Water and Environmental Studies
Department of Thematic Studies
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COMPARATIVE ANALYSIS OF BIOGAS SLURRY AND URINE AS SUSTAINABLE NUTRIENT SOURCES FOR HYDROPONIC VERTICAL FARMING

Vlad A. Dumitrescu

Master's programme

Science for Sustainable Development

Master's Thesis, 30 ECTS credits

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ABSTRACT

Sustainable alternatives to using mined nutrients in agriculture must be found in order to limit environmental impacts such as eutrophication, habitat destruction and greenhouse gas emissions. Biogas slurry and urine recycled to hydroponic food production (a type of soilless agriculture) have the potential of providing inorganic nitrogen and phosphorus, the main essential nutrients required for plant growth. A Life Cycle Inventory Assessment (LCI) methodology has been used to compare the systems of producing artificial fertilizer, biogas slurry and urine based nutrient solutions for the growth of *Brassica rapa* L. (Chinese cabbage) in the context of a large scale hydroponic vertical farm. Costs and energy requirements have been the basis of the comparison and results show that both biogas slurry and urine are considerably cheaper than the commercial alternative and based on the nutrient content they have the potential of being successful nutrient solutions after dilution and nutrient supplementation. Filtration might also be required in order to remove suspended particles and pathogens.

KEYWORDS: biogas slurry, hydroponics, LCI, urine

LIST OF ABBREVIATIONS

CEAC	Controlled Environment Agriculture Center (Arizona, USA)
EC	Electrical Conductivity
EPD	Environmental Product Declaration
GHG	Greenhouse Gas
IFA	International Fertilizer Industry Association
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
UNDP	United Nations Development Program
WHO	World Health Organization

* Note: **Fig. 1** and **2** (page 9) have been used with permission from the copyright owner, Plantagon AB

1. INTRODUCTION

Intensifying agricultural production in support of the rapidly increasing population has lead to severe environmental effects worldwide. Land use change has increased the agricultural potential (Foley *et al* 2005), whilst the use of fertilizers has amplified the inputs of major nutrients (nitrogen and phosphorus) in aquatic systems, causing eutrophication which ultimately leads to oxygen depletion in major water bodies (Rockström *et al* 2009, Smith 2009).

Urban agricultural practices have been known to have a more rational approach to resource use than rural practices, focusing on recycling waste towards food production, thus limiting their impact on the environment (Smit *et al* 2001, Pearson *et al* 2010, Despommier 2011). In many cases the practice of hydroponics, a type of soilless culture, is being used in urban agriculture. It involves growing plants using inorganic nutrient solutions in closed systems (greenhouses), which ensure maximum yields and no resource leakage as well as plant production independent on seasonality (Lennard and Leonard 2006, Raviv and Lieth 2007, Despommier 2011). Such systems are also attributed to vertical farming, which implies stacking greenhouses on top of each other to limit land use impacts and multiply production per square meter (Despommier 2011). Local food production in urban centers also minimizes transportation costs and emissions (Ohyama *et al* 2008).

In order to respond to future food security requirements and limit eutrophication as well as land use change, vertical farming in urban environments is a plausible solution. However, it must also use sustainable nutrient sources, since most nutrients required for plant growth contained in fertilizers are obtained from mineral deposits, the most important being phosphate rock, which is expected to be depleted in the next 50-100 years (Cordell *et al* 2009). Nitrogen is being captured from the atmosphere during a very energy intensive process, called the Haber-Bosch process (Galloway *et al* 2008).

Using organic nutrients in hydroponics is possible by using microbial degradation, but require more effort and knowledge to function accordingly and provide high yields (Shinohara *et al* 2011, Morgan 2012). Possible alternatives are the usage of biogas slurry or urine due to their high inorganic nitrogen and phosphorus content (Mackowiak *et al* 1996, Liu *et al* 2009, Udert and Wächter 2012).

This research project was initiated by the Swedish-American company Plantagon AB, which will build a vertical greenhouse in Linköping, Sweden in 2014 (Plantagon 2013). The company has expressed its interest in investigating the possibility of using biogas slurry as a nutrient solution for the hydroponic production of Chinese cabbage (*Brassica rapa* L.), also known as *pak choi*, in order to avoid using commercial nutrient solution (Ernback 2013, personal communication).

1.1. AIM

The aim is to compare the usage of biogas slurry and urine, respectively, as sustainable nutrient sources for the hydroponic production of *pak choi* cabbage in the Plantagon vertical greenhouse in Linköping, Sweden. Investigations are made as to assess the cost and energy requirements of these alternatives and compare them with the one based on commercial hydroponic nutrient solution.

Thus, the following **hypothesis** has been tested: biogas slurry and urine are sustainable and economically viable alternatives to commercial fertilizer for hydroponic plant production in large scale greenhouses.

1.2. RESEARCH QUESTIONS

In order to test the hypothesis, the following research questions have been posed:

i) What are the components of the hydroponic production systems using commercial hydroponic solution, biogas slurry and urine?
ii) What are the constraints of each system? Do the alternative systems provide adequate nutrition compared to the commercial solution?
iii) What is the estimated overall cost for running each system?

2. BACKGROUND

2.1. LAND USE AND EUTROPHICATION

In recent decades food and energy demands worldwide have shaped **land use** patterns through increases in energy, water and fertilizer consumption to the detriment of the environment. Croplands and pastures have become amongst the largest terrestrial biomes on Earth, covering approximately 40% of the land surface (Foley *et al* 2005). In order to maintain high yields of food and fodder crop production, these arable lands have been exposed to extensive fertilizer use. Intensive agricultural practices have also lead to soil salinization and erosion coupled with fertility loss. It appears that "*modern agricultural practices may be trading short-term increases in food production for long-term losses in ecosystem services, including many that are important to agriculture*" (Foley *et al* 2005: 570).

The main nutrients needed for plant development and contained in fertilizers are nitrogen (N) and phosphorus (P). The over enrichment with nutrients (mainly N and P) is known as the process of **eutrophication**, which today represents an issue of critical importance for streams, lakes and marine environments worldwide (Smith 2009, Rockström *et al* 2009). Changes in the biogeochemical cycling of these main nutrients alter ecosystem services over both space and time (Smith *et al* 2006). The nutrient excess is enhancing cyanobacteria blooms which later lead to turbid and anoxic waters (Rockström *et al* 2009). Eutrophication occurs mostly around densely populated areas such as the Baltic, Mediterranean and Black Seas and the Mississippi Delta (Gren *et al* 2009).

The biogeochemical cycle of N is being altered by increasing the availability of usable nitrogen. In its gaseous form, N_2, nitrogen is nutritionally unavailable. In order to convert it to an available form, such as ammonia (NH_3), the Haber-Bosch process, which involves the reaction with hydrogen gas (H_2), has been used. Ammonia can then be converted to nitric acid (HNO_3) using the Ostwald process. As a result, more concentrated doses have been artificially introduced to ecosystems, as opposed to aquatic or atmospheric transport which involve dilution to various degrees

Unlike N, P is a resource that is mined from phosphate rock, which is created during sedimentation processes lasting hundreds of thousands of years. At modern exploitation rates, this mineral is expected to be exhausted in the next 50-100 years. Also, the extremely uneven deposit distribution around the world can lead to political instability (Cordell *et al* 2009). This makes the recycling of this major nutrient of crucial importance for future agricultural production.

In addition, considering the global population is expected to exceed 9 billion by 2050 and that more than 80% of people will live in cities (United Nations 2009), providing food security without increasingly deteriorating the state of the environment due to artificial fertilizers is a great challenge.

2.2. URBAN AGRICULTURE

Urban agriculture has been proposed as a solution for the extensive land use change and the need to feed the rapidly growing population (Smit *et al* 2001, Bon *et al* 2010, Pearson *et al* 2010, Despommier 2011).

> Urban agriculture is *"an industry that produces, processes and markets food, fuel and other outputs, largely in response to the daily demand of consumers within a town, city, or metropolis, on many types of privately and publicly held land and water bodies throughout intra-urban and peri-urban areas…* [and] *applies intensive production methods, frequently using and reusing natural resources and urban wastes, to yield a diverse array of land-, water-, and air-based fauna and flora, contributing to the food security, health, livelihood, and environment of the individual, household, and community."*
>
> Smit *et al* 2001, Ch.1:1

As stated in this definition, urban agriculture involves plant production and animal husbandry in urban areas. The focus of this thesis is only directed towards plant production. Although at a first glance *urban* and *agriculture* can be perceived as contradicting terms, with agriculture being regarded as the quintessential rural activity, urban agriculture is a significant economic activity for the lives of tens of millions of people throughout the world. Cuba, Vietnam, Nicaragua and Ghana are amongst the countries where urban agriculture is an important practice (Smit *et al* 2001). Pearson *et al* (2010) classify the main types of urban agriculture based on scale in **Table 1.**

Table 1. Scale of urban agricultural production

Scale	Examples	Ownership of land and produce
Micro	✓ Green roofs, walls, courtyards	✓ Private, corporate
	✓ Backyards	✓ Private
	✓ Street verges	✓ Public
Meso	✓ Community gardens	✓ Private on public land
	✓ Individual collective gardens (allotments)	✓ Private
	✓ Urban parks	✓ Public
Macro	✓ Commercial scale farms (turf, dairy, orchard, grazing etc.)	✓ Private, corporate
	✓ Nurseries	✓ Private, corporate
	✓ Greenhouses: floriculture and vegetables	✓ Private, corporate

Source: Pearson (2010)

As **Table 1** shows, there are many forms of urban agriculture with different scales and ownership rights, ranging from backyard gardens or green roofs to large commercial greenhouses. If food production is to match the increasing urban population, initiatives must occur at all scales. However, large scale projects have the capability of competing directly with existing fossil fuel driven agricultural production (Despommier 2011).

When tackling the environmental problem of eutrophication due to nutrient leaching, nutrient recycling is key. More rational nutrient sources that are based on recycling have been used and proven successful in both rural and urban agriculture. Among them are wastewater reuse (Kurian *et al* 2013, Despommier 2011), excreta reuse (WHO 2006), composting organic waste (Bon *et al* 2010) or using biofertilizer from biogas production (Liu *et al* 2009, Deublein and Steinhauser 2008). Some argue, however, that the least impact towards nutrient loading is attributed to closed systems.

While considering existing agricultural practices in the context of climate change, future temperature and precipitation trends will severely impact food production (Despommier 2011, Rockström *et al* 2009), and the scarcity of available agricultural land will be a main issue for feeding a 9 billion population. **Controlled environment agriculture** represents the practice of producing plants inside greenhouses (CEAC, 2013). Greenhouses guarantee a more reliable plant production due to their independence from seasonality (Raviv and Lieth 2007, Ingram *et al* 2011). By using enclosed agricultural environments, resource inputs can be significantly smaller, such as 70% less water than outdoor farming (Despommier 2011). and no pesticides or herbicides whilst limiting resources from escaping into the surrounding environment. Such systems can be easily placed in urban environments, which entails that CO_2 emissions from transportation are greatly reduced (Ohyama *et al* 2008).

In order to decrease the agricultural footprint and the land use impacts, such greenhouses can be stacked on top of each other, multiplying the production per square meter by up to ten fold through **vertical farming** (Despommier 2011: 233). There are many vertical farms in urban centers worldwide, and the spread of this practice seems to increase more and more (Urban Agriculture Summit Linköping 2013). Commercial scale vertical farms are currently functioning in Japan (NuVege 2013), Canada (Local Garden 2013), S Korea (Omega Garden 2013), Singapore (SkyGreens 2013), US (Vertical Harvest 2013, The Plant 2013) etc. and a vertical greenhouse with a 4000 m^2 cultivation area is planned to be built in Linköping, Sweden in 2014 by the Swedish-American company Plantagon AB (Plantagon 2013).

2.3. HYDROPONICS

Hydroponics is a type of soilless culture which involves growing plants in nutrient solutions. It is very common to use substrates which help stabilize the plant and also provide inert matrixes that hold water, although plants can be grown without substrates as well. Materials commonly used as a substrate in hydroponics are pumice, expanded clay or sand. Because the plants are not grown in soil, the practice uses soluble fertilizers in order to provide the plants with necessary nutrients for their development (Raviv and Lieth 2007). Also, because the system is closed, all remaining water and nutrients are recycled (Despommier 2011).

The plant irrigation systems can differ, however there are three main types of irrigation solutions (Lennard and Leonard 2006, Raviv and Lieth 2007):

1. Nutrient Film Technique (NFT) – where the nutrient solution is pumped in the form of a shallow stream that submerges the roots; the thin stream provides adequate oxygenation;
2. Media based and Deep Water Circulation (DWC) – involves using substrate on which the plants can develop their root systems when being completely submerged in hydroponic solution;
3. Aerohydroponics – involve spraying the roots of the plants with the nutrient solution which ensures a proper oxygenation.

Since no soil is involved, all nutrients must be provided in the nutrient solution in order for the plant to develop. Although more than 50 elements have been found in various plants, not all are considered essential to plant growth. An **essential element** is an element that is required for the normal life cycle of a plant which cannot be replaced by another element. Except for carbon, which is absorbed via foliage from the air, the basic nutrients are taken up by the roots. Hydrogen and oxygen are being provided from water molecules during photosynthesis (Raviv and Lieth 2007). In **Table 2** the macro and micronutrients necessary for hydroponic production are shown, along with available ionic form for plants and required concentrations.

Different plants have different nutrient requirements, which involve different nutrient solutions. Although all plants need the macro- and micronutrients presented in the table below, some might require additional elements for maximum yields (such as nickel for legumes). Also, the nutritional demands are not constant during the crop's life cycle, exhibiting sharp changes during tissue and reproductive organ formation (Raviv and Lieth 2007).

Table 2. Essential element concentrations in nutrient solutions and plant tissues with required annual amounts for maximum yields

Element	Form available to plants	Nutrient solution	Plant tissues	Annual consumption
Macronutrients		mg l^{-1}	g kg^{-1}	kg $ha^{-1}y^{-1}$
Ca	Ca^{2+}	40-200	2.0-9.4	10-200
Mg	Mg^{2+}	10-50	1.0-2.1	4-50
N	NO_3^-, NH_4^+	50-200	10-56	50-300
P	HPO_4^{2-}, $H_2PO_4^-$	5-50	1.2-5.0	5-50
K	K^+	50-200	14-64	40-250
S	SO_4^{2+}	5-50	2.8-9.3	6-50
Micronutrients		mg l^{-1}	µg kg^{-1}	g $ha^{-1}y^{-1}$
B	H_3BO_3, HBO_3^-	0.1-0.3	1.0-35	50-250
Cu	Cu^+, Cu^{2+}	0.001-0.01	2.3-7.0	33-230
Fe	Fe^{3+}, Fe^{2+}	0.5-3	53-550	100-4000
Mn	Mn^{2+}	0.1-1.0	50-250	100-2000
Mo	MoO_4^{2-}	0.01-0.1	1.0-2.0	15-30
Zn	Zn^{2+}	0.01-0.1	10-100	50-500

Source: Raviv and Lieth (2007)

2.4. Nutrient Sources

Since essential elements are exclusively inorganic, nutrient solutions contain broken down, inorganic nutrients. A conventional nutrient solution/stock solution such as the Hoagland solution (Hoagland and Arnon 1950) is made from chemicals produced in the chemical industry, based on minerals or fossil fuels.

The main source of phosphorus fertilizer is apatite, also known as calcium phosphate (Allaby 2005), a mineral which is treated with acids (sulphuric or nitric acid) after being mined in order to extract the phosphate (Olanipekun 2003).

The production of ammonia (NH_3) through the Haber Bosch process requires the most energy in order to be provided with hydrogen gas. Nitrogen is available in the atmosphere, whilst hydrogen is produced from natural gas, coal or heavy oils. Modern plants use 28 GJ for producing a ton of NH_3. About half of the produced NH_3 is converted to nitric acid (HNO_3) through oxidation and reacted with the remaining NH_3 to produce ammonium nitrate (NH_4NO_3). The entire production chain of nitrogen based fertilizer is associated with GHG emissions from the carbon in the fossil fuel used. Nitrous oxide (N_2O) is also generated when producing HNO_3 (Ahlgren *et al* 2012, Udert and Wächter 2012, IFA 2013).

Potassium is being obtained from potash, salt rich deposits being harvested either through conventional shaft mining or solution mining, which involves drilling a hole in the deposit and pouring water which dissolves the sought after salts. The enriched solution is then pumped out and refined (US Geological Survey 2008).

Calcium (Ca) is the fifth most abundant element by mass on Earth and is extractable through electrolysis from Ca salts (Dickson and Goyet 1994). Sulphur (S) is a byproduct of many industrial processes, therefore it does not need to be extracted for use in agriculture. Other micronutrients used in fertilizers come from mineral deposits (IFA 2013).

As seen in **Table 2**, the highest concentrations in a commercial nutrient solution are of N, K and Ca. Given that concentrations of micronutrients are very small in comparison and that the negative impacts are mostly attributed to N and P, these two macronutrients as well as K will be the main concern of the thesis.

In addition to the high energy requirements, mining is also known to cause environmental impacts such as habitat destruction, soil toxicity, acid mine drainage or lowering of water tables (Hester and Harrison 1994). There is no doubt that this way of producing fertilizers is taking a serious toll on environmental quality and more sustainable systems are needed. So, in order to limit mining and promote a more closed loop approach to resource use, renewable sources of these essential nutrients for hydroponic production should be found. A natural first step is to think of applying organic principles to hydroponics.

Because plants require inorganic nutrients exclusively, the use of organic fertilizers in hydroponics is known to cause phytotoxic effects that lead to poor plant growth (Mackowiak *et al* 1996). However, studies have shown that **organic hydroponics** are possible and successful by using microorganisms to convert organic compounds from organic fertilizer into plant usable nutrient ions (Shinohara *et al* 2011, Morgan 2012). Nonetheless, such systems can prove unreliable due to the difficulty of maintaining a balanced nutrient solution. This often leads to nutrient deficiencies and lower yields, therefore such systems require more knowledge to run properly (Morgan 2012).

An alternative organic nutrient source that can be used in hydroponics is the residue of biogas production, known as **biogas slurry** (Mackowiak *et al* 1996, Wenke *et al* 2009, Liu *et al* 2011). It is a mixture rich in inorganic N and P, as well as other nutrients and it is commonly used as biofertilizer on agricultural land (Deublein and Steinhauser 2008). Because applying biofertilizer on land does not address the nutrient leaching problems, its usage in a closed system such as in hydroponics is advised (Liu *et al* 2011). Also, the slurry has a variable water content depending on the biomass introduced for anaerobic degradation (Deublein and Steinhauser 2008), which can potentially benefit the hydroponic production by using less water.

Providing inorganic nutrients for agriculture can also be achieved through ecological sanitation, which implies recycling human excreta to agriculture (WHO 2006). **Urine** alone contains 88% of excreted N and 67% of excreted P and has the fertilization capability of a 300-400 m^2 wheat crop from one person in one year (WHO 2006). A study indicated that wetland treated septic tank effluent has been successful in hydroponic vegetable production (Cui *et al* 2003). However, studies regarding only urine usage in hydroponic systems have not been found. Nevertheless, due to its water (about 99%) and nutrient content, urine might possibly be adapted as a hydroponic nutrient solution.

In conclusion, intensive agriculture and the use of commercial fertilizer coupled with land use change have been major factors causing the eutrophication of large water bodies around the world. Through urban agriculture and thus, local food production, a more sustainable approach towards nutrient usage has been promoted (such as using urban waste). Closed systems such as greenhouses with hydroponic production have the capability of considerably reducing resource input, without any nutrient emissions. To address the land use change issue, greenhouses can be stacked on top of each other through vertical farming, increasing yields to up to ten fold per square meter and provide more food for an increasing urban population.

2.5. VERTICAL FARMING IN LINKÖPING, SWEDEN

As mentioned in the Introduction, this thesis represents a research project initiated by the urban agriculture company Plantagon AB (Plantagon 2013). Plantagon is a Swedish-American company which aims to be a leading brand in urban agriculture worldwide. They have designed vertical greenhouses in collaboration with Sweco AB and Tekniska Verken AB that can be either standalone (**Fig. 1**) or adapted to existing buildings in urban areas. The goal is to produce local food with a low environmental impact by using hydroponics.

Fig. 1. Plantagon vertical greenhouse designs. Upper right: will be built in Linköping Sweden in 2014 (Source: Plantagon © 2013)

The greenhouse's integration within the urban infrastructure will, of course, depend on local conditions. An example can be viewed in **Fig. 2**. The pilot project for Plantagon's first greenhouse has been set in Linköping, Sweden and it is expected to be built in 2014 (Urban Agriculture Summit Linköping 2013)

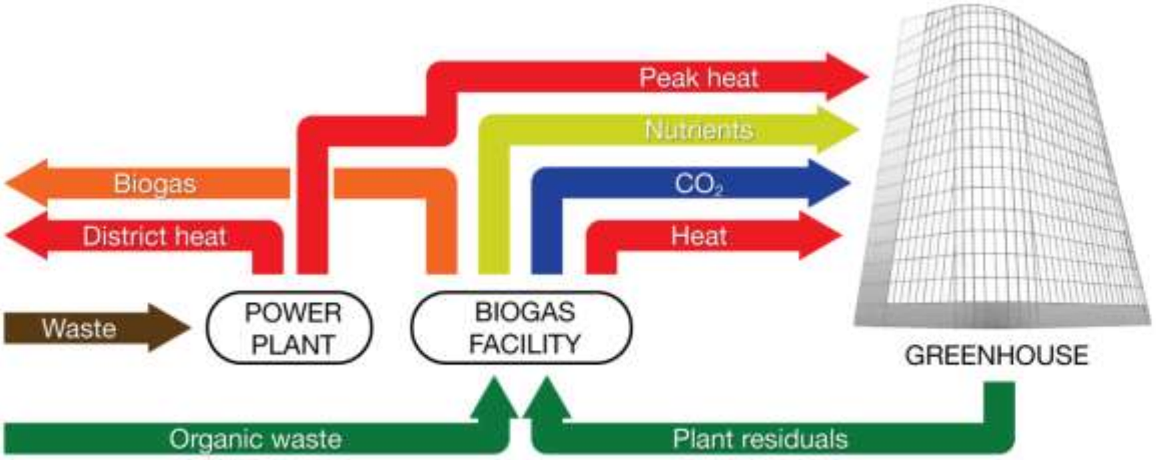

Fig. 2. The PlantaSymbioSystem (Source: Plantagon © 2013)

The Plantagon greenhouse will be a hybrid building, meaning that a part of the building will be used for the hydroponic production and the rest will accommodate a research centre for vertical farming and also office space for rent. The placement of the greenhouse was chosen as to ideally connect to Linköping's incineration heat and power plant, Gärstad, and the biogas plant Svensk Biogas, both owned by Tekniska Verken. Although the system is envisioned to be very similar to the representation in **Fig. 2**, for the pilot project in Linköping the system will not have all the envisioned flows. At the moment the plan is to use excess heat and CO_2 from Svensk Biogas and excess heat from the incineration plant. However, commercial industrial fertilizers are to be used for the hydroponic production of Chinese cabbage (*pak choi*/*bok choi*), which will be the initial produced crop (Urban Agriculture Summit Linköping 2013). Plantagon have expressed their interest in investigating the usage of biogas slurry as a nutrient solution and also in finding alternatives for sustainable nutrient sources to further lower the impact of the greenhouse (Ernback 2013, personal communication).

3. MATERIALS AND METHODS

3.1. LITERATURE REVIEW

Firstly, a literature review was conducted so as to outline the activities involved in producing commercial fertilizer as well as their environmental impacts. Further literature has been investigated in order to ascertain whether the usage of biogas slurry and urine in hydroponic plant production has been previously tested and also identify components of such systems as well as any limitations. Peer reviewed scientific articles, scientific books and other relevant documents have been investigated for the assessment of each system.

3.2. LCA ELEMENTS

The methodological framework most suitable for the analysis has been identified as Life Cycle Assessment (LCA). LCA is *"the assessment of the environmental impact of a product across its life cycle"*(Bauman and Tillman 2004: 9, ISO 2006). A standardized method of performing this analysis is constantly being developed within the International Organization for Standardization (ISO). In the 2006 LCA standard ISO 14040:2006 four phases have been deemed as necessary: goal and scope definition, inventory analysis, impact assessment and interpretation (ISO 2006).

Given time constraints, the complexity of each system (commercial solution, biogas slurry and urine fertilization systems) and the multitude of nutrients required for the hydroponic solution, a "*cradle-to-grave*" analysis has not been performed. However, elements of LCA (mainly inventory analysis) have been used to address each system within the scope of the thesis and based on available data. Bauman and Tillman (2004) suggest that based on the goal and scope of the analysis, an LCA tries to answer certain questions by using a methodology. Transparency is required in order to make the reader aware or the choices made during the course of the analysis and it can be achieved by clearly defining the functional unit, system boundaries and allocation procedures and indicating the type of data used.

FUNCTIONAL UNIT

The functional unit represents an established measure linked to the function of the analysed product which can be used as a benchmark in comparative systems (Bauman and Tillman 2004). Given the fact that Plantagon have no estimates on how much nutrient solution is needed and that relating nutrient solution quantity to *pak choi* production is difficult to estimate, a volume of 10 m^3 of final nutrient solution has been chosen as the functional unit. As for nutrient concentrations, 164 mg/l N 36 mg/l P and 213 mg/l K represent the main macronutrient amounts required by the *pak choi* crop to grow with high yields and thus have been chosen as part of the functional unit. These concentrations amount to a NPK ratio of about 5:1:6.

SYSTEM BOUNDARY

The goal and scope definition phase is in line with the thesis aim and research questions, meaning that the boundary of the system only encompasses the production of each fertilizer. Due to Plantagon's nutrient recycling and enclosed system, the vertical greenhouse will not contribute to the nutrient enrichment of local water bodies. Also, the greenhouse will be a CO_2 sink and the recipient of excess heat from the local incineration and biogas plant, thus considerably lowering its environmental impact. For these reasons the end of the life cycle of the given fertilizer has not been taken into account. Such analyses are commonly referred to as "*cradle-to-gate*" assessments (Bauman and Tillman 2004).

The overall system for the production of *pak choi* in Linköping, Sweden has been represented in **Fig. 3**. For the analysis, the **system boundary** has been set to encompass the processing of the nutrient source and production of the nutrient solution.

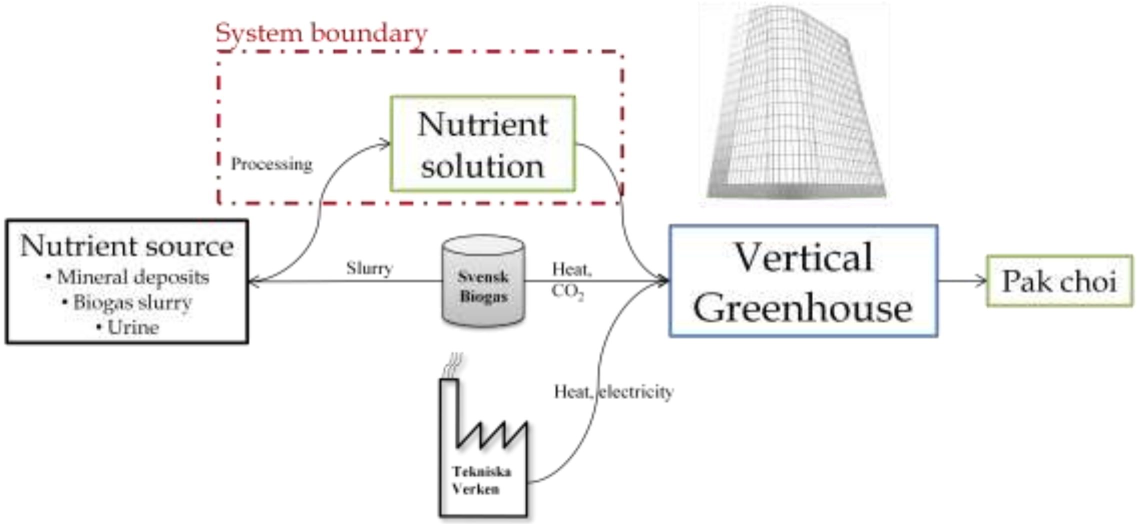

Fig. 3. Global system outline and analyzed system boundary

INVENTORY ANALYSIS

The Life Cycle Inventory Analysis (LCI) phase represents the analytical framework used in outlining the model for each system. In LCI the system model contains all environmentally relevant components and processes within a certain system boundary, which is decided in the goal and scope definition phase. The inputs (such as raw materials) as well as the outputs (products, waste) are of importance when representing the material and energy flows within the model. Flows may also be omitted if they are not of environmental relevance (Bauman and Tillman 2004).

Activities of LCI include (Bauman and Tillman 2004):

1. Constructing the **flow model** according to the system boundaries decided in the goal and scope definition phase. The model is represented as a flow chart of the activities of the system (processes, production, transports, usage and waste management) as well as the flows between such activities;
2. **Data collection** for all activities which includes inputs and outputs such as raw materials, products, solid waste and emissions to water and air;
3. **Calculation** of the amount of resource use and pollutant emissions.

According to Bauman and Tillman (2004) and ISO (2006), many raw materials used are by-products of other industries. This means that they share the environmental load with other products and their environmental impact is then more difficult to allocate.

In the case of fertilizers, especially hydroponic solutions, where the elements required for plant nutrition are originating from different minerals and are processed for use in the chemical industry, a full LCI would be very time consuming. So, for the commercial nutrient solution production, energy inputs have not been estimated. Also, because the biogas slurry and urine used as fertilizers are part of recycling systems, they have been regarded as superior to the commercial nutrient solution from a sustainability point of view.

The analysis has focused on the production of each fertilizer alternative in respect to **energy usage** as an environmental impact indicator and **costs** so as to compare the viability of each alternative with the commercial nutrient solution given the available data. Also, the main focus has been on N, P, K and identifying limiting factors.

3.3. DATA COLLECTION

For estimating impacts attributed to components of the nutrient solution based on mined resources, Environmental Product Declarations (EPDs) have been used. EPDs are standardized (ISO 14025) quantified environmental datasets with pre-set parameter categories for environmental impacts such as eutrophication, fossil fuel usage, emissions etc. (EPD 2013).

Since this analysis is based on the hydroponic production of Chinese cabbage in Linköping, Sweden, the data regarding the content of the required commercial nutrient solution for the *pak choi* crop has been provided by Plantagon (Hultin 2013, personal communication). In addition, scientific literature has been used to obtain information about nutritional deficiencies and toxicities as well as the physiological effects they cause.

Regarding the content of the biogas slurry, the data has been provided by Svensk Biogas, one of the local biogas companies in Linköping as mean yearly concentrations for each element, as well as values for pH (Nilsson-Pålendal 2013, personal communication). The electrical conductivity of the biogas slurry has been measured from a sample obtained from Svensk Biogas using a Hach HQ301 EC meter with a CDC401 probe.

For the chemical content of urine, two Swedish sources have been used. The main source has been a report on the composition of urine, faeces, greywater and biowaste (Jönsson 2005). The values for sodium, chloride, EC and pH, being unavailable in the previous source, were obtained from a study ran by the Kirchmann and Pettersson (1994).

3.4. LIMITATIONS

Mean values have been used for parameters such as nutrient concentrations for biogas slurry (yearly mean) and urine (daily mean). However, in the case of biogas slurry the nutrient content varies monthly due to changing substrate composition (Nilsson-Pålendal 2013, personal communication). Also, the value for EC is a onetime measurement in April 2013. In the case of urine, values can differ considerably even on a daily basis, depending on the food intake of the person (Jönsson et al. 2005).

Due to the lack of accurate values, pumping energy requirements have been estimated using random values. However, this is not a major limiting factor to the comparison of the three systems due to the fact that the cost for providing the water necessary for the dilution also includes the costs for pumping the water, which accounts for most of the total pumping costs for producing the final nutrient solutions based on biogas slurry and urine.

4. RESULTS

In the following section the results are being summarized starting with the system outlines, followed by the nutrient contents and the energy and cost balances of the systems.

4.1. SYSTEM OUTLINES

COMMERCIAL NUTRIENT SOLUTION

A simplistic portrayal of the production system can be observed in **Fig. 4**. It contains the following activities: **mining**, **ore treatment**, **chemical processing** and **transport**, which yield the required nutrients that are to be added in the final nutrient solution. The input **flows** are those of fossil fuels and electricity (for transport and machinery) as well as water and various chemicals used in the extraction processes. After these resources are being used in the system, output flows of concentrated nutrient solutions or nutrient salts occur, as well as waste products such as mining waste, wastewater and GHG emissions. Because commercial nutrient solutions are sold in very concentrated forms or made by dissolving nutrient salts, they require dilution for obtaining a usable nutrient solution, process which takes place at the hydroponic production site.

Mining alone is a very resource demanding activity with considerable GHG and particle emissions to the atmosphere (due to incineration and transportation), ground and surface water (due to leaching from waste dumps and tailing dams). The processing of raw ore differs depending on the mineral type and involves liquid, chemical and/or thermal treatment (Hester and Harrison 1994, Durucan *et al* 2006).

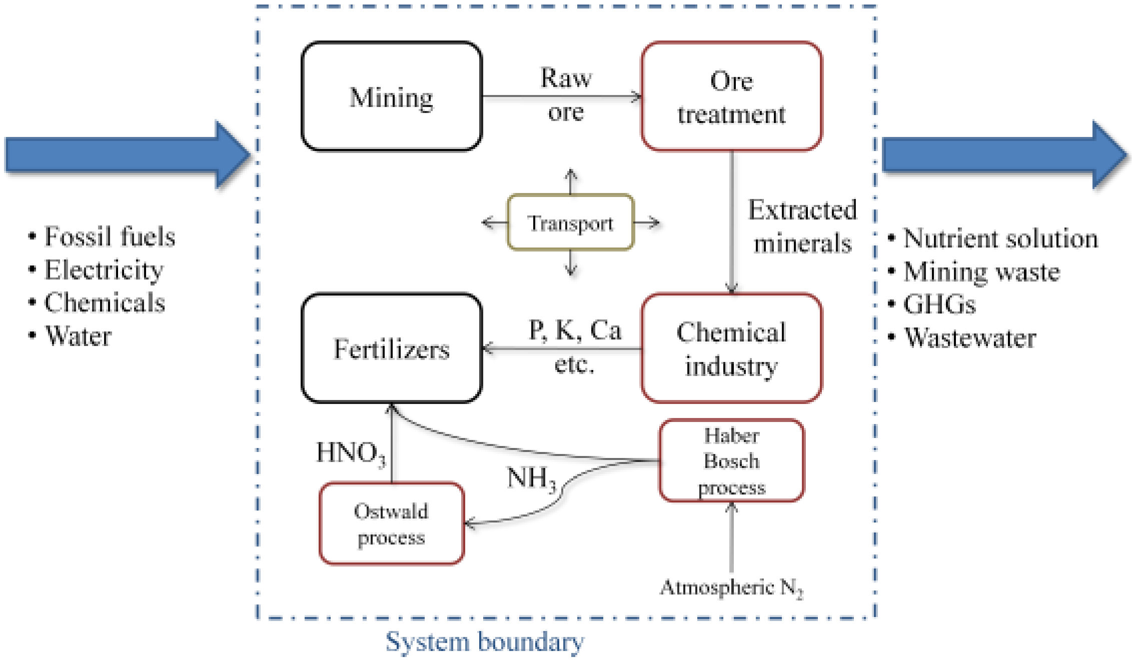

Fig. 4. Commercial nutrient solution production system

To give some perspective regarding the impacts of producing fertilizer components based on the three main macronutrients (N, P, K), **Table 4** has been created. It contains values for variables indicating impact in different categories involving production processes and transport in between production and regional storage. The data has been obtained from Ecoinvent, the Swiss Center for LCI working with EPD 2008 methodology (Ecoinvent 2013).

Table 4. Quantified impacts for the N, P and K sources of the commercial nutrient solution

Impact category	**Unit**	**N – $Ca(NO_3)_2$**	**N – NH_4NO_3**	**N – KNO_3**	**K_2O – KNO_3**	**P_2O_5 – H_3PO_4***
Global warming (GWP100)	kg CO_2 eq/kg	3.836	8.500	15.878	0.865	2.018
Ozone layer depletion (ODP)	kg CFC_{11} eq/kg	6.27 e-07	5.75 e-07	9.15 e-07	1.57 e-07	2.08 e-07
Photochemical oxidation	kg C_2H_4 eq/kg	0.002	0.002	0.002	0.0005	0.002
Acidification	kg SO_2 eq/kg	0.011	0.023	0.040	0.002	0.031
Eutrophication	kg PO_4 eq/kg	0.004	0.010	0.016	0.001	0.045
Non renewable, fossil	MJ eq/kg	63.544	57.950	88.592	15.210	32.190

Source: Ecoinvent 2013

*Note: The values refer to the production of phosphorus pentoxide (P_2O_5), the extracted salt which is then hydrated to form phosphoric acid (H_3PO_4)

The transport of materials within the system is also an important factor towards environmental impact due to GHG emissions (Hester and Harrison 1994). In the case of Sweden, mining deposits of iron, sulfide and gold ores are currently being exploited (Geological Survey of Sweden 2013). This implies that most of the nutrients required for the nutrient solution are originating from deposits outside of Sweden, whilst adding to the GHG emissions of the production system due to transportation.

BIOGAS SLURRY SYSTEM

Biogas slurry is the waste product of Svensk Biogas' anaerobic degradation process. The plant in Linköping uses organic waste from the local food industry (37%), household waste (28%), slaughterhouse waste (27%) as the main substrates for biogas production. They produced 84200 tons of biofertilizer (slurry) by processing 80400 tons of organic material in 2011 (Svensk Biogas 2012). The amount of biofertilizer was higher than the organic material input because the fermented substrate is stored in tanks that allow the accumulation of rainwater. This is how a 95% water content is achieved. At the moment the slurry is being distributed to farmers around Linköping, which pay the transportation costs and are satisfied with the product (Nilsson-Pålendal 2013, personal communication).

Given the findings concerning the nutrient content of the biogas slurry, the system has been defined as in **Fig. 5.** The main activities have been identified as being the **transport, pumping, dilution, storage** and **nutrient supplementation** of the biogas slurry in order to provide an adequate nutrient solution for the hydroponic production. The input **flows** are biogas slurry, water, nutrient salts, electricity and fossil fuels. The main output flow of the system is the finished nutrient solution and the transport activity emits GHGs. Depending on the source of electricity used in the pumping, emissions can differ for this activity. Given the fact that energy is being provided by the local incineration plant, GHG and excess heat would be the emissions in question, and because the heat will be used in the greenhouse, such emissions can be omitted.

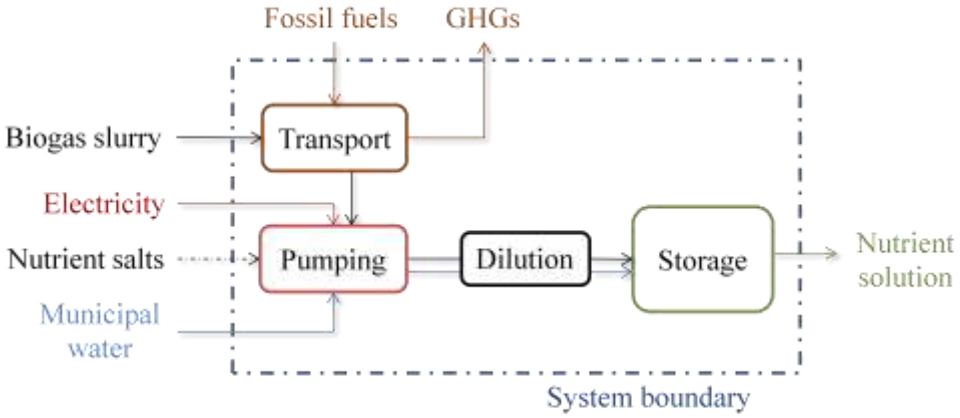

Fig. 5. The biofertilizer processing system

Ensuring transport from the biogas plant to the greenhouse can be done by using trucks, which are used in the current distribution network of the Svensk Biogas biofertilizer (Svensk Biogas 2012). Since the two buildings will be about 500 m apart (**Fig. 6**), the emissions due to transportation are very small. In 2012, Svensk Biogas estimated that based on 0.13 tons of CO_2 were emitted for every m^3 of biofertilizer transported (corresponding to a transport distance of approximately 1 km).

Fig. 6. Placement of the greenhouse (Google Earth 2013)

Electrical pumps can be used for transporting the slurry so it can be stored and used within the hydroponic system. The dilution process can be done during pumping through ensuring a proper volume ratio when pumping the slurry and municipal water into the storage tank. Because the suspended solids are very small in size and have a very high retention factor, the pumping of the slurry poses no problem (Nilsson-Pålendal 2013, personal communication). Pumping can also ensure that the nutrient solution is homogenous, which is very important (Canna Gardening 2013, General Hydroponics Europe 2013). If the nutrient solution is unbalanced and needs supplements, these can be added by dissolving nutrient salts and introducing them in the storage tank by pumping, ensuring homogenization. The nutrient supplementation issue will further be addressed in the nutrient content section.

URINE DIVERSION SYSTEM

The urine diversion system is based on the assumption that urine diversion toilets would be installed in the Plantagon building and that the urine would be collected on site, treated and used in the hydroponic system. The collection process involves specially designed toilets which separate the urine from the faecal matter and collect the excreta in separate tanks. Water may or may not be used in the collection process depending on the system (Esrey 2001).

Based on the nutrient content findings, the following activities have been identified within the urine diverting system: collection of urine from the Plantagon building, which is to be **stored**, **sterilized**, **diluted** and **enriched** with additional required nutrients. The outline of this system is presented in **Fig. 7**. **Flows** include the collected urine, water, nutrient salts and electricity as inputs and the finalized nutrient solution as the main output.

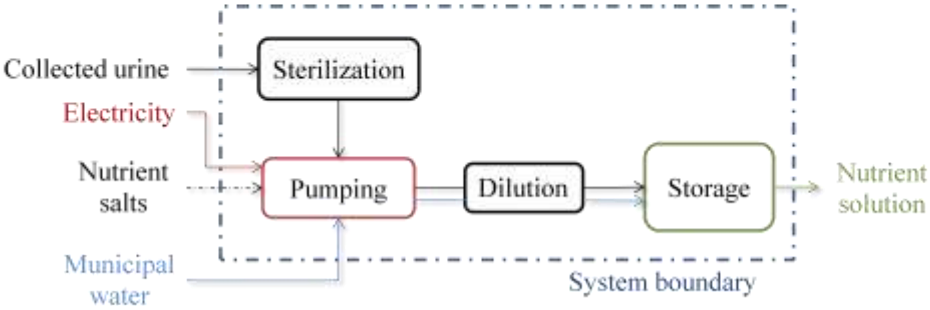

Fig. 7. Urine diversion system outline

The sterilization process merely requires sealed storage in order to minimize nitrogen loss through ammonia volatilization. The pH, which rises to about 9, ensures a 90% pathogen die-off after as little as 5 days (20^0C), but can be extended to months depending on temperature and dilution. It has been shown that the sterilization process is more effective at higher temperatures and in undiluted samples. Urine can be used in agriculture with a higher degree of safety than sludge or wastewater due to lower heavy metal and pathogen contents (Esrey 2001, WHO 2001, WHO 2006). So, in order for the urine to be safe to use from a human health perspective, dilution must be done after sterilization.

As in the case of the biogas slurry system, the homogenization of the finished nutrient solution is to be done passively, during pumping. Also, the nutrient supplementation issue will be discussed in the following section.

4.2. NUTRIENT CONTENT

The technology that is to be used for distributing the nutrient solution in the vertical greenhouse is a type of media based irrigation, namely ebb-and-flow technique (Plantagon 2013). This technology involves growing the plants in inert media filled trays with a nutrient solution reservoir from which the plants are irrigated 2-4 times per day. The trays contain pots which are submerged 2-5 cm from the bottom during irrigation, which can last between 5-20 min, after which the solution is drained back into the reservoir below the tray. In between irrigation events, the media has the property of maintaining moisture so that the roots do not dry out whilst also providing proper root oxygenation (Raviv and Lieth 2007).

Plantagon plans on using trays containing pots filled with pumice, each tray being equipped with a nutrient solution reservoir. Trays have been chosen because they can travel down a conveyor belt from the top to the bottom of the greenhouse. Also, capillary mats, as in nutrient film irrigation systems, are to be used at the bottom of the trays to protect plants from drought. The excess nutrient solution is recovered, disinfested and reused (Plantagon 2013).

COMMERCIAL NUTRIENT SOLUTION

The composition of nutrient solutions available on the market are difficult to come by, due to the fact that most producers are very secretive about the subject. However, NPK ratios are indicated and such nutrient solutions are available for sale in the form of hydroponic concentrates. They must usually be diluted 500 times to provide the necessary nutrient concentrations for growing crops (General Hydroponics Europe 2013, Canna Gardening 2013).

Since Plantagon has no definitive information on a nutrient solution provider, experiments are being conducted with manufactured nutrient solutions at the Swedish University of Agricultural Sciences in Uppsala. In order to obtain the required nutrients, salts are used (**Annex III**) (Hultin 2013, personal communication). The required content of the commercial nutrient solution can be viewed in **Table 5**.

Table 5. Nutrient contents before and after dilution and required supplementation per nutrient

	Commercial solution	Biogas slurry	Slurry diluted 20x		Urine	Urine diluted 41x	
	mg/l	mg/l	mg/l	required suppl. mg/l	mg/l	mg/l	required suppl. mg/l
N$_{total}$	164	6000	300	-136	7225	176	-13
N$_{inorganic}$	164	4250	213	-48	6765	165	-1
P$_{total}$	36	750	38	-1	591	14	22
P$_{inorganic}$	36	-	-	-	532	13	23
K	212	1375	69	144	1576	38	174
Ca	94	2000	100	-6	15	0.35	94
S	65	200	10	55	463	11	54
Mg	48	100	5	43	2	0.04	48
B	2	-	-	1	0.44	0.01	1
Na	0.63	-	-	0.63	960	23	-23
Mn	0.61	0.5	0.03	0.58	0	0	0.61
Zn	0.46	8.7	0.44	0.02	0.2	0	0.45
Cu	0.05	2.08	0.1	-0.05	0.07	0	0.05
Mo	0.04	-	-	0.04	-	-	0.04
Fe	0.63	20	1	-0.37	0.19	0	0.63
Cl	0	750	38	-38	2400	59	-59
EC (mS/cm	1.5	20.95	1.19		19	0.65	
pH	6-7	7.9	-		8.9	-	

Sources: Hultin (2013), personal communication (commercial solution), Nilsson-Pålendal (2013), personal communication, Svensk Biogas (2013) (biogas slurry), Jönsson (2005) Kirchmann and Pettersson (1994) (urine)

Notes: * the coloured bars correspond to the values in one column ** the diluted EC values have been calculated considering a 0.2 EC for the dilution water (Tekniska Verken 2009)

The mineral content of the commercial nutrient solution hereby presented has been used as a benchmark for the comparison of the biogas slurry and urine diversion systems, given the fact that they accurately correspond to the nutritional needs of the *pak choi* crop. If the minimal nutritional requirements of the plant are not met, crops can show signs of tissue damage or reduced growth, thus lowering productivity. More detailed deficiency effects for each nutrient can be viewed in **Annex I**.

Although higher nutrient concentrations increase growth and nutrient accumulation in plants, the minimal requirements are usually fulfilled in order to save costs. In conventional agriculture, excessive fertilizer use causes more nutrient leaching and more severe eutrophication (Cassman *et al* 2003, Dufour and Guérin 2005, Liu *et al* 2011, Parks and Murray 2011). In closed systems, however, leaching is not a problem and higher nutrient concentrations can be used without environmental risks. However, excess nutrients cause toxicity, limiting plant growth. Some effects are presented in **Annex II**, although toxicity is not as well documented as deficiency.

BIOGAS SLURRY SYSTEM

In order for the biogas slurry to be approved as a biofertilizer, certain criteria have to be fulfilled that ensure its safe use in agriculture. Contents of N, P, K, Ca, Mg and Cl, as well as heavy metal concentrations must also be included for toxicity reasons. However, the biofertilizer from Svensk Biogas has all heavy metal concentrations below required Swedish limits (Svensk Biogas 2012). The biofertilizer is also checked for pathogens such as *Salmonella* and *E. Coli* and is regarded as fit for use in agriculture (Nilsson-Pålendal 2013, personal communication).

When comparing the nutrient content between the biogas slurry and the commercial nutrient solution, it is observed that the biofertilizer has significantly higher concentrations than the commercial solution, thus requiring dilution. Also, data was unavailable for several nutrients (B, Na, Mo), which implies either that they are not contained in the digestate or that their concentrations are unknown. The EC value corresponds to the EC in April 2013, and other monthly values are unknown. As for the pH, it remains rather stable between 7.8 and 8 throughout the year (Nilsson-Pålendal 2013, personal communication).

Nonetheless, the dilution factor is yet to be discussed. Based on the content of various nutrients, the biogas slurry must be diluted 26 times ($N_{inorganic}$), 20 times (P_{total}, Ca), 6 times (K). The uneven nutrient distribution indicates that if one dilution factor is chosen, the solution should be adjusted so that the concentrations of other nutrients reach required values.

Given the fact that P is a limited resource, the dilution factor of 20 is recommended for the biogas slurry analyzed. As a result (**Table 5**), there will be no need to supplement the diluted slurry with P, N, Ca and Cu. Still, K, S and Mg might need to be added. The Cl concentration would be down to 37 mg/l and the EC to 1.19 mS/cm after dilution with 0.2 EC drinking water provided by Tekniska Verken, which should not pose a problem to the crop. However, this dilution factor is based on the total P content, not on the inorganic P content (due to unavailability). A lower quantity of plant available P in the slurry would lower the dilution factor.

According to Liu *et al* (2009), biogas slurry has a varying nutrient content that can be supplemented with required nutrients in order to be adequate for plant growth. It can be looked upon as an adjustable liquid fertilizer. However, if nutrient supplementation is needed, it involves either using mineral fertilizers, which will increase the environmental impact of the system, or finding renewable sources for the deficient nutrients, which could prove problematic. In this case it is assumed that mineral fertilizer salts are used to supplement the deficient nutrient solution.

URINE DIVERSION SYSTEM

The nutrient content of urine, based on Swedish sources (Kirchmann and Pettersson 1994, Jönsson 2005) can be viewed in **Table 5**. According to the presented data, urine contains far more nutrients than required and, as in the case of the biogas slurry, requires dilution. Based on the different nutrient concentrations, the urine should be diluted about 41 times ($N_{inorganic}$), 15 times ($P_{inorganic}$), 7 times (K) and, quite remarkably, 1520 times based on the Na content. As seen in **Table 5**, the Na and Cl content of urine is very large, making it extremely rich in salt. Although the commercial nutrient solution contains no Cl, this micronutrient is used by plants in photosynthesis and cell division, and is usually obtained from the irrigation water (Taiz and Zeiger 2002).

High NaCl concentrations inhibit the plant's water and nitrate uptake and can also induce Ca and/or K deficiencies (multiple authors cited in Raviv and Lieth 2007). However, such problems may be solved by dilution. If diluted 41 times (as seen in **Table 5**), the P content decreases below the required value. The high Cl and Na concentrations are lowered but it is still uncertain whether they still pose a problem.

In addition, the nutrient concentrations after this dilution require more supplements than the biogas slurry. Almost all nutrients except N, Na and Cl must be added in order to fulfill the crop requirements. If the dilution factor decreases, then the NaCl concentration increases, which may affect plant growth. Also, given the fact that many nutrients will have to be added after dilution in the form of nutrient salts which will increase the EC, a rather low EC after dilution is desirable.

Regarding the collection of urine and volume requirements in relation to the functional unit, 0.24 m^3 of urine are necessary for producing 10 m^3 of nutrient solution using a 41 dilution factor. Given the fact that the average person excretes 1.5 l of urine per day (Jönsson 2005) and assuming that 40% of the urine would be collected on site, 0.6 l can be collected daily from one person. Assuming that 100 people will be working within the building (including Plantagon staff, researchers and rented office space employees), 60 l can be collected daily. This would imply that in 4 days the required volume for producing 10 m^3 of nutrient solution can be collected. This rough estimation indicates that providing enough urine should not be a problem.

4.3. ENERGY AND COST BALANCE

The energy required to produce commercial nutrient solution is clearly higher than the energy required to produce biogas slurry and urine, which are waste products. However, the difference of nutritional content between biogas slurry and urine requires different processes in order to produce an adequate nutrient solution, which might imply different energy needs. Also, in order for biogas slurry and urine to be used as sustainable alternatives to artificial hydroponic fertilizer, they must also be competitive when it comes to costs.

COMMERCIAL NUTRIENT SOLUTION

There are multiple brands worldwide which produce hydroponic solutions. Such solutions are sold in very concentrated forms with varying costs. In Sweden, prices for complete nutrient solutions that must be diluted 500 times can vary between 2.75 and 4.60 € per liter, with imported products from either Europe or the United States (Hydrogarden 2013). Assuming that diluting these solutions would be free of cost, the final nutrient solution would cost between 0.005 and 0.009 € per liter. In relation to the functional unit, producing 10 m^3 of nutrient solution for *pak choi* growth would cost somewhere between 50 and 90 € excluding dilution costs.

BIOGAS SLURRY SYSTEM

When addressing the energy balance of this system, the allocation problem arises. Bauman and Tillman (2004) claim that this is the case when several products are produced in a process, or when many different products are jointly treated in the same waste treatment process, for example. The problem lies in how to relate the environmental load of one of these products. In this case, where energy consumption is looked upon as an environmental load indicator, attributing a value for the production of a quantity of biogas slurry is problematic. This is the case due to the fact that the slurry is a byproduct of the biogas yielding process. So, the organic matter is treated, stored in anaerobic conditions and heated so the fermentation process can occur, energy intensive processes that yield both biogas and slurry (biofertilizer). However, expanding the system in order to include the production process of the slurry will further complicate the analysis. Also, because the slurry is regarded as a waste product and part of a renewable fuel generating industry which uses excess heat for the reactors, its energy input has been regarded as null. As for the cost of the biofertilizer provided by Svensk Biogas, it has also been regarded as null since the company holds no profit from distributing it to local farmers.

The energy balance will then concern the energy requirements of the slurry processing (pumping, dilution, storage). At the moment, the slurry at Svensk Biogas is stored at somewhere between 5 and 20 ^{0}C (Nilsson-Pålendal 2013, personal communication). So, with indoor **storage**, the slurry should not require additional temperature regulation.

The energy and costs required **pumping**, as well as **dilution**, which is a result of the pumping, have been calculated by firstly determining how much energy is required to pump water using a 50 m^3/h flow and a head difference of 5 m. Such values have has been chosen given the lack of accurate values, which should suffice for this analysis. The following formula has been used to calculate the pumping power:

$$P = \frac{Q * \rho * g * h}{3.6 * 10^6}$$

P = pump power (kW) ρ = density (kg/m^3) h = head difference

Q = volume flow (m^3/h) g = specific gravity (9.8 m/s^2)

Assuming that the density for all fluids to be pumped in both biogas slurry and urine diversion systems is relatively the same as the density of water (1000 kg/m^3), the required pumping power is that of 0.68 kW. For pumping 50 m^3 in 1h, 0.68 kWh is the required energy. This indicates that the energy demand of the pumping activity, which also ensures dilution and homogenization, will be very small, as well as the environmental impact.

Given that the Swedish price per kWh is 0.2 € (Europe's Energy Portal 2013) and that it takes 5 times less time to pump 10 m^3 with a 50 m^3/h flow pump, 0.027 € is the cost for pumping a volume of fluid equal to the functional unit. However, supplying water for dilution comes at the price of 0.54 € per m^3, cost which also includes pumping (Tekniska Verken 2013). Assuming that obtaining 10 m^3 of final nutrient solution involves pumping the water and concentrated nutrient solution (commercial, slurry, urine) only once, all three systems would have the same energy requirement for producing the functional unit. However, this balance shifts considerably when accounting for the production energy inputs of the nutrient sources, making the commercial nutrient solution very energy demanding compared to biogas slurry and urine. The cost comparison of all three systems is presented in **Table 6.**

Table 6. Cost balance comparison before nutrient supplementation

	Concentrate V (m^3)	Water V (m^3)	Concentrate cost (€/m^3)	Required concentrate cost (€)	Pumping cost (€/m^3)	Required pumping cost* (€)	Water cost (€/m^3)	Required water cost (€)	**Total** (10 m^3) (€)
Commercial (1:500)	0.02	9.98	2750-4600	54.9-91.8	0.003	0.001	0.54	5.39	60.3-97.2
Biogas (1:20)	0.48	9.52	0	0	0.003	0.013	0.54	5.14	5.2
Urine (1:41)	0.24	9.76	0	0	0.003	0.006	0.54	5.27	5.3

Sources: Hydrogarden (2013) (commercial solution prices) Tekniska Verken (2013) (water cost)

*Note: The required pumping cost accounts only for pumping the concentrated solutions, since the water cost also includes the cost for its pumping

Given the results of this cost estimation, biogas slurry and urine based nutrient solutions are considerably cheaper, since they can be obtained free of charge and the costs apply only for providing water and pumping. Also, the main factors affecting the total cost have been the price of the concentrated solution and for providing water, with the costs for pumping being negligible.

The nutrient supplementation needs have been estimated through the use of nutrient salts (**Annex III**). For providing a proper NPK ratio, K supplementation is required (144 mg/l). This will increase the total cost of the slurry based nutrient solution. The cheapest way of supplying K is through KCl, which in industrial quantities is priced at around 290-450 € per ton (Industrial Minerals 2013). However, adding Cl to the hydroponic solution is not desirable due to salinity effects. Another alternative is KNO_3, which costs between 540 – 800 € per ton (Alibaba Global Trade 2013), but has the issue of adding N to the solution. In the case of the slurry, after being diluted 20 times, the N content is rather high, and adding more N might cause toxic effects. In order to add 144 mg/l of K, 373 mg/l of KNO_3 are required. This implies 3.73 kg of KNO_3 for 10 m^3 of nutrient solution. This would increase the total cost of the slurry solution equivalent to the functional unit with 2 – 3 € and the N concentration with 52 mg/l.

As for the environmental impact of adding KNO_3 in the nutrient solution, quantified values are available in **Table 4**.

URINE DIVERSION SYSTEM

Due to the fact that urine is a form of human excreta, its energy input to the system has been regarded as zero. The energy required to collect the urine is provided by gravity in urine diverting systems. As for sterilization, collection tanks are usually placed indoors and the ambient temperature would ensure an effective pathogen die-off. The energy requirements would then apply for the pumping and dilution of the urine.

As before mentioned, the energy requirements for processing would most likely be very similar for the three alternatives, with the costs possibly differentiating the biogas slurry from urine. However, **Table 6** indicates that even though urine's required dilution factor is double than that of the slurry, the total costs are more or less the same. The differentiation between these two systems will then have to depend on the nutrient content and chemical properties.

Supplementation of mainly K (174 mg/l) and Ca (94 mg/l) is required in order to obtain a balanced nutrient solution using urine. For increasing the K concentration with 174 mg/l, 451 mg/l KNO_3 must be added. By using the same K source as for the biogas slurry supplementation and in relation to the functional unit, 4.5 kg of KNO_3 must be added, which increase the total cost with 2.4 – 3.6 € and the N concentration with 62 mg/l.

Ca supplementation can be achieved by adding 386 mg/l $Ca(NO_3)_2$. Prices for this salt are between 190 – 300 € per ton (Alibaba Global Trade 2013). For producing 10 m^3 of nutrient solution 3.86 kg of $Ca(NO_3)_2$ must be added, increasing the Ca and N concentrations with 94 mg/l and, respectively, 66 mg/l and the total price with 0.7 – 1.2 €.

An additional 23 mg/l of P are required for achieving the minimum P requirement of the *pak choi* crop, which can be obtained by adding 53 mg/l of phosphorus pentoxide (P_2O_5). For 10 m^3, 5.3 kg are needed; and with the cost for P_2O_5 being somewhere around 760 – 1220 €/ton (Alibaba Global Trade 2013), 4 -6.5 € would be added to the total cost. Although P_2O_5 is not the sole mean of supplementing the nutrient solution with P, other alternatives are also expensive (phosphoric acid, calcium triphosphate, single superphosphate etc.) due to their low content percentage of P_2O_5, thus requiring larger amounts (ICL Fertilizers 2013, IPNI 2013).

An overall effect on the total costs for all analyzed systems can be viewed in **Table 7**. Even after nutrient supplementation the costs of slurry and urine based nutrient solutions are competitive with the commercial alternative. Even though small quantities of micronutrients as well as S and Mg might still need to be added in both slurry and urine solutions in order to obtain a balanced nutrition, the overall cost should not be significantly influenced.

Table 7. Cost balance comparison after nutrient supplementation

	P suppl. (€)	**K suppl. (€)**	**Ca suppl. (€)**	**Cost before suppl. 10 m^3(€)**	**Cost after suppl. 10 m^3 (€)**
Commercial (1:500)	0	0	0	60.3 – 97.2	60.3 – 97.2
Biogas (1:20)	0	2 - 3	0	5.2	7.2 – 8.2
Urine (1:41)	4 – 6.5	2.4 – 3.6	0.7 – 1.2	5.3	12.4 – 16.6

Sources: Industrial Minerals (2013), Alibaba Global Trade (2013), ICIS Pricing (2013)

The quality of the dilution water will also determine the supplementation requirements due to the salt content. The water provided by Tekniska Verken in Linköping has concentrations of 16 mg/l Ca, 31 mg/l S, 11 mg/l Cl, Fe 0.06 mg/l, Cu 0.001 mg/l (Tekniska Verken 2009), which implies that some nutrients might not need to be supplemented. S, Mn and Cu for example, would no longer need to be added.

The addition of Ca from dilution water would not significantly alter the overall cost of the urine solution. However, these nutrient values for drinking water content are yearly mean values (Tekniska Verken 2009), meaning that the content will vary and, just as the contents of biogas slurry and urine, will need to be properly monitored so as to provide a balanced final nutrient solution.

5. DISCUSSION

In the following section the different system outlines, nutrient contents as well as energy and cost balances will be discussed based on the presented results. Implications of using slurry and urine in the hydroponic system are also discussed.

5.1. SYSTEM COMPARISON

Because the production processes of the biogas slurry and urine have been disregarded, the system outlines for these two alternatives differ significantly from the outline of the commercial solution system, which also includes activities for extracting and processing the raw minerals or atmospheric N. However, the slurry and urine systems might require additional activities to ensure the production of safe hydroponic solutions. Such activities are linked to the health requirements of hydroponics.

HEALTH REQUIREMENTS

A crucial issue in large scale food production involves ensuring that health requirements are met regarding pathogens and waterborne diseases (WHO 2006). Although biogas slurry and urine (after sterilization) are safe to use in conventional agriculture, they may not be as safe in hydroponics. In the absence of soil and, consequently, a rich microbial flora and fauna, pathogens are more likely to survive and be taken up by the crop. It is also known that hydroponically produced crops are more prone to diseases, making sterilization very important for both recycled soilless media and nutrient solutions (Raviv and Lieth 2007, Montana State University 2009).

This might imply the need for ultraviolet (UV) treating or filtering for both biogas slurry and urine before introduction to the hydroponic system. Filters are available for the different particle sizes, from rapid sand filters that remove large particles to porous membranes removing ions. Pathogens are removed successfully with slow sand filters, a solution with very low costs (Raviv and Lieth 2007). UV water treatment is also effective for removal of pathogens. However, it has the worst environmental impacts of all disinfection techniques due to its high energy consumption (Vince *et al* 2008). Beavis and Lundie (2003) conducted an LCA study on the impacts of UV treatment for water disinfection and the results showed that treating 1 m^3 of water consumes 1 MJ of energy and emits 0.08 kg of CO_2. Chlorination had significantly lower impacts in the same study, but in the case of nutrient solutions adding Cl is not an option.

5.2. NUTRIENT SOLUTION COMPARISON

An important matter concerning the feasibility of using biogas slurry and urine as hydroponic nutrient solutions is the nutrient content. As shown in the results section (**Table 5**), ratios between nutrient concentrations vary between the different alternatives. And given the fact that all alternatives are available in concentrated forms, dilution is required.

DILUTION FACTORS

Concerning the biogas slurry and urine diversion systems, the dilution factors must be based on the main macronutrient (NPK) concentrations due to two main reasons: firstly, the environmental implications of producing the macronutrient in question, making P the most important due to its eutrophication impacts as well as scarcity and global distribution (Cordell *et al* 2009), followed by N which is the main cause of eutrophication when dispersed in water bodies (Rockström *et al* 2009). Secondly, dilution factors must be also chosen based on the concentrations of other macro- or micronutrients post dilution, so as to not cause toxic effects.

Given the fact that the biogas slurry and urine contain mostly water, around 95% (Nilsson-Pålendal 2013, personal communication) and 99% (Jönsson 2005), less water is required overall to produce an adequate nutrient solution. Considering the inorganic N content, a concentrated hydroponic solution must be diluted 500 times in order to be used in plant production, compared to 26 times for biogas slurry and 41 times for urine.

Two Chinese studies (Wenke *et al* 2009, Liu *et al* 2011) point out that diluting biogas slurry 5 times generate healthy lettuce (*Lactuca sativa* L.). One case required P and micronutrient supplementation (Liu *et al* 2011) and the other had better yields when supplemented with the amino acid glycin (Wenke *et al* 2009). However, in both cases the nutrient content of the slurry was considerably lower than the one originating from Svensk Biogas. Such slurries contained around 700 mg/l N, 30 mg/l P, 700 mg/l K with a pH of 7.8 and EC of 6 mS/cm.

This accounts for about 6 times less inorganic N, 25 times less P, 2 times less K and a 3.5 times smaller EC. So, a higher dilution factor will be required for the analyzed slurry in order to lower nutrient concentrations and EC, indicating that the recommended dilution factor of 20 times for the slurry based on the P content is well founded.

A study (Borghesi *et al* 2013) which treated lettuce (*Lactuca Sativa* L.) with various concentrations of $CaCl_2$ showed that the increasing salinity (up to 20 mol/m^{-3}, which accounts for 1420 mg/l Cl) and EC (up to 6.5 mS/cm) has not influenced the development of the plants. Apparently, for lettuce growth starts to be affected at concentrations of $CaCl_2$ higher than 60 mol/m^{-3} (4260 mg/l Cl) (Borghesi *et al* 2013). Shannon and Grieve (1998) suggest that for lettuce an EC of 8 mS/cm decreases the yield by 50%, which would make the results from Borghesi *et al* 2013 seem a bit optimistic. Nonetheless, compared to lettuce, *pak choi* has a higher tolerance to salinity (yield is reduced by 50% at EC 17 mS/cm in NaCl) (Shannon and Grieve 1998), and the EC of 0.65 mS/cm post a 41 times dilution seems to indicate that salinity will no longer be a problem.

With the most adequate dilution rates possibly being 20 times for biogas slurry and 41 times for urine, the resulting solutions require nutrient supplements, K being the highest requirement (144 mg/l to be added for slurry and 174 mg/l for urine). The main concern is that the diluted urine will require P supplementation, which is not ideal given that P is a limited resource, thus making biogas slurry a better alternative based on the nutrient content.

The micronutrients are basically absent after dilution for both urine and slurry and need to be supplemented. However, very low concentrations are needed for the growth of the plants (ranging between 0.04 – 0.63 mg/l), which will not be significant in terms of environmental impacts or costs when scaled up for the full production of *pak choi*.

NITROGEN SOURCE

Another issue concerns the N source in the nutrient solution. In commercial nutrient solutions, most of the nitrogen is available as nitrate (NO_3^-), whereas in both biogas slurry and urine it is available as ammonia (NH_4^+). Although both forms are accessible to plants, they can affect the uptake of other nutrients. Studies have shown that the uptake decreases and salinity sensibility increases when ammonia is present as the main nitrogen source. This is the reason why most commercial fertilizers have a high nitrate content (Shannon and Grieve 1998, Raviv and Lieth 2007). However, ammonia can be nitrified in the presence of specialized bacteria and oxygen, but they are time consuming processes (Udert and Wächter 2012) and can affect the availability of nutrients for the plants if the process is to take place in the system.

HYDROPONIC SYSTEM IMPLICATIONS

The main concerns regarding nutrient contents are linked to **variability**. Since mean values of the nutrient contents of slurry and urine have been used for the comparison, the full variability of these two systems is not obvious. Biogas slurry has different nutrient distributions on a monthly basis due to changing substrates in the anaerobic degradation process, with N concentrations varying between 3000 – 5500 mg/l, P between 500 – 1000 mg/l and K between

1250 – 1500 mg/l (Nilsson-Pålendal 2013, personal communication). As for urine, the content is variable based on diet, and N concentrations can vary between 3300 – 7300 mg/l, P between 270 – 590 mg/l, and K remains rather constant at around 1600 mg/l (Jönsson 2005).

Such fluctuating values will modify the NPK ratios as well as the other macronutrients and micronutrients, thus influencing dilution factors and supplementation requirements. The implications of these fluctuations towards the cultivation of the crop will also play an important part in the success of these alternatives.

For established commercial nutrient solution, the EC and pH are sufficient indices of when the solution has reached the required nutrient balance and when the recycled solution must be concentrated or diluted based on the water and nutrients that the crop has taken up. However, EC does not indicate which nutrients are present and if they are contained in the correct ratio. This makes regular testing important during the life cycle of the crop (Parks and Murray 2011). The dilution water must also be tested for nutrient composition, since it can affect the nutrient distribution in the final nutrient solution (Raviv and Lieth 2007) and its content can be variable.

Given the fact that commercial solutions have very precise recipes, their management throughout the production process is not as tedious as managing slurry and urine, which, based on their varying nutrient content, should be tested for composition before deciding dilution rates and required supplements. Additional testing is also time and resource consuming, making the two renewable sources more difficult to manage. However, if the balance is not correct, deficiency or toxicity can set in. The main issue is that they are hard to differentiate because: many symptoms appear similar, multiple deficiencies or/and toxicities can occur simultaneously, false deficiency symptoms can appear or plants can even be asymptomatic in deficient or toxic conditions (Montana State University 2009). Therefore, thorough **nutrient content analyses** must be performed before the solutions are introduced in the system.

The biogas slurry's dry content could prove problematic in the hydroponic system. The **suspended particles** may clog pump nozzles or the capillary mats thus altering the even distribution of nutrient solution to the entire crop. Also, the particles in the biogas slurry are very fine, with diameters of a few µm (Nilsson-Pålendal 2013, personal communication), which could also clog the pores of the pumice if accumulated, affecting its water retention capability. If even after dilution the particles still pose a problem, it can be solved through filtration. Filtration is commonly being used to remove undissolved materials from nutrient solutions (Parks and Murray 2011). Pathogens and small particles are effectively removed using slow sand filtration (Raviv and Lieth 2007), which is also the filtration technology that Plantagon plans on using for disinfesting the excess nutrient solution. However, experiments should be developed in order to ascertain whether filtering the suspended particles in the diluted slurry is necessary before introduction in the system and what the effects may be on a long term perspective.

Urine, on the other hand, has a very low suspended particle content even before dilution, which makes it superior to the slurry in this respect.

5.3. ENERGY AND COST COMPARISON

Given the identified system components for the three analyzed systems, it is clear that the production of the commercial nutrient solution has higher environmental impacts than recycling biogas waste and urine to hydroponic food production. Although the representation of the commercial solution production system is simplistic, energy intensive processes are present and the environmental impacts are considerable. Whether the nutrients are readily mixed in a hydroponic concentrate or made from mixing nutrient salts, water for dilution and solubilisation is required, also involving energy and costs for providing water, just as for the biogas slurry and urine diversion systems.

Because the processing of concentrated nutrient solutions is more or less the same, involving pumping and dilution with slightly different water demands, the energy requirements are very similar for all three systems. However, when including the production impacts, mined fertilizers make commercial nutrient solutions very unsustainable.

Results indicate that biogas slurry and urine, as waste products, are also cheaper than commercial hydroponic nutrient solutions. The very low cost involved in obtaining slurry and urine make them very competitive nutrient sources.

Adjusting the nutrient balance after the dilution of the biogas slurry and urine must be achieved by adding nutrient salts, which increase environmental impacts of these two systems. Based on the nutrient content, urine requires more supplements, including P, which is more scarce and expensive than other macronutrients such as K or Ca, which are also required. The macronutrient content of the biogas slurry is slightly more balanced, only requiring K supplementation.

However, due to the fact that macronutrients are provided from renewable sources, the use of urine or biogas slurry in hydroponics has the potential of contributing to decreasing the dependence on mined fertilizers in food production.

If the suspended particles in the biogas slurry are found to pose problems in the system, filtration would be required before introducing them in the production system, which would add to the overall costs. Also, for safety precautions, pathogen removal techniques could be introduced in the processing of the slurry and urine, which would again increase costs.

The variability of the biogas slurry and urine diversion system contents will cause these two alternatives to have fluctuating costs. Since different dilution factors and nutrient supplementations will be required, the costs will vary as well. Market fluctuations will also influence the prices of commercial nutrient solutions and fertilizer salts.

ADDITIONAL CONSIDERATIONS

A crucial factor deciding the success of using urine as a fertilizer in food production is its **social acceptance**. Preconceptions about the hazard of using human excreta in food production do exist, although manure is and has been considered safe to use for a long time (Smit *et al* 2001, Drangert and Nawab 2011). Such concerns can be alleviated if pathogen treatment is conducted before using the urine in the food production system.

Regarding the usage of biofertilizer, as it is currently being used by farmers, introducing it to a large scale hydroponic system might limit its availability to farmers that are usually applying it on their fields. As a result, such farmers might need to relocate their fertilizer source, which could imply using mineral fertilizers.

IDENTIFIED RESEARCH OPPORTUNITIES

The results indicate that, on paper, biogas slurry and urine are very likely to be successful in hydroponic food production, given proper processing. The next step would then be to conduct experiments in order to test the possibility of overcoming existing limitations and possibly identifying other factors that would influence the use of these renewable nutrient sources in soilless agriculture. Issues such as suspended particles in the slurry, salinity in urine and pathogens in both urine and slurry should be thoroughly investigated. Also, the availability of the nutrients in the slurry should be investigated, since data regarding the inorganic content of all nutrients has not been available in this study.

6. CONCLUSIONS

The environmental impacts associated with mining in order to produce fertilizers are considerable. Although hydroponic systems ensure that no nutrient leakages occur to the detriment of local water quality, reliance on mined fertilizers must be limited. Biogas slurry has been used successfully in small scale experiments after dilution, and urine is a very plausible option due to its high nutrient content. Because these two nutrient sources are waste products, they are renewable and, thus, superior to commercial mined fertilizers currently being used in hydroponics.

For the hydroponic production of *pak choi*, biogas slurry requires K supplementation after dilution in order to have a balanced NPK ratio and support the crop growth. Urine has a very high N content and requires a higher dilution rate than the slurry. However, P, K and Ca must be supplemented for sustaining the crop. For both alternatives micronutrients must also be added.

The variable nutrient content of slurry and urine solutions will affect the dilution rates and supplementation requirements. More frequent nutrient content analyses will be required than for a commercial nutrient solution, which has a very precise balance. Based on the analyzed nutrient content, biogas slurry seems to be a better alternative than urine.

The health concerns of using urine and slurry in hydroponic food production may need to be alleviated through pathogen removal, which can be achieved by filtration prior to introducing the nutrient solutions in the hydroponic systems. This would also solve the suspended particles issue of the slurry.

Regarding the costs, biogas slurry and urine are very competitive even after nutrient supplementation due to the fact that they can be obtained relatively free of charge, compared to the rather expensive commercial nutrient solutions. Given the available data, the biogas slurry solution is the most cost effective alternative.

This desk study indicates that both biogas slurry and urine are very promising solutions to producing large scale hydroponic *pak choi* based on renewable nutrient sources, with biogas slurry possibly being the better option. However, empirical studies should be conducted as to test this hypothesis.

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APPENDICES

Annex I. Nutrient Deficiency Effects

	Plant use	**Deficiency effects**
N	amino acids, nucleic acids, plant cells	inhibits plant growth, chlorosis (yellowing of leaves), accumulation of anthocyanin (purple pigment)
P	plant cells, sugar-phosphate intermediates of respiration and photosynthesis, ATP, DNA, RNA	stunted growth, dark green leaf coloration, necrotic tissue spots, accumulation of anthocyanin
K	regulating osmotic potential of cells, activates enzymes in respiration and photosynthesis	marginal chlorosis, leaf deformations
S	2 amino acids, coenzymes, vitamins	inhibits plant growth, chlorosis (yellowing of leaves), accumulation of anthocyanin (purple pigment)
Ca	cell wall synthesis, cell division, messenger for environmental and hormonal signals, regulates metabolic processes	necrosis, leaf deformations, short and highly branched roots
Mg	enzyme activation for respiration, photosynthesis, DNA and RNA synthesis, chlorophyll	chlorosis, premature leaf abscission (seasonal leaf dropping)
B	cell elongation, nucleic acid synthesis, hormone responses, membrane function	necrotic tissue
Cu	redox reactions	dark green leaves, necrosis, malformed leaves
Fe	redox reactions	interveonous chlorosis
Mn	enzyme activation in Krebs cycle, photosynthesis	small necrotic spots
Mo	enzymes which catalyze the reduction of nitrate to nitrite, used by nitrogen fixing microorganisms	can cause nitrogen deficiency, prevent flower formation
Zn	chlorophyll synthesis	reduction in internodal growth, chlorosis, necrosis
Ni	one enzyme in plants, used by nitrogen fixing microorganisms	seldom necrosis
Na	carbon fixation	chlorosis, necrosis, plants fail to form flowers
Cl	photosynthesis, cell division	chlorosis, necrosis

Source: Taiz and Zeiger (2002)

Annex II. Nutrient toxicity effects

	Toxicity effects
N	delayed plant maturity, lowered water use efficiency (increased transpiration), tissue lesions
P	reduced Fe, Mn and Zn uptake, causing deficiencies
K	reduced Mg and Ca uptake, causing deficiencies
Micronutrients	not thoroughly documented; metals may interfere with micronutrient uptake and cause deficiencies

Source: Montana State University (2009)

Annex III. Salts (and phosphoric acid) used in preparing the nutrient solution

Salt	**mg/l**
$Ca(NO_3)_2$	386.3
KNO_3	551.1
NH_4NO_3	60.03
$MgSO_4$	246.48
$MnSO_4$	1.69
$ZnSO_4$	1.15
$NaMoO_4$	0.08
Fe-EDTA ($C_{10}H_{13}FeN_2O_8$)	3.89
NaB_4O_7	4.84
$CuSO_4$	0.125
H_3PO_4	68 ml (conc. 85%)

Source: Hultin (2013), personal communication