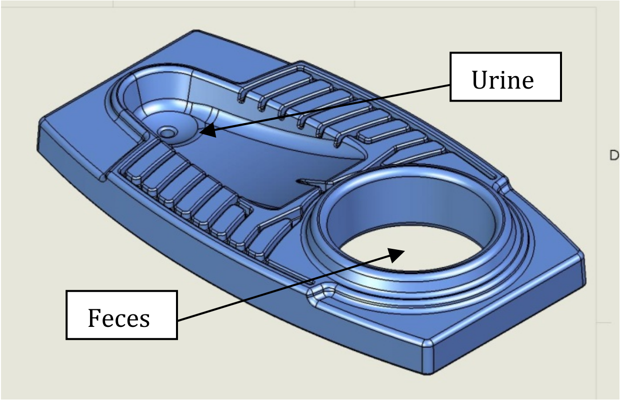
THE RECYCLING OF HUMAN WASTE IN VIETNAM

On a yearly basis a human produces roughly 500 liters of urine and 50 liters of feces, and these two products contain enough nutrients to grow most of the plants that this person needs as food.

But instead of utilizing these 550 liters as a valuable resource, we mix it with roughly 15,000 liters of water and all goes down the drain. Before it reaches the sewage plant, if there is one, this slurry gets mixed with hundreds of pollutants along the way. The conventional sewage plant rarely retains or destroys all bacterial and viral contaminants, it produces a large amount of sludge generally unfit for agriculture, and it causes severe pollution in freshwater and seawater ecosystems.

This end-of-pipe solution recycles nothing. It takes valuable resources and transforms them into pollutants. As fertilizer prices rise throughout the world, and as water becomes an increasingly scarce commodity, this approach is not sustainable and makes no sense.

Modern agriculture gets the nitrogen it needs from ammonia-producing plants that utilize fossil fuels such as natural gas, LPG or petroleum naphtha as a source of hydrogen. This energy-intensive process dumps carbon dioxide into the atmosphere and consumes a finite hydrocarbon resource. Modern agriculture gets the phosphorous it needs from phosphorous-bearing rocks. But these reserves are rapidly dwindling and increasingly contaminated with pollutants such as cadmium. In as little as 25 years apatite reserves may no longer be economically exploitable.



If we are serious about achieving sustainability in this regard, our first, and perhaps most important duty, lies in not mixing urine with feces. Within the human body these two wastes are produced and stored separately, they are excreted separately, and afterwards they should be contained and processed separately. A double-outlet toilet, one for urine and the other for feces, is all that is needed (see drawing).[1]

Closing the loop on human feces is quite simple. The double-outlet toilet should also be a composting toilet,[2] and after undergoing an initial round of composting in this toilet, feces can be composted thermophilically at decentralized composting facilities. Afterwards it can be processed in one final sanitizing step by the action of red worms. This will assure the total destruction of pathogens.

In so far as urine is not mixed with feces, it is, in most cases, sterile and pathogen-free. Soon after it exits the human body, it comes into contact with bacteria that catalyze the hydrolysis of urea $(NH_2)_2CO$ into ammonia NH_3 and bicarbonate HCO_3^-. This provokes a rise in pH from about 6.2 to about 9.1.

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[1] Beautiful designs of pedestal double-outlet toilets are easy to find.

[2] Some designs of composting toilets in Holland claim to be totally odor-free. A slightly negative pressure within the composting chamber does not allow odors to escape.

In one option to recover nutrients from urine, it would flow by gravity from the toilet into a urine storage container. Even though a large percentage of nitrogen is in the form of ammonia, NH_3 is highly soluble in water, and the exchange of ammonia between solution and gas is very slow. This means that ammonia does not so easily volatilize in the urine storage vessel resulting in a significant loss of nitrogen.

In urine almost all phosphorous is in the form of soluble PO_4 anions, and these anions will quickly interact with cations of magnesium and calcium present in the urine, forming magnesium ammonium phosphate hexahydrate (struvite) $MgNH_4PO_4.6H_2O$ and calcium phosphate (hydroxyapatitie) $Ca_5(PO_4)_3(OH)$ respectively. Occasionally calcite $CaCO_3$, epsomite $MgSO_4{\cdot}7H_2O$ and brucite $Mg(OH)_2$ will form. Up to about 30% of the soluble phosphorous in the urine will precipitate out in solid form and can be seen as sediment on the bottom of the urine storage vessel. Since there is not enough magnesium and calcium present in urine, the remaining PO_4 cannot react and settle out.

Struvite is highly soluble at an acidic pH and highly insoluble at an alkaline pH. The pH for maximal struvite recovery lies in the range of 9.0 to 9.5. The pH of hydrolyzed urine is ideal for struvite formation. No pH adjustment is needed, and the reaction is quite fast. The formation reaction of struvite is:

$Mg^{2+} + NH_4^+ + PO_4^{3-} + 6H_2O \rightarrow MgNH_4PO_4{\cdot}6H_2O$

So if urine is stored over a period of time, the supernatant will no longer contain magnesium and calcium. The phosphates crystallized in this initial step are excellent slow-release fertilizers. Here phosphorous is in a very concentrated form, and it is free of sodium chloride, hormones, pharmaceuticals and other unwanted urine compounds.

Struvite in its simplest form by weight is: 9.90% Mg, 7.35% NH_4, 38.70% PO_4 and 44.05% H_2O, while calcium phosphate by weight is: 39.89% Ca, 56.72% PO_4 and 3.39% OH. If enough magnesium ions were added to the urine, the remaining phosphorous would be recovered in the form of struvite. If enough calcium ions were added to the urine, the remaining phosphorous would be recovered in the form of calcium phosphate. But magnesium offers two big advantages over calcium.

Firstly, with the one input of magnesium, two plant nutrients (NH_4 and PO_4) are recovered in solid form. Calcium carbonate only captures PO_4. Secondly, the quantity of precipitate produced through the addition of magnesium is many times less than the quantity of precipitate produced through the addition of calcium hydroxide. The magnesium precipitate is far more concentrated than the calcium precipitate.

In struvite formation, potassium may substitute ammonium giving $MgKPO_4{\cdot}6H_2O$, and in calcium phosphate formation, potassium may substitute calcium giving KH_2PO_4, K_2HPO_4, or K_3PO_4. But since the molar total ammonia concentration in urine is nearly five times higher than the potassium concentration, very little potassium is substituted.

Magnesium can be added to urine in several forms: magnesium oxide MgO, magnesium chloride $MgCl_2{\cdot}6H_2O$, magnesium hydroxide $Mg(OH)_2$ and magnesium sulfate $MgSO_4{\cdot}7H_2O$.[3] Generally it

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[3] Magnesium chloride disassociates faster than magnesium hydroxide, but magnesium hydroxide has the effect of raising the pH making it hard to control magnesium concentration and pH independently.

takes less than a kilogram of MgO to capture almost all (>99%) of the phosphorous in a metric ton of undiluted urine. Along with phosphorous, sometimes as much as 38% of the nitrogen in the urine can also be captured in struvite form.

All of the above magnesium compounds are relatively expensive. But Vietnam has a waste by-product called bittern that contains as much as 50% magnesium compounds. Bittern is a viscous semi-clear liquid of a relatively high density (sometimes as high as 1.31) left over after salt has been evaporated from seawater.[4] It sells in Vietnam for approximately \$10/m^3.

After magnesium compounds are added to the urine, the limiting factor becomes phosphorous. There are not enough phosphorous anions present in urine to capture the remaining nitrogen and potassium ions. One way to solve this problem is through the addition of phosphorous in stoichiometric quantities.

Phosphorous could be added in the form of technical grade phosphoric acid, sodium phosphate or commercially available fertilizers such as triple superphosphate (which contains no sulfur). But instead of adding any of these sources of phosphorous directly to urine, they could first be added to bittern as a low-cost means of extracting from bittern the magnesium needed in the processing of the urine.

Jose A. Fernandez Lozano et al, in a paper called *Multinutrient Phosphate-Based Fertilizers from Seawater Bitterns*,[5] outlines a procedure to capture nutrients from a bittern through the addition of commercial grade monohydrated sodium phosphate NaH_2PO_4 followed by neutralization with sodium hydroxide NaOH. Lozano explains that this reaction occurs best at a bittern dilution of 100% by volume and at a pH of 10. Very little sodium or chlorine compounds are present in the end products. The basic chemical reaction is:

$$4MgCl_2+KCl+3NaH_2PO_4+6NaOH \rightarrow MgKPO_4+Mg_3(PO_4)_2+9NaCl+6H_2O$$

In another paper entitled *A Novel Process for the Production of Multinutrient Phosphatic Base Fertilizers from Seawater Bittern and Phosphoric Acid*,[6] Lozano gets the same end products by using phosphoric acid H_3PO_4 (purity 85%) and sodium hydroxide. Lozano explains that the recovery of Mg, K and PO_4 reach 100% at pH 10, while the recovery of B reaches 90% at the same pH. Once again he shows that phosphate reactions occur best when bittern is diluted. The basic chemical reaction here is:

$$4MgCl_2+KCl+3H_3PO_4+9NaOH \rightarrow MgKPO_4+Mg_3(PO_4)_2+9NaCl+9H_2O$$

The processing of bittern by means of sodium phosphate or phosphoric acid could take place along the coast where the bittern is produced, as Lozano suggests, and the magnesium and potassium phosphates could be transported to the sites where the urine would be processed. This would

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Magnesium sulfate adds sulfates into the equation, and this may not always be desirable. The addition of NaOH to raise pH in struvite formation is more efficient than the addition of lime or $Mg(OH)_2$.

[4] The composition of bittern from a solar evaporation salt company located in Vinh Hao is: 26.75% Cl^-; 10.32% SO_4^{2-}; 9.36% Mg^{2+}; 1.96% K^+; 8.22% NaCl; 3.74% KCl; 26.75% $MgCl_2$; 12.90% $MgSO_4$.

[5] See http://www.scielo.org.ve/scielo.php?script=sci_arttext&pid=S0378-18442002000900009&lng=en&nrm=iso

[6] http://www.interciencia.org/v24_05/fernand.pdf

eliminate the cost of transporting bittern to the urine processing sites, and it should give much better control in achieving stoichiometric and operational balance in the processing of the urine.

Since this would be a one-step procedure, it might even be possible to process urine at its source within the urine storage container connected to the double-outlet toilet. This offers the enormous advantage of eliminating the transport of urine. The on-site processing of urine on an annual or semi-annual basis at the level of the household should be feasible given an abundance of low-cost labor such as seen for example in Vietnam in the case of scavengers who do an excellent job in recycling paper, cardboard, glass, metals and plastics. The same scavenger infrastructure, so vibrant and resourceful throughout the whole of Vietnam in recycling waste materials, could be called upon to process urine and sell its extracts to fertilizer companies.

The application of soluble fertilizers directly to plants is not always ideal. If soil conditions are not right, fertilizers leach out and contribute to the eutrophication of freshwater and seawater ecosystems. In this approach, phosphorous, free of cadmium and other heavy metals, would capture nutrients from two waste products before being delivered to plants in slow-release form.

Therefore, why apply phosphorous directly to plants, when this same phosphorous is so efficient in capturing nutrients from bittern and urine? If it makes sense, especially for use in tropical regions, to produce low solubility phosphate fertilizers[7] rich in magnesium and potassium, as Lozano suggests, would it not make even more sense to produce essentially the same phosphate fertilizers that would also be rich in ammonium? The phosphate industry in Vietnam would not only add value to their product, but it would also play a major role in the recycling of two waste products.

Nonetheless someone might argue that the use of a finite resource such as phosphorous is not ideal. Taking into account this objection, we turn to another paper by Lozano entitled *Recovery of Potassium Magnesium Sulfate Double Salt from Seawater Bittern*,[8] and there we find clues on how to avoid the addition of phosphorous to capture the remaining ammonium and potassium after urine has been treated with bittern. This brings us to a second approach which shifts focus from phosphates to sulfates.

In this paper Lozano explains that bittern contains potassium sulfate and magnesium sulfate, and that these two salts can be selectively precipitated as a double salt (hydrated potassium magnesium sulfate) from bittern using methanol. Lozano explains that potassium and magnesium sulfates are less soluble in aqueous methanol solutions than other salts present in bittern, and based on this, they can be selectively precipitated. It appears that methanol depresses the solubility of certain inorganic salts while hardly affecting the solubility of others.[9]

At low methanol concentrations, most of the sodium chloride and sodium sulfate within the bittern remain in the liquid phase, while most of the potassium and magnesium sulfates settle out as potassium magnesium sulfate $K_2SO_4 \cdot MgSO_4 \cdot H_2O$ with varying levels of hydration. Lozano explains that best results are obtained on a bittern of 1.31 specific gravity or greater, that the precipitation of potassium magnesium sulfate takes place ideally at temperatures between 30-40°C, that the maximum yield of crystals is reached within 30 to 40 seconds of introducing the methanol, and that a salting time of three minutes is sufficient. Lozano also shows that ethanol is a more effective salt

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[7] The solubility of struvite in water is 0.02g/100ml water. It is highly soluble in dilute acidic solutions and highly insoluble in alkaline solutions.

[8] http://pubs.acs.org/cgi-bin/abstract.cgi/iepdaw/1976/15/i03/f-pdf/f_i260059a018.pdf?sessid=6006l3

[9] See http://cat.inist.fr/?aModele=afficheN&cpsidt=2514376

dehydrating agent than methanol, but that methanol is preferred as a precipitating agent because of its higher selectivity for potassium sulfate.

Lozano says that the recovery efficiencies with methanol are high, and that the loss of methanol after distillation is only 0.21%. He also says that the NaCl and $MgCl_2$ by-products from this process are present in quantities sufficient to defray in large part the cost of recovering the products.

Elsewhere we see that alcohols, such as methanol, ethanol, butanol, and isopropanol cause the precipitation of ammonium sulfate $(NH_4)_2SO_4$ from an aqueous solution.[10] Because methanol is relatively cheap compared to these other alcohols, it is the preferred alcohol in this precipitation process. Preferentially four to five times more methanol than ammonium sulfate is added by weight to the aqueous solution. The reaction takes place at temperatures ranging from 15 to 30 C, and methanol can be recovered by distillation and cycled back into the process.

When aluminum sulfate $Al_2(SO_4)_3$ $18H_2O$ is added to urine,[11] hydrogen ions are produced lowering the pH and converting ammonia to ammonium. The ammonium then reacts with sulfate ions to form ammonium sulfate $(NH_4)_2{\cdot}SO_4$ and potassium sulfate K_2SO_4. These two sulfates can be precipitated out of solution by means of methanol as Lozano describes.

Instead of using aluminum sulfate, one might consider using sodium sulfate Na_2SO_4, a byproduct of the production of hydrochloric acid from sodium chloride by treatment with sulfuric acid. Sulfuric acid H_2SO_4 could also be used as a source of SO_4.

However if we look closely at the composition of Vietnams's Vinh Hao bittern, we see that it contains more than 23% sulfur compounds, and this would suggest that the addition of sulfate ions might be minimal.

If this methodology were followed, then the treatment of urine would be carried out in three steps:

1) The first step would involve treating hydrolyzed urine with enough magnesium to precipitate out all of the phosphates. This reaction could take place in the urine storage container. These phosphate precipitates would be removed from the process as finished products.
2) The second step would consist of treating the supernatant with sulfates to form ammonium and potassium sulfates.
3) The third step would consist of precipitating out the ammonium and potassium sulfates by means of the addition of methanol.

Ammonium sulfate consists of 27.30% ammonium and 24.27% sulfur, and sulfur of course is an important plant nutrient. Ammonium sulfate fertilizer blends are stable and do not melt under conditions of high humidity. Unlike ammonium nitrate, ammonium sulfate cannot be used in the manufacture of bombs.

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[10] See http://www.freepatentsonline.com/3902859.html as well as http://books.google.com/books?id=Q7srXhd4irQC&pg=PA153&lpg=PA153&dq=ammonium+sulfate+methanol+mixing&source=web&ots=XM8v4VW1yh&sig=HzbewIudV7TQDZpd1oxpZPe8UB0&hl=en&sa=X&oi=book_result&resnum=2&ct=result#PPA153,M1 p. 153, as well as http://www.freepatentsonline.com/3709666.html

[11] See http://www.aces.edu/pubs/docs/A/ANR-1202/

Once again the processing of bittern by means of methanol to produce hydrated potassium magnesium sulfates could take place along the coast where the bittern is produced, and the extracted sulfates would be transported to the sites where the urine would be processed.

This second approach presupposes the formation of magnesium ammonium sulfate hexahydrate[12] $Mg(NH_4)_2(SO_4)_2{\cdot}6H_2O$ and potassium ammonium sulfate hexahydrate when the hydrated potassium magnesium sulfate would be added to urine. Magnesium ammonium sulfate hexahydrate, like magnesium ammonium phosphate hexahydrate, is considered to be very good slow-release fertilizer.[13] Both contain magnesium, ammonium and water, while one contains P of an atomic weight of 30.974 and the other contains S of an atomic weight of 32.066.[14]

Instead of adding methanol to precipitate ammonium and potassium sulfates, we might consider using polyvinyl alcohol $(C_2H_4O)x$. [15] As a solid PVA is freely soluble in water at room temperature, it is relatively inexpensive and would not have to be recovered through distillation.

So far we have outlined two approaches to extract nutrients from urine. The first approach involves the addition of the anion PO_4. This gives magnesium and potassium ammonium phosphates. The second approach involves the addition of the anion SO_4. This gives ammonium and potassium sulfates. Both approaches are feasible, and both approaches could be implemented to produce multi-component fertilizers capable of satisfying the needs of a broad range of soil types.

A third approach to capturing the remaining nitrogen and potassium after the initial pre-treatment with magnesium might lie in the use of ion exchange resins. These are insoluble synthetic polymers normally supplied in the form of granules, beads or sheets. Some resins have a dense internal structure with no discrete pores and are described as microporous, while other resins have a multi-channeled, porous structure and are described as macroporous.

These ion exchange resins contain two types of ions. The first type of ion is bound within the structure of the polymer and is fixed. The second type, having a charge opposite to that of the first, is free to detach itself from the polymer and be exchanged for ions of a similar charge within the surrounding medium. This second type of ion is referred to as the counter-ion.

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[12] Magnesium ammonium sulfate hexahydrate is one of a large number of isomorphous compounds called Tutton's salts. Tutton's salts are double sulfates with one monovalent positive ion like K or NH_4 and one divalent positive ion like Mg or Ca. See http://rruff.geo.arizona.edu/doclib/zk/vol117/ZK117_344.pdf, http://www.isis.rl.ac.uk/isis2000/reports/11372.PDF, and http://www.galleries.com/minerals/sulfates/picromer/picromer.htm. It is also known as Boussingaultite http://www.handbookofmineralogy.org/pdfs/boussingaultite.pdf

[13] See http://books.google.com/books?id=gJhgCQF2wPkC&pg=PA5&lpg=PA5&dq=%22magnesium+ammonium+sulfate%22+fertilizer&source=web&ots=wHcqxnu6V3&sig=JFMdNxPqUhY4HWxYh74YCX04je8&hl=en&sa=X&oi=book_result&resnum=1&ct=result

[14] Patent WO/2008/013510 describes a procedure to make boussingaultite $(NH_4)_2SO_4$-$MgSO_4{\cdot}6H_2O$ from ammonium sulfate. See http://www.wipo.int/pctdb/en/wo.jsp?wo=2008013510

[15] See http://www3.interscience.wiley.com/journal/104525864/abstract

The counter-ion could be a cation or an anion, and the force that binds ions could be strong or weak. Thus there are four types of ion exchange resins: strong or weak cation exchange resins, and strong or weak anion exchange resins.

Strong cation exchange resins contain sulfonic acid groups or the corresponding salts. They behave like strong acids, they are highly ionized, and they operate independently of the pH of the solution.

Weak cation exchange resins contain carboxylic acids groups or the corresponding salts, they behave like weak organic acids, and they do not operate independently of the pH of the solution. Below a pH of 6.0 they typically have a limited capacity.

Strong anion exchange resins contain quartenary ammonium groups. They are highly ionized and are not influenced by the pH of the solution. Weak anion exchange resins contain ammonium chloride or hydroxide, and their degree of ionization is strongly influenced by the pH of the solution. If urine is pretreated by mixing it with bittern to precipitate out phosphorous, then anion exchange resins would not be required.

When cation exchange resins are exhausted, they can be removed from use and can be regenerated. Strong cation resins can be regenerated with salt or acids. Sulfuric acid is one of the cheapest chemicals used. Hydrochloric acid is also used. Since the hydrolyzed urine to be presented to cation resins contains no calcium or ferrous ions, calcium and iron sulfates will not form and foul up the resin. The amount of regenerated concentrate is quite small compared to the original volume of urine treated (1%-5%). [16]

The order of affinity for some common cations is approximately: $Hg_2^+ < Li^+ < H^+ < Na^+ < K^+ \approx NH_4{}^+ < Cd_2^+ < Cs^+ < Ag^+ < Mn_2^+ < Mg_2^+ < Zn_2^+ < Cu_2^+ < Ni_2^+ < Co_2^+ < Ca_2^+ < Sr_2^+ < Pb_2^+ < Al_3^+ < Fe_3^+$. Since sodium cations have less affinity than potassium and ammonium cations, sodium cations within the urine should not prematurely saturate or exhaust the resin. However if too much magnesium cations are added to the urine in the first pretreatment step, magnesium cations could quickly exhaust the resin.

The ion-binding capacity of a resin is expressed in terms of equivalents or milliequivalents per unit of weight or volume. An equivalent is the molecular weight of the ion in grams divided by its electrical charge or valence. For example, if a particular resin has a total exchange capacity of 3.8 eq/kg, and if the urine after treatment with bittern contains 7830 g NH4/m3 and 2730 g K/m3, then under ideal conditions it would take approximately 132 kg of this resin to capture all NH4 and K in a cubic meter of urine.

But some weak cation exchange resins have a total exchange capacity as high as 10 eq/kg. [17] If they could be used in this application, then in theory it would only take only about 50 kg of this resin to do a similar job. Cation exchange resins have been used to capture ammonium from a simulated wastewater. [18] They have also been used to capture potassium.[19]

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[16] See http://www.nzic.org.nz/ChemProcesses/water/13D.pdf

[17] See http://www.sigmaaldrich.com/aldrich/brochure/al_pp_ionx.pdf

[18] Jorgensen and Weatherley conducted a study to remove ammonium from simulated wastewater. The ion exchangers used in this study were clinoptilolite and two polymeric exchangers, the gel resin Dowex 50x-x8 and the maconet resin Purolite MN500. Dowex 50w-x8 showed the highest uptake of ammonium, followed by

Cation exchange resins require very little energy, and regenerant chemicals are relatively cheap. If chlorine is not present, resins are known to last as long as 20 years.[20] These resins could be located at the household in much the same way that a water-softening unit is set up to remove cations of magnesium and calcium from tap water.

This third approach to urine processing would consist of two steps:

1) The first step would involve treating hydrolyzed urine with enough magnesium compounds so to precipitate out all of the phosphates. Once again, this reaction could take place in the urine storage vessel, and the phosphate precipitates would be removed from the process as finished products.
2) The remaining liquid, free of calcium, magnesium and phosphates, would report in a second step to cation exchange resins to remove the remaining ammonium and potassium.

In this third approach, a scavenger could visit the household from time to time to collect the struvite and calcium phosphate concentrates from the first step, to empty the urine storage vessel and replenish it with magnesium ions, to transfers liquids from step one to step two, to regenerate the resins used in step two, and to collect the regenerant concentrate. The concentrates from both steps would be brought to a centralized site where they would be processed and blended into multi-component fertilizers.

So far we have outlined three approaches to capture nutrients in urine. All three involve the addition of magnesium ions in a first step to capture phosphates and some ammonium within the urine. But they all differ on how to capture the remaining ammonium and potassium ions after this initial treatment.

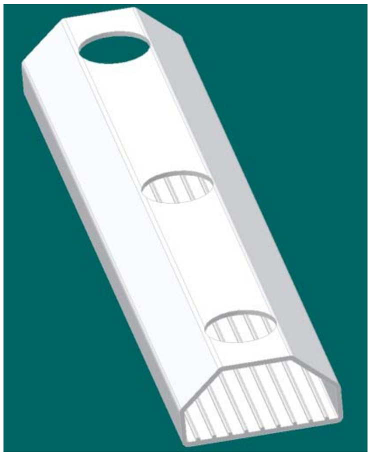
Free anions of phosphorous could be added (approach one). Free anions of sulfur could be added (approach two). Bound anions consisting of sulfonic or carboxylic acid functional groups could be added (approach three). Much testing will be required to determine which approach is the simplest and most economical, and which approach produces the best fertilizers at the lowest cost for Vietnamese soils. In any case it should be abundantly clear that both urine and bittern are valuable resources and should not be wasted.

Approach one is the simplest and involves but a single step that could be carried out on site where the urine is produced. Approach two is more complicated, and in this approach only a pretreatment with magnesium compounds could take place on site. Approach three could be carried out on site, provided the resin reactor would be located on site in much the same manner as a water-softening unit. The cost of setting up a resin reactor at the level of the household should be no greater than the cost of connecting a household to a conventional sewage plant.

MN500 and clinoptilolite. See http://www.zeolite-products.com/ktml2/files/uploads/Ammonia%20removal%20from%20wastewater.pdf

[19] See http://www.nature.com/nature/journal/v182/n4649/abs/1821594a0.html and http://soil.scijournals.org/cgi/content/abstract/27/2/153 and http://www.patentstorm.us/patents/5110578.html and http://www.informaworld.com/smpp/content~content=a776211691~db=all~order=page and http://pubs.acs.org/cgi-bin/abstract.cgi/iecred/1998/37/i05/abs/ie970690o.html

[20] http://www.ion-exchange.com/service/pdf/reprints/Maintaining_IXbased_Systs.pdf



Since only a small part of Vietnam is connected to conventional sewage plants, Vietnam has a unique opportunity to by-pass this antiquated technology and to derive a significant percentage of the fertilizers it needs from human waste.

In all three approaches outlined so far, the central idea has been to capture ammonium and potassium ions after an initial pretreatment step. In a fourth approach, we depart from this notion of capturing nutrients and creating fertilizers, and instead we bring the pretreated urine directly into contact with the roots of plants.

For this concept to work, we must avoid the costly transport of urine over long distances, and to do so, we need, on the one hand, a lot of people producing a lot of urine in a small geographical area, and on the other hand, we need a form of agriculture which occupies little space and can be located in close proximity to this large supply of urine. This agriculture must be incredibly intense and productive, having an enormous capability of taking in nutrients. We find all of this in hydroponics.

Hydroponics is the cultivation of plants in water rather than in soil. Nonetheless it uses only 10% of the water used in conventional agriculture. Water filled with nutrients is continually circulated in a closed loop, and no water is lost through evaporation. Unlike conventional agriculture, plant nutrients cannot escape the system to contaminate our lakes, river and oceans.

There is one particular hydroponic system that does not employ any growing medium or solids.[21] A thin film of oxygenated water flows at the bottom of an extruded plastic channel 100 mm wide and 50 mm high. Water filled with nutrients continually nourishes the roots of plants, and the plants are held in place by means of holes at the top of the channel. The productivity here is quite amazing.

Each finishing hole of this extruded channel can produce up to 26 crop turns per year. In a space of less than 23 square meters, one can grow, for example, 288 heads of lettuce per week, 1,152 heads of lettuce per month or almost 15,000 heads of lettuce per year. If we were to extrapolate this level of productivity over an entire hectare, the production would be:

- over 128,000 heads of lettuce per week,
- over 515,000 heads per month and,
- over 6,700,000 heads per year.

This represents an incredibly high level of food productivity, perhaps the highest in the world. This NFT (nutrient file technique) channel is ideal for growing basil, cilantro, parsley, arugula,

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[21] See http://www.amhydro.com/

watercress, fancy lettuce, head lettuce, bak choy, mazuna, strawberries and a lot more. The cool highland areas of Vietnam are ideal for this technology.

But many plants grown in this particular manner cannot tolerate high levels of ammonia or ammonium, and therefore pretreated hydrolyzed urine would not be suitable. In hydroponic systems, the preferred forms of nitrogen are calcium nitrate and potassium nitrate.

The simplest way to proceed with urine routed to hydroponic systems would be to work along the same lines as in aquaponics. But instead of fish supplying nitrified water to plants, humans would supply nitrified urine to plants. But what would it take to make this work?

We must first do the pretreatment step outlined above. This removes magnesium, calcium and phosphorous and some ammonium as solids, and these solids can be later introduced to the hydroponic system. If we do not remove these solids beforehand, they might settle out in the nitrification step that follows. Prior to nitrification, the urine would be diluted to reduce the concentration of Na and Cl ions.

In nitrification two distinct groups of bacteria are involved. One group converts ammonia to nitrite (*Nitrosomonas*, *Nitrosospira*, *Nitrosococcus*, and *Nitrosolobus*), and the other group converts nitrite to nitrate (*Nitrobacter*, *Nitrospina*, and *Nitrococcus*). These autotrophic bacteria require a pH between 8 and 9. They also require oxygenated water and a large surface area. This is the same technology that aquaponics employs, and it is also the same technology used in every aquarium.

The pretreated, diluted and nitrified urine would be routed directly to the hydroponic system described above. The plants would extract the remaining nitrate and potassium ions, and at this point, the struvite crystals from the pretreatment step could be introduced. These crystals would go easily into solution at the slightly acidic pH required for hydroponic systems, and at an acidic pH, there would be no danger of their precipitation within the hydroponic channels.

Of course plants would leave behind Na and Cl ions. We could continually dilute these ions out the circuit, but this undoubtedly would waste too much water. One simple means to prevent the accumulation of these unwanted ions would be through reverse osmosis, and water free of Na and Cl ions would be returned to circuit to dilute the incoming urine. Reverse osmosis in this case would not be expensive, since it would be employed only to remove Na and Cl ions.[22]

In some aquaponics systems in Australia, the nitrification process is greatly enhanced by the introduction of liquefied or mineralized red worm castings. Exactly how this works has not been clearly documented. Similarly liquefied red worm casting could be added to the hydroponic processing of nitrified urine.

If feces from composting toilets were composted a second time at thermophilic temperatures, and if this compost in turn were presented to red worms, the destruction of pathogens, as stated previously, would be complete. If these castings together with nitrified urine were presented to hydroponic systems, then the whole of human waste would be returned to nature in a closed loop.

Hydroponics is not only one of the most efficient means of growing plants, but, when located near or within urban areas, it may also prove to be a feasible means of recycling human waste. Human

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[22] Reverse osmosis is often used in hydroponic systems in making sure that the water brought into the system does not contain salts.

waste does not have to be transported long distances to the farmer, and the plants cultivated on this waste do not have to be transported long distances to the consumer. The urban farmer can sell directly to the consumer without involving wholesalers and retailers, and finally, in utilizing human waste, the farmer pays virtually nothing for fertilizers.

It is easy to understand, therefore, why urban agriculture in America is quickly becoming the new paradigm in food production, and how it has the potential of creating within this vast economy tens of millions of new jobs within the next few decades.

However, one problem with this fourth option lies in the fact that the urine cannot be processed on site. It has to be transported to a hydroponic system serving a relatively large number of households.

But there is an aquatic plant called duckweed that can be grown on site with none of the complexity of a hydroponic system. This flat, ovoid plant is the smallest of all flowering plants, and yet it is one of the fastest growing plants on earth. As it floats on the surface of the water, it extracts nitrogen, phosphorous, potassium and other nutrients from water through all surfaces of its leaf.

With warm temperatures and sufficient sunlight, it can reduce quantities of N, P and K in water down to almost undetectable levels, and unlike most plants, duckweed can tolerate relatively high concentrations of salts (up to 4000 mg/liter total dissolved solids).[23]

In a near-optimum environment, certain duckweed can double its mass within a period of only 16 hours. Also under optimal conditions, up to 79 tons of duckweed (dry weight) can be harvested from one hectare of duckweed pond in a single year. Duckweed grows 30% faster than water hyacinth, and unlike water hyacinth, it is highly nutritious and thoroughly digestible.

Its protein content is one of the highest in the plant kingdom. The protein content of some species of duckweed on a dry basis reaches as high as 45%. It is also rich in beta carotene, xanthophylls, as well as vitamins A and B. Since it does not have to support upright structures, duckweed contains very little fiber or indigestible matter. Duckweed can be fed, fresh or ensiled, to fish, pigs, cattle, goat, sheep, chickens and, of course, ducks.

Even without a urine-diverting toilet, it is easy to set up a small 2 x 2 or 2 x 6-meter duckweed pond to process the urine of a single household. See the picture of a 2 x 6-meter duckweed pond located near a small restaurant in the Mekong. Connected to this pond is nothing more sophisticated than an inexpensive conventional flush toilet used only as a urinal by both men and women. This toilet discharges water and urine into one end of the duckweed pond, and water is pumped from the other end of the duckweed pond back to the reservoir of the toilet. Feces is deposited into a

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[23] See: http://www.lrrd.org/lrrd7/1/3.htm

completely separate device, an aerated storage unit,[24] where it is processed by black soldier fly larvae and red worms. See the picture below of duckweed harvested from this urine processing pond.

Eventually biopods will be set up for the harvest of BSF larvae,[25] and the harvested larvae and the duckweed will be cooked into a soup and fed to pigs.[26] In this way all of the nutrients in human waste will be integrated back into the food chain. The same approach will be applied in the Mekong to the processing of pig waste. Pig feces will be shoveled into biopods, and pig urine will be flushed into duckweed ponds. The larvae and duckweed from this combined approach will return to the pig as food.

So in conclusion we have examined five strategies to extract nutrients from urine. Some are more appropriate for developed countries (1 to 3), and some are more appropriate for developing countries (4-5). For rural Vietnam, the fifth strategy is particularly appealing, since it completely does away with the notion of an independent sewage treatment plant. Why should sewage treatment be anything other than an important and vital aspect of sustainable food production?

We talk a lot about sustainability, but we will never relate to nature in a truly sustainable manner until we give back to nature, in a closed loop, all of the nutrients that she needs to sustain us. Capturing all of the nutrients within our waste (even human waste) and making these nutrients available to the life processes that support us is surely our first and most important obligation as citizens of planet Earth.

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[24] The design of an aerated storage bin is quite simple. See: http://www.esrla.com/pdf/composting.pdf or http://www.esrla.com/pdf/ait.pdf or http://www.esrla.com/pdf/xuantho.pdf Into this same bin is placed all biodegradable material from a residence.

[25] On biopods, see: http://www.esrla.com/pdf/Brazil.pdf

[26] The energy required to cook the larvae and duckweed will be derived from rice hull and coffee bean gasifiers. See: http://www.esrla.com/pdf/gasifier.pdf