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I. MAN AND BIOSPHERE

LIFE SUPPORT SYSTEMS BEYOND LOW EARTH ORBIT ADVOCATES FOR AN IMPROVED RESOURCES MANAGEMENT APPROACH

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Abstract: Nowadays, there are still many challenges to overcome in order to enable long-termed human space exploration beyond low Earth orbit (LEO) and metabolic resources management (reliable air, water and food supply for the crew) is of utmost importance. Currently, Environmental Control and Life Support Systems (ECLSS) aim to overcome the challenge of constant re-supply from Earth requirement by revitalization of air and water. Here, we provide an overview of the existing and operating ECLSS on-board the International Space Station (ISS) as well as identify potential areas of technology development for biological ECLSS for long-term human space missions focusing on the inclusion of waste treatment and food production.

Keywords: Regenerative Life Support Systems, MELiSSA, Mars Transit Mission, ECLSS

INTRODUCTION

The desired extended space exploration beyond low Earth orbit (LEO) with longer human stay in space introduces a new mission element: the constrained access to consumables and resources [1], [2]. The logistics required to keep the crew safe and healthy during these missions beyond International Space Station (ISS) is a first-order driver in mass and volume requirements [3]. Nowadays, ISS logistics are uploaded on demand in cargo vehicles and waste products are either vented out or loaded into descent cargo modules for subsequent destruction upon re-entry [2], [4], [5]. This *modus operandi* is not feasible for space exploration missions beyond Earth orbit, such as a Mars Transit Mission (MTM), which will require a high level of resources management. Hence, it is of utmost importance to develop a roadmap to expand the consumables as potential resources enabling human space missions to be independent from Earth resupply. Regenerative Environmental Control and Life Support Systems (ECLSS) have become an unique alternative to overcome the aforementioned limitations [6]. The European Space Agency (ESA) has been a pioneer in the development of highly regenerative ECLSS with the implementation 30 years ago of the European Project: Micro-Ecological Life Support System Alternative (MELiSSA) [5], [7]–[11]. The driving elements of MELiSSA is a closed life-support system based on a circular approach focusing on a global overview of the complete life-support system aiming for the production of food, water (H_2O), and oxygen (O_2) from the organic wastes of the mission.

The objectives of this article are not to propose an ECLSS design for a Mars Transit Mission, but more modestly to give an overview of the currently operating ECLSSs on-board ISS, to identify the needs for future human explorations, to formulate some high level recommendations and to highlight some of the MELiSSA developments.

STATE-OF-THE-ART ON ECLSS ON-BOARD ISS AND IMPLICATIONS FOR MARS TRANSIT MISSION

Human metabolism requires as a minimum 5kg/day/person, distributed as 1.62 kg of drinking H_2O, 2.57 kg of food and 0.84 kg of O_2 [2], [4], [5]. To date, ECLSSs in space have only been studied and developed for LEO purposes, and due to the Earth proximity [12], [13], a limited concern over robustness, long-term operations and maintenance has been raised. Developments have first been driven by CO_2 and humidity control, as well as metabolic needs (e.g. O_2 supply). Over the years, this approach has progressively been extended to H_2O recovery from urine and to technology demonstrators for O_2 recovery from CO_2 [14]–[16]. Yet, a large number of the mission consumables (i.e. packaging, tissues or clothing), have still never been considered as potential re-used resources, neither included as elements of ECLSSs developments. Additionally, due to the rather high frequency of Earth cargo resupply to ISS, the quality of the long-term stored resources (e.g. food), has faced limited questioning. For the same reasons, the ISS ECLSS has been designed with limited priority given to maintenance. For deep-space missions, ECLSSs will face the challenges of relying on absolutely no Earth re-supply in terms of metabolic needs or spare parts [17], [18]. Additional challenges will come into play with the higher radiation exposure beyond the Van Allen belts.

The following sections provide an overview of the current state-of-the-art for the major ECLSS sub-systems currently operating on-board ISS and the perspective for ECLSSs evolution in the

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context of a MTM. For ease of reading, each sub-system has been addressed separately. However, it is important to remember that for a MTM scenario these sub-systems will be interdependent and cannot be disconnected from one to another, be it from fluxes (e.g. gas, liquid, solid), neither from an operational or mission perspective. Table 1 provides a summary of the identified current logistics for ISS and ECLSSs in place as well as opportunities and enabling technology for deep space exploration.

