Zurich University
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Life Sciences and
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Institute of
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Biochar-Based Life Support Loop (SpaceLooP)

An innovative concept for a lunar base, based on ecological engineering

PROJECT REPORT

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ABSTRACT

In the present study a new concept for ecological life-support systems based on complete oxygen, water and food recycling for a future moon base was developed. Starting from the hypothesis that the pyrolysis of human feces to biochar would be a suitable waste treatment measure, a conceptual design for a life-support-system including hydroponic food production and O_2-generation, water recycling and CO_2-balancing with biochar incineration was proposed. In the system, the biochar can be used as plant substrate or fertilizer in the hydroponic, or can be incinerated to provide CO_2 for plant production. Based on literature review and modelling of mass flows in the system, using a mass-balancing approach, several benefits of the inclusion of pyrolysis into a life-support-system were identified. Pyrolysis ensures complete destruction of pathogens, fibers and organic micropollutants contained in feces that could be harmful for hydroponic food production and human health. Pyrolysis further is a treatment process that does not require oxygen (like incineration). The treatment of wastes can therefore be achieved even without consuming the oxygen required by the crew. Moreover, carbon, and nutrients can be stored in a sterile and stable char and reused when there is need. Difficulties in nutrient recycling from biochar and pH balances in the system were identified as threats to the system. Further research needs to confirm the feasibility of fecal biochar as a hydroponic substrate of fertilizer and its impact on pH balances.

CONTENTS

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1 INTRODUCTION

Human life in a permanent moon base as envisioned by ESA (European Space Agency, 2017). It will require a highly sophisticated life-support system. Inhabitants will have to be provided with everything needed for their survival during a significant time span.

On the moon, solar energy will be available, water, oxygen and food however will have to be either carried along, or regenerated. According to Sulzman and Genin (1994)"*a crewmember of typical size requires approximately 5 kg (total) of food, water, and oxygen per day to perform the standard activities on a space mission, and outputs a similar amount in the form of waste solids, waste liquids, and carbon dioxide*". The mass breakdown of these metabolic parameters is as follows: 0.84 kg of oxygen, 0.62 kg of food, and 3.52 kg of water consumed, converted through the body's physiological processes to 0.11 kg of solid wastes, 3.87 kg of liquid wastes, and 1.00 kg of carbon dioxide produced. (Wikipedia 1).

In the past, there have been extensive investigations on "environmental control and life support system (ECLSS)" and how they can best be set up for long space flights, for moon bases or for bases on other planets. Ecosystems found on Earth were used as templates for these attempts. One well-known example for a "natural life support system" was Biosphere-2 (Arizona, USA) (Wikipedia 2). Its main aim was, to explore how ecosystems and their functions, as they are found on the planet Earth, can be rebuilt and assembled to be used in a constructed artificial ecosystem, in order to reach an internal equilibrium that allows a crew to survive in it, ideally for an unlimited time. Biosphere 2 was in use between 1991 and 1995, but "ran into problems including low amounts of food and oxygen, die-offs of many animals and plants included in the experiment" (Wikipedia 2).

One approach for ECLSS is the Micro-Ecological Life Support System Alternative (MELiSSA) of ESA. The concept aims to combine selected microbial compartments and plants to a regenerative life support system. "MELiSSA is a loop of interconnected bioreactors, wherein each step has been inspired by the natural organic waste reconversion cycle taking place in a natural lake ecosystem" (Lasseur et al., 2010).

The MELiSSA loop is an attempt to assemble microbiomes to a cycle that treats human waste and CO_2, and transforms it to food and oxygen. Each step takes over the products of the previous step and transforms them until the crew can reuse the result. However, although the concept resembles an ecological cycle, from an ecological point of view, it neglects a fundamental feature always found in natural ecosystems: Material stocks and buffers.

Material stocks are found throughout nature and they play a crucial role in natural cycles. Limestone for example is nature's main storage for large amounts of carbon that were removed from atmosphere in a geological time scale (Carbon Neutral Commons, undated). Without this large stock, the global C-cycle would be completely different, and the planet Earth would probably still be hostile to life, as we know it. Crude oil, coal or peat are also stocks of carbon that were built up millions of years ago (Carbon Neutral Commons, undated). Looking at lake ecology, and a much shorter time scale, precipitation of carbonates from lake water into sediments is an important factor (Kelts and Hsü, 1978). By continuously taking dead organisms and minerals out of the water and building up sediments, the chemical equilibrium of a lake is stabilized.

The temporary or permanent removal of matter, and the formation (and sometimes dissolution) of stocks buffer the system and help keeping it stable. Reactor based liquid systems with microorganisms as "motors" are, other than lakes, dimensioned for a continuous turnover. They perform best in a rather narrow range of operating conditions and can be quite sensitive to disturbances. This factor is even more relevant in the MELiSSA loop because it relies on "minimal communities"(Hendrickx and Mergeay, 2007). It was quite surprising for us to see that this factor was not included when the MELiSSA loop was formulated, because stability is a major issue in small and isolated ECLSS's.

Furthermore, the contamination of the MELiSSA loop with micropollutants contained in HSW of the astronauts (such as heavy metals, hormones, transformation products of pharmaceutical drugs) may be a challenge to the minimal communities in the reactors. "Insights into the behaviour and effects of these compounds in natural ecosystems and closed loop systems are largely unknown" (Hendrickx et al., 2006) and may potentially lead to instability or even the collapse of the system.

1.2 HYPOTHESIS AND RESEARCH QUESTION

Ecological engineering is a holistic approach to engineering that aims to use concepts derived from nature for system design. It is based on the observation of ecological systems and the deduction of design principles from it. Schoenborn and Junge (in preparation) propose seven principles as a guideline for ecological engineering design on planet Earth:

1. Avoidance instead of treatment
2. 100% renewable energy (for operation)
3. 100% recycling (during operation)
4. Ecological processes and organisms as tool or model for design
5. No externalized environmental costs during the life cycle
6. Design aims for multifunctionality
7. Enhancement of quality of life

The necessity to fulfil criteria 2 and 3 are self-evident for the design of a moon base. We think that criteria 1, 4 and 6 may be helpful to find sustainable solutions geared to long-term operability, and we see criterion 7 as crucial for the well-being of a crew in a moon base. As an example, material stocks are an element found in ecosystems on Earth (e.g., sediments, sediment rocks) that contributes to their buffering capacity and inertia. Multiple functions of processes are another phenomenon (e.g., the carbonate system in lakes that controls the availability of CO_2, the pH and is linked to C-storage). Organisms are drivers of processes in nature (e.g., the photosynthesis of plants that produces O_2). Diversity ensures the resilience and adaptability of ecosystems against rapid change. Finally, avoidance (e.g., of toxic substances) is a way to design materials that need to be introduced into an ECLSS from outside.

The key element of any ECLSS is sanitation. Since humans need to eat, they need to get rid of their bodily wastes (feces, urine). These in turn are the only readily available source of nutrients and one important source of water. Consequently, the design of the sanitation process in an ECLSS is crucial for its operativeness. In this project, we mainly focus on feces.

We hypothesize that source separation of human solid waste (HSW) and its pyrolytic conversion to biochar is a promising approach to achieve stability in an ECLSS. Pyrolysis allows a near 100% recovery of most nutrients from HSW (Bleuler, 2016). It guarantees a complete removal of potential pathogens and undesired contaminants from the HSW (>300℃). The pyrolytic process of HSW has been proven feasible (Gold et al., n.d.) and the resulting biochar is of good quality (Bleuler 2016). The objective of this project is to work out the concept and design of a SpaceLooP: a human solid waste management scheme for an ECLSS using pyrolytic conversion of HSW to biochar as its main building block.

1.3 SCOPE OF THE PROJECT

Given the current research interests of NASA and ESA the most interesting application of a closed life support system like the SpaceLooP system would be either a long term space flight (e.g. mars mission), or a long term planetary base (on Moon or Mars) (Dunbar, 2017; European Space Agency, 2017). The boundary conditions for the design of a SpaceLooP vary for the scenarios “Mars”, “Moon” and “Space-Travel”.

The following differences in boundary conditions were identified.

	Mars	**Moon**	**Space-Travel**
Gravity	Yes (38% of Earth’s gravity)	Yes (16.6% of Earth’s gravity)	No gravity
Available gases from atmosphere	CO_2, some N_2	Almost no atmosphere	No
Duration of natural light/dark cycle	24h	28 days (at equator)	individual
Solar radiation apt for plant growths	Only at some latitudes	Yes at light cycles and at certain latitudes	depends
Soil potentially usable for plant cultivation	Yes (Wamelink et al., 2014)	Yes but difficult (Wamelink et al., 2014)t	No soil
Heat demand	yes	yes	No (e.g. ISS excess heat)
Additional Supply vehicles	Very rare / very costly	Possible / costly	no
Water present	Some water ice	Some water ice	no

The boundary conditions imply the following recycling needs for nutrients, water, oxygen and carbon.

	Mars	**Moon**	**Space-Station**
Nutrient Recycling	yes	yes	yes
Water recycling	Yes to a high extent	Yes to a high extent	Yes completely
oxygen	Yes to a high extent	Yes to a high extent	Yes completely
Carbon recycling	no	yes	yes

Based on the boundary conditions and recycling as well as the probability of a future mission, we conceptualize the SpaceLooP for a future moon base and will no longer consider other scenarios.

2 LITERATURE RESEARCH

In order to conceptualize and design the SpaceLooP the current state of the art knowledge of waste management in space, ecological life support systems, pyrolysis in the space context and further relevant technologies was collected in a literature research.

2.1 CURRENT STATE OF THE ART: HUMAN WASTE MANAGEMENT IN SPACE

Human wastes to be expected on a moon base include vomitus, feces, urine, diarrhea, wipes and sanitary napkins (Fisher et al., 2008).

2.1.1 Requirements to be fulfilled

Four main tasks of waste management are 1) Crew health and safety, 2) Crew quality of life, 3) planetary protection, 4) cost reduction (Fisher et al., 2008). This implies the collection of human waste in a way to minimize the risk of escape of fecal contents and bacteria, the control of odor, volume reduction, water recovery, stabilization of the wastes, safe containment of the wastes apart from crew and planetary surface and resource recovery (e.g. oxygen, nitrogen, foot, activated carbon) (Fisher et al., 2008).

2.1.2 Collection of wastes

On space missions, feces and urine are usually collected separately under continuous air flow. The collection of feces in individual bags and storage in a canister or tank has been shown to be superior to joint collection in terms of crew health (bacterial contamination) and quality of life(odors) (Broyan Jr., 2007; Fisher et al., 2008)*.* The same procedure may be adequate for the gravity conditions on the Moon.

2.1.3 Drying

Some human waste treatment techniques require a drying step before the actual process to allow for a controlled process without any unwanted chemical reactions. Available and technically ready options include heat melt drying, air-drying, microwave drying and freeze drying (Fisher et al., 2008). If pyrolysis or torrefaction are considered as a further treatment step microwave drying can be included in a microwave powered pyrolysis or torrefaction apparatus (Serio et al., 2015, 2002).

2.2 PYROLYSIS OR TORREFACTION OF SPACE MISSION WASTES

Previous studies identified pyrolysis or torrefaction (mild pyrolysis) as viable options for the treatment of human waste in space environments (Brewer et al., 2011; Serio et al., 2014, 2000)

The process known as *pyrolysis a "thermochemical decomposition of biomass into a range of useful products, either in the total absence of oxidizing agents or with a limited supply that does not permit gasification to an appreciable extent. It also forms several initial reaction steps of gasification. During pyrolysis, large complex hydrocarbon molecules of biomass break down into relatively smaller and simpler molecules of gas, liquid, and char."* (Basu, 2013a)

Whereas *"torrefaction or mild pyrolysis "a thermochemical process in an inert or limited oxygen environment where biomass is slowly heated to within a specified temperature range and retained there for a stipulated time such that it results in near complete degradation of its hemicellulose content while maximizing mass and energy yield of solid product. Typical temperature range for this process is between 200°C and 300°C*".(Basu, 2013b).

Torrefaction makes biomass lose its fibrous natures. The low temperatures compared to pyrolysis maximize the solid yield while minimizing gas and liquid yield (Basu, 2013b).

2.2.1 Secondary treatment

Up to date oxidation, pyrolysis/torrefaction or biological treatment of organic space wastes was proposed as secondary treatment options (Fisher et al., 2008; Hendrickx and Mergeay, 2007; Serio et al., 2014, 2000)

Oxidation of space wastes is one desirable option that can produce water, carbon dioxide for plants or other substances (depending of the process) while reducing the amounts of solids and stabilizing the material. Mineral nutrients can potentially be recovered from ash. Available and technically ready oxidation options include incineration and hydrothermal oxidation (Fisher et al., 2008).

Biological treatment of space waste include aerobic, and anaerobic microorganisms, treatmetns with mushrooms and fish (Fisher et al., 2008). Treatment steps with microorganisms can be followed by the treatment with higher plant compartments (Lasseur et al., 2006).

Research on pyrolysis and torrefaction will be summarized more in detail in the following chapter.

2.2.2 Pyrolysis for space missions

Serio et al. (2000, 2001) developed a two stage pyrolysis reactor for primary pyrolysis (600°C) and subsequent cracking of gas and liquid products (1000 – 1100°C) in a secondary pyrolysis step. The reactor was developed with the purpose of pyrolysing space waste. Tests were performed with a reference mix consisting of 10 wt. % polyethylene, 15% urea, 25% cellulose, 25% wheat straw, 10% Gerepon TC-42 (space soap) and 5% methionine, which is regarded as a representative composition of wastes in space travel.

Pyrolysis products (liquid, gas, solid) were analyzed for several pyrolysis temperatures up to 900°C. Main pyrolysis gases were (CH_4, H_2, CO_2, CO, H_2O, NH_3). Liquid tars made up up to 30.2 wt% of the end product, but could be thermally or catalytically cracked into the above mentioned gases under higher temperatures (>700°C) in a post-pyrolysis step treating the not yet condensed gases.

Besides the gas and liquid products, a carbon rich, inert char was the pyrolysis product.

In later experiments the authors included a post oxidation step into a microwave powered pyrolysis unit to transform high amounts of CO into CO_2 (Serio et al., 2010).

In a Japanese life support system trial, human and animal waste were carbonized as a pretreatment for incineration (Tako et al., 2010). Pyrolysis gases were further oxidized to supply CO_2-for plant growth.

2.2.3 Torrefaction for space missions

Serio et al.(2015, 2014) used a fecal simulant according to a recipe by Wignarajah et al.(2006) to test torrefaction for human waste in the space context. They concluded that compared to prior pyrolysis experiments torrefaction could reduce the waste storage volume without significantly increasing the volume of gases that must be immediately used, stored or discarded.

In fact, the formation of heavy oils and tar were not observed in the condenser of the torrefaction reactor at temperatures lower than 300°C. The authors analyzed char gas and liquid composition resulting from torrefaction of fecal simulant.

2.2.4 Powering of pyrolysis / torrefaction in space

Pyrolysis as well as torrefaction can be powered by microwave heating, heating spirals or direct use of solar irradiation (Lédé, 1999; Serio et al., 2015; Zeng et al., 2017). As pyrolysis is an exothermic process for most dry waste material an energy self-sufficient process can be achieved by heating with energy from combusting pyrolysis gases (Marcel Nick, 2015). This is not an option for torrefaction, which is a predominantly endothermic process.

2.3 LIFE SUPPORT SYSTEMS

2.3.1 CELSS (controlled ecological life support systems)

Research on controlled life support systems has been conducted since the 1960's with the aim of enabling long distance space travel or planetary bases. Guo et al. (2017) review the historical and recent development in life support systems. The authors state that first systems focused on the cultivation of microalgae for food production & oxygen generation, later research attempted to integrate higher plants and even animals into the systems.

The major CELSS research projects were:

- Russia BIOS-3 1960-1980]
- USA Biosphere 2 1991-1994
- USA ILSSTF 1997
- Japan CEEF 2000
- China Space Ecosystem 2012
- China Lunar Palace 2014
- ESA: Melissa Loop 1989 - ongoing

Food production in the systems was achieved with hydroponics or in soil media. In most experiments, the systems were able to supply sufficient oxygen but not enough food for the test subjects. In some cases the atmosphere for plant production and for the human living space were kept separated from one another (e.g. USA ILSSTF 1997, Japan CEEF). But generally there was a direct gas exchange between humans (animals) and plants. Urine was partly reused in the mentioned systems while solid waste recycling remained a challenge in most systems.

In the review the authors conclude, that further research is needed amongst others in the fields of waste treatment, namely:

- long-term water cycle and purification management, combined with microbial and physical-chemical technologies
- long-term efficient control of solid waste treatment and the stable recycling of products
- integration technique of solid waste and waste water recycling.

2.3.2 Hydroponic food growth

Growing higher plants in space has several functions contributing to a livable environment for astronauts. They contribute to food production, CO_2 reduction, O_2 production, waste recycling and water management. Furthermore they can have a beneficial effect on psychological health of the crew (Zabel et al., 2016).

Up to date plant growths systems were tested on the Salyut Space Stations (beginning 1971), the Mir (beginning 1991) in Space Shuttle missions (1982 onwards) and on the International space Station (2001 onwards) (Zabel et al., 2016). The systems tested on space missions were all pilot systems with growing areas no larger than 0.17 m^2 (Veggie System on the ISS). Test were performed with cabbage, kale, turnip, radish, wheat, soybean, lettuce, rice, tomato, onion, herbs, carrots and some other crops.

Most of the experiments with the aim of developing life support systems for space missions were, however, conducted on Earth. Kennedy Space Center performed a long series of experiments with hydroponic food production systems destined for space applications (Bucklin et al., 2004; Levine et al., 2008; Li et al., 2000; Rygalov et al., 2010; Wheeler, 2010, 2003, Wheeler et al., 2008, 1998). Amongst other, investigating the effects of light sources and colors, carbon balances, elevated CO_2-concentrations, air circulation and heat exchange under reduced pressures on various crops. Hydroponic production of agronomic species that are not traditionally grown in hydroponics such as wheat, soybeans, rice, potato and peanut were investigated (Wheeler, 2010). This research provided insight on water and nutrient use and the control of pH in the hydroponic systems.

The great success of the large-scale hydroponic food growth under controlled conditions on Earth still needs to be replicated in space, where ecosystems in general and plants in particular can be affected by various external factors such as altered strength of magnetic and electromagnetic fields, cosmic radiation, weightlessness or microgravity. The space environment can potentially disturb the processes of photosynthesis, gas exchange, transport of water and solutes and the stability of the plant genome (Mashinsky and Nechitailo, 1997; Wolff et al., 2014)

2.3.3 Urine in hydroponics

Yang et al.(2015) successfully performed hydroponic experiments with source separated human urine for the production of water spinach. After pre-treatment of urine, namely urea hydrolysis, induced struvite precipitation and ammonia stripping and 1:50 dilution, growth characteristics of plants were comparable with those grown in nutrient solution.

Paradiso et al.(2014) introduced urine without pretreatment into hydroponics experiencing lower soybean production than in the control grown with nutrient solution; this was attributed to NH_4-toxicity and an unsuitable NH_4/NO_3 ratio.

In a Russian life support system (Bios-3) an experiment returning urine to the nutrient solution for wheat growth resulted in rising (but not yet harmful) sodium levels in the nutrient solution and the plants(Salisbury et al., 1997).

2.3.4 Biochar in hydroponics

Biochars have successfully been tested in soilless cultivation of various vegetables. Rice husk biochar in combination with a perlite substrate increased the yield of leafy vegetables by a factor of 2 (Awad et al., 2017).

The use of olive stone biochar as a growing medium in a hydroponic tomato growing system resulted in higher yields than growing media containing perlite and coco peat (Karakaş et al., 2017). Dunlop et al. (2015) tested different growing media containing sawdust, pine and biochar derived from tomato biomass for tomato production. Although the authors stated that, the pH of substrates containing biochar was higher than is advisable for tomato growth, the plant growths was not negatively affected by biochar.

Biochar was evaluated favorably by Barrett et al.(2016) when reviewing environmentally sustainable growing media for soilless plant cultivation systems. The authors stated that biochar has the potential to not only provide nutrients and reduce nutrient leaching from a soilless cultivation system, but also to improve the biological and physical properties of growing media as a whole.

2.4 MAIN RESEARCH GAPS

From the literature review, it becomes obvious that the main current research gaps are:

- Pyrolysis/torrefaction of real feces and other space wastes and the composition of gas, liquid and solid products
- Application of urine and fecal biochar in hydroponic systems
- Nutrient extraction from biochar for hydroponic system
- Plant availability of nutrients from fecal biochar

3 SPACELOOP-MODEL V1

The design of the SpaceLooP is based on the idea of a closed system that recycles every all essential compounds (water, oxygen, food) for supporting human life with a minimal need of external supply and a minimal loss of mass through wastes.

The SpaceLooP- Model is based on the conceptual design in Figure 1.

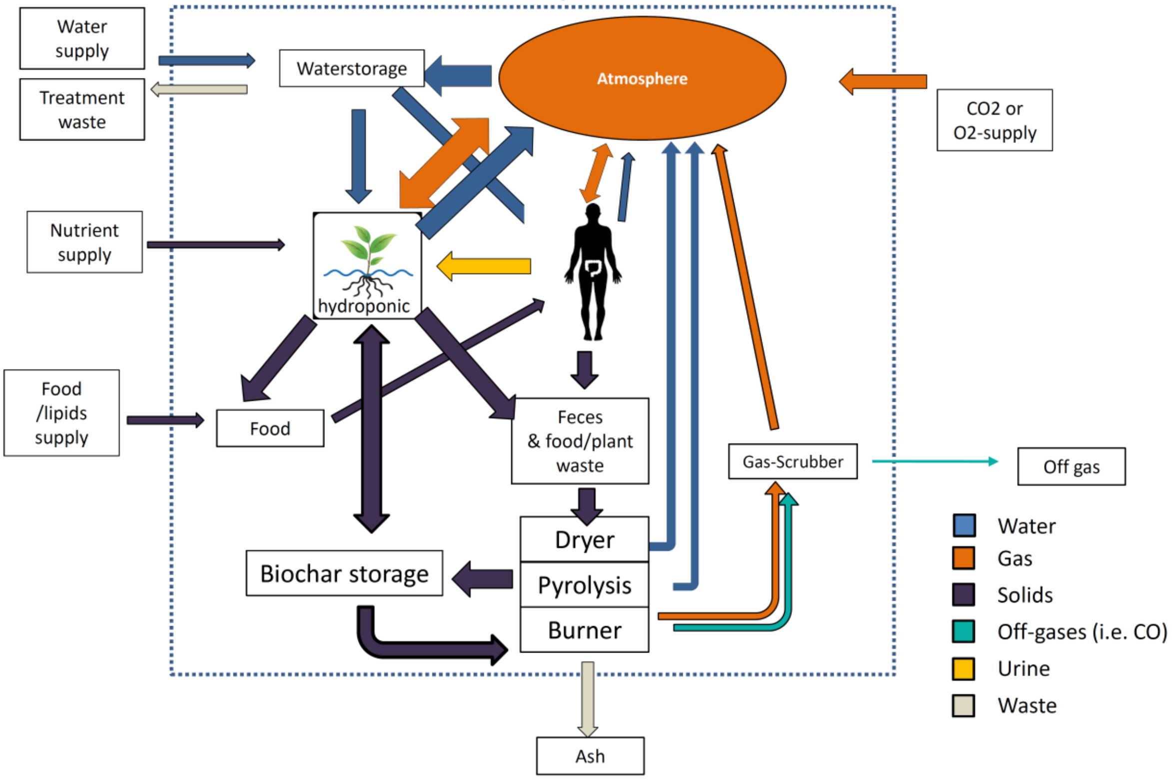


Figure 1 Concept of the SpaceLooP

The model for simulating the behavior of the SpaceLooP is a static, deterministic model based on the principle of mass balancing. Changes over time are simulated by coupling the results of several static model runs.

The Lavoisier principle - matter cannot be created or destroyed - is the basis of the life support system model. In any closed system the total mass of every element (e.g. C, H, N, S, O…) is constant over time (Bérangère and Laurent, 2012).

Chemical reactions are generally written as a single or a system of stoichiometric equations in which elements should be conserved. A given element, such as C, for example, can shift from one compound to another due to chemical reaction, but the total amount of C is conserved.

For each compound, the rate of accumulation of an element is calculated from the rate of input of this element minus the rate of output of this element.

Without external input to the system, the net rate of accumulation and the net rate of production/consumption of all elements is zero in the system. Moreover, for each reaction, the net balance for all elements must also be equal to zero (Bérangère and Laurent, 2012).

3.1 SPACELOOP MODEL V1 SETUP

The model proposed for the SpaceLooP is composed of **storage** and **process** modules (see Figure 2).Outside of the system boundaries there will be external supply modules which can supply food, water, nutrients, O_2 or CO_2 if need be (see Figure 2).

Process modules are always mass-balanced; there is accumulation or depletion of elements in the module. Therefore, for each chemical element the following must be true

$$\mathrm{mass}_{in} = \mathrm{mass}_{out}$$

However, the composition of matter or the molecular form of the atoms in input can be different from output.

Storage modules allow for an accumulation or depletion of matter. The input mass for each element does not have to be equal to the output.

$$\mathrm{mass}_{in} \neq \mathrm{mass}_{out}$$

Accumulation in one storage module implies depletion in another storage module or external input to the system and vice versa.

Supply modules are considered able to provide infinite mass, with the aim being to minimize the need for external supplies to the system. The supply modules are outside of the system boundaries.

Waste modules are considered able to take on an infinite mass. They take up wastes that are non-recyclable and is a mass sink. The input to waste modules should be minimized.

The elements considered in the mass balance were limited to CHNSO and a sum parameter for inorganic compounds (also known as ash). We assume that due to the relatively small amounts of single elements contained in the ash parameter, the external supply of each of the elements as necessary will be more easily achieved and their recycling is less critical.

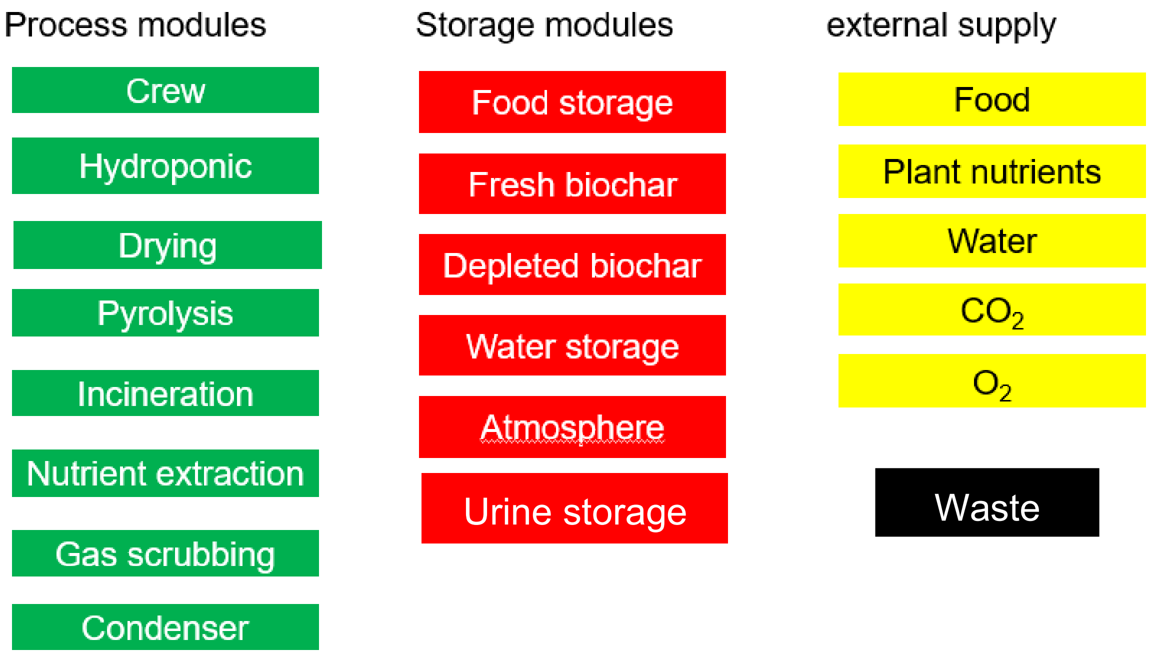


Figure 2 Modules of the artificial ecosystem

We further assume that system is not light or energy limited. Although at the mood equator there is a 14 day/night cycle on the moon, we assume that there is enough energy available on the moon base to provide LED lighting to the plants. Therefore, energy requirements for all processes are not considered in this model.

Greywater produced by body hygiene (washing, taking showers) or possibly by cleaning clothes is neglected in this study.

3.1.1 Module descriptions

In the following, the function of each process and storage module will be briefly described. Only the processes relevant to the mass balance model considered, the technical components associated with each module will be described in chapter 6.

Process modules

Crew module

Astronaut diet (food, water intake) is based on Poughon et. al 1997 (Melissa –Loop Definition).

The diet is based on tomato, rice, lettuce, potato, soybean, spinach, onion and wheat - all grown hydroponically. In the hydroponic production process including all above-mentioned crop species. The percentage of edible biomass is 45% versus 55% inedible plant waste. The edible biomass has a water content of 36% the inedible biomass of 27% (Poughon, 1997). Supplemental fats and salts are assumed to be provided additionally, are not recycled by the system and will eventually end up in the waste.

The composition of *Human fecal matter* (feces and urine) is based on a review by (Rose et al., 2015). Some values were additionally added from (Jönsson et al., 2005; Liu et al., 2014; Ward et al., 2014). The exact composition of all biomasses used in this mass balance is stated in appendix 1.

The mass of the crew's oxygen intake and carbon dioxide output as well as their water intake (through drinks, food) and output (through urine, feces, respiration, transpiration) is based on (Fisher et al., 2008).

Drying module

The drying module will act as a preliminary step for the pyrolysis of fecal matter and plant waste, while at the same time being used to dry hydrated, depleted biochar rests originating from the hydroponic as a pretreatment for incineration. We assume that all input is dried to 100% dryness with all H_2O entering the atmosphere as water vapor.

Pyrolysis module

When converting biomass through pyrolysis, the characteristics and distribution of resulting products (gas, liquid, solid) depend mainly on the pyrolysis temperature (Basu, 2013a; M.Kaltschmitt and H.Hartmann(Hrsg.), 2001). We chose an appropriate pyrolysis temperature according to criteria listed in Table 1.

Table 1 Pyrolysis temperature and its influence on selected parameters considered relevant for SpaceLooP.

Pyrolysis temperature °C	**<300**	**500**	**>1000**
Nutrient availability	high	middle	low
C in char	high	middle	low
Tar-development	low	middle	low (tars are cracked)
pH	9	11	?
Production of gases other than CO_2	low	middle	high
Carbon stability (aromatic structures)	low	middle	high
N-conservation in char	high	middle	low
Heavy metal availability in chars	hjgh	middle	low
Volume reduction	low	middle	high

Sources: (Basu, 2013a; Bleuler, 2016; Lopez-Capelm et al., 2016; M.Kaltschmitt and H.Hartmann(Hrsg.), 2001)

We consider a temperature of about 300°C to be most suitable for the application of pyrolysis in a moon-base. A temperature of 300°C is high enough to ensure a sterile and stable char (Basu, 2013a) while producing fewer tars and complex gases (Serio et al., 2015) during pyrolysis. At the same time the higher availability of nutrients and a higher conservation of nitrogen in the char (Bleuler, 2016) is favorable for its reuse as fertilizer.

We consider a high volume reduction less important in the context of a storage volume because biochar needs to be provided and char can always be incinerated if storage space becomes critical.

The composition of gaseous, liquid and solid products resulting from a low temperature pyrolysis (300°C) are based on experimental data by (Liu et al., 2014; Serio et al., 2015; Ward et al., 2014) who produced char from fecal sludge, fecal simulant and human feces respectively. Detailed information on the resulting char, gas and liquid composition used in the mass balance can be found in appendix 1.

In several pyrolysis studies with feedstocks similar to human feces carbonyl sulfide was the most abundant gas compound containing sulfur. (Ro et al., 2010) found in experiments with the pyrolysis of animal manures that sulfide concentrations were an order of magnitude higher than the rest of S-containing gases. (Serio et al., 2015) observed carbonyl sulfite (COS) being the only detected S-containing gas. We therefore assume COS to be the only S-containing compound in the gas phase. In future tests, the formation of other potentially toxic sulfuric compounds like H2S and SOx need to be regarded in detail.

Incineration module

The processes in the incineration module are based on the stoichiometric reactions for the oxidation of all compounds in the char and in the pyrolysis gases.

Oxygen consumption by the char combustion process was calculated from the oxygen demand for the full oxidation of all C, H and S in the charcoal to CO_2, SO_2 and H_2O minus the oxygen comprised in the char itself.

Is has been reported that in clean combustion over 95% of N is oxidized to NO (Zhou, Haosheng; Jensen, Anker Degn; Glarborg, 2007). To simplify the model we assume that 100% of N is oxidized to NO disregarding further oxidized NO_x compounds.

The oxygen consumption of the pyrolysis gas combustion was calculated considering the full oxidation of the main pyrolysis gases CO, CH_4, CH_2O and COS to CO_2, SO_2 and H_2O.

Since very small amounts of pyrolysis gases other than CO_2 are produced at low temperature pyrolysis, the oxygen demand for gas combustion is very small (<1%). compared to the combustion of char.

The combustion process is an idealized process in the mass balance. In a technical system the full oxidation of all compounds cannot be presumed and closer attention needs to be paid to carbon monoxide, NOx and SOx compounds.

Gas Scrubbing

There are advanced technologies to remove nitrous or sulfurous compounds from off-gases of incineration or pyrolysis (e.g. (Chang et al., 2004). The technology itself will not be discussed in detail here. We assume that all NO and SO_2 can be scrubbed from the combustion gas and will be lost (→ Waste module), while the required scrubbing water can be fully recovered.

Nutrient solution module

The nutrient requirements for the hydroponically grown food vary with variety of plants.

Nutrients in the hydroponic nutrient solution originate from urine (fresh or stored, treated if necessary as proposed by (Yang et al., 2015)), from the nutrients comprised in the fecal biochars and (optionally) from additional nutrient supply.

For the mass balance we assume, that the nutrients comprised in the fecal biochar can be extracted and made plant available. Whether the nutrients are extracted from the chars and the extracts added to the nutrient solution, or the plants are grown directly in a support medium consisting of biochar is left open. The biochar that undergoes an extraction step is assumed to have a water holding capacity of 100wt% a value observed previously for fecal sludge derived biochar (Bleuler, 2016). The water held by the biochar is no longer available for the nutrient solution.

Nutrients from urine in form of urea has been tested for soybean hydroponic cultivation (Roberta Paradiso et al., 2014) with mediocre success, the authors attribute the lower yield of soybean treated with urea (compared to nitrate) to potential ammonium toxicity resulting from NH_4 formed through urea hydrolysis. In the mass balance, we assumed that nitrogen resulting from urea can be assimilated by the hydroponically grown plants. A pretreatment of the urea (Yang et al., 2015) or the addition of NO_3 to achieve a suitable NH_4/NO_3 balance (R. Paradiso et al., 2014) could be an option to achieve the successful utilization of human urine as an N source for hydroponics.

Nutrients required by the hydroponic system are equivalent to the mass of nutrients taken up by the plants. In a real hydroponic system, a surplus of nutrients would have to be provided for efficient plant uptake. This is not considered in the mass balance.

Hydroponic module

Hydroponics for the growths of food in space have been extensively studied before, e.g., by the Nasa Kennedy Research Center and the ESA Melissa foundation (Chybion, 2011; De Micco et al., 2009; Goins et al., 1997; R. Paradiso et al., 2014; Roberta Paradiso et al., 2014; Stutte et al., 2011, 2009; Wheeler et al., 1994; Wignarajah et al., 2001; Wright et al., 1988; Zabel et al., 2016;Graham et al., 2016; Graham and Wheeler, 2015a, 2015b; Jiang et al., 2016; Massa et al., 2016).

Each plant has different requirements. As a mean value, the hydroponic CO_2 uptake was chosen as 100g m-2 day -1 a comparable value was found by (Barta, 2016) in a 65 days hydroponic experiment.

Richards et al.(2004) tested the effect of different CO_2 atmosphere concentrations on the yield of radish, onion and lettuce, with the aim of growing the crops on ISS. The authors state that an elevated CO_2 concentration of 1200 ppm had a significantly positive effect on the yield of all three crops regardless of the light intensity. The target value for CO_2 concentration in our mass balance was therefore set to 1200 ppm with a minimum value of 1000 ppm. If CO_2-concentration drops below the minimum value, additional CO_2 is externally supplied.

Oxygen generation and water consumption by the plants were calculated from the CO_2 uptake and net photosynthesis reaction.

The plant evapotranspiration rate was set to 3’965 g/m2/day as found as a average rate for the growth of soy bean, tomato, lettuce, wheat and potato by (Wheeler et al., 2008).

To maintain model simplicity nitrogen, uptake through symbiosis with nitrogen fixing bacteria from the atmosphere was not included in the mass balance as it depends on many factors like plant variety, plant growth state and bacterial community.

Condenser module

We assume that all water vapor entering the atmosphere is recovered by condensing and enters the liquid state.

Storage modules

Atmosphere

Atmosphere is shared by plants and humans. It is assumed to have a pressure equivalent to Earth atmosphere (about 100 kPa). Initial atmosphere composition is considered to be as on Earth, except with slightly elevated CO_2 levels for optimal plant growth (O_2 21mol%, CO_2 0.12mol%, H_2O 1mol% and N2 78mol%).

According to Malesky, 2017 the minimum O_2-concentration for human respiration should not be lower than 19.5 mol%. If the limit is reached, external oxygen supply is triggered.

The mole fraction of CO_2 on the other hand was set to 0.12 mol% (or 1200 ppm) for optimal plant growth (Richards et al., 2004). This slightly elevated CO_2-concentration promotes plant growth and is not yet harmful to humans (Kane International Limited, 2016).

In the model additional oxygen or carbon dioxide can be provided externally if the levels can not be respected.

Other storage modules

If input > output food, urine, fecal biochar, depleted fecal biochar and plant biochar are considered to be stored in the corresponding modules without any alteration of the stored product. This includes fresh, hydrated food.

If input < output external supplies to the system must be activated.

3.1.2 Module interconnections

The modules described in the previous chapter are connected to other modules in the system, forming a fully closed cycle with some optional external inputs (supply modules).

Substances in the gas phase, the liquid phase (mainly water) and the solid phase can pass from one module to another. Phase changes can occur in the process modules.

Figure 3 to Figure 5 represent the interconnection of the modules separated in gas, liquid and solid state. The detailed elemental mass flows between the modules are summarized in appendix 2.

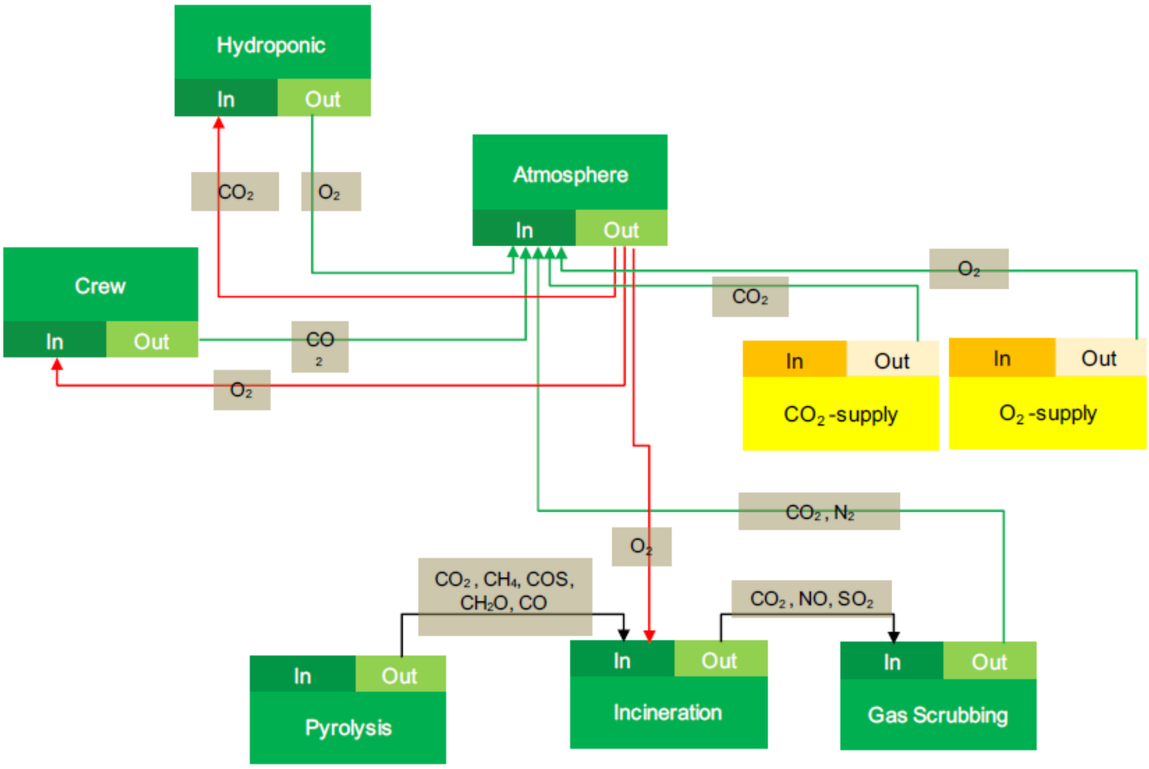


Figure 3 Interconnection of the modules (Gas)

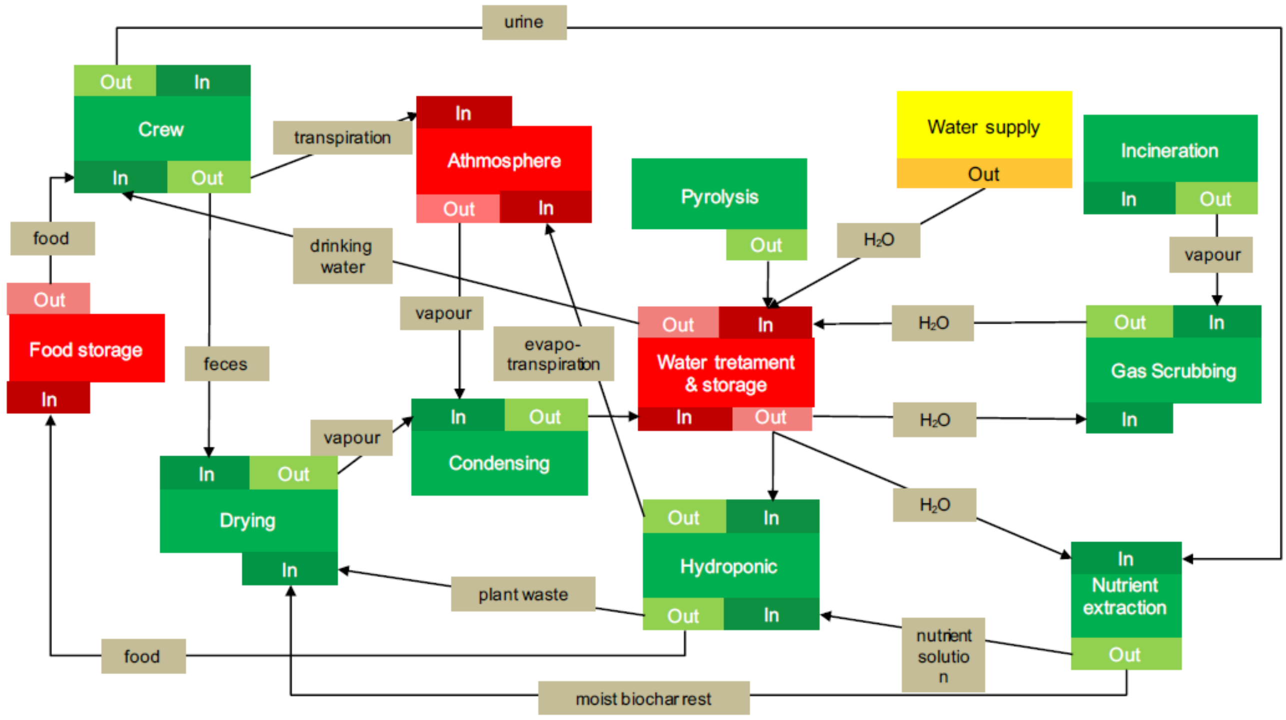


Figure 4 Interconnection of the modules (water)

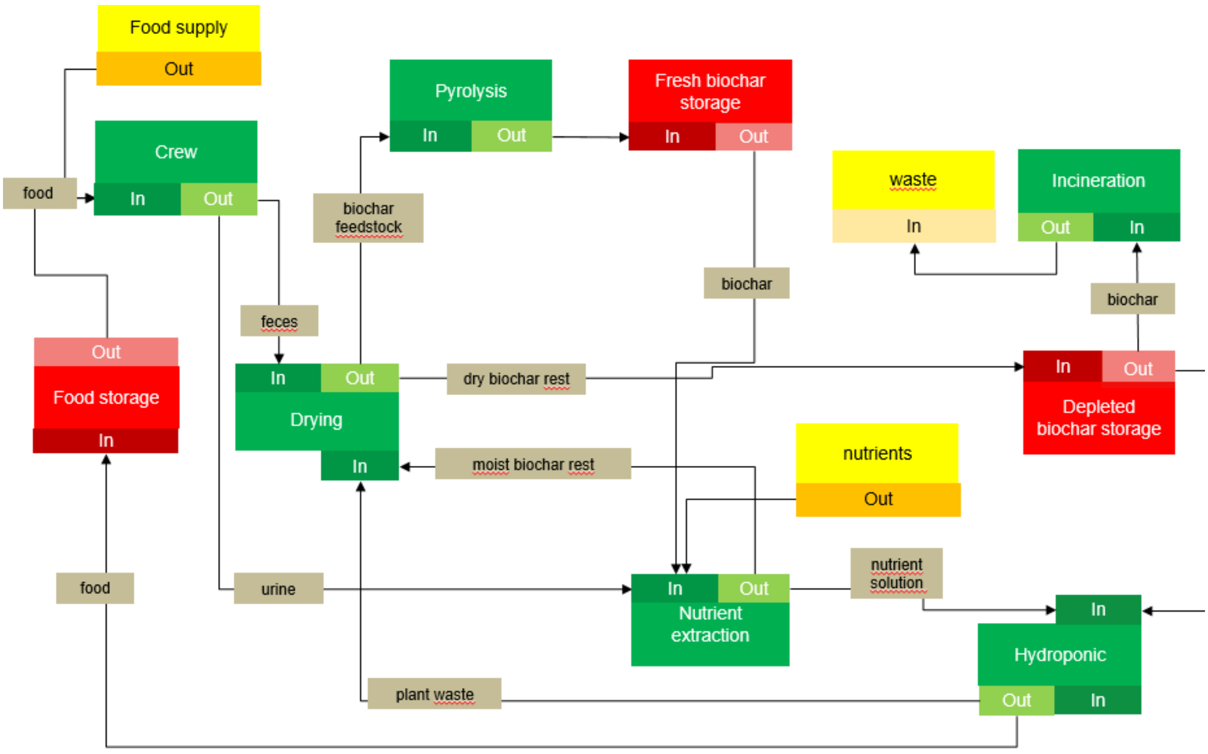


Figure 5 Interconnection of the modules (solids)

3.1.3 Model V1 variables

After the connecting of all modules, model variables were defined.

The **parameters (independent variables)** include:

- number of crew members
- volume of atmosphere
- surface area of hydroponic
- percentage of total urine added to hydroponic
- percentage of fresh fecal biochar used for nutrient extraction
- percentage of depleted fecal biochar and plant biochar that is incinerated

The **observed (or dependent) variables** are:

- food production & and external food resources required
- atmosphere O_2
- atmosphere CO_2 (and additional CO_2 supply)
- water in storage
- fresh biochar in storage
- depleted biochar in storage
- additional nutrients required
- waste produced (scrubbing residues, burner ash, water treatment)

Besides the above-mentioned depended variables, the mass balance model allows to observe masses and mole fractions of all substances, molecules or chemical elements in each module.

3.2 SPACELOOP MODEL V1 RESULTS & INTERPRETATION

Four different scenarios were simulated with in the static mass balance model. As the model does not allow for a time component, the succession of events were modelled by changing parameters and subsequently adding accumulation /depletion in the storage modules. Thus achieving a sum-curve of the simulated mass in the modules.

The four scenarios were:

1. The hydroponic establishment with one astronaut present over a period of 16 days. To achieve this scenario the hydroponic surface was gradually increased.
2. A minimum scenario with two crew members, stable hydroponic surface and char combustion. Dimensioned in order to minimize external inputs.
3. Changing number of crew with a constant hydroponic surface and balancing of CO_2-levels with adaption of biochar combustion.
4. Sudden failure of the hydroponic.

Assumptions for all scenarios:

- Lipids, trace minerals, salts that cannot be produced by the system are externally supplied to the crew.
- No loss of elemental mass in the processes.
- Nutrient extraction efficiency = 100%

As the aim of the life support system is to minimize the external supplies, the mass changes in the storages are depicted below. If the depletion of a storage is higher than the production in the system over an extended period of time, external supplies are inevitable.

Detailed legend for all following depictions:

- **Food stored & water stored in food**: change in the storage of hydrated food resources.

  Negative range: not enough food is produced by the system, externally supplied or previously produced food is consumed.

  Positive range: more food than needed is produced, stock in food grows.
- **Water stored:** The amount of water that is stored for later use. Output: all drinking water hydroponic water and scrubbing water. Input: water recovered from condensation, excess urine treatment and used scrubbing water.

  Negative range: more water is consumed than is recovered.

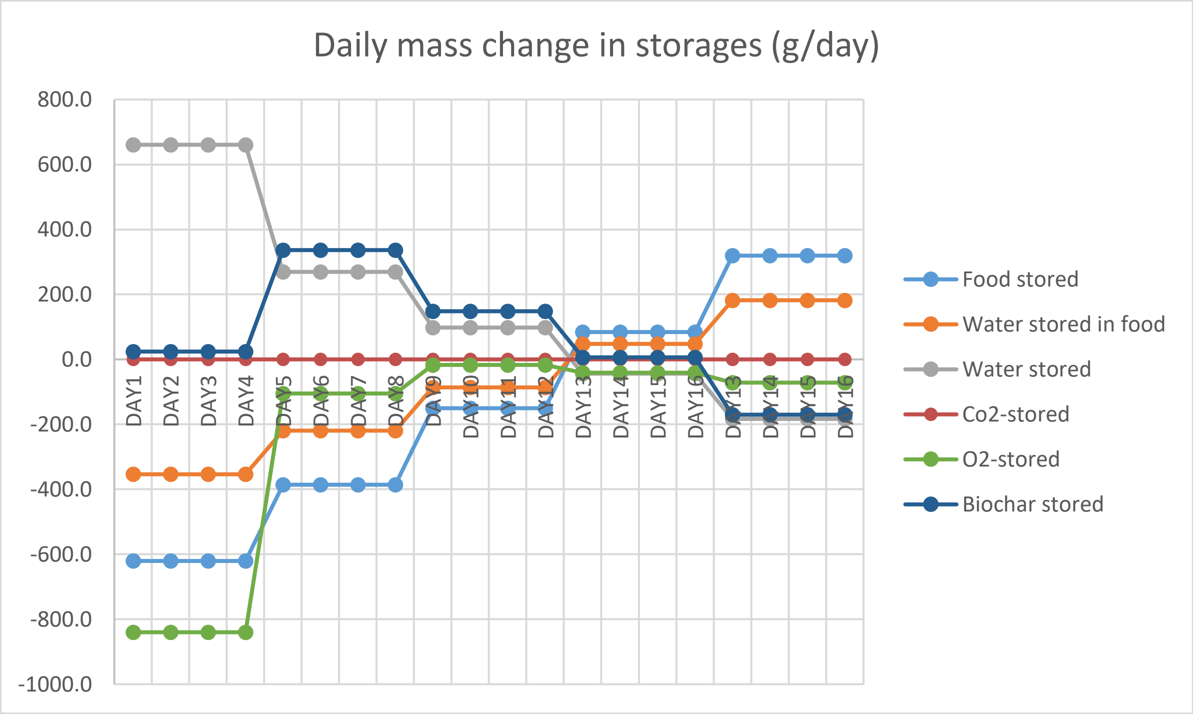
  Positive range: more water is recovered than is consumed (e.g. originating from hydrated foods)

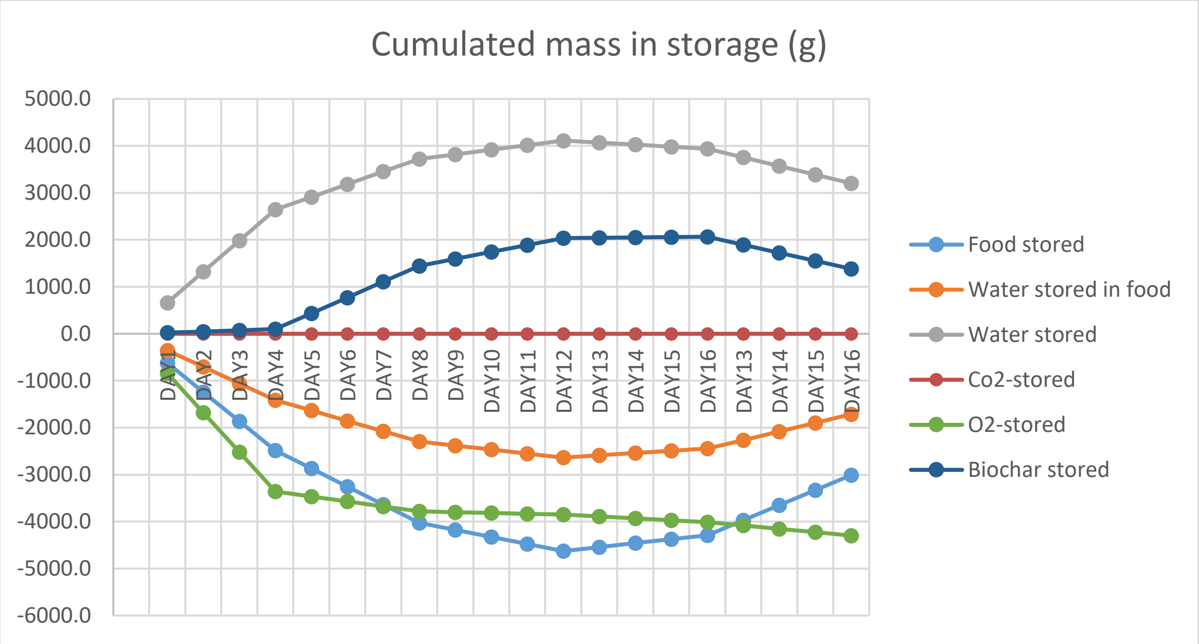
- **CO_2-stored:** The amount of carbon dioxide that needs to be externally supplied to keep the CO_2-concentration in the atmosphere in the desired range to favor optimal plant growth without being harmful for humans.
  Negative range: Volume CO_2-in storage decreases.
- **O_2-stored:** The amount of oxygen that needs to be externally supplied to keep the O_2-concentration in the atmosphere in the desired range to human respiration.
  Negative range: Volume O_2-in storage decreases.
- **Biochar stored:** Mass of biochar that is produced (plant & fecal biochar) less the amount of biochar that is incinerated for CO_2-production.
  Negative range: Biochar in storage decreases.
  Positive range: Biochar in storage increases.

3.2.1 Scenario 1: Hydroponic establishment

Parameter settings:

Nr. of astronauts	1
Volume of atmosphere	1000 m^3 (comparable to ISS)
Surface of hydroponic	0 (4d), 10 (4d), 20 (4d), 30 (4d), 40 (4d)
Biochar used for hydroponic	0% (4d), then 100%
Biochar burned for CO_2 production	0% (8d), 67 %(4d), 99%(4d), 116%(4d)
Urine added to hydroponic	0%(4d), 61%(4d), then 100%
Nutrient extraction efficiency from biochar	100%
Water loss in system	0%





Results & interpretation:

In the establishment phase the hydroponic cannot produce sufficient food or O_2 for the crew, both need to be supplied externally. Biochar is produced from human feces and stored.

Water that is ingested through hydrated food or metabolically produced (Fisher et al., 2008) , is excreted as urine or human transpiration/respiration and cannot yet be taken up by plants. It is therefore recovered and stored (in a real hydroponic scenario, the water might be used in the establishment phase regardless of plant growth).

After full establishment, the hydroponic produces more food than needed for one crewmember. Fresh hydrated food therefore needs to be stored.

If the hydroponic surface is dimensioned too small for the size of the crew (e.g. days 1-12), food and oxygen need to be supplied.

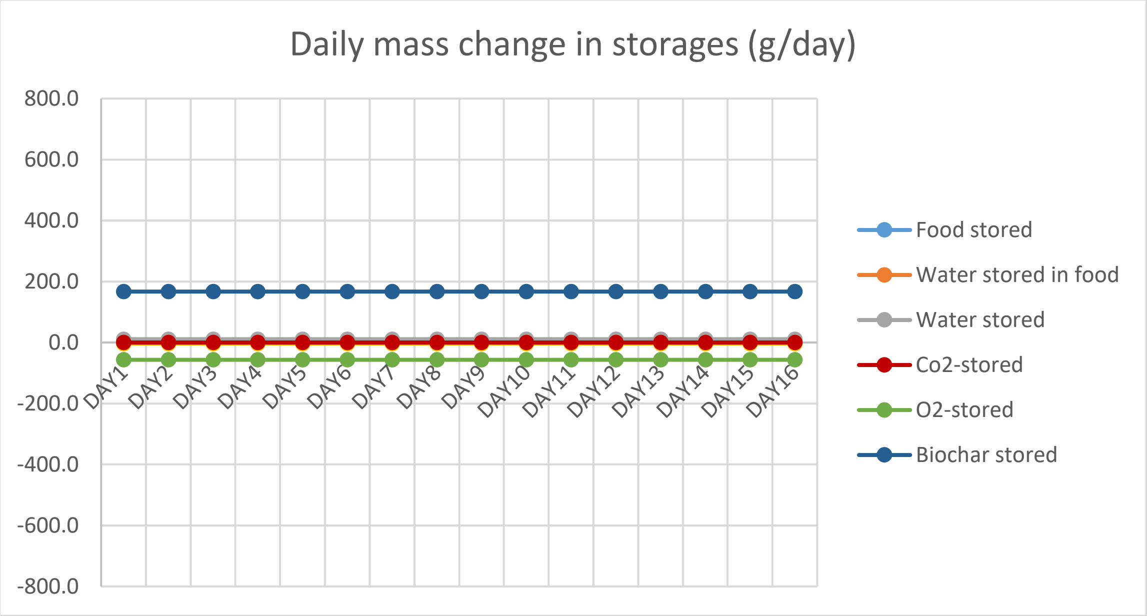
If the hydroponic surface is dimensioned too large (e.g. days 13 -16) water, nutrients and carbon need to be supplied which are then stored in the growing food, biochar stock.

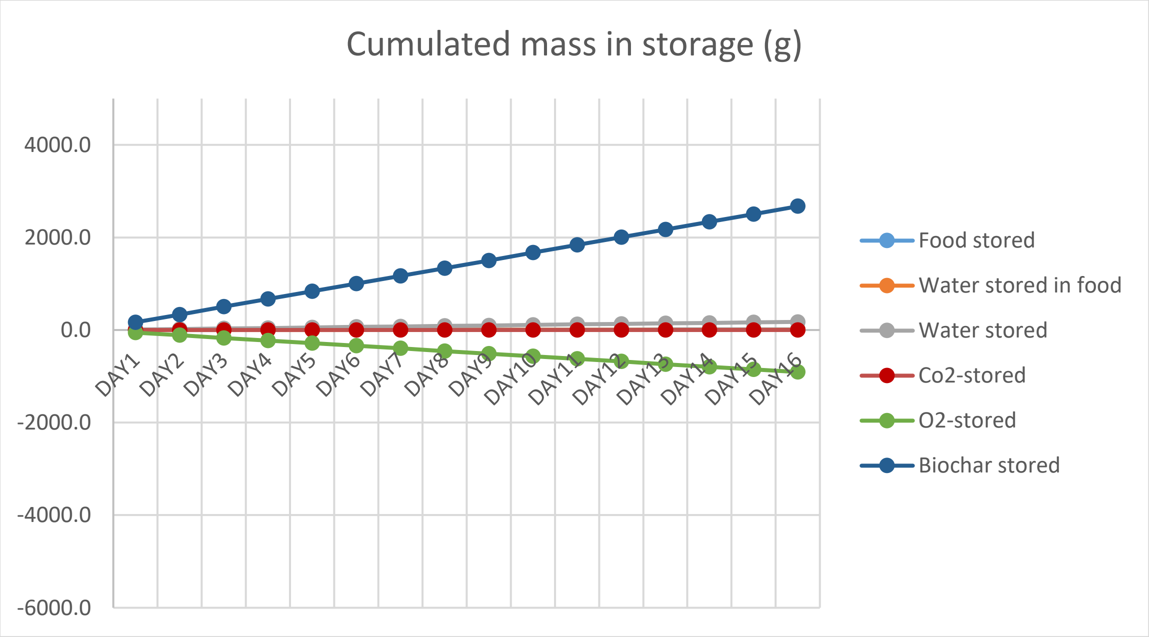
CO_2- levels can be effectively managed with biochar, if the stock is sufficient.

3.2.2 Scenario 2: Steady Scenario:

Scenario minimizing supply need.

Nr. of astronauts	2
Volume of atmosphere	1000 m^3 (comparable to ISS)
Surface of hydroponic,	52.80 m^2
Biochar used for hydroponic	100%
Biochar burned for CO_2 production	90%
Urine added to hydroponic	100%
Nutrient extraction efficiency from biochar	100%
Water loss in system	0%

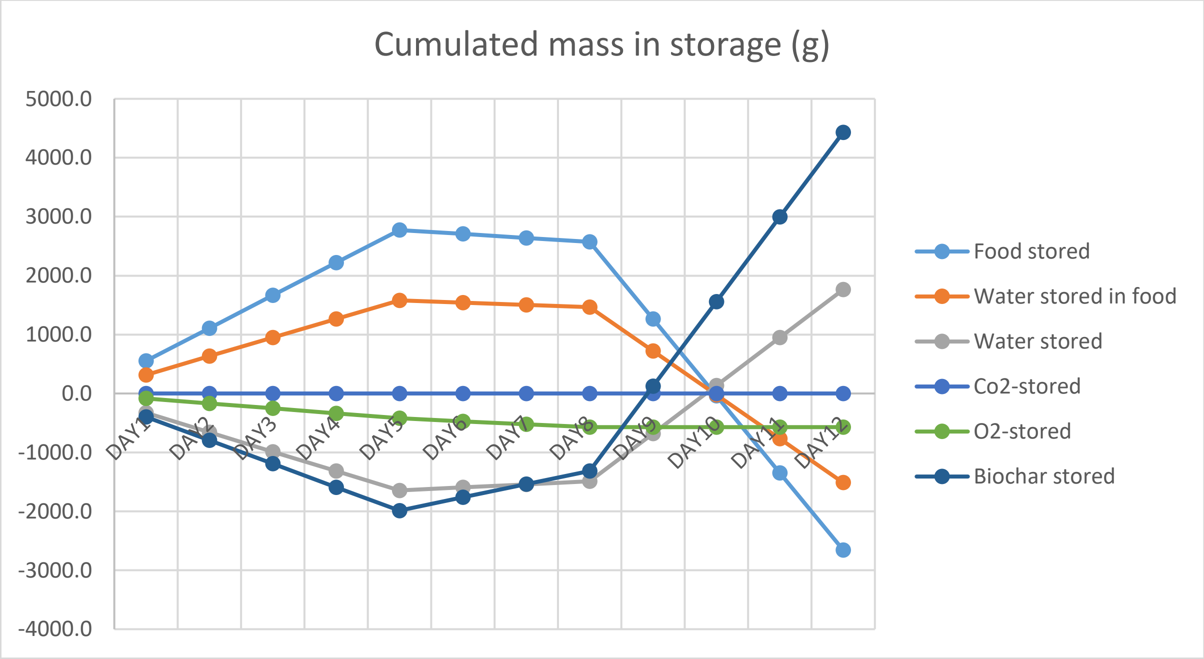


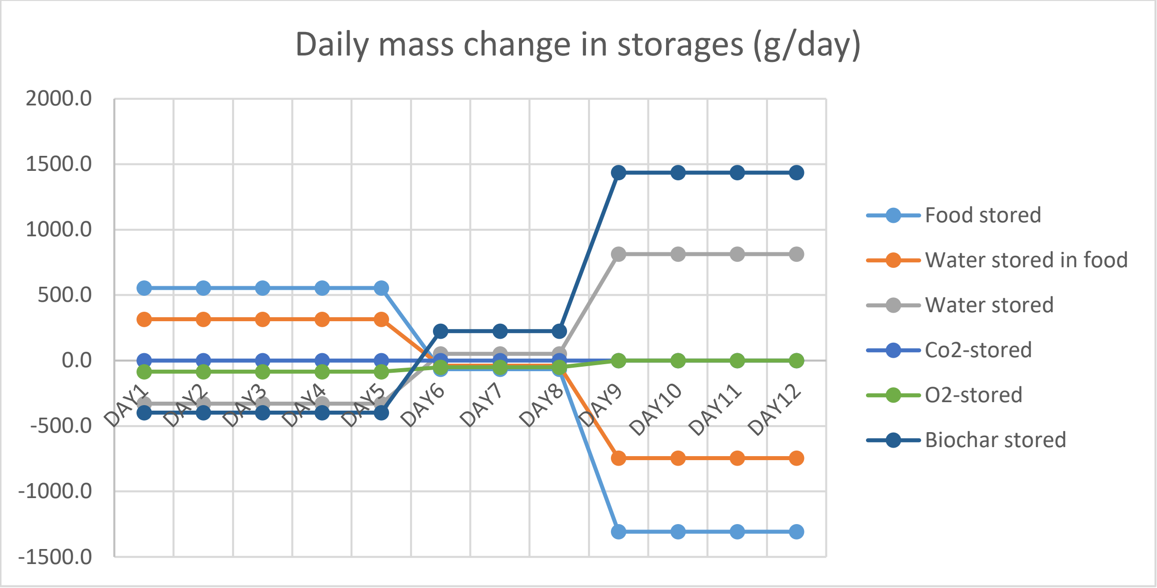


Results & Interpretation: The hydroponic size is dimensioned exactly large enough to produce enough food for two astronauts. While being able to do so, it is unable to provide enough oxygen. In other life support system oxygen could be sufficiently provided by crops introduced (Guo et al., 2017). The oxygen deficiency in this system is not a problem of insufficient O_2-generation by plants, but of high O_2 consumption in the incinerating process needed to maintain high CO_2 levels.

3.2.3 Scenario 3: Changing number of crew with biochar C-balancing:

• Nr of astronauts	1 (5 days), 2 (3 days) , 4 (3days)
• Volume of atmosphere	1000 m^3 (comparable to ISS)
• Surface of hydroponic	50.00 m^2
• Biochar used for hydroponic	100%
• Biochar burned for CO_2 production	126% (6days), 86%(3days), 12%(3days)
• Urine added to hydroponic	100%,
• Nutrient extraction efficiency from biochar	100%
• Water loss in system	0%





Results & Interpretation:

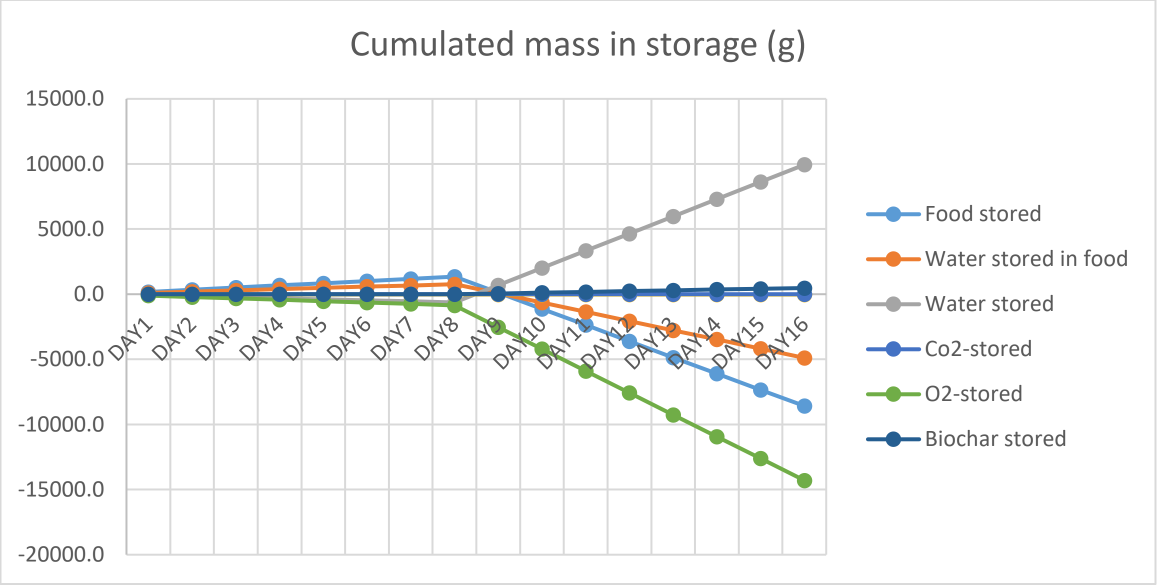
Even if the burning of biochar is immediately stopped in the case of a hydroponic failure the O_2- levels are not high enough to support the crew long term.

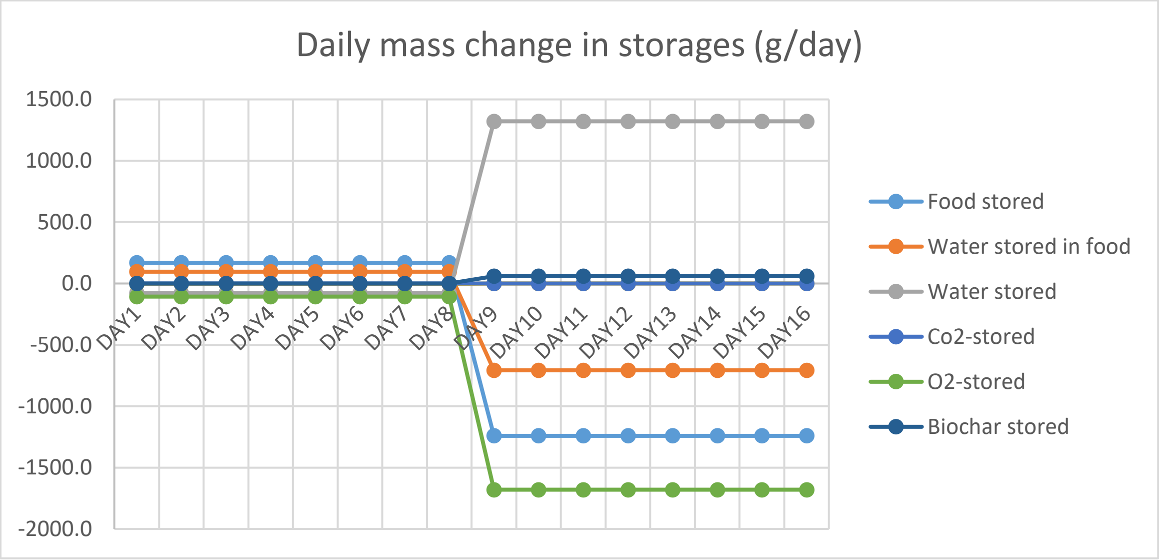
Food needs to be supplied. O_2 can should be generated from water.

Supplies must be sufficient to allow for a reestablishment period of the hydroponic, or a safe return of the crew in case of an irreversible hydroponic failure.

3.2.4 Scenario 4: Hydroponic failure

Nr of astronauts	2
Volume of atmosphere	1000 m^3 (comparable to ISS)
Surface of hydroponic,	50.00 m^2
Biochar used for hydroponic	100%
Biochar burned for CO_2 production	100% (8d), 0%(8d)
Urine added to hydroponic	100%,
Nutrient extraction efficiency from biochar	100%
Water loss in system	0%





Results & Interpretation:

Even if the burning of biochar is immediately stopped in the case of a hydroponic failure the O_2- levels are not high enough to support the crew long term.

Food needs to be supplied. O_2 needs to be externally supplied.

Supplies must be sufficient to allow for a reestablishment period of the hydroponic, or a safe return of the crew in case of an irreversible hydroponic failure.

3.2.5 Summary

The results of the four SpaceLooP Model V1 scenarios (setup and parameters: chapter 3.1) can be summarized as follows:

- O_2 provided by the hydroponic module is not sufficient (all scenarios)

- This is even the case, when the hydroponic module is set up to fully cover the astronauts' demand for food (Scenario 2)
- One reason is the O_2 demand of burning biochar for CO_2 production in order to match the plant needs
- A failure of the hydroponics quickly leads to very low O_2 concentrations (Scenario 4)
- O_2 has to be supplied from outside the system (all scenarios)
- It is difficult to dimension the surface of the hydroponic accordingly to the food and oxygen need of the crew. The depletion of certain storages, involves the accumulation in another storage.
- CO_2 can be balanced according to plant needs with biochar incineration

Also a limitation of the model was identified that contributes to the necessity of oxygen supply to the system: As fatty acids (see Figure 6) are externally supplied to the system, proportionally more C is supplied than O. If carbon and oxygen are stored in form of food or char, there is still proportionally more carbon in the system. To maintain the correct O_2 / CO_2 balance oxygen need to be supplied, if the model is run with the aim of minimizing the external carbon supply.

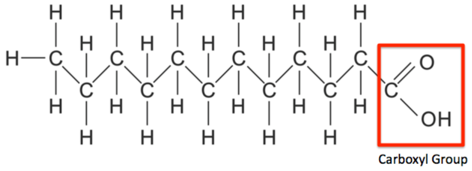


Figure 6 Exemplary fatty acid

Although the behavior of the model mainly reflects the basic model setup that was chosen by the authors of this study, the four scenarios demonstrate the fragility of the current SpaceLooP model setup. The critical issues are: a) balancing O_2 needs of the crew vs. CO_2 requirements of the hydroponics, and b) dealing with fluctuating occupancy.

Compared to Earth, balancing O_2 and CO_2 in SpaceLooP is necessarily a much greater challenge: SpaceLooP is several magnitudes smaller than Earth, and it is designed solely for its human inhabitants SpaceLooP's atmospheric CO_2 concentration is not buffered by large global reservoirs.

4 ANALYSIS OF PERFORMANCE

Model and literature research allowed to identify benefits, threats and potential measures to improve or control the system.

4.1 POTENTIAL BENEFITS

CO_2-Management

- Compact storage of elemental carbon as biochar
- Combustion of biochar for CO_2 production allows for targeted fertilization for plant growth
- Unlike incineration, the issue of CO_2 management can largely be decoupled from the issue of waste management as not all of the carbon is immediately converted to CO_2.

Stabilization and sterilization of human waste

- Stabilization and sterilization of human waste (as biochar). Destruction of hormones, organic micropollutants and bacteria contained in the fecal part of the human excreta.

Degredation of fibres

- In previous life support systems, the resistance to degradation of fibrous plant cell walls composed of cellulose, hemicellulose, pectin and lignin posed difficulties (Hendrickx and Mergeay, 2007). Human fecal matter contains 6-7 g/p day of fibers (Jönsson et al., 2005). Pyrolysis or torrefaction achieves a complete breakdown of the cell structures of bio-mass (Basu, 2013b) an could solve the problems with resistant fibrous material.

Reduced storage volume

- Reduction of storage volume of the waste materials, while important elements such as carbon and nitrogen can be efficiently stored in the form of pyrolysis char and later recovered by gasification or incineration when needed.

Water recovery

- Recovery of moisture and generation of additional pyrolysis water from solid waste (as feedstock often contains large amounts of oxygen and some hydrogen)

Nutrient storage

Nutrients (e.g. N, P, K) are stored in biochar and can be reused.

4.2 THREATS TO THE SYSTEM

Atmosphere

- CO_2 generation relies on oxygen consumption in the incinerating process. Meeting the plants CO_{2-} needs could temporarily lead to low oxygen levels that would be harmful to the crew.
- CO, NO_x, SO_x gases can be formed during pyrolysis, more so if temperatures rise above 300°C (Basu, 2013a). In higher concentrations, these gases are harmful to humans.
- With unknown amounts of sulfur and nitrogen in human feces, SH- and NH_2-containing compounds could develop, causing an unpleasant smell during drying and pyrolysis of feces. This could impair the well-being and performance of moon-base inhabitants.

pH in system

- Although urine itself is believed to be relatively sterile , if there is no cross-contamination with feces (Rieck et al., 2012) storing urine for at least a month prior to use in food production is recommended. Storing urine leads to an increase in pH (>9) due to the decomposition of urea into ammonia/ammonium and hydrocarbonate. Now both biochar and stored urine have a relatively high pH (>8) (Lopez-Capelm et al., 2016). When using biochar and urine in a hydroponic system this could lead to an increase in pH that could potentially be harmful to crops. Increase pH will furthermore lead to the conversion of NH_4 in to NH_3, which will outgas from the liquid solution. NH_3 is harmful to sensitive ecosystems and human health in high doses (Behera et al., 2013). The process further causes the loss of nitrogen from the nutrient solution.
- Although during the low temperature pyrolysis we expect only few complex gases (other than CO_2) to be formed, there is still the threat of their formation if the pyrolysis process is not properly controlled. Gaseous acetic acid is a substance known to form through pyrolysis of wood condensing to form low pH pyrolysis liquids. The same could occur during the pyrolysis of crop residues or feces. The acidic liquids could potentially harm the equipment they come in contact with.

Potentially harmful byproducts, substances or bacteria

- The formation of hydrocarbons which potentially condense to form so called bio-oils or tars could disturb subsequent processes e.g. in the incinerator.
- High sodium (Na) levels in biochar or urine originating from could lead to saline nutrient solution which could be harmful to plant growth (Bleuler, 2016; Brewer et al., 2011).

- Pure and stored urine has corrosive properties when in contact with different metals, leading to potential damaging of equipment (Rieck et al., 2012).
- In loop systems the accumulation of certain substances can lead to collapse or decrease of its performance. Substances, that might accumulate include NaCl or its ions, cleaning agents, fertilizers, metallic substances from technical equipment, calcium precipitation from human bone degradation.
- Contamination of the living space or the hydroponics with undesired bacteria could occur in case of failure of the pyrolysis unit.

Recycling of nutrients in biochar & urine

- Reusing biochar substrate in hydroponic plant production is still a new field. Although some experiments have been documented in literature (Arbestain, 2015; Awad et al., 2017; Karakaş et al., 2017), a specification for the situation on the moon still needs to be developed. It remains unclear if nutrients are extractable/available to plants and in which time frame they become available.
- On Earth, microorganisms contribute to the decomposition of biochar and make nutrients available to plants. In a huge open system like Earth, suitable microorganisms will automatically settle where they find material to decompose. In an artificial ecosystem, it could be a challenge carrying along the right microorganisms to perform the tasks.
- Even though theoretically there should be enough macronutrients in the nutrient solution to support plant growth, is has been reported, that in biochar e.g. nitrogen or phosphorous are in a form that plants have difficulty to access. Nutrients might not be plant available in the chars.
- NH_4 originating from urine is the primary nitrogen source in the nutrient solution. For a successful plant production the right NH_4/NO_3 ratio is essential (Zhao et al., 2016). The nitrification process (conversion of NH_4 to NO_3 by specialized bacteria) occurring in the hydroponic might not be enough to achieve the correct ratio.
- The focus of the current design lies on elements making up the major mass of the system (CHNSO, ash). Hydroponics however can fail from trace nutrient deficiency and humans can experience deficiency syndromes.
- Some micropollutants like pharmaceutical residues or hormones in urine will outlast the storage process and will still be present when the urine is recycled in the hydroponic. They could have a negative impact on bacterial communities and plants.

Effects of space environment

- Pyrolytic biomass decomposition and biochar production may be affected by microgravity, similar to combustion processes that are known to be affected by microgravity (Ronney, 1998).
- Plants are affected by strength of magnetic and electromagnetic fields, cosmic radiation, weightlessness and microgravity. The space environment can potentially disturb the processes of photosynthesis, gas exchange, transport of water and solutes and the stability of the plant genome.

General Stability of the system

- The failure of one part of the system (e.g. hydroponic or pyrolytic unit) could immediately lead to the quick collapse of the system (see model scenario 4).
- In all scenarios some storages decreased while others increased .The complete depletion of certain storages could be the case after a long time of consistant operation of the system.

4.3 FACING THE THREATS

The threats identified in the previous chapter can be met with the according measure (see Table 2). This included the adaption of the system design or the close control of critical parameter. In some cases, the exact processes are not completely known and will need to be further researched.

Table 2 Threats and measures for a safer and more stable SpaceLooP operation

Threat	**Measure**
pH	
Rise of pH in hydroponic caused by urine/biochar	The pH of the nutrient solution should be monitored and adjusted if necessary. A pH –buffer (e.g. carbonates) can be present in the hydroponic nutrient solution to be capable to buffer some pH –changes.
Acidic liquid pyrolysis product	pH of pyrolysis liquids should be controlled and equipment designed to withstand a certain acidity.
	Research: Could acidic pyrolysis liquids be used to stabilize the pH in the nutrient solution?
Atmospheric control	
SOx, NOx CO in the atmosphere	These compounds should be monitored and the scrubber adapted in order to be able to remove the harmful substances that cannot be oxidized in the incinerator.
NH_3-outgassing	Set pH in the nutrient solution to a relatively low pH of about 6 to control ammonia outgassing.
O_2-depletion through CO_2 production	In some model scenarios, O_2 needed to be supplied externally, while the H_2O storage increased. Interconnecting the two processes by creating the possibility to generate O_2 from H_2O through electrolysis (NASA, 2016) could further minimize the need for external O_2-supply. The CO_2-levels in the atmosphere (1200 ppm in the model) could be adapted according to current O_2-levels, namely allowing for lower CO_2-levels over short periods.
Smell developments	Collection, drying & pyrolysis process should be designed in order to mostly avoid contact of fecal matter with breathing air. Off-gas from drying and incineration should be scrubbed before returning to the atmosphere, including the possibility to vent the off-gases out of the moon base.

Damaging byproducts and potential toxins	
Condensable hydrocarbons (tars)	It should be made sure, that the pyrolysis gases do not get the chance to condense before entering high temperature incinerator. Acetic acid and hydrocarbons will be oxidized to form CO_2 and H_2O in the incineration process.
High Na-input into hydroponic	Salt input should be monitored, and the salinity (e.g. electrical conductivity of the nutrient solution should be monitored).
Corrosive nature of urine	For piping and urine storage polyethylene (PE), polypropylene (PP) or polyvinyl chloride (PVC) should be employed (Rieck et al., 2012)
Accumulation of damaging/toxic substances	Monitor substances, chose cleaning agents/fertilizers with high degradability.
Bacterial contamination due to pyrolysis failure	Feces must still be able to be safely contained, stored and disposed of. Individual bags and sealable containers and /or a redundant system to sterilize wastes should be foreseen.
Nutrients	
Lack of nutrients / unbeneficial nutrient ratios	The total mass of trace elements and nutrients that the system needs to function will be small compared the major components. To establish stability certain amounts of nutrients should be carried along when establishing the SpaceLooP. Amounts should be sufficient to ensure the functioning of the system over an extended period, if the recycling of the elements proved to be not feasible.
Low nutrient availability from biochars	**Research**: define methods to reuse nutrients contained in biochar/ or biochar ash
Micropollutants/hormones contained in urine	**Research** : concentrations and potential danger of micropollutants in a hydroponic system operated with urine
Nutrient availability from urine	**Research** : nutrient availability and in a hydroponic system operated with urine
Insufficient decomposition of biochar through microorganisms.	**Research** : biochar decomposition and microorganisms present in a hydroponic system including biochar
Space environment	
Microgravity	**Research**: Impact of microgravity on the pyrolysis process
Plant damage by space environment	Protection through shielding, further research on exact impacts on plants is currently performed.

System stability	
Depletion of storages/accumulation of other storages	Large storages will enable the system to be sustained over a longer period of exceptional operation like higher occupancy than intended.
Collaps of single system components	Create redundancy's for most critical system components: Additional O_2-generating system (e.g. electrolysis, woody crops independent of food production) Additional CO_2 removal storage or re-introduce decoupled from O_2-consupmtion through incineration (e.g. artificial carbonate system). Additional C-storage and slow CO_2/O_2 regulation with the introduction of woody crops. They can be pyrolysed or incinerated to generate CO_2 if need be.

When including the mayor system adaption for system stability in the SpaceLooP concept the material flows in the system change as shown in Figure 7 to Figure 9.

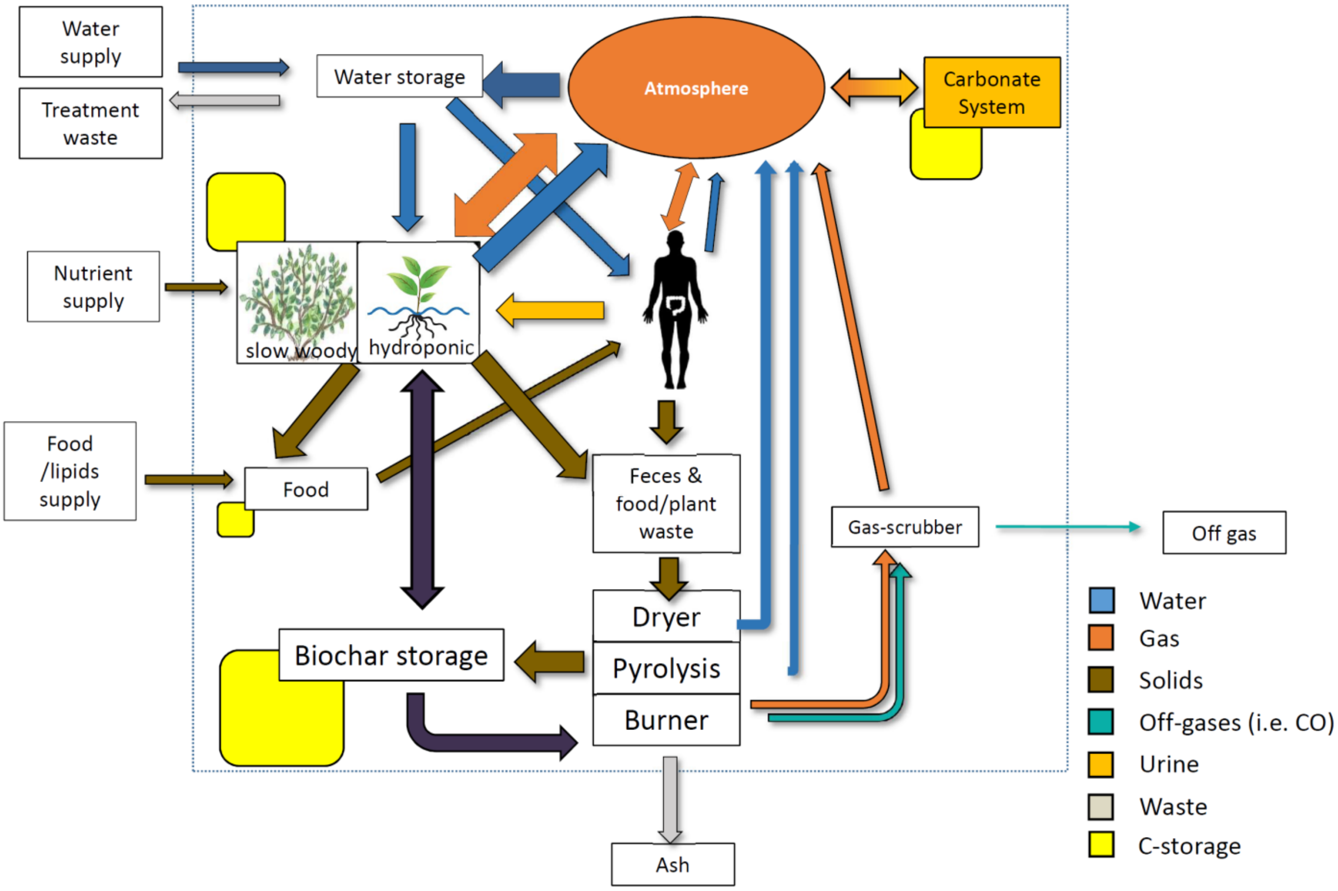


Figure 7 Improved C-Cycle in SpaceLooP

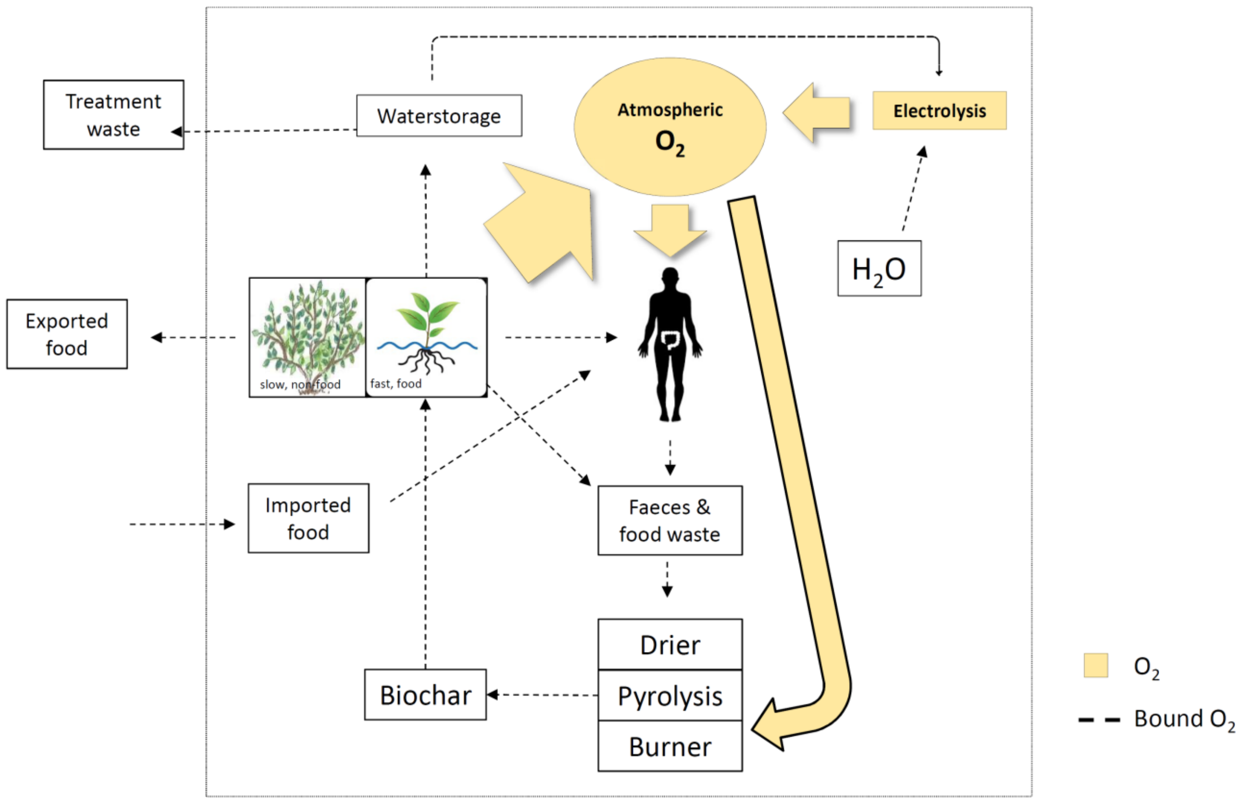


Figure 8 Improved O_2-Cycle in SpaceLooP

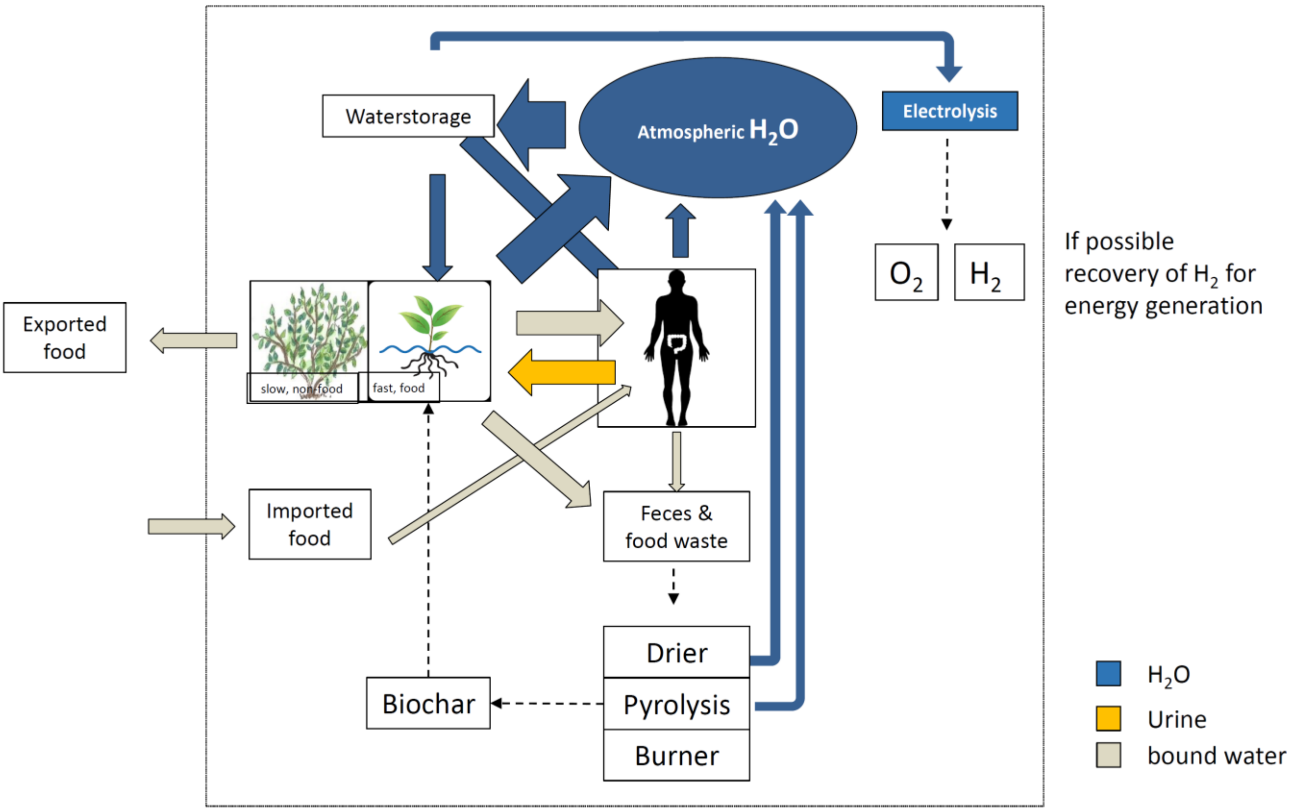


Figure 9 Improved Water Cycle in SpaceLooP

5 PYROLYSIS EXPERIMENTS AND BIOCHAR ANALYSIS

The launch of the pyrolysis reactor “Pyreka” at the Institute of Natural Resources Science IUNR was delayed. A reduced set of the experiments foreseen was started in Nov. 2017, after bringing the reactor into service. The following steps were performed:

- Human feces were collected from voluntary donors on the campus of IUNR in Wädenswil over a period of 2 weeks resulting in a total of 5 kg of fresh feces.
- Prior to pyrolysis, the samples were stored in starch based biodegradable plastic bags in the freezer for 1 to 10 days.
- Drying of the fecal material overnight at 105°C resulted in a mass loss of about 72% and an estimated volume reduction of about 70%.
- Preliminary experiments with dried manure in the pyrolysis reactor on campus Wädenswil showed that at a low heating temperature of 300°C a reactor residence time of 20 minutes was sufficient to ensure a complete carbonization of the samples.
- 1 kg of human feces was processed resulting in 600 g of char (see Figure 10), which corresponds to a mass loss of 45% and an estimated volume reduction about 35% (depends if porous sample is further ground).
- This corresponds to a total mass loss 85%, total volume reduction 80%.

Figure 10 Dried human feces and resulting biochar after (mild) pyrolysis at 300°C for 20 min.

Before analysis, the biochar samples were dried to 100% dryness at 60°C. Then chars were ball milled for about 30s at 50Hz (MM400 Retsch) which resulted in a fine homogeneous powder.

Electrical conductivity (EC) was measured according to the Methods Book for the Analysis of Compost (Federal Compost Quality Assurance Organisation, 2003) in analogy to DIN ISO 11265 at ZHAW Wädenswil. EC was measured with a standard EC probe (CDC401, Hach-Lange) in the filtrate after shaking of 2 g sample (instead of 20 g) with 20 mL (instead of 200ml) of deionized water for one hour at 500 rpm (Duomax 1030, Heidolph) and filtration of the suspension (Munktell Folded Filters 8 µm). Temperature correction to 25°C was automatically performed by the EC probe.

The mean of the triplicate analysis resulted in an **electrical conductivity of 2.01 (+-0.06) mS/cm** (standard deviation in parentheses).

In previous experiments with biochar from composting toilet substrate and fecal sludge the measured EC values were much higher (4.9 – 9.7 mS/cm) which can possibly be contributed to the presence of large amounts of urine in the feedstocks in the above described study (Bleuler, 2016). The measured EC values are in the range of EC of charred sewage sludge (Hossain et al., 2011; Khanmohammadi et al., 2015; Méndez et al., 2013) and swine manure biochar (Zornoza et al., 2016).

Germination tests with salt sensitive lettuce planted in highly saline biochars (9.7 mS/cm) showed a strong germination inhibition with increasing biochar doses (Bleuler, 2016). This problem will most likely be less pronounced with biochar produced purely from human feces without urine, containing most of the excreted salts.

The **pH** of the biochars was determined according to ISO 10390:2005-02. 25 mL of a 0.01 M CaCl2-solution was added to 2.5 g of dried and milled biochar sample. The pH of the suspension was measured with a pH electrode (PHC301, Hach-Lange, Switzerland) after shaking the suspension at 100 rpm for one hour (Duomax 1030, Heidolph).

The mean of the triplicate analysis resulted in a **pH of 9.07 (+-0.11)** (standard deviation in parentheses).

This is in line with previously tested biochar produced at 350°C from fecal sludge (pH 9.2). Higher pyrolysis temperatures when producing char from fecal sludge and composting toilet substrate lead to even higher pH between 9 and 11 (Bleuler, 2016).

Carbon hydrogen and nitrogen (CHN) contents in the biochar sample were analyzed according to DIN 51732. Therefore, 0.1 g of sample were weighed into a tin foil and subsequently analyzed in a CHN-analyzer (Leco-Tru-Spec).

Elemental contents of 54.3 (+-0.01) wt% carbon, 5.49 (+-0.01) wt% hydrogen and 4.95 (+-0.0) nitrogen (standard deviation in parentheses) were determined.

The results confirm our model assumptions of 53wt% carbon and 5.2wt% nitrogen with the hydrogen value being slightly lower than expected (7.4 wt%).

Carbon, hydrogen and nitrogen contents are however somewhat lower than reported by a previous study (Ward et al., 2014). The authors pyrolysed pure human feces at 300°C and found 58.2, 6.1 and 5.19 wt% of carbon, hydrogen and nitrogen respectively. This can potentially be attributed to a relatively high heating rate in the reactor at ZHAW that cannot be controlled. Ward et. al (2014) used low heating rates of 1.6 C/min. High heating rates are linked to a higher amount volatiles (Basu, 2013a) which could explain higher loss through volatilization of carbon, hydrogen and nitrogen.

To be able to have further information about **nutrients** contained in the fecal biochar we decided to also analyze phosphorous which is (together with potassium and nitrogen) the most crucial plant nutrient. Contrarily to nitrogen, it is contained in the ash-part of the biochar and does usually not volatilize.

Water extractable respectively plant available phosphorous in biochar are most important for future hydroponic setups. Therefore a simple water extraction(1:4) and an extraction with 2% formic acid (1:100), which corresponds to plant available phosphorous (Wang, 2013), were performed.

0.31 (+-0.03) g phosphorous per kg biochar were water extractable, while 6.29 (+-0.69) g phosphorous per kg biochar were extractable by 2% formic acid solution and can therefore be considered plant available.

The water extractable phosphorous of under 1 g/kg is in line with previous results originating from the pyrolysis of human feces & wood chips (Bleuler, 2015). The formic acid extractable P is lower than in biochars derived from fecal sludge and composting toilet substrate (Bleuler, 2016). In the cited study formic acid, extractable phosphorous contents were as high as 21 – 36 gP/kg. This could be attributed to the presence of urine, which has high P contents (Rose et al., 2015), in the feedstock of the previous work. The value of about 6 gP/kg lies however in the same range as values found for several animal manure based biochars (Subedi et al., 2016; Troy et al., 2013; Wang et al., 2012).

Conclusion

The preliminary analyses of pH, electrical conductivity, CHN and extractable nutrients revealed that the biochar produced at ZHAW is comparable to other biochars produced under similar conditions and from similar feedstocks. We therefore conclude that the results of future hydroponic substrate tests will be somewhat transferrable to other biochars produced from human feces.

Next steps

In order to set up hydroponic tests with the biochar substrates other extractable nutrients will be tested with ion chromatography. The focus will lie on ammonia (NH_4) and nitrate (NO_3).

With this data, we will derive the fertilizer value of biochars in a hydroponic system and determine the suitable extraction ratios and nutrients to be added (if necessary).

6 TECHNICAL DESIGN PROPOSALS

In order to perform the desired processes in each module of the system as described above, we propose the following technical features are to make up the SpaceLooP.

Separating toilet and storage issues

Human fecal matter (liquid and solid) collection will be achieved in separating-toilets which are already a standard in space missions (Broyan Jr., 2007; Fisher et al., 2008). The use of individual bags has proven to be a feasible and odor-containing method of feces collection (Broyan Jr., 2007) and is proposed in the SpaceLooP system. Biodegradable starch-based polymers as base material could be an option that would allow the direct pyrolysis and reuse of the fecal matter including the bag. The pyrolysis of the bag was not included in the model discussed prior, but would need to be considered in order to avoid any plant harming substances in the char. We suggest daily pyrolysis of human solid waste to minimize the time where unsterile feces must be stored and in order to limit the dimensions of the pyrolysis -reactor.

To avoid contact with fecal matter and minimize odors we propose a vessel system with different lids and grids that allows for storages, drying, pyrolysis and possibly nutrient extraction without removing the feces or biochar from the vessels (see Figure 11).

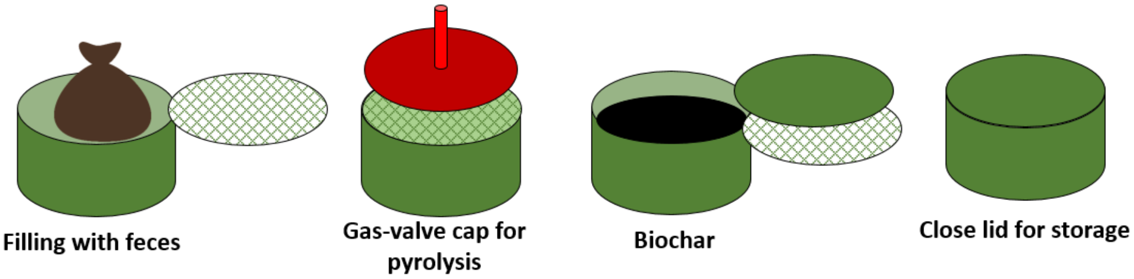


Figure 11 Proposed vessel system for the storage of feces, pyrolysis and nutrient extraction from biochar

For urine on the other hand to ensure a complete hygienisation it should be stored for a month before usage (Rieck et al., 2012). Odor tight storage space of about 42 L per person is therefore needed. The degradation of urease leads to a pH rise in the storage tank that needs to be controlled and kept below a pH of 8.5, in order to avoid losses of nitrogen to the atmosphere of the moon station as NH_3.

Water recovery, treatment and storage

Reclaiming of latent water from the cabin atmosphere is a standard procedure in space travel used e.g. on the International Space station (ISS) with high recovery rates (Carter et al., 2015).

Incineration

Incinerators for space applications were developed for waste management purposes (Fisher, 2000) and the disposal of inedible plant biomass in biological life support systems (Dai et al., 2018). There is technology available to ensure the clean combustion of pyrolysis gases and biochar. Including the incineration/oxidation unit with the pyrolysis unit could be considered.

Gas Scrubbing

There are advanced technologies to remove nitrous or sulfurous compounds from off-gases of incineration or pyrolysis (e.g. (Chang et al., 2004) which will not be discussed in detail here.

Integrated pyrolysis, drying and burner unit

For simplicity's sake, the processes of drying and pyrolysis of biomass are assumed to take place in the same apparatus

For the powering of the pyrolysis/torrefaction electrical heating spirals, microwave system of the direct use of solar radiation (Lédé, 1999; Zeng et al., 2017) could be considered.

For a moon base, a direct use of solar energy would be less recommendable because of the necessity to pyrolysis/torrefaction in the 14-day darkness period on the surface of the moon. (Serio et al., 2015) compared microwave heating and electrical heating spirals concluding that microwave heating allows for a better control of the process. The samples began heating right away, the temperature distribution in the samples was uniform and the samples start cooling directly after pyrolysis stops. We therefore propose a microwave unit.

A microwave pyrolysis (torrefaction) unit including the capability to dry the feedstock and recover water was developed by Serio et. al in a long term NASA project (Serio et al., 2015, 2014, 2006, 2002, 2000). A similar system is envisioned for SpaceLooP. The unit has been tested with fecal simulant but not validated with real feces yet.

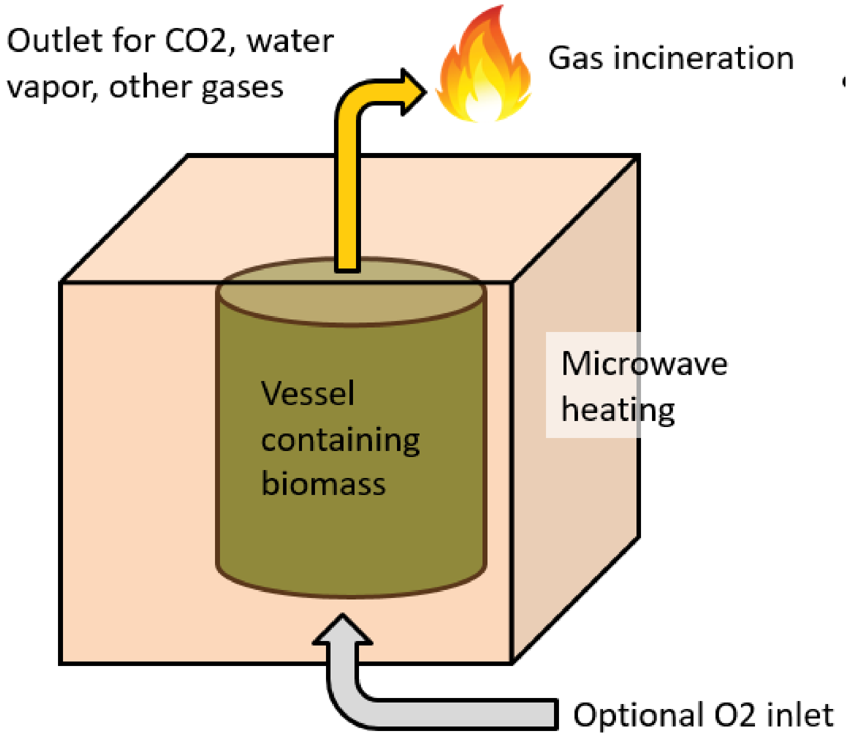


Figure 12 Concept for integrated drying/pyrolysis/incineration unit

Hydroponics for space applications

Hydroponics for the production of food in space were extensively studied, e.g., by the NASA Kennedy Research Center and the Melissa Foundation.

Nutrient solution with nutrient extraction from fecal biochar or directly planting into biochar have not been researched to a large extent.

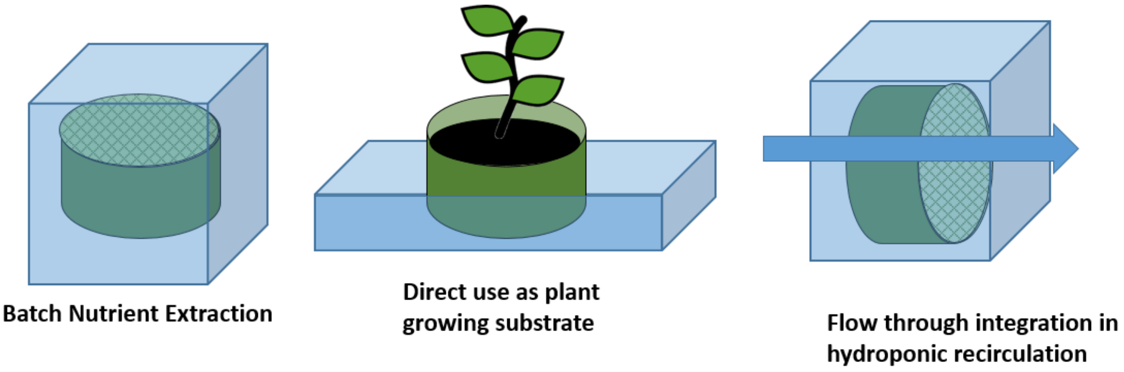


Figure 13 Options for nutrient extraction

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Carbonate system unit

The natural acid-carbonate equilibrium as depicted in Figure 14 is contributes to CO_2-balancing on Earth. The introduction of a highly buffered liquid compartment into the system could help in balancing the CO_2-in the atmosphere.

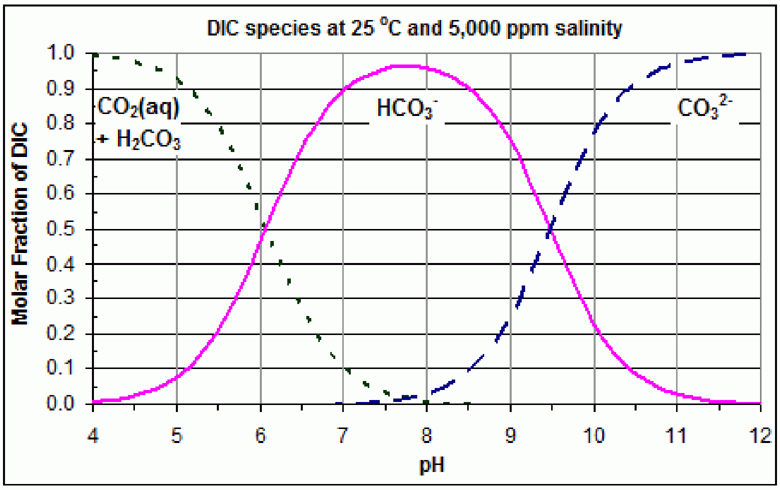

Figure 14 Natural acid-carbonate equilibrium (Source, Wikipedia)

The equilibrium between atmospheric CO_2 and carbonates could on the one hand be achieved through natural exchange between air and liquid phase according to henry's law. Alternatively, it could be forced by bubbling air through the buffered water solution and therefore increasing the gas exchange surface and the withdrawal/introduction rate of CO_2-into the atmosphere of the lunar base.

System control and regulation

For the correct functioning of the system pH, temperature, nutrient concentrations, toxic compounds, light intensities etc. need to be permanently monitored and adjusted if need be.

7 CONCLUSION AND APPLICATIONS ON EARTH

We hypothesized at the beginning, that source separation of human solid waste (HSW) and its pyrolytic conversion to biochar is a promising approach to achieve stability in an ECLSS. Modelling SpaceLooP Model V1 indicated that source separation indeed could contribute to a stable supply of nutrients and CO_2 in a moon base. However, it also showed that the assumptions made for model V1 led to a rather fragile system and showed that the pyrolytic process needs to be embedded in an extended scheme with an integrated O_2 / CO_2 – management. SpaceLooP model V1.1 needs to be extended with long-term storage elements, such as woody non-edible plants (for additional O_2 production as well as for CO_2 storage in woody biomass) and with additional options for quickly removing and re-introducing O_2 / CO_2 to the SpaceLooP atmosphere. Finally, exporting food should get a higher priority in the model V1.1, because one of the main tasks of this system will probably be to supply outbound space ships with food.

Regarding potential applications on Earth, the following outcomes are envisioned:

- A compact and functional on-site toilet system that directly eliminates pathogenic organisms (no more risk in handling them) while preserving the nutrients and trace elements in fecal matter.
- Apart from emergency situations, such a toilet could also be used in normal houses, thus avoiding the use of drinking water for flushing
- Sterilization of human or animal feces that can potentially be stored or transported before use may become a means to close nutrient cycles not only within a region but also between different regions
- If we succeed to find a way to utilize fecal biochar in hydroponics, this may be an additional way to re-connect nutrient cycles
- Closed-loop systems are much more prone to an accumulation of harmful substances than linear, open systems. Consequently, the use of such systems increase the pressure to follow a “cradle to cradle” zero-waste policy (100% recycling during operation) by avoiding substances that are harmful to the environment and to people

In our view, the implementation of closed-loop systems in space can significantly help to promote closed-loop thinking and applications on the Earth and help to develop more sustainable practices.

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1. Appendix: Biomass and pyrolysis product compositions used for mass balances

Table A1 H_2O, Ash, C,H,N,S,O of biomass, urine, feces and chars

	H_2O wt%	**ASH wt% dry base**	**C wt% dry base**	**H wt% dry base**	**N wt% dry base**	**S wt% dry base**	**O wt% dry base**
URINE	96.0%	40%	13%	5%	20%	2%	21%
FECES	78.9%	10.7%	49.8%	7.5%	4.9%	1.1%	26.2%
CHAR derived from feces	3.2%	11%	53%	7%	5%	1.0%	22.0%
CHAR derived from plant biomass	3.2%	1.4%	57%	4.00%	1.6%	0.3%	36.0%
FOOD from veggies	36.3%	1.2%	46.0%	5.3%	1.9%	0.193%	45.4%
PLANT WASTE MATERIAL	27.0%	1.3%	49.7%	5.9%	1.0%	0.9%	41.1%
Biomass MATERIAL TOTAL	31.2%	1%	48%	6%	1%	1%	43%

Table A2 Distribution of pyrolysis products (gas, liquid, solid) According to Serio et. al 2015 Torrefaction of fecal simulant at 300°C.

			Dry base	
	Char		88.8%	basic
	Water (pyrolytic)		5.3%	-
Gas	Carbon monoxide	CO	0.1%	
Gas	Carbon dioxide	CO_2	1.1%	
liquid	Formic acid	HCOOH	0.1%	acidic
liquid	Acetic acid	CH_3COOH	0.4%	acidic
Gas	Carbonyl Sulphite	COS	0.01%	
liquid/gas (boiling point 56°C)	Acetone	C_3H_6O	0.1%	
	Tar (by difference)		4.1%	
	Total Mass		**100%**	

2. Appendix: Detailed model description

In this following section, the inputs and outputs for each module are depicted they are partly based on stoichiometric reaction occurring within the module. In some cases the conversion of input to output is a “blackbox” and the underlying stoichiometric reactions are not known in detail (e.g. input of food = > conversion to feces). The input output balance and the principle that matter cannot be created or destroyed within the module is still respected.

CREW	**LINKED MODULE**	**INPUT**
FOOD EXTERNAL	EXTERNAL FOOD SUPPLY	CHNSO-ash
WATER IN FOOD EXTERNAL	EXTERNAL FOOD SUPPLY	H_2O
Lipids (external)	EXTERNAL FOOD SUPPLY	$CH_3(CH_2)_nCOOH$
NaCL and other ash intake (external)	EXTERNAL FOOD SUPPLY	ASH
FOOD HYDROPONIC	FOOD STORAGE	CHNSO-ash
WATER IN FOOD HYDROPONIC	FOOD STORAGE	H_2O
BREATHING	ATHMOSPHERE	O_2
WATER DRINKING	WATER STORAGE	H_2O
WATER FOOD PREP	WATER STORAGE	H_2O
		OUTPUT
RESPIRATION	ATHMOSPHERE	CO_2
TRANSPIRATION/RESPIRATION	ATHMOSPHERE	H_2O
URINE	URINE STORAGE	CHNSO-ash
WATER IN URINE	URINE STORAGE	H_2O
FECES	DRYING	CHNSO-ash
WATER IN FECES	DRYING	H_2O

NUTRIENT EXTRACTION	**LINKED MODULE**	**INPUT**
CHAR	FRESH BIOCHAR STORAG	CHNSO-ASH
WATER (STORAGE)	WATER STORAGE	H_2O
S WATER (SCRUBBER)	GAS SCRUBBER	H_2O
WATER (SCRUBBER)	GAS SCRUBBER	H_2SO_3
URINE	URINE STORAGE	CHNSO-ASH
WATER IN URINE	URINE STORAGE	H_2O
NUTRIENT EXTRACTION		**OUTPUT**
NUTRIENTS FROM BIOCHAR EX	HYDROPONIC	CHNSO_ASH
NUTRIENTS FROM URINE	HYDROPONIC	CHNSO_ASH
WATER IN NUTRIENT SOLUTION	HYDROPONIC	H_2O
S IN NUTRIENT SOLUTION	HYDROPONIC	H_2SO_3
BIOCHAR REST	DRYING	CHNSO-ASH
BIOCHAR REST (water)	DRYING	H_2O
EXCESS WATER (STORAGE)	WATER STORAGE	H_2O

HYDROPONIC	LINKED MODULE	INPUT
WATER	WATER STORAGE	H2O
WATER (nutrient solution)	NUTRIENT EXTRACTION	H2O
NUTRIENTS FROM BIOCHAR	NUTRIENT EXTRACTION	CHNOS-ASH
NUTRIENTS FROM URINE	NUTRIENT EXTRACTION	CHNOS-ASH
S FROM OFF GAS SCRUBBING	NUTRIENT EXTRACTION	H2SO3
add NUTRIENTS (required)	NUTRIENT SUPPLY	ASH / N
NET CO2-UPTAKE PHOTOSYNTHESIS	ATHMOSPHERE	CO2
NITROGEN FIXIATION (?)	ATHMOSPHERE	N2
	LINKED MODULE	**OUTPUT**
PLANT EVAPOTRANSPIRATION (based on size of hydroponic)	ATHMOSPHERE	H2O
PHOTOSYNTHESIS	ATHMOSPHERE	O2
DRY FOOD	FOOD STORE	FOOD
WATER IN FOOD	FOOD STORE	H2O
DRY WASTE BIOMASS	DRYER	PLANTWASTE
WATER IN WASTE BIOMASS	DRYER	H2O
Nutrient solution waste	WASTE	Waste ASH / NUTRIEN
Nutrient solution waste water (assumption 1% of nutsol)	WASTE	H2O

DRYING	LINKED MODULE	INPUT
FECES	CREW	CHNSO-ash
WATER PART OF FECES	CREW	H2O
WASTE PLANT BIOMASS	HYDROPONIC	CHNSO-ash
WATER IN WASTE BIOMASS	HYDROPONIC	H2O
FECAL BIOCHAR REST	NUTRIENT EXTRACTION	CHNSO-ash
WATER IN FECAL BIOCHAR REST	NUTRIENT EXTRACTION	H2O
DRYING		
DRY FECES	PYROLYSIS	CHNSO-ash
DRY PLANT BIOMASS	PYROLYSIS	CHNSO-ash
WATER VAPOUR	CONDENSER	H2O
DRY FECAL BIOCHAR REST	DEPLETED BIOCHAR ST	CHNSO-ash

PYROLYSIS	**LINKED MODULE**	**INPUT**
DRY FECES	DRYING	CHNSO-ASH
DRY PLANT BIOMASS	DRYING	CHNSO-ASH
PYROLYSIS ATHMOSPHERE N2	GAS STORAGE	N2
INTERMEDIATES		
PYROLYSIS GAS FECES		CO
PYROLYSIS GAS FECES		CO2
PYROLYSIS GAS FECES		CH4
PYROLYSIS GAS FECES		CH2O
PYROLYSIS GAS FECES		COS
PYROLYSIS GAS BIOMASS		CO
PYROLYSIS GAS BIOMASS		CO2
PYROLYSIS GAS BIOMASS		CH4
PYROLYSIS GAS BIOMASS		CH2O
PYROLYSIS GAS BIOMASS		COS
PYROLYSIS LIQUID FECES		HCN
PYROLYSIS LIQUID FECES		HCOOH
PYROLYSIS LIQUID FECES		CH_3COOH
PYROLYSIS LIQUID BIOMASS		HCN
PYROLYSIS LIQUID BIOMASS		HCOOH
PYROLYSIS LIQUID BIOMASS		CH_3COOH
PYROLYSIS WATER FECES		H2O
PYROLYSIS WATER BIOMASS		H2O
TARS		waste
PYROLYSIS		
PYROLYSIS WATER	WATER STORAGE/TREATME	H2O
PYROLYSIS OTHER LIQUIDS	WATER STORAGE/TREATME	CHNSO
PYROLYSIS FECAL BIOCHAR	FRESH FECAL BIOCHAR ST	CHNSO-ASH
PYROLYSIS PLANT BIOCHAR	DEPLETED BIOCHAR STORA	CHNSO-ASH
PYROLYSIS ATHMOSPHERE N2	GAS STORAGE	N2
TARS	WASTE	waste
PYROLYSIS GAS	BURNER	CO
PYROLYSIS GAS	BURNER	CO2
PYROLYSIS GAS	BURNER	CH4
PYROLYSIS GAS	BURNER	CH2O
PYROLYSIS GAS	BURNER	COS

BURNER	**LINKED MODULE**	**INPUT**
OXYGEN for CHAR-C-H-S COMBUS	ATHMOSPHERE	O2
CHAR	DEPLETED BIOCHAR STORAGE	CHNSO-ASH
PYROLYSIS GAS	PYROLYSIS	CO
PYROLYSIS GAS	PYROLYSIS	CO2
PYROLYSIS GAS	PYROLYSIS	CH4
PYROLYSIS GAS	PYROLYSIS	CH2O
PYROLYSIS GAS	PYROLYSIS	COS
OXYGEN for GAS COMBUSTION	ATHMOSPHERE	O2
INTERMEDIATES		
CHAR COMB		CO2
CHAR COMB		SO2
CHAR COMB		H2O
CHAR COMB		N2
CO OX		CO2
CH4 OX		CO2
CH4 OX		H2O
CH2O OX		CO2
CH2O OX		H2O
COS OX		SO2
COS OX		CO2
O2 FOR CHAR		O2
O2 FOR CO		O2
O2 FOR CH4		O2
O2 FOR CH2O		O2
O2 FOR COS		O2
BURNER		**OUTPUT**
OFF-GAS COMBUSTION	SCRUBBER	CO2
OFF-GAS COMBUSTION	SCRUBBER	SO2
OFF-GAS COMBUSTION	SCRUBBER	H2O
OFF-GAS COMBUSTION	SCRUBBER	NO
ASH	WASTE	ASH

GAS SCRUBBER	LINKED MODULE	INPUT
OFF-GAS	BURNER	CO2
OFF-GAS	BURNER	SO2
WATER VAPOUR	BURNER	H2O
OFF-GAS	BURNER	NO
SCRUBBING WATER	WATER STORAGE	H2O
GAS SCRUBBER		**OUTPUT**
SCRUBBING WATER USE	NUTRIENT EXTRACTION	H2O
SCRUBBING WATER USE	NUTRIENT EXTRACTION	H2SO3
SCRUBBING WATER STORE	WATER STORAGE	H2O
SCRUBBING WATER STORE	WATER STORAGE	H2SO3
CLEAN GAS	ATHMOSPHOERE	CO2
CLEAN GAS	ATHMOSPHOERE	N2
CLEAN GAS	ATHMOSPHOERE	O2

ATMOSPHERE	LINKED MODULE	INPUT
PLANT PHOTOSYTHESIS	HYDROPONIC	O2
CREW RESPIRATION	CREW	CO2
CREW RESPIRATION	CREW	H2O
CREW GAS	CREW	H2
PLANT EVAPOTRANSPIRATION	HYDROPONIC	H2O
GAS SCRUBBING	SCRUBBER	CO2
GAS SCRUBBING	SCRUBBER	O2
CO2 BALANCING	EXTERNAL	CO2
O2 BALANCING	EXTERNAL	O2
ATMOSPHERE		**OUTPUT**
PLANT PHOTOSYTHESIS	HYDROPONIC	CO2
CREW RESPIRATION	CREW	O2
CHAR BURNING	BURNER	O2
WATER VAPOUR	CONDENSER	H2O
GAS BURNING	BURNER	O2

CONDENSATION	**LINKED MODULE**	**INPUT**
BIOMASS DRYING	DRYER	H2O
AIR WATER VAPOUR	ATHMOPHERE	H2O
CONDENSATION		**OUTPUT**
CLEAN WATER	WATER STORAGE	H2O

WATER STORAGE	**LINKED MODULE**	**INPUT**
WATER CONDENSATION	CONDENSATION	H2O
WATER PYROLYSIS	PYROLYSIS	H2O
PYROLYSIS OTHER LIQUIDS	PYROLYSIS	CHNSO
WATER SCRUBBING	SCRUBBER	H2O
COMPONENTS FROM SCRUBBING	SCRUBBER	H2SO3
EXCESS WATER NUTRIENT EXTRACTION	NUTRIEN EXTRACTION	H2O
WATER SUPPLY	EXTERNAL	H2O
WATER STORAGE		**OUTPUT**
DRINKING WATER CREW	CREW	H2O
FOOD PREP WATER CREW	CREW	H2O
WATERING HYDROPONIC (replenish water)	HYDROPONIC	H2O
WATER SCRUBBING	SCRUBBER	H2O
WATER NUTRIENT EXTRACTION	NUTRIEN EXTRACTION	H2O
TREATMENT WASTE	WASTE	CHNSO-ASH

FOOD STORAGE	**LINKED MODULE**	**INPUT**
FOOD	HYDROPONIC	CHNSO-ASH
WATER IN FOOD	HYDROPONIC	H2O
FOOD STORAGE		**OUTPUT**
FOOD	CREW	CHNSO-ASH
WATER IN FOOD	CREW	H2O

URINE STORAGE	**LINKED MODULE**	**INPUT**
Urine	CREW	CHNSO-ASH
Urine water	CREW	H2O
URINE STORAGE		**OUTPUT**
Urine	NUTRIENT EXTRACTION	CHNSO-ASH
Urine water	NUTRIENT EXTRACTION	H2O
Urine water	WATER STORAGE	H2O
Urine salts/ash	WASTE	CHNSO-ASH

DEPLETED BIOCHAR & PLANT BIOCHAR	**LINKED MODULE**	**INPUT**
DEPLETED FECAL BIOCHAR	DRYING	CHNSO-ASH
FRESH PLANT BIOCHAR	PYROLYSIS	CHNSO-ASH
DEPLETED BIOCHAR & PLANT BIOCHAR		**OUTPUT**
COMPLETE BIOCHAR	BURNER	CHNSO-ASH

FRESH BIOCHAR STORAGE	**LINKED MODULE**	**INPUT**
CHAR	PYROLYSIS	CHNSO-ASH
FRESH BIOCHAR STORAGE		**OUTPUT**
CHAR	NUTRIENT EXTRACTION	CHNSO-ASH

WASTE IN	**LINKED MODULE**	**INPUT**
WATER TREATEMENT WASTE	WATER STORAGE	CHNSO-ASH
ASH	BURNER	ASH
WASTE TARS	PYROLYSIS	TAR
WASTE URINE ASH/SALTS	URINE	CHNSO-ASH
SUPPLY OUT		**OUTPUT**
Dry FOOD EXTERNAL	CREW	CHNSO-ash
Water in FOOD EXTERNAL	CREW	H2O
Lipids (external	CREW	CH3(CH2)nCOOH
NaCL and other ash intake (externa	CREW	ASH
WATER	WATER STORAGE	H2O
ADDITIONAL NUTRIENTS	HYDROPONIC	CHNSO-ASH
CO2 BALANCING	ATHMOSPHERE	CO2
O2 BALANCING	ATHMOSPHERE	O2