, that can, if the treatment have not been performed correctly still be potentially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

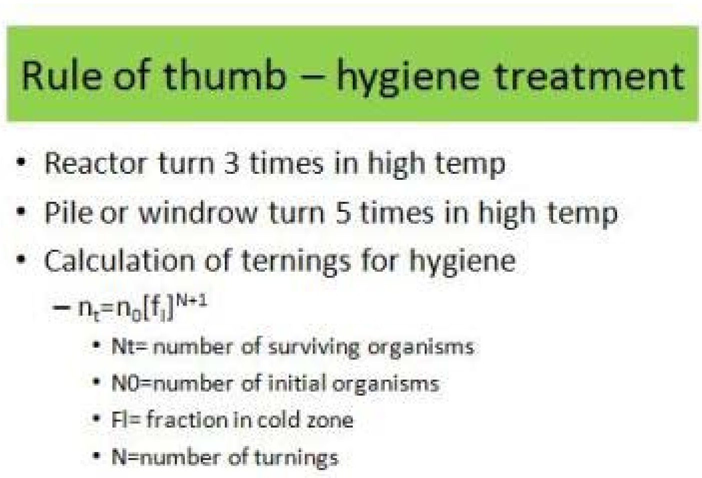
More information on composing can be found in chapter 4 module 2.



Heat inactivation 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 growt 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.

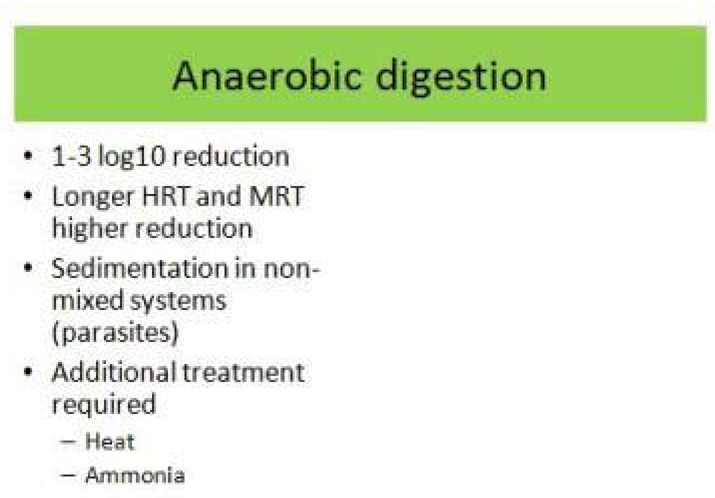
For most efficient heat transfer the moist heat is more efficient compared to dry heat. The example with the protein albumin shows the difference in temperature requirement depending of the water content and with less water the more heat is required for an efficient treatment. This is exemplified with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



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 will not act as a functional sanitisation. Within the process of a mesophilic digestor 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 alterntive can be addition of ammonia or a base for performing an ammonia based sanitisation of the treated material.