Water Management

On-board ISS, water contributes to the majority of the mass requirements when compared to other life support consumables, including: (1) drinking water for crew, (2) water for food preparation and hygiene, (3) flush water, (4) water for use in O_2 generation by electrolysis, (5) water for spacesuits cooling and (6) water to various payloads as required [19]. To meet these needs, the largest available sources of water are humidity condensate (from crew sweat, respiration and hygiene) and urine, followed by CO_2 reduction (i.e. Sabatier) and wet trash and fecal water. Waste water is collected from the above mentioned sources and subsequently processed by the Water Recovery System (WRS) into potable water. The WRS includes the Urine Processor Assembly (UPA), which is responsible for the urine water recovery of pre-treated urine via Vapor Compression Distillation [19]. However, this process is restricted by the solubility of various compounds in the pre-treated urine (i.e. calcium phosphate and calcium sulfate, from the crew bone loss in microgravity). This produces concentrated brine requiring further processing in support of water recovery [20]. Sustainable and efficient processes still need to be identified to reduce the impact of contaminants on the waste water treatment system efficiency [21]. The ISS WRS is also still limited in terms of lifetime and durability due to the need for several processing steps and resupply of hazardous chemicals and filter units to allow the system components to maintain their targeted performance [19], [21].

Closing the water loop above 98% on a MTM is often presented as one of the key challenges of mission mass reduction. This number should however be put in perspective with the hardware mass, energy budget and crew time values as well as with the associated spare parts and consumables mass values. Nowadays, on board ISS, water recovery from urine is estimated to be around 75% [19], but higher efficiency shall be reached. Investigations should now include both incremental improvements of existing systems, including investigation of yet unproven innovations. Higher recycling performance and reliability could be achieved by developing a system with independent recycling paths for condensate, used wash water and urine and flush. As an example, wastewater brine produced from water recovery systems contains chemical species that can be processed into a potential fertilizer for future plant systems, hence reducing the need for uploaded fertilizers [22].

Oxygen Management

Today, when in operation, the ISS Oxygen Generation System (OGS) produces O_2 for the crew to breathe, recovering approximately 42% of the required O_2 from metabolic CO_2. The system consists of the Oxygen Generation Assembly (OGA) and the Carbon Dioxide Reduction Assembly (CDRA)[23]–[25]. The OGA electrolyzes water provided by the Water Recovery System (WRS), yielding O_2 and Hydrogen (H_2) as by-products [19]. The O_2 is delivered to the cabin atmosphere while the H_2 is either vented into space or fed to the CDRA where it is used along with CO_2 exhaled by the crew in a Sabatier reactor. The by-products of this process are methane (which is vented to space too) and water for the crew.

The challenge of 75% O_2 recovery from $CO_{2,}$ often targeted by exploration programme of space agencies and which in terms of stoichiometry is the highest possible value, questions seriously the suitability of the OGA for a MTM scenario. Thus, this challenge will imply major efforts in terms of process understanding, reliability and maintainability [26]. In this respect, air regeneration via the well-known stoichiometry of photo-synthesis (e.g. photo-bioreactor or green house) is an interesting alternative to overcome the 75% efficiency challenge. It would enable O_2 recovery as well as and Nitrogen (N_2) recovery while contributing to food complement production (i.e., proteins) [27]. A reasonable part of the produced biomass could be included in crew diet or material spare parts (Ink from Organic Waste for Additive Manufacturing in Space, Blue Horizon, https://www.melissafoundation.org/download/737).
Today, several low Technology Readiness Level projects exist for the demonstration of the photo-bioreactor functionality and performance of the microgravity-sensitive components, such as gas exchange, biomass/liquid separation, on board ISS [28].

Table 1: Summary of the identified current logistics for ISS, ECLSSs in place and enabling technology for deep space exploration.

