reusing waste nutrients in the urban environment for food production

a research paper

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Foreword:

As a person, I love both metropoles as I do love nature, however, for a metropole to exist, huge areas of land have to be covered in farmland, feeding the millions of people packed together in the metropole, but pushing away more and more of pristine nature. My dream is to help build a world where metropoles are self-reliant, transforming the metropole into a true ecosystem and leaving space for nature and wildlife outside the city boundaries.

It should be clear how this dream has lead me to a fascination with commercial urban farms, which promise to feed the world from the city rooftops. Typically, these farms are fertilized with fertillizer sourced from outside the city, while an extensive sewer systems and an army of garbage trucks haul organic waste out of the city, to be processed in the hinterlands.

I saw an opportunity to feed the farm with organic waste, and feed the building with the farm. Mostly from a nutrient point of view, but also from a water and energy perspective.
That is why I chose the subject of supplying these farms with urban waste as the center of my graduation research.

In the following pages, I will explain on how a building ensemble would be able recycle its own waste into food.

Wessel de Jong

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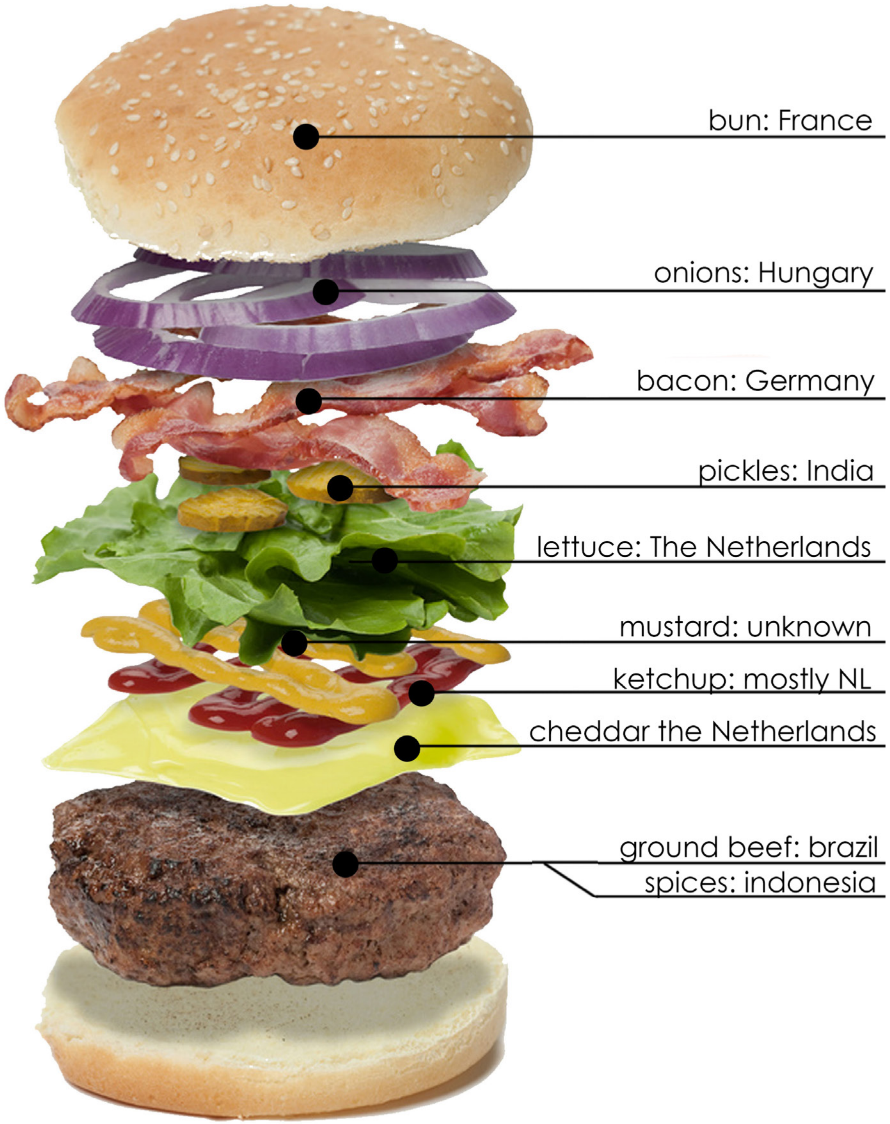


ill. 0.1: a global burger, based on likely import countries in the Netherlands

Relevance:
As globalization and urbanization progressed during the last century, they have transformed society. Nowadays, the majority of people live in urban areas. With many of them living in metropoles so huge, that agricultural areas are a rare sight for its inhabitants.

In the meanwhile, globalization has meant that food is traded across the globe. A random meal can be assembled from components that span all of the globe.

Together, these two movements in society have made that people have gotten less and less connected to the origin of the food they eat.

This is where urban farms come into the picture. Urban farms have been on the rise in the last decade. With initiatives ranging from window farms or communal gardens on empty plots of lands to commercial rooftop greenhouses or AH moestuintjes. Each of them with their own merits, but all very popular.

Parallel to urban farming's surge, organic food as well has become more and more common. Organic food has increased its market share rapidly in recent years from none up to 5% despite its extra costs (bionext, 2015). People pay this premium because they believe that organic food is healthier, tastier and more environmentally friendly (Hugghner, Prothero e.a. 2007).

These two trends suggest that people are longing to get back in touch with their food, as they lost trust in the conventional agricultural system and are willing to pay a premium for trustworthy food. Commercial urban farms are the apex of this trend, as companies construct capital intensive greenhouses in which considerable volumes of produce are grown professionally. The crops of these companies are marketed as an ultra fresh, sustainable and honest alternative. By mixing the growing of crops with public tours, events and trendy marketing, they reach a wide range of people and let them experience the 'making of' their food. These marketed claims are doubtful as will be explored hereafter, together with the business case and management priorities of an urban farm.

ill. 0.2: One of the things people worry about when buying anonymous food. source: Euractiv

ill. 0.3: beans grow in cans, right?

ill. 0.4: Rooftop farm in Rotterdam, The Netherlands. source: Rob de Voogd

ill. 0.5: Rooftop greenhouse in The Hague, The Netherlands. source: rosalieruardy.nl

Research Question:
The research question in this research will be:

How can urban agriculture and the urban environment fulfill each others needs by the reuse of organic waste?

The topic of this research touches upon many issues, ranging from biodiversity, to energy efficiency, congestion, global warming, food safety, alienation from nature, energy, several social issues etc. etc. etc. To prevent this paper from diverting from the main topic, a very clear and limited research question will be asked, which this paper will answer. This does not mean that the final design, resulting from this question, will not address the other issues, but it does mean that those topics will be less researched and therefore less founded.

Method:
Many things have already been undertaken in this field. Intensive agriculture has already managed to squeeze the maximum yield out of a set amount of area. Other companies are already using innovative ways to produce fertilizer out of human refuse.

Therefore a sizable part of this research will be done by interviewing experts out of the field about their techniques and knowledge.
visited experts are:

- **Redstar**: a traditional tomato grower
- **Desah BV**: builder of anaerobic digester sanitation systems
- **Wageningen University**: builder of experimental energy efficient greenhouses

This will be complemented by literature study. The final selection of methods will be made by optimizing flows manually, and by more or less abstract design of the total project, which, with its list of requirements, will be the final result of this research.

On Urban Waste

In urban areas, a lot of things are consumed, and all that is consumed, will produce waste in some form. Every building type produces its own waste mix. Offices produce lots of paper waste, while restaurants mainly deal with organic waste. Companies can have very specific waste profiles.

To make this research about more than just a niche, but a wide applicable solution, I choose for common urban functions to base the waste research on: offices and housing. In table 0.1 you can find the results for what is produced there.

daily waste	office/fte	apartment	total
organic waste	0	0.28 kg	11 kg
residual waste	0.1 kg	0.18 kg	31 kg
paper waste	0.13 kg	0.08 kg	34 kg
glass waste	0.02 kg	0.03 kg	6.0 kg
plastic waste	0.02 kg	0.04 kg	6.4 kg
feces	0.03 kg	0.09 kg	11 kg
urine	0.38 L	1.2 L	140 L
grey water	1.0 L	150 L	6200 L

tab. 0.1: daily waste production in 3600 m^2 of office and 40 apartments

As this research is focussed on the growing of food, nutrients for crop growth are the main focus. Plant nutrients in cities are available in a few waste streams: the black water, organic waste and grey water. Therefore, these waste flows will be the focus of the research and these will be the waste flows which will have to be 'harvested'.

ill. 0.6: a considerable amount of organic waste is burned in incinerators with the household waste

ill. 0.7: a municipial composting facility source:watnzooi.nl

ill. 0.8: wastewater treatment: considerable effort is spent to remove nutrients from the water. source: ehspedia.com

The best way to recover urban nutrients

Already, nutrients of urban waste flows are recovered, for example by composting facilities or wastewater treatment. Composting facilities are effective in recovering nutrients in organic wate but require seperated collection. Besides of that, it only recovers a minor part of urban nutrients, as the majority of urban waste nutrients are present in black water (Morée, Beusen & al, 2013). A final remark is that during the composting process considerable amounts of methane and nitro-oxides are emitted, contributing to global warming (Hao, Chang et all, 2001).

Waste water can be treated and nutrients recovered, nowadays this is done with a centralized system which requires an extensive system of sewer pipes to collect the wastewater. During this collection this water is diluted by a large amount. This dilution makes it difficult to effectively remove pollutants, while the water is still way too polluted to be dumped. This makes waste water treatment an energy intensive process.

A process has to be found which effectively recovers nutrients from both waste water and from solid organic waste. In agriculture, this process is already widely used. It is called anaerobic digesting and will be expanded upon on page 13.

ill. 0.9: anaerobic digestion of agricultural waste
source: farmingfutures

On Urban agriculture

Urban agriculture is already a widespread, but rare, phenomena. In cities around the globe you can find companies which grow crops in urbanized areas. These companies can be fully commercial, or can take a more socially involved approach. One thing they have in common though, which is a dedication to let people experience food production once again.

Urban farms are often heralded as the sustainable alternative of the future for agriculture. However, these claims are doubtful to say the least. Here are a few common claims on urban agriculture:

1: Urban farming could make cities (largely) self-sustainable

Even with urban farms on all available places, food production will still be largely taking place in rural areas (Grewal & Grewal, 2012). As food produced in urban farming is expensive due to scale constraints and property value, it does not significantly increase food safety of the poorest (Santo, Palmer e.a., 2016). As such, urban farming will not replace conventional agriculture. It can, nonetheless, provide a supplement of high quality food to more resourceful citizens.

2: Rooftop greenhouses are a sustainable way of growing food

Sustainability is often a major aspect of the marketing of commercial urban farms. However, as food miles only encompass a small fraction of the carbon footprint of food (Weber & Matthews, 2008), this claim is doubtful. In contrary, due to less professional management and loss of economies of scale, urban farming can be more polluting than conventional agriculture (Mcwilliams, 2009). It all depends on the design and management of the farm. This will be further explored further at page20.

ill. 1.0: Rooftop greenhouse in Brooklyn, USA.
source: Gotham Greens

ill. 1.1: A tour in an urban farm
source: goodfoodfestivals.com

ill. 1.2: Rooftop farm in Brooklyn, USA.
source: Brooklyn Grange

3: Urban farms bring people back in touch with the origin of their food

Unlike conventional agriculture, urban agriculture is very visible for metropolitan dwellers, as it is happening right upon their doorstep. Added to this, urban farms generally try their very best to get people to see and feel the growing of the food (Schans, van der, 2016). This is a major part of their business case and helps them to convince people that their food is worth a premium. As the farms have proven to be popular companies, it is clear that they do fulfill a demand and bring people back in touch with their food.

In conlusion urban agriculture is an enterprise which is not sustainable by definition, but that is not where its added value is. Urban agriculture's value is that it can show people once again how food is grown.

The urban agricultural business case

The urban agricultural business model is in an entirely different league than conventional agriculture. Costs are inevitably higher, as property prices are considerable and growers have to deal with the scale constraints that urban areas impose. Therefore, their crops are in another price segment than ordinary crops.

By marketing the crop as local, sustainable, ultra fresh and healthy, the companies can sell their products to wealthy customers at a premium. By skipping intermediary brokers, more of the selling price will end up at the grower (UrbanFarmers, n.d.).

Besides of the profit derived directly from the crops, urban agriculture firms also spend considerable effort educating the public about their business. Such as the 'Dakakker' in Rotterdam, which educates local schools about the growing of food (Bauman, 2016).

What crops to grow:
Conventional agriculture is very specialized, growing one crop in huge quantity. Urban agriculture is generally more diversified, growing a variety of crops. Urban farmers want to be able to select their crops depending on what is in demand and for what crops they can get a premium (Schans, van der, 2016). For example: edible flowers or uncommon vegetables. Besides of that, the limited population size of people served by the greenhouse, means that it is hard to sell a large quantity of one crop.

Therefore, also in this project, flexibility in crop selection should be built in. However, every plant has its own requirements and different optimum growing conditions. This means that the grower has to be able to tweak the conditions in the greenhouse. In temperature, light and fertilizer. This will mean that a minor part of nutrients will still have to be added from external sources. This required addition will differ from crop to crop.

This needed adaptability of the crop selection does not present a clear choice for a crop to focus on, but focussing on all crops at once makes it hard to narrow the reserach down. That is why this research was adapted to the majority of scientific literature on the growing of crops, which, for reasons unknown, focus on tomato growing.

However, whilst taking design decisions, the possibility of control over the growing conditions, always was a major consideration and the end result is a greenhouse where the growers have the freedom to grow what they wish.

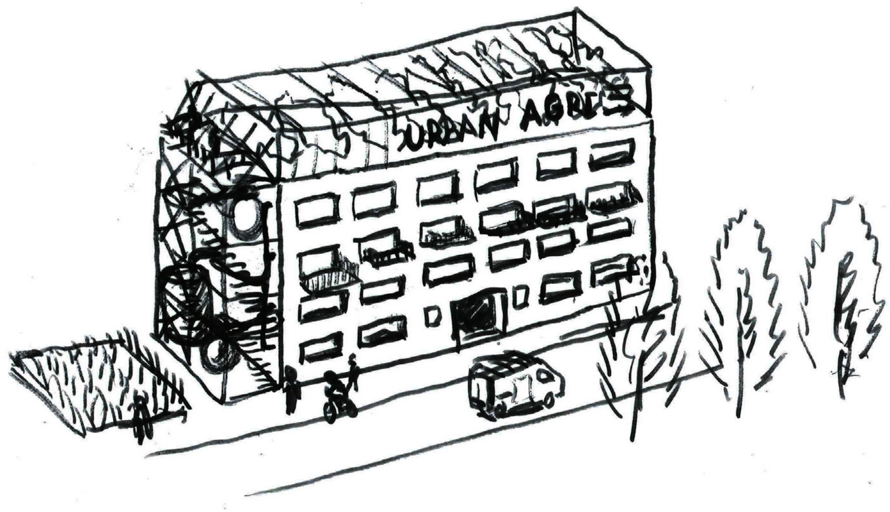
ill. 1.3: Microgreens are a popular crop in urban agriculture, as it grows extremely quick and sells for a nice margin. The variety of crops grown here is typical for urban agriculture. source: New York Times

Selected program

Based on the waste flows and needs derived from the analysis of the urban environment and greenhouses, a program has been selected. This program encompasses:

- 40 apartments
- 3600 m^2 of office space
- 1000m^2 of greenhouse

In this program, on average, 100 people will be present on any moment.



ill. 2.1: Sketch of what the building could look like.

In the following pages, each aspect of the program will be explored and decisions will be made for optimal functioning of such a closely integrated flow within one building.

Nutrients: what are they and how do you acquire them?
Nutrients are just as crucial to plant growth as CO_2 and improper supplementation of nutrients can lead to slow plant growth, bad flavour, misshapen crops and even plant starvation.

Nutrients for plants can be divided into two major categories: macro nutrients: nutrients which have to be supplied in sizable amounts and micro nutrients: nutrients which are required, but only in very small quantities. Macro nutrients are, for example, nitrate and phosphate, while micro nutrients consist of heavy metals and other minerals.

Human refuse is extraordinarily rich in plant nutrients, and treated as well as untreated it has been proven to be a substitute for commercial fertilizer as a nutrient source for plants (Pradhan, Holopainen & al, 2009). However, several factors inhibit direct application of human refuse as a biofertilizer:

- Pathogens: excreta are rich in pathogens and when applied without adequate measures, can prove a danger food safety.
- Ammonia: Nitrogen in human refuse is mainly in the form of ammonia, which is toxic to plants in high concentrations (Neal & Wilkie, 2014). Only after nitrification (the conversion of ammonia to nitrate by micro organisms) plants can absorb the nitrogen. This conversion can happen naturally in soil, or by aeration of ammonia rich fluids (Shonhara, Aoyama & al, 2011).

However, by proper treatment of human refuse, these difficulties can be overcome.

Besides of human refuse, organic waste is present in this project in a few major forms: food waste of apartments and hospitality services, plant waste of the greenhouse and clippings of public and private greenery.

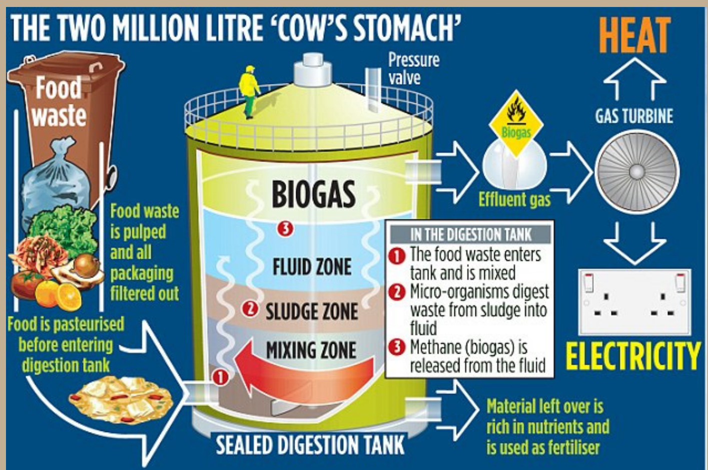
Methods for reuse of nutrients
A large part of waste nutrients in urban systems are disposed of via the water treatment system. Another part is disposed of via organic waste.

Only anaerobic digestion can handle these two flows properly and in the same time converts it into biogas, nutrient rich effluent and a small amount of solid sludge.

ill 2.2: The black tank is an anaerobic digester which digests the black water and kitchen organic waste from 300 households in Sneek, The Netherlands.

On Anaerobic Digestion
Anaerobic digesting works by feeding organic matter, dissolved in fluid, into a sealed tank, in which micro organisms digest the matter anaerobically and has been widely used in agriculture for decades as a way to produce energy from waste.

Via several intermediate steps by a wide variety of micro organisms, the organic carbon is finally converted into biogas (65% CH_4, 35% CO_2). Suspended solids settle at the bottom, forming a sludge, and other products are removed via the removal of effluent. Anaerobic digesting can work at several temperature ranges: The two main ones are thermophilic (65 °C) which has a short retention time (around a week) and mesophilic (20-30 °C) with retention times of 15 to 20 days. Thermophilic digesting is known for its high biogas yield, compactness due to short retention times and its total pathogen reduction (Burh, H. & Andrews, J., 1976)(Gray. D. & Hake, J., 2004). However, thermophilic digesting is much less stable than mesophilic digestion and needs to be more carefully managed.



ill. 2.3: a simple explanation of AD. source: dailymail

Pathogen reduction in anaerobic digestion
It is crucial that the fertilizer is thoroughly sanitized before it is applied for the growing of food. Anaerobic digestion is an adequate way to do so when properly implemented.

As the waste water is retained at high temperature, pathogens are being reduced. Thermophilic digestion is known to reduce the pathogen number to undetectable levels (Buhr & Andrews, 1976).

Normal digesters are designed in such a way that pathogens can bypass the retention and infect the effluent. By using a plug-flow type reactor, which is designed so that an equal retention time is guaranteed for all of its content, this threat is eliminated.

And even when pathogens manage to get through the reactor extra safety mechanisms help to keep the food safe. As food gets infected by direct contact with pathogens (plants do not absorb pathogens, but an insect could transfer it to the fruit by subsequently landing on a pathogen rich spot and a fruit). By injecting fertilizer under the surface, pathogens are kept out of indirect contact with the fruits (Rahube, Marti & al, 2014).

Together, these measures are adequate to prevent infection of the fruits, but European Law mandates that a 10 month minimum period lays between use of (ground injected) sewage sludge and harvest (European Commision, 2016).

Hopefully, after proving that the system effecitvely and constantly removes pathogens, implementation can be made legal.

ill 2.4: the result of supplying to much K^+ to tomatoes, which results in weak cel membranes

(mg/L)	modified digester effluent*	fertilizer aim	legal limits
NH_4^+	2.8	<9.0	-
K^+	528	254	-
Na^+	118	325	-
Mg^{2+}	118	87	-
NO_3^-	1008	1153	-
SO_4^{2-}	-	309	-
PO_4^{3-}	66	76	
Fe^{2+}	11	1.1	5.0
Mn^{2+}	2.8	0.3	0.2
Zn^{2+}	3.8	0.37	2.0
Cu^{2+}	5	0.038	0.2

Macro and micro nutrients in digester effluent, fertilizer and legal limits. source: Liedl, Bombardiere & al, 2006
Feigin, Ravina & al, 2012

** Modified digester effluent = digester effluent which has been diluted with a factor 5 and thorougly nitrified. This modifies toxic ammonia to beneficial nitrate and brings concentrations down to proper levels.*

Fertilizing potential of anaerobic digestion effluent (ADE)
Research has shown great potential for fertilization with ADE after nitrification of the ADE, with research showing superior yields compared to commercial fertilizer over a six year period (Liedl, Bombardiere & al, 2006). However, heavy metal levels are significantly higher than fertilizer used by tomato growers and many times higher than legal norms allow (Feigin, Ravina e.a. 1991). It is unclear where these heavy metals come from, as the ADE is directly sourced from humans, which should be fed with norm compliant food.

As can be seen, the macro nutrients (NO_3 and PO_4) are OK. Other nutrients, such as the exces K, can inhibit absorption of other, more crucial, elements, resulting in suboptimal plant growth.

Mainly the copper concentratoins are far beyond legal limits. Even though concentrations this high are considered acceptable by some, or even beneficial, as copper deficiency is common in European soil (European Copper Institute, n.d.), use of ADE for the commercial growing of food is prohibited. It has been proven possible to remove this copper effectively and selectively from waste water in industrial applications, even though this process is not yet being applied in practice (Illhan, Nourbakhsh & al, 2004). It should be noted that heavy metal concentrations are significantly higher in industrial waste water and these results are therefore not automatically applicable to black water.

So even though the fertilizing potential of ADE is known and well researched, heavy metal contents prove problematic to the application of sewage sludge for agricultural uses (Chu & Wong, 1987). After removal of phosphate and nitrogen, the effluent will, however, be compliant with treated wastewater limits and cna be dumped on surface water(Chipasa, 2003).

As direct application of ADE for the growing of food crops is ill advised, non-food crops might be an alternative which still will be able to produce useful products out of the waste nutrients.

Final System:
The finally selected system for the recovery of nutrients has at its heart an anaerobic digester which digests black water and organic waste.

By making sure that the digester is from the plug-flow type and operates at thermophilic temperature, complete annihilation of pathogens can be achieved.

However, heavy metal contents are very high and well beyond legal limits. Although this does not seem to impede plant growth, it does exceed legal limits. As such, a work around must be found. This could be done by choosing not to grow food.

Waste to resource: water
Water is just as crucial to plant growth as nutrients or carbon dioxide. Also, it is used by almost all buildings for several functions, from flushing toilets to running washing machines.

Water usage in housing/offices
Water usage in a Dutch person is 120 L a day (Vitens, n.d.), a major part of this water is used for things like showering, washing machines etc. Only a tiny fraction is used for drinking, therefore, for the majority of uses, the water is unnecessarily clean. However, houses which separately provide grey water and clean water are rare, as the extra difficulties in use and installation are cumbersome and social acceptance is not self-evident.

After usage, the majority of water has only been polluted lightly. This grey water is in conventional sanitation systems mixed with the heavily polluted black water (from toilet use) and rain water. This results in a water flow which is too polluted to be treated lightly, but too diluted to be treated effectively (Flameling, Evenblauw & al, 2010).

By separating black and grey water at the source and treating them separately, energy and cost reductions can be achieved. This can be done with the use of an anaerobic digester for black water, which recovers nutrients and biogas from the wastewater. System as these are already developed, in use and have been proven technically and financially (Desah, n.d.). As such, they already make a lot of sense. However, such systems will be double as useful as it could provide fertilizer for the farm.

As water is purified on site, options for reuse also open up, enabling sizable water savings though problems with social acceptance might show up. As the use of these systems requires very concentrated black water, vacuum toilets are used instead of regular toilets. This cuts the water use of flushing with 80% to 1 liter per toilet visit, so a limited water savings will already be made no matter what with the implementation of such a system.

ill. 2.5: left: black water, right: grey water
source: ecofyt.nl

Water usage of greenhouses
Water savings are often heralded as a major environmental benefit of high tech urban farming (weburbanist.com, 2015). However, a proper managed greenhouse can get all of its needed water already from precipitation (Redstar, 2016). Therefore it is very hard to improve upon this matter.

But these systems use large rain water buffers to be able to supply a reliable flow of rain water. In my system, this buffer would be 260m^3. This is very large in a place where space is precious. Therefore, it would make more sense to use locally treated clean water to water the plants, as the grey water treatment produces a very reliable source of abundant clean water.

How to treat grye water and the effluent:
Even though anaerobic digestion can recover a majority of pollutants in water, its effluent still has to be treated in order to be considered clean enough to be dumped on surface water. The same goes for grey water. Therefore the ADE and grey water are combined in a treatment node which will further remove pollutants.

Desah does this using an aerobic digester, which is a relatively compact tank in which air is mixed through the water, after which micro-organisms aerobically digest the pollutants and accumulate as sludge on the bottom of the aerobic digester. This process is compact but energy intensive and yields sludge, which is mixed in the anaerobic digester. After treatment, the effluent can be dumped on surface waters.

Another common way is the use of constructed wetlands, in which plants and their soil fauna absorb the pollutants. This method does need a lot of space, making it a very visible component and saves considerable on necessary energy as the amount of necessary pumps and air blowers is minimal compared to aerobic digestion. As a last virtue, constructed wetlands do accumulate heavy metals effectively (especially Cu and Zn, which are the biggest pollutants in the ADE) in the sediment (Gill, Ring et al, 2013). The vegetation itself remains relatively free of heavy metals and can be used as a substrate after it is harvested yearly.

Final system:
The final selected system will have at its heart have an anaerobic digester which removes carbon from the waste water. The effluent will be nitrified and diluted with clean water. Now it can be fed to the crops, after which it will flow into a constructed wetland, where grey water is added. Here, final treatment is given, after which the water can be reused by bringing it back into the greenhouse, bringing it back into the homes for non-potable reuse or the excess will be dumped onto surface water.

ill. 2.6: a constructed wetland
source: limnos

Carbon assimilation by plants

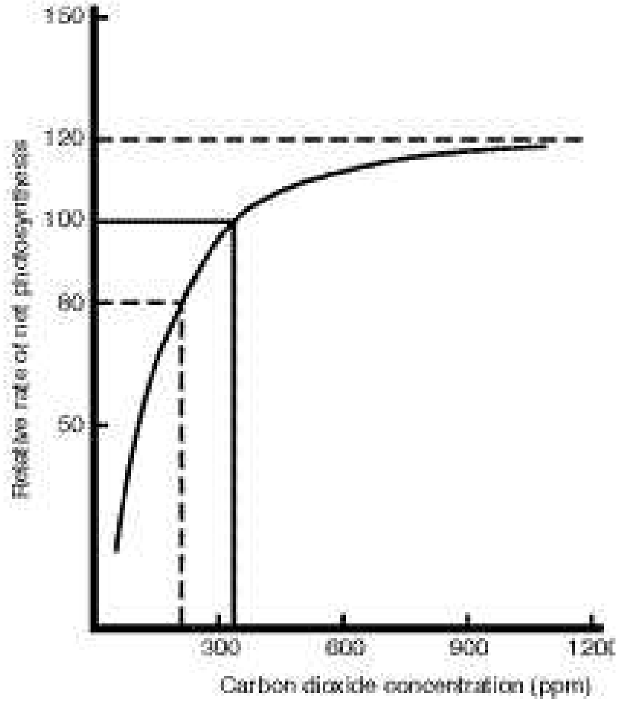
It is no secret that plants fare well with high CO_2 concentrations. The gas is a requirement for all plants on earth to grow and is omnipresent. The beneficial effect of high CO_2 concentrations on plant growth makes greenhouse growers around the globe supplement their greenhouses with added CO_2, often obtained by burning natural gas. A doubling of carbon dioxide from the atmospheric 400 ppm to 800 ppm comes with a 20% increase of photosynthesis, resulting in a bigger harvest (Blom, Straver & al, 2002). This is a great method for increasing yields, but sadly is little sustainable. However, in this project, a 100% sustainable source is present.

Breathing people make the CO_2 concentrations rise indoor, CO_2 concentrations are therefore commonly used as an indicator for indoor air quality. Usually, designers try to keep indoor concentrations below 1000 ppm (EPA 1991), but often lower concentrations are taken as a target.

By venting this building ventilation air into the greenhouse, this CO_2 can be used to aid plant growth.

Ideally, CO_2 has to be supplied by the building occupants 24/7 at high concentrations (800 ppm or higher). As almost all functions do not have constant occupancy, this has led to the choice for a combination of functions which complement each other in usage patterns: office and residences. Together, these allow for constant occupation of people.

One persons exhales around 1 kg of CO_2 per day (EPA, 2011). In interviews, growers stated that they had to add around 70 kg of CO_2 per year per m^2 in a closed greenhouse to sustain plant growth. By doing some simple math, this means that 191 people will provide sufficient CO_2 for the 1000 m^2 greenhouse to get a continuous flow of fertile air. CO_2 is a relatively simple resource to harvest, as most buildings already choose for a central air exhaust due to the perks of energy recovery, a simple pipe running from building exhaust to

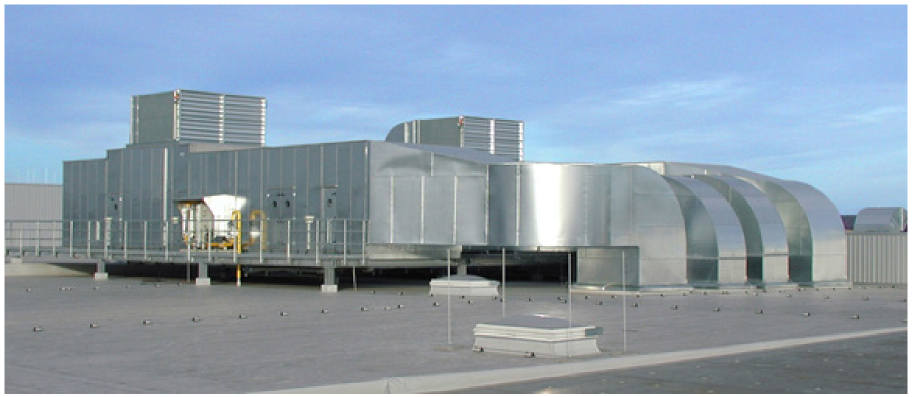


ill 2.7 plant growth at different CO_2 concentrations
source: ontario ministry of agriculture, food and rural agriculture.

greenhouse intake will suffice, making the whole system relatively easy and affordable to build. It will be beneficial however to move the heat recovery to a position after the greenhouse.

If supply fails, plant growth will be slowed, but not harmed if measures to supply CO_2 in another way are timely undertaken, such as opening the windows to provide ambient CO_2 to fill the greenhouse.

ill 2.8: Gas fired CO_2 generator which can even be used in summer. source: shandong jienuo



ill. 2.9: a continuous flow of fertile air
source: AL-KO NL

Carbon release:
Once the plants have assimilated the carbon, it has become a plant.

The carbon assimilated as fruit, will be sold to people, after which the carbon enters the cycle again as CO_2 or it is defeceated, which makes it go into the anaerobic digester, together with non edible parts of the plants, such as roots, sterns and leaves.

In the anaerobic digester, the carbon is converted into biogas, which will be burned for heat and power. After combustion the carbon will again, as CO_2 enter the cycle.

As such, the carbon cycle is a closed loop on paper. In practice it will be a very open system though, but that makes little difference.

CO_2 from combined heat/power
Besides of the CO_2 from occupants, also the use of biogas, produced by the anaerobic digester, produces biogas, which is fed into a combined heat/power unit. These exhaust gasses can be added to the greenhouse.

Final System
In the final system, a central ventilation system sucks of used indoor air and feeds this through the greenhouse. The same is done with the exhaust from the combined heat/power unit, which produces heat and power out of biogas. This free CO_2 aids plant growth for free with ~20%. The quantity of CO_2 provided is synchronized with the CO_2 demand of the greenhouse, by choosing for office as main function (which is occupied during daylight hours). When CO_2 levels drop due to low supply, windows will open to provide ambient CO_2.

Energy management
Energy consumption will be the sum of the consumption of the parts of this project: office, housing and greenhouse. As energy consumption is a major component of CO_2 emissions of most enterprises, special attention should be paid to the minimization of energy consumption.

The Greenhouse
Greenhouses are known for their large energy consumption. This is due to heating, CO_2 fertilization and additional lighting, which are all energy intensive processes. On the other side, greenhouse yields are unequalled by the much less energy intensive open air growing of crops and pesti-, herbi- and fungicides are largely unnecessary to the possibility of creating a pest free environment in greenhouses.

Conventional greenhouses use around ~60 m^3 of gas a year. This can be reduced drastically (see right).

By the implementation of a similar system. The greenhouse can supply itself and underlaying buildings with heat, cutting back on energy consumption.

ill. 2.10: how not to grow food sustainably.
source: Roel Dijkstra

Energy Efficient Greenhouses
Greenhouses are structures which both harvest a lot of solar energy during the summer, and need an huge amount of heating during the winter. As they are such large consumers of energy, considerable research has been done in the field of energy efficient greenhouses. Tremendous gains (energy savings of ~80%) have been realized in pilot projects, but as of now, no economically competitive design has been found, especially since energy prices have plummeted, preventing widespread implementation.

This research is, however, about circularity and reuse and is not focussed on acquiring the biggest return on investment. As such, it is certainly worth the effort to consider how a greenhouse's summer solar gains can be reused in winter for space heating.

This concept has already been realized by the Wageningen University in Bergerden, The Netherlands. By extracting heat using heat exchangers in summer, they could harvest 450 MJ/m^2 a year of low temperature heat. As an extra, this resulted in a greenhouse which could be cooled actively, resulting in a yield gain of €2-3,-/m^2 a year (Zwart, de, Hemming & al, 2011). This heat was stored in underground aquifers and used for the heating of nearby spaces in winter. However, the heat exchangers used considerable amounts of energy (80 kWh/m^2) to store the energy. Still this means a 70% decrease in fuel usage, while ignoring the excess heat harvested which could lower the energy bill of nearby buildings.

Zero energy housing

Nowadays it is very well known how to make dwellings zero-energy (which implies that on a year to year basis, the same amount of energy is produced as is consumed). This is done by minimizying energy use by:

- Very good insulation
- recovering heat from ventilation air
- using heat/cold storage to provide left over heat demand
- using PV-panels to offset left over energy consumption.

ill. 2.11: a renovated zero energy dwelling among its old fashioned neigbours. Note the solar panels on the roof
source: bouwend nederland

Office/Housing

A newly constructed apartment uses about 500 m^3 of natural gas per year (milieucentraal.nl, n.d.). However, by paying good attention to energy effiency and by the addition of PV-systems, it is possible to realize zero-energy dwellings, in which no energy is consumed on a year-to-year basis. Typically, around 3500 KWh of locally produced energy is needed to offset the leftover energy consumption. Usually this is done with ~25 m^2 of PV panels, but this is impossible when the roof is occupied by a rooftop farm. As the rooftop farm adds extra energy consumption, there is no way to make this complex energy neutral.

This does not mean that this complex will be less sustainable than a zero-energy complex, as a building consumes more then just energy and this building saves mostly on all but energy (including space in rural areas, which could be utilized to lay down a solar farm).

Zero energy dwellings get their heat by storing excess heat from the summer. Not all heat can be supplied this way though, and usually an extra heat pump is build in for extra heat in the coldest of days.

By adding a greenhouse to the system, a lot of extra heat is harvested. This can replace the extra heat pump and save further on energy.

Biogas

As the anaerobic digester will provide a steady production of biogas, this gas can be used on site to generate energy. The most direct use of this gas would be to use it as cooking gas. As this use is very direct, it suggests that it is also the most effective use. But as cooking on gas yields a thermal efficiency of just 40%, while cooking using electric induction can hit a thermal efficiency up to 84%. So when the electricity for this cooking is produced using a combined heat power unit (electric efficiency of 45%) this means that you get almost the same efficiency using CHP and combustion when directly using gas.

As an extra, you also yield 45% thermal efficiency, as waste heat is harvested by CHP-units, meaning that a sizable amount of hot tap water can be produced as well by the biogas. CHP's are therefore the way to go.

Biogas is a renewable energy source but has one unique advantage over other renewable energy sources: you can burn it whenever you like. As such, it is possible to not produce electricity when there is an excess of energy (due to sunny or windy weather) and help out during shortages. However, it should be noted that the impact of this project will be small, even on a local scale.

Carbon:Nitrogen Ratio in Anaerobic Digestion

The C:N ratio is very important in the field of anaerobic digestion and composting. It is a number based on the ratio of carbon to nitrogen atoms in the digester feed. The optimal ratio is 25-30 (Hills, 1979). When using this ratio, biogas production is quickest and most efficient.

This ratio can be obtained by mixing different ingredients into the feed. As feces and especially urine have a very low C:N ratio (<10), and woody materials have a high ratio, these are usually mixed in a process called 'co-digesting' (homecompostingmadeeasy, 2008)

As common commercial anaerobic digesters have energy production as their main goal, a big effort is put into obtaining a right mixture. When digestion is used for waste water treatment, however, the main goal is water treatment, and a lower biogas yield and suboptimal retention time are accepted.

In this project it would be unobtainable to get a right C:N ratio. As the human waste is very nitrogen rich, 400 kg of shredded paper, or 1200 kg of woody plant trimmings would have to be added daily. As such, an suboptimal C:N ratio has to be accepted.

How To Run a Greenhouse Sustainably

As stated previously, greenhouses can use enormous amounts of energy due to heating, CO_2 supplementation and added lighting, which all increase yield.

- Heating: in a greenhouse, it is hard to get around heating, as during nights and colder months heating is necessary to prevent the crops from being damaged. The majority of this heating is necessary during the coldest months (December to February). These months are the least productive of all (low light levels). By stopping the growing of crops during these months, only a 10% loss in yield is experienced, while heating costs drop with 40%.

- Lighting: lighting uses considerable amounts of energy (80 W/m^2, even when using LEDs) and even though it improves yield, it is by far not worth it from an energetic point of view. Growers have reported that lighted greenhouses provide 20% more yield than unlighted greenhouses in similar conditions.

- CO_2 supplementation: CO_2 supplementation is a logical thing to do when CO_2 is freely available at the location, such as when the gas heater is on. But in greenhouses, also in summer, gas is being burned. Not for heat, but for the CO_2 it provides. As CO_2 can be provided with used ventilation air, this supplementation can be done continiously, improving energy use and yield.

So by choosing for a suboptimal yield (do not grow during the midst of winter and do not use lighting) a significant savings in energy of up to 30% on heating per kg of produce and 100% on lighting can be aquired!

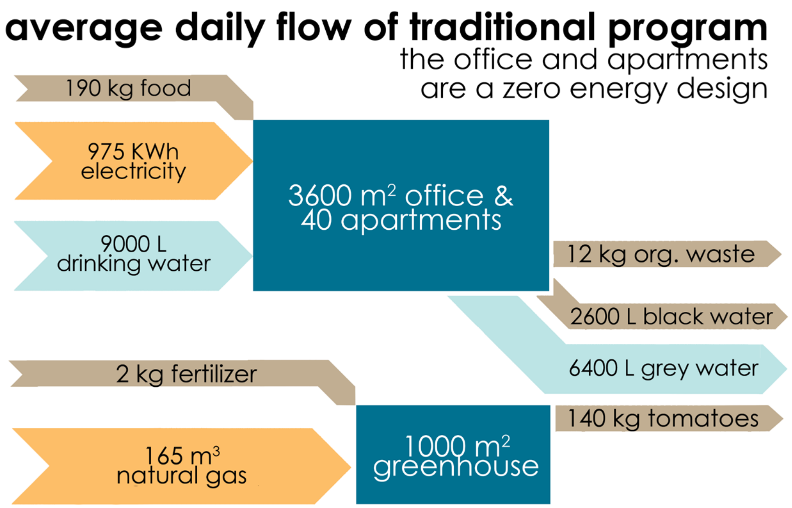
Final System

The final system is based on two proved concepts: zero energy dwellings and the ZoWaKas from the Wageningen University. The greenhouse and dwellings/office share a heat/cold storage, which stores summer heat for use in winter. This way, both the greenhouse as the dwellings/office are heated with the minimum expenditure of energy.

Biogas is produced in the anaerobic digester, this biogas is fed into a combined heat power unit, which provides electricity (only about 5% of total electricity need) and heat for hot tap water.

Sadly, the system will still need a lot of energy from external sources. However, energy savings down the line, by not needing centralized water treatment are not taken into account. In total, this project still provides a considerable savings above the modern status quo.

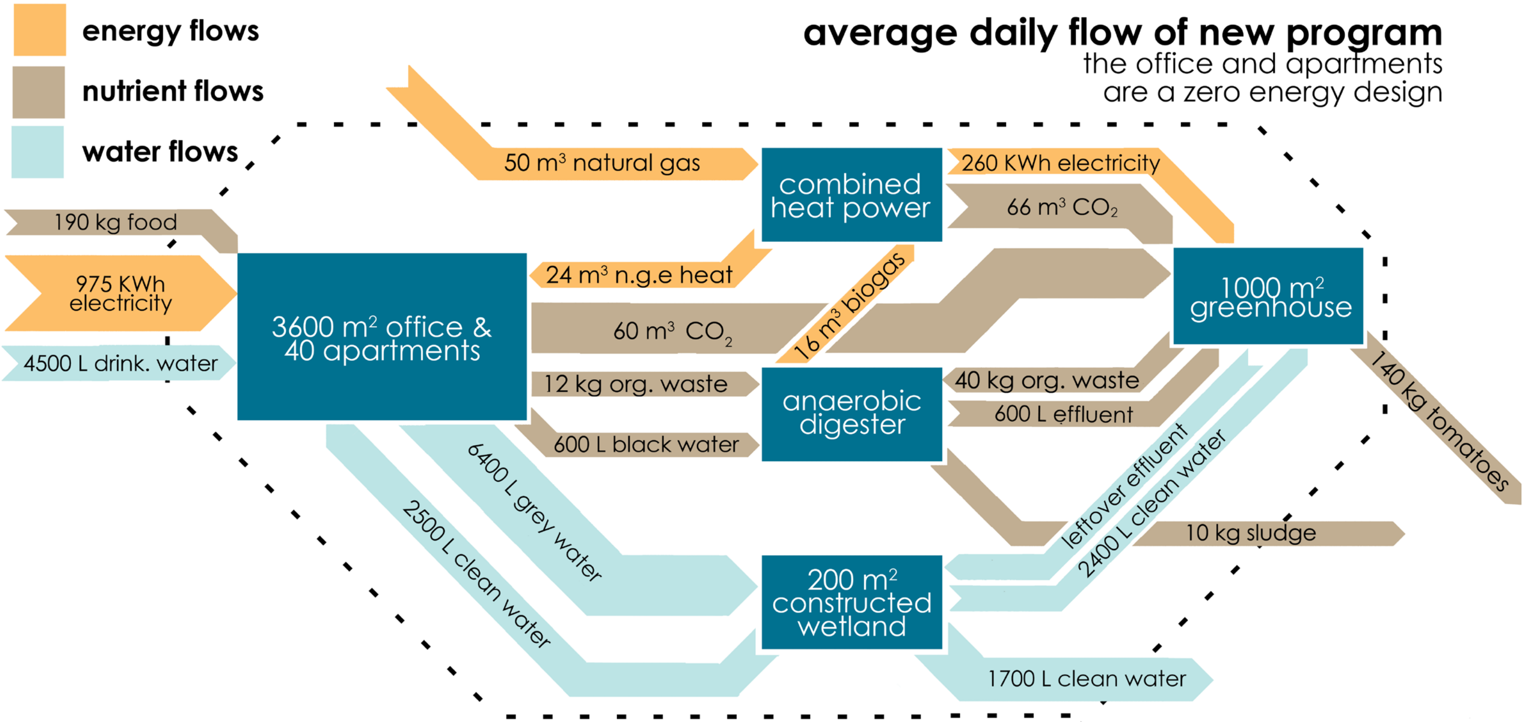
Overview of new v old material flows



As can be seen in these material flow analyses, the new situation would eliminate both inputs as outputs of the traditional system. Energy and water input will stay necessary, but organic waste is almost entirely eliminated within the system boundary (building scale).

One might notice that the amount of water going into the system differs from the amount of water exiting the system. Largely, this is because of evaporation within the greenhouse.

The sludge will be removed once a year. This has to be incinerated.



Program of requirements for new system

To combine the growing of crops in a greenhouse with a building which supples this greenhouse with its organic waste you need the following:

10 m² of greenhouse per person in the average occupation
2 m² of constructed wetland " "
0.25 m³ of biogas buffer " "
0.25 m³ of anaerobic digester " "
0.10 m³ of grey water buffer " "
0.01 m³ of fertilizer buffer " "
heat cold storage in an aquifer
well insulated greenhouse
well insulated apartments and/or office
nitrifier
heat recapturing device for air exiting the greenhouse

These all should be connected to each other in such a way that the amount of pumping and transport is minimal, when possible, gravity should be the driving force for water flows.

Proper sun exposure for the greenhouse is paramount. Therefore, an elevated postition, like on the roof, is perfect. The larger the scale the more efficient the system will become, as boundary losses will become smaller.

The case for this building had an average occupation of one hundred persons. This implies the following:

1000 m² of greenhouse per person in the average occupation
200 m² of constructed wetland " "
25 m³ of biogas buffer " "
25 m³ of anaerobic digester " "
10 m³ of grey water buffer " "
1 m³ of fertilizer buffer " "

Conclusion: do not try this at home

This research has explored the possibilities of eliminating organic waste in urban areas and reusing it for food production by constructing an urban rooftop farm and an anaerobic digester. In conclusion it must be stated that such an endeavor is not as simple as the first indicators suggested.

Nutrients:

Nutrients in urban waste are mainly present in black water, which is currently treated in large waste water treatments. Anaerobic digestion has been proved as a viable way to break down and sterilize organic waste in black water into a nutrient rich effluent on which plants can grow successfully. As an extra upside, it produces energy, instead of consuming energy like regular wastewater treatment.

However, due to high heavy metal contents in the effluent, this water is not suited for the irrigation of crops. The water is clean enough to be dumped on surface water, but food irrigation laws are more stringent. There have not been found proven technologies for selectively removing heavy metals in such low concentrations nor have there been found crops that do not absorb these heavy metals in considerable amounts. Therefore, effluent from black water digesting is not suited for the irrigation of food crops.

Carbon and Energy:

Carbondioxide in the urban environment is produced during combustion processes and by peoples metabolism. By the building of a rooftop greenhouse, CO_2 from ventilation air can be reused as fertilizer for plants. Resulting in a 20% yield increase compared to the growing of crops without CO_2 supplementation. Parallel to that, heat cold storage would allow for considerable energy savings by using the greenhouse as a large solar collector in summer and storing the excess heat to warm the greenhouse and building in winter.

Biogas produced by the digestion process will be used in a combined heat power unit, which produces electricity by combusting the biogas and uses the waste heat to heat water, providing electricity and warm water to the building.

Water:

Anaerobic digestion is already a financially feasible method of treating urban wastewater on site. By secondary treatment this water can be cleaned further until it is clean enough to be dumped on surface water or reused locally. For example for the washing of hands, the flushing of toilets, laundry or other non-potable uses.

Together, these measures would create a very closely integrated system of both greenhouse and building which do effectively support each other. Already, each of the parts are cost effective on their own (rooftop greenhouses are being build as a business model, small scale anaerobic digestion has been proved to be a more economic way of treating wastewater and centralized ventilation and heat cold storage have proven their worth long ago in architecture.) Close integration would only have further expanded on their profitability and effectiveness.

The result would have been an urban farm/building which is improved. It would have been more environmentally friendly and more productive than comparable projects which are realized now.

But as direct food production from waste water is not viable as of now and the reuse of urine only reuses a small portion of the waste nutrients other ways of reusing the nutrient rich effluent should be sought. For example: the growing of non-food crops. Future research could search for less direct ways of providing food production, in which intermediary steps add extra value to the chain and provide the much needed extra food security.

Reflection:
When I started this research in February, I genuinely believed that it was possible to think of a viable system in which urban waste nutrients are reused completely, and that by widespread implementation of such a system, cities could be fed, eliminating a large part of the need for rural agriculture.

Quickly I learned that this was a pipe dream. Urban farms are, even after widespread implementation, not a method to feed urbanites sustainably, as it produces very little crops or at very high energy needs, and I discovered that the added value of urban farms is in the experience, not the actual food.

Many issues arised whilst I attempted to produce fertilizer from anaerobic digester effluent and many were resolved after research, apart from the heavy metal concentrations. This taught me finally that growing food on feces on site is an unviable endeavor.

Discussion: the Overlooking of Urine
In hindsight, I unintentionally overlooked the possibility of only using urine for crop fertilization. In urine, heavy metal concentrations are nil, while phosphate andfvmicro nutrients would be added manually.

This would, however, still discard a major part of plant nutrients, as urine is just a fraction of available nutrients. As such the conclusion that the growing of non-food crops is the best way to reuse urban waste nutrients is correct.

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