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Nitrogen cycling in Bioregenerative Life Support Systems: Challenges for waste refinery and food production processes

Peter Clauwaert[a,*], Maarten Muys[b], Abbas Alloul[b], Jolien De Paepe[a], Amanda Luther[a], Xiaoyan Sun[a], Chiara Ilgrande[a], Marlies E.R. Christiaens[a], Xiaona Hu[a], Dongdong Zhang[c], Ralph E.F. Lindeboom[a,d], Benedikt Sas[e], Korneel Rabaey[a], Nico Boon[a], Frederik Ronsse[c], Danny Geelen[f], Siegfried E. Vlaeminck[a,b]

[a] Center for Microbial Ecology and Technology (CMET), Ghent University, Coupure Links 653, 9000 Gent, Belgium
[b] Research Group of Sustainable Energy, Air and Water Technology, Department of Bioscience Engineering, University of Antwerp, Groenenborgerlaan 171, 2020 Antwerpen, Belgium
[c] Department of Biosystems Engineering, Ghent University, Coupure Links 653, 9000 Gent, Belgium
[d] Section Sanitary Engineering, Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628CN Delft, The Netherlands
[e] Department of Food Quality and Food Safety, Ghent University, Coupure links 653, B-9000 Gent, Belgium
[f] In Vitro Biology and Horticulture Lab, Department of Plant Production, Faculty of Bioscience Engineering, Ghent University, 653 Coupure Links, 9000 Gent, Belgium

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ABSTRACT

In order to sustain human life in an isolated environment, an efficient conversion of wasted nutrients to food might become mandatory. This is particularly the case for space missions where resupply from earth or in-situ resource utilization is not possible or desirable. A combination of different technologies is needed to allow full recycling of e.g. nitrogenous compounds in space. In this review, an overview is given of the different essential processes and technologies that enable closure of the nitrogen cycle in Bioregenerative Life Support Systems (BLSS). Firstly, a set of biological and physicochemical refinery stages ensures efficient conversion of waste products into the building blocks, followed by the production of food with a range of biological methods. For each technology, bottlenecks are identified. Furthermore, challenges and outlooks are presented at the integrated system level. Space adaptation and integration deserve key attention to enable the recovery of nitrogen for the production of nutritional food in space, but also in closed loop systems on earth.

1. Introduction

At present, human life in space flights and in the International Space Station (ISS) is guaranteed by a regular resupply of food and water. However, in order to explore deep space with long-term missions and space habitation with increasing crew size, resupply from and return of waste to earth becomes difficult because of the long transport time and high costs associated with mass and volume restrictions for transportation [1–3]. The mass requirements of 5500–12800 kg per crew member per year for Open Life Support Systems (OLSS) without recycling can be lowered to 340–470 kg per crew member per year in a Physicochemical Life Support System (PLSS) (e.g. ISS) by in situ generation of oxygen and water recycling, consuming ~300 W per crew member [1]. The current launch cost advertised by SpaceX service is about $12600 per kilo [1]. In order to further decrease this payload mass and costs for resupply for long-term exploration or permanent habitation in life support systems, in situ food production has been proposed. Such systems are called Bioregenerative Life Support Systems (BLSS) or Closed/Controlled Ecological Life Support Systems (CLSS) [4].

Certain physicochemical methods for recovery of water and air have been developed for use in PLSS and are currently in use at the ISS, but technologies for food production based on nutrient recovery are neither validated nor available for space deployment. On earth, we rely on a vast set of biological production systems to produce food, mainly based on plants and animals, which are in essence based on inorganic nutrients often supplied as fertilizers [5]. In BLSS research, the development of an engineered bio-based system for food production has been investigated by major governmental space research agencies for the past half century [6–9]. The shared focus of these BLSSs has

* Corresponding author.
E-mail address: peter.clauwaert@ugent.be (P. Clauwaert).

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been the integration of different biological and physicochemical technologies for the breakdown and conversion of waste products into useful building blocks for plant food production in a closed material recycle. Nitrogen is a critical nutrient for this cycle, and will be the focus of this review. Processes for nitrogen retention, recovery, and resupply in a closed system will be considered here.

2. Refinery stages: converting waste into a fertilizer

There is currently no reuse of nitrogen on the International Space Station (ISS). Fecal material is collected, stored and returned to earth without nutrient recovery, while fresh urine is treated by chromium trioxide and sulfuric acid dosing to avoid microbial growth, which would convert urea into volatile and potentially harmful ammonia. Water is recovered from pretreated urine by vapour compression distillation (VCD) through which nitrogen ends up in a brine which becomes a nitrogen dead end as well [10].

Human activity and crop production in a BLSS result in the production of different types of organic wastes, all containing nitrogen. A dietary protein intake of 0.8–1.5 g protein kg^{-1} body weight for a crew member with a body weight between 65 and 85 kg is expected to result in a urinary excretion of between 7 and 16 g N d^{-1} (assuming ~16% N in proteins and ~80% N-excretion via urine [7,11,12]). Fecal nitrogen excretion is typically in the order of 1–2 g N d^{-1} [13] (Fig. 1). Based on the assumptions of Hu et al. [8], 5–6 g N d^{-1} per crew member would be collected as inedible biomass (crop residues, kitchen waste) in the proposed BLSS and ~1 g N d^{-1} would be collected as epithelial associated organic waste (hair, nails, saliva solids, dead skins cells, …). In order to make this nitrogen available again for the production of food in a BLSS, these waste streams need to be treated to produce fertilizers adapted to the specific needs of the food production processes. Different technologies have been proposed over the past decades for BLSS (Fig. 2) for conversion of organic wastes into carbon dioxide, water and nutrients. For recovery of this nitrogen in a bioavailable form, three main strategies can be distinguished: biological or physicochemical ammonification, and nitrification.

2.1. Biological ammonification

Most of the nitrogen in the organic waste streams in BLSSs is bound in organic compounds. Although using organic nitrogen (amino acids, urea) for plant production may have biostimulatory effects [14–17], providing inorganic nitrogen (ammonia and nitrate) is often preferred as it allows online monitoring and control of the nitrogen loading and uptake by crops in hydroponic systems and by bacteria in bioreactors for microbial protein production. The first step in converting this organic nitrogen to the desired form for food production is biological ammonification of the organic waste (Fig. 2): proteins and peptides are converted into amino acids by proteases produced by living organisms, while amino acids and other amide containing molecules can be

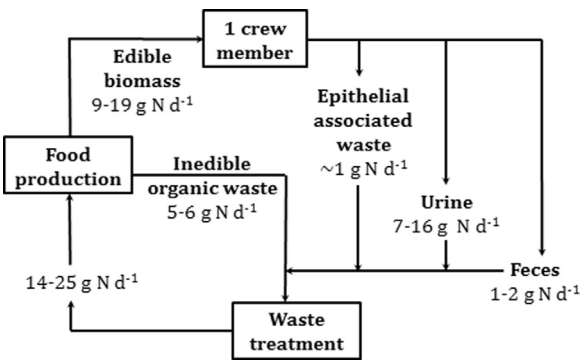

Fig. 1. Schematic diagram of the theoretically calculated nitrogen balance in a BLSS for one crew member, based on values from [7,8,13].

hydrolyzed by amidases to form ammonia. Urea ($CO(NH_2)_2$), which contains more than 90% of the nitrogen in fresh urine [18], can be ammonified by the widespread enzyme urease or by urea amidolyase [19].

In several concepts of the BLSS, microbial hydrolysis of organic waste occurs in a dedicated aerobic [8,20–23] or anaerobic [24–26] bioreactor. Besides hydrolysis of organic compounds, biological ammonification and the release of other nutrients from the organic matrix is established with the help of microorganisms. In the current concept of the BLSS of the European Space Agency (ESA), the 'Micro-Ecological Life Support System Alternative' (MELiSSA), organic waste is fermented in a thermophilic anaerobic membrane bioreactor at pH 5.3 to inhibit methanogenesis and to maximize the formation of volatile fatty acids (VFA). Typically, between 18% and 71% of the organic nitrogen in the waste (plant residues and fecal material) could be converted into ammonium at a rate between 17 and 30 mg NH_4^+-N L^{-1} d^{-1} in this waste treatment compartment [27–30].

The main challenges in aerobic ammonification systems are the difficulty of diffusion driven aeration under microgravity conditions and the high microbial sludge yield growth under aerobic growth. The lower sludge yield under anaerobic conditions is advantageous on one hand, but the separation and downstream processing of the gases that are produced (methane, hydrogen) is challenging on the other hand. Additionally, if nitrate rich organic crop residues are treated in anaerobic conditions, nitrate could be reduced to ammonia via dissimilatory nitrate reduction but denitrification, resulting in gaseous nitrogen losses, is likely to occur.

Bioreactors with immobilized urease enzymes have been proposed to convert the urea in human urine into ammonia and carbon dioxide for space applications [31]. Nicolau et al. [32] combined this concept with electrochemical oxidation of the ammonia for electrical power production.

2.2. Physicochemical ammonification

Hydrolysis of nitrogen-containing organic compounds can also be achieved by means of physicochemical processes. Hydrolysis of proteins occurs under acidic and alkaline conditions, but also the use of microwave radiation, high pressure and enzymatic treatment as well as combinations of such treatments have been described [33,34].

Hot water conversion is one commonly tried method to physicochemically hydrolyze nitrogenous compounds. Hydrolysis in hot water is only effective at temperatures above 140–160 °C (and at corresponding pressures to keep water in a liquid state), as below these temperatures only denaturation and insolubilisation of proteins occur [35–37]. Hydrolysis of proteins into amino acids has the highest yield in the temperature range of 200–290 °C [38–40]. When water is heated to just below its critical point (T_c=374 °C and p_c=22.1 MPa [41,42]), its ionic product will rise from 10^{-14} at ambient temperature, to 10^{-11} at near-critical conditions [43]. As a consequence, the higher concentration of protons and hydroxyl ions from the dissociation of water will lead to a higher extent of acid and base catalyzed reactions with nitrogenous organic compounds [44]. Further increasing the temperature in the sub-critical region (i.e. between 250 and 374 °C) will enhance deamination reactions of the amino acids as intermediates, yielding free NH_4^+ and carboxylic acids [45,46], although competing polymerisation reactions such as amide formation and Maillard type reactions (i.e. reactions with sugars) [47,48] could occur.

With respect to BLSS, Lissens et al. [27] reported that 95–100% of all nitrogen present in the biosolids from an anaerobic digester could be converted into water-soluble components through hydrothermal degradation (~350 °C and ~240 bar). The anaerobic digester was fed with a mixed organic stream (food crops, fecal material, algae) resembling a concentrated organic waste stream produced by humans. About 60% of the nitrogen in the effluent of the hydrothermal unit could be identified as NH_4^+-N and NO_3^--N, while the remaining