	Consumables		***Consumable Rate Today: ISS*** $^{1-5}$	***ECLSS Technology Today: ISS***	***Recycling Level Today (x%, Technology Demonstrator, etc.)***	***ECLSS Technology Future: Deep space***
Life support and environmental monitoring	Oxygen	O_2 metabolic Cabin air leakage	0.82 kg/crew/day 0.0045 kg/day	Water electrolysis, Sabatier reaction	Targeted ~50 % from metabolic carbon dioxide (not obtained so far) [43] < 6 months mean time before failure	> 75% O_2 recovery from CO_2 > 30 months mean time before failure Alternative technologies (algae cultured in photo-bioreactor)
	Nitrogen	Cabin air leakage/ullage	0.5 kg/tank	Resupplied from Earth		> 90% N_2 recovery from urine Fertilizer recovery from urine
	Food	Food	0.62 kg/crew/day	Resupplied from Earth	0	*In-situ* production (e.g. from algae)
		Food packaging	0.27 kg/crew/day	Resupplied from Earth	0	Packaging repurposed upon microbial inhibition Biodegradable/reusable packaging
	Water	Potable water	2 kg/crew/day	Urine water recovery via Vapour Compression Distillation. Sabatier reactor product water	~75% H_2O recovery from Urine Process Assembly [44]	> 98% H_2O recovery
		Hygiene	0.4 kg/crew/day		0	
		Food rehydration	0.5 kg/crew/day		0	
		Medical	0.05 kg/crew/day		0	
		Flush	0.23 kg/day		0	
Logistics	Towels	Towel	0.022 kg/crew/day	Resupplied from Earth	0	Lighter and washable fabric Textile fabric compatible with bio-polymer for 3D printing Biodegradable fabric
		Hygiene wash	0.069 kg/crew/day	Resupplied from Earth	0	
		Washcloth	0.009 kg/crew/day	Resupplied from Earth	0	

Hygiene	Toothpaste; shampoo/soap (non-rinse); deodorant; hair brush/comb; dental floss; lip balm; skin cream; ear plugs; razors; sleep mask	0.079 kg/crew/day	Resupplied from Earth	0	Limited recovery
Clothing		0.22 kg/crew/day	Resupplied from Earth	0	Long wear lighter and washable clothing Biodegradable fabric
Healthcare	Personal medications and other medical items that are specific to the crew. Does not include medical equipment that are part of the spacecraft.	0.09 kg/crew/day	Resupplied from Earth	0	Limited recovery
Trash bags		0.03 kg/crew/day	Resupplied from Earth	0	Bags repurposed Biodegradable materials
Waste collection	Faecal canisters Urine pre-filter Fecal/urine collection bags LiOH canisters	0.22 kg/crew/day 0.02 kg/crew/day 0.17 kg/crew/day 1.75 kg/crew/day	Resupplied from Earth Includes urine filters, funnels, hoses & pre-treatment Used for waste collection rate. Used for regenerative CO_2 removal system.	0 0 0 0	Bags/foam repurposed for 3D printing Biodegradable/reusable packaging
Waste	Total (metabolic and non-metabolic)	2 kg/crew/day	Stored, disposed and burnt upon re-entry	0	Resource recovery (water, Carbon, Nitrogen, etc) On-orbit manufacturing of tiles for shielding

1: [19]**, 2:** [45]**, 3:** [46]**, 4:** [47]**, 5:** [48]

Nitrogen Management

Any airtight structure exposed to high pressure gradient is prone to leakage. The ISS is no exception, with roughly 100 kg lost per year in N_2 (80%), O_2 (20%) and some additional mass loss mainly due to EVA activities [29], [30]. These leaks are today fully compensated by re-supply from Earth. Therefore, in the context of a MTM, the management of N_2 cannot be handled by the deployment of an existing ISS sub-system. Water recovery from urine is already well demonstrated and operated on board ISS. Yet, urine includes other resources of potential interest [30]–[32]. As an example, the urea produced via proteins degradation during human metabolism functions shows a high nitrogen content. Early estimations demonstrated that around 6.4L of N_2 gas could be recovered per crew on a daily basis and could compensate for the majority of the vehicle leaks. Preliminary feasibility results via nitrification/denitrification have been already obtained (Siegfried et al. Unpublished data).

Food management

The primary role of the current ISS food system is nutrition delivery focusing on fulfilling crew nutritional requirements. Despite preliminary investigations (e.g. Veggie), it fully relies on logistics support. Although this system has evolved overtime to reach the highest possible level of cost effectiveness and acceptance by the crew, recent advances demