Final report

Executive summary

ValueFromUrine is a collaborative research project Wetsus, centre of excellence for sustainable water technology (NL), Luxembourg Institute of Science and Technology (LU), Universidade do Minho (PT), Magneto special anodes (NL), DeSaH (NL), MAST Carbon International (UK) and Abengoa Water (ES). The project is funded by European Union's Seventh Programme (Grant Agreement No. 308535) and coordinated by Wetsus. The ValueFromUrine project will develop, demonstrate and evaluate an energy-efficient system for the recovery of nutrients from urine.

Context

About 80% of the nitrogen load and 50% of the phosphorus load in domestic wastewater originates from urine, but urine only contributes about 1% to the volume of this wastewater. Separation of urine from other wastewater streams is therefore an interesting option to keep these valuable nutrients concentrated in order to develop a suitable nutrient recovery concept. In ValueFromUrine, two processes are combined to recover nutrients and energy from urine. In the first process, phosphorus is recovered through struvite precipitation, which requires the additions of magnesium. The produced struvite can be separated from the urine and used as fertilizer and / or source for phosphorus. In the second process, a Bio-Electrochemical System (BES) is used to recover energy and ammonia. Inside the BES applied in ValueFromUrine, bacteria catalyse the oxidation of organic matter (electron donor) found in urine at the bio-anode. This oxidation is coupled to the reduction of an electron acceptor at the cathode. Two types of reduction reactions are investigated in our BES, the oxygen reduction reaction (ORR) and the hydrogen evolution reaction (HER). Anode and cathode in our BES are separated by a cation exchange membrane (CEM). Due to the electron transport from the anode to the cathode, ammonium ions are transported from anode to cathode through the CEM. As a result of the ORR or HER, the pH in the cathode chamber increases, transforming ammonium ions into ammonia gas, which can be recovered. The application of this specific type of BES allows us to recover ammonia (nitrogen) and energy (hydrogen or electricity) at the same time. Ammonia can then be used as a fertilizer.

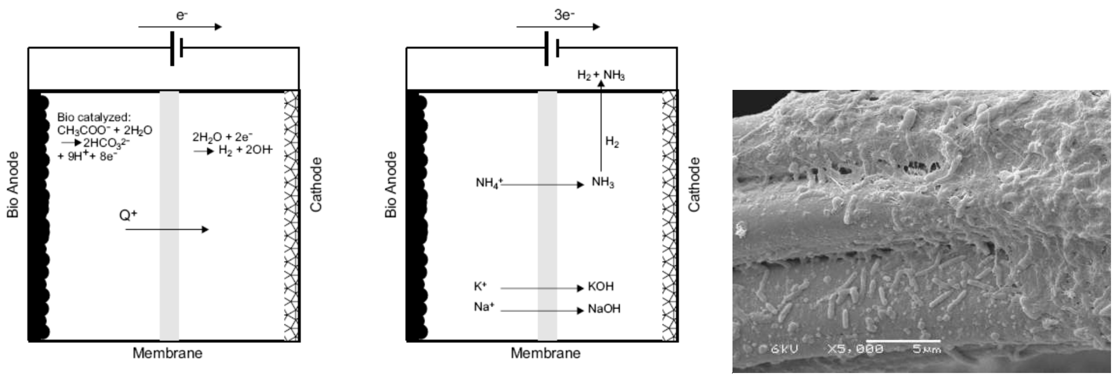

Figure 1 Working principle of the MEC: fatty acids, organic acids, etc. present in urine are oxidized by bacteria growing on the anode, generating electrons. These electrons are utilized at the cathode for the reduction protons. A power supply connected to the MEC adds the necessary energy for the reduction of protons. (b) The electron transport induces a cation transport from the anode chamber to the cathode chamber to maintain overall charge neutrality of the system. The water reduction results in hydroxyls production at the cathode, which leads to a pH increase and a formation of volatile ammonia. (c) bacteria growing on the anode in a bioelectrochemcial system converting organic substance into electrical energy.

Objectives

The objective of the ValueFromUrine project is to develop, demonstrate and evaluate an effective energy-efficient system for the recovery of nutrients from urine. The treatment system will be able to recover >95% of the phosphorous (as struvite) and nitrogen (as struvite and ammonia / ammonium sulphate) while producing energy. These products can substitute salts used by the chemical industry, the artificial fertiliser industry and the agricultural sector which are currently obtained in a non-renewable and unsustainable way. Urine can provide 18% of the phosphorous and 25% of the nitrogen currently used for soil fertilisation in the EU. The final goal of the project was to build a prototype, able to process 100 L of urine per day at a recovery of 95% of nitrogen and phosphorous.

Figure 2 ValuefromUrine Pilot

Summary description of the project content and objectives

Scope

The EU is currently relying on phosphorous ore imports and the energy intensive production of ammonia to produce necessary fertilizers. These fertilizers are needed in agriculture to ensure a sufficient food production. The recovery of valuable nutrients (phosphate and ammonia) from waste streams will help to overcome future shortages and reduce the need for phosphorous ore imports and energy intensive ammonia production. Phosphorus is an essential nutrient; it is applied as phosphate salts (fertilizers) to the soil. Phosphorus is a scarce and non-replaceable resource; "once depleted: there is no substitution" (J. L. Barnard 2009). Based on proven reserves it is estimated that these phosphorus reserves will be depleted within 50 to 100 years. At the same time the quality of the phosphorous ore is decreasing, due to heavy metal contamination (Driver et al., 1999, Cordell et al., 2009). Therefore, there is a great need to develop sustainable processes which close the phosphorus cycle. Nitrogen, on the other hand, can be recovered as ammonia from nitrogen gas (N_2) present in the atmosphere. However, this ammonia recovery process is energy intensive and currently heavily depending on fossil fuels.

Phosphate and ammonia in urban wastewater are largely lost during treatment in conventional wastewater treatment plants (WWTPs). Nitrogen (N) is mainly removed by sequential biological nitrification and de-nitrifcation, after which it is lost as N_2-gas to the atmosphere. The energy consumption of this nitrogen removal process is 45 $kJ/g_{N\text{-}removed}$. The Haber-Bosch process is applied globally for the recovery of nitrogen from the atmosphere in the form of ammonia (NH_3). The energy consumption of the Haber-Bosch process is 37 $kJ/g_{N\text{-}recoverd}$. In WWTPs, phosphorus (P) is immobilized in the sludge by precipitation with iron or by the Enhanced Biological P Removal (EBPR) process, the latter requires 28 $kJ/g_{P\text{-}recovered}$ (Maurer et al., 2003). However, the sludge from WWTP is not suitable for direct re-use due to the large volume and contaminants also immobilized in the sludge. The sludge can be digested, dewatered and incinerated to reduce its volume and remove organic contaminants. The remaining ash is rich in P, but also in heavy metals. Moreover, the P is mainly bound to iron; therefore its solubility is too low to be used as a fertilizer.

The project

The bio-electrochemically-assisted recovery of valuable resources from urine (ValueFromUrine) project developed, optimized and evaluated an innovative bio-electrochemical system (BES) that allows for the recovery of phosphorus (P), ammonia (NH_3) and electricity (E) or Hydrogen (H_2) from urine. The innovative principle is that biological oxidation of organics (present in urine) at a bio-anode drives both the transport of ammonium over a membrane (which allows for the recovery of NH_3) and the production of alkalinity (which can be utilized for the precipitation of P-salts).

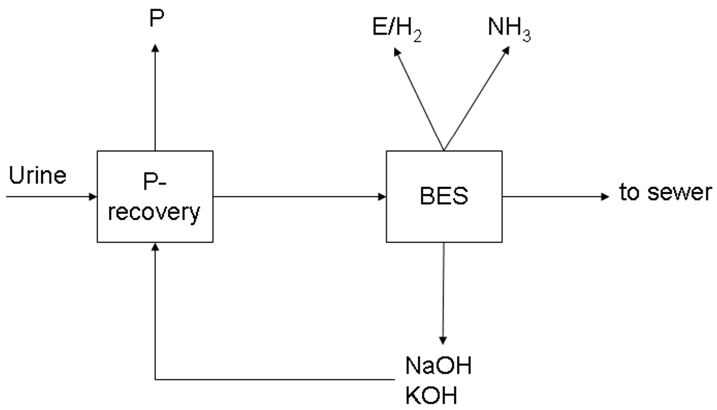

Figure 3: Proposed recovery scheme for source-separated urine.

Urine contributes only 1% to the volume stream of conventional domestic wastewater, however it contributes to about 80% of the N load and 50% of the P load (Figure 4a). One person produces on average 1.5 L of urine per day, which contains about 9.1 g N /L and 1 g P /L. These high nutrient concentrations in urine make it possible to develop more effective and energy efficient recovery technologies. Separation of urine from other wastewater streams is therefore an interesting option to keep these valuable nutrients concentrated in order to develop a suitable nutrient recovery concept.

Based on this knowledge, European research groups started investigating treatment options for so called “source separated urine” starting in the 1990s (Kirchmann and Pettersson, 1995; Larsen and Gujer, 1996) in order to promote sustainability of wastewater management. Source separation of urine means that a dilution with other wastewater streams is prevented by using for example special urine separation toilets and urinals (Figure 4b).

Figure 4b shows toilets and urinals that collect urine separately from other wastewater streams. Recently, these toilets are increasingly installed in newly constructed utility buildings or during renovation of old buildings. Unlike any state-of-the art technology, the ValueFromUrine technology not only has the potential to recover over 95% of the P and NH_3 from urine, but also to produce chemicals (NaOH, KOH) and energy.

(a) (b)

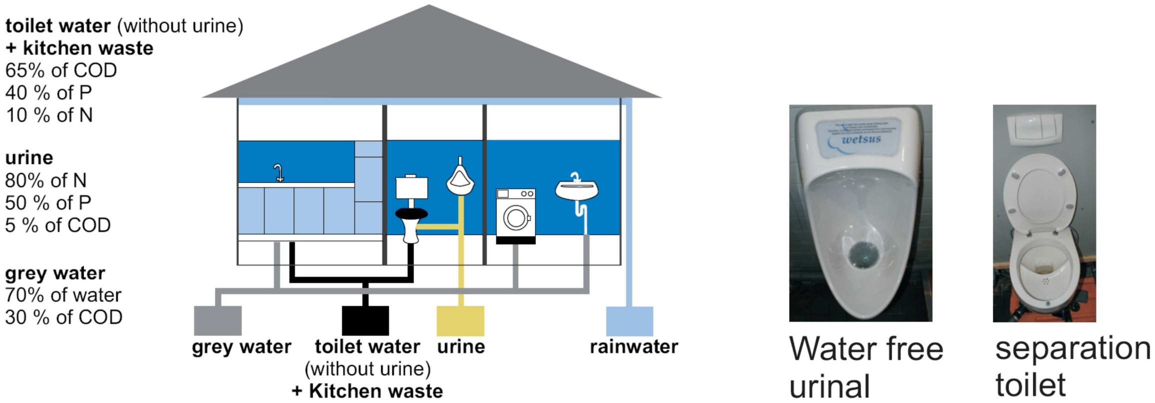

Figure 3: (a) Schematic representation of wastewater streams originating from households. 80 % of the nitrogen and 50 % of the phosphorus originate from urine. (b) Urine diverting toilet and water free urinal for urine collection.

We have determined the EU wide potential for phosphorus and ammonium recovery from urine. Currently 10 Mt of nitrogen and 1.5 Mt phosphorous are used yearly in the EU for the production of artificial fertilisers. Nutrient recovery from urine can provide 18% of the needed phosphorus and 25% of the needed nitrogen. Table 1 lists the currently consumed N and P fertilizer in the EU and the potential maximum coverage of nutrients recovered from urine. Therefore, efficient phosphate and ammonia recovery from urine can reduce phosphorous ore import to the EU and reduce the energy consumption for nitrogen fixation.

Table 1.1: Overview of fertilizer usage and maximum coverage

Phosphorus				**Nitrogen**			
P used for artificial fertilizers	1.5	Mt/a	[1]	N used for artificial fertilizers	10	Mt/a	[1]
Inhabitants	502.5	Million	[2]	Inhabitants	502.5	Million	[2]
Excrete P (urine)	0.275	Mt/a	[3]	Excrete N (urine)	2.476	Mt/a	[3]
Maximum coverage	18	%		Maximum coverage	25	%	

[1] European Fertilizer Manufacturers Association (EFMA), [2] Eurostat, [3] Maurer et al., (2006)

Barnard, J.L., (2009). Elimination of eutrophication through resource recovery. International Conference on Nutrient Recovery from Wastewater Streams, Vancouver, Canada.

Cordell et al., (2009). Preferred future phosphorus scenarios International Conference on Nutrient Recovery from Wastewater Streams, Vancouver, Canada.

Bisschops et al., (2010). Betuwse Kunstmest: Winning van stikstof en fosfaat uit urine, in: 2010-30, S. (Ed.). STOWA, Amersfoort, p. 98.

Driver et al., (1999) Why recover phosphorus for recycling, and how? Environmental Technology 20, 651-662.

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Eurostat (2011). European demography 110/2011 http://epp.eurostat.ec.europa.eu/; Accessed 1/09/2011.

Kirchmann et al.,(1995). HUMAN URINE - CHEMICAL-COMPOSITION AND FERTILIZER USE EFFICIENCY. Fertilizer Research 40, 149-154.

Larsen et al.,(1996). Separate management of anthropogenic nutrient solutions (human urine). Water Science and Technology 34, 87-94

Maurer et al., (2003) Nutrients in urine: energetic aspects of removal and recovery, pp. 37-46

Maurer et al., (2006). Treatment processes for source-separated urine. Water Research 40, 3151-3166.

The objectives

The aim of the ValueFromUrine project is to develop, demonstrate and evaluate an effective energy-efficient system for the recovery of nutrients from urine. The treatment system will be able to recover >95% of the phosphorus (as struvite) and nitrogen (as struvite and ammonia / ammonium sulphate) while producing energy. These products can substitute salts used by the chemical industry, the artificial fertiliser industry and the agricultural sector that are obtained in a non-renewable way. Urine can provide for 18% of the phosphorus and 25% of the nitrogen currently used for soil fertilisation in the EU. These fertilizers are necessary to secure the food production in the EU. The ValueFromUrine project will address the 3 specific objectives of the topic as follows:

i. Reduced input – After implementation the ValueFromUrine technology will reduce the dependency of the Europe fertilizer industry on non-renewable resources. The recovery of P from urine will decrease the dependency on phosphorous ore and the recovery of NH_3 will reduce the dependency on the energy intensive N-fixation process. Furthermore, the ValueFromUrine technology will effectively lower the nutrient and COD load to Wastewater Treatment Plants (WWTPs), resulting in additional energy savings.
ii. Re-use, Recycle & Recover – By recovering nutrients from urine and reusing them as fertilizer, a significant part of the urban nutrient cycle is closed, as urine contains 80% of the N and 50% of the P excreted by humans.
iii. Alternative solutions – Our innovative recovery concept will open the market for a decentralized nutrient recovery, which leads to production and services connected to valuable fertilizers in urban environments.

The consortium

The ValueFromUrine consortium is made up of complementary knowledge institutes, SMEs and an industrial partner, each of them leading in one or more relevant fields (electrochemistry, membrane technology, microbiology, micro-pollutants and pathogens, decentralized wastewater treatment and life cycle analysis).

- Wetsus, centre of excellence for sustainable water technology (NL)
- Luxembourg Institute of Science and Technology (LU)
- Universidade do Minho (PT)
- Magneto special anodes (NL)
- DeSaH (NL)
- MAST Carbon International (UK)
- Abengoa Water (ES)

Description of main S&T results/foregrounds

During the ValuefromUrine project the consortium focussed on the different Work packages (1-5) as described in the work plan. The main results are summarized here.

Work package 1 focused on the BioElectrochemcial Systems (BES) development with special interest in improving the biological anode, the cathode and the recovery of ammonia from the catholyte. Several systems were operated on (synthetic and real) urine and their performance was analyzed. The anode performance was investigated using different electrode materials and analyzing the conversion of chemical energy stored in the organic matter into electrical energy by the electroactive bacteria. In general high current efficiencies were found during these experiments. A carbon based anode material was developed by Mast Carbon which exhibit excellent properties for the applications in Bio Electrochemical Systems. The different cathode materials were investigated as alternatives for costly platinum based cathodes. Promising results were obtained using mixed metal oxide materials during electrochemical tests. A new ammonia recovery concept was developed and successfully tested. The new recovery concept integrates a gas permeable hydrophobic membrane in the cathode chamber for a better extraction of ammonia. Additionally, a novel electrochemical system was designed, constructed and tested for ammonia recovery promising high removal rate and an energy efficient recovery. The MECs tested in the laboratory scale reached current densities up 23 A m^{-2} and removal rates of 173 g m^{-2} d^{-1}. The electrode chemical systems were operated at current densities of up to 50 A m^{-2} and removal rates of 350 g m^{-2} d^{-1}. By including the hydrophobic membranes it is possible to reach over 95% recovery of the ammonia/ammonium nitrogen. A simplified model was developed and validated to control the electrochemical and bio electrochemical system to guarantee high recoveries at low energy input.

Work package 2 focused on the development of a struvite reaction for phosphorus recovery and its integration of the BES technology for ammonia recovery. As a first step, an in-depth study of the precipitation of struvite as a means for P recovery was performed to find optimum process parameter. Afterwards several prototypes were constructed and tested leading to the development of a continuous struvite recovery step. The developed prototype is able to recover more than 95% in continuous operation and is able to treat more than 100L urine per day. The analysis of the composition of the produced struvite showed high purity and compliance to Dutch fertilizer legislation. Furthermore, the produced struvite was tested for its fertilizer performance showing very good results. The integration of the Phosphorus recovery step with the BES showed promising results. Additionally, in a very early stage a BES operation outside a laboratory environment was investigated as potential end-user in the Netherlands. The results of this testing reveal further insights useful for the up scaling and automatization of the process.

Work package 3 focused on the piloting of the ValuefromUrine technology. As a first step a simplified flow scheme model was developed to assist with the design and operation of the developed technology. After assembly of the different components and placement at its final testing side (at Wetsus), the pilot housed in a container unit was extensively operated and tested over period of 16 months. Two different prototypes of the BES were tested at a scale of 0.5 – 1 m^2 anode surface area. The results obtained were used to help in reaching the final goal, designing a pilot able to treat 100L urine per day. While the phosphorus recovery unit developed can be easily scaled up to treatment capacities of 100-200L urine per day, the BES system was more complex to scale up. This also led to the development of a novel electrochemical system which can be operated at much higher current density, which lowered the need for electrode surface area significantly. The Pilot results showed it is possible to recover >> 95% of the phosphorus and up to 50% of the ammonia form the collected urine during continuous operation. Higher ammonia recoveries were reached in the laboratory during continuous operation. The produced struvite and ammonium sulfate comply with Dutch fertilizer regulation. Especially, the struvite with its low heavy metal content is an interesting fertilizer product.

Work package 4 focused on the evaluation of the ValuefromUrine technology based on environmental, economic and acceptance indicators. Inventory data to describe technology operation and infrastructures were collected by all partners involved in the WP. The collected information was then computed by LIST to perform the Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) study. Both tasks showed benefits of the implementation scenarios of the ValuefromUrine technology, mainly driven by the lower electricity consumption and infrastructures volume at the wastewater treatment plant for the LCA, and by the flushing water savings for the LCC. Even if uncertainty and sensitivity analyses were performed to understand the effects of inputs uncertainty on the results, several limitations remain, whose influence is difficult to predict. Regarding the socio-economic characterization, the technology acceptance study gave some improvements possibilities for the technology and the communication needed for a commercial deployment. It appeared clearly that incentives and barriers are not the same for each target and that the marketing argumentation has to be adapted to every segment needs and considerations. Despite the bias related to the environmental friendly actors interviewed, a real potential of adoption seems to exist for such a technology in the future.

Work package 5 focused on the dissemination of the results of the ValuefromUrine project to a broad audience from scientific specialists to the general public. This was achieved through communication in peer reviewed journal, conference attendance, attending and organizing workshops with a wide audience. In total 84 distinct dissemination activities were performed during the project. The highlights were the two organized workshops in Seville (Spain, 2014) and in Leeuwarden (The Netherlands 2016), with over 50 Persons attending both workshops. Next to this several newspaper article and interviews were published. Another highlight was being selected as one of the success stories by DG Research and the exposure of the results to a Europe wide audience thereafter.

The potential Impact

The final results of ValuefromUrine include a model, cell design, operational protocols and working prototypes of the technology for the recovery of key nutrients (phosphorus and nitrogen) from urine. Furthermore, the long list of dissemination activities help to draw further attention of the general public to the idea of nutrient as a counter idea to the removal and destruction of nutrients.

Continuous Struvite reactor allows for phosphorus recovery and produces a high quality fertilizer product

The successful development of a continuous and automated struvite reactor for phosphate recovery allows recover a high quality product, which complies with current Dutch Regulation for nutrient recovery. The technology can be adapted to different phosphate rich wastewater streams. Using simple control mechanism, the technology can be operated in decentralized wastewater treatment concepts. As the reactor design only recovers phosphate and a small fraction from the ammonia nitrogen present in the urine, the effluent is suitable for the treatment in ES systems for ammonia recovery. DeSah B.V., the lead developer of this technology, is on the route to commercialize this phosphate recovery system. The potential application of this recovery system are …

Current driven ammonia-nitrogen recovery with a potential broad field of application on different wastewater.

The development of a simplified model for ammonium transport in electrochemical and bio electrochemical system allowed us to fine to tune the ammonia recovery in electrochemical systems (ES), which includes bioelectrochemical systems. Since ES utilize electric current to transport ammonium across a cation selective membrane to the cathode from where ammonia can be recovered, these systems can be optimised by the so-called load ration. The load ratio describes the current in comparison to the ammonia-nitrogen loading and can predict the energy demand and recovery potential. The integration of gas permeable hydrophobic membranes in ES, allow for energy efficient ammonia recovery and reduce the need to circulated large amount of gasses. The product of the ammonia recovery is a fertilizer liquid such as ammonium sulphate or nitrate. The application of current driven ammonia recovery expends beyond the sole treatment of urine and could potentially be applied to different wastewater streams. The use of a more energy efficient ES for ammonia recovery, which does not rely on the available organic matter in the wastewater guarantees, which ammonia recoveries and removal rates. This allows us to expand the range of application of these technologies.

Expected impact

The advantages of the ValuefromUrine technology are mainly driven by the lower electricity consumption, infrastructures volume at the wastewater treatment plant and by the flushing water savings. The Success of this implementation will depend on lowering main infrastructure costs and operational costs of the develop systems. We have shown that we can successful recovery phosphorus and ammonia-nitrogen from urine and expanding range of wastewater stream being utilized within our technology will further enhance the chance for successful adaptation of nutrient recovery from wastewater streams. The products especially struvite could become attractive fertilizer products in the future and will allow to reduce the need to import phosphorus ore. The energy efficient nitrogen recovery in our ES can lead to a more energy efficient wastewater treatment. Recovery of nitrogen in a useful form ammonium salts/solution will reduce the need to use energy intensive process to produce ammonia from nitrogen. Wide spread adaptation of urine treatment will depend next to the technological challenges, the economic driving forces. Whereas urine separation might be simply included in new buildings or during renovations, adaptation on a larger scale will depend on willingness to change larger part of the infrastructure for wastewater collection and treatment. Additionally, logistical challenges (transportation of products and required services) of decentralized wastewater treatment will need to be addressed to make this technology a success.

In general urine could provide significant quantities of the nitrogen and phosphorus which are used in the EU according to our estimates about 18% of the phosphorus and 25% of the nitrogen.

Address of Website

www.valuefromurine.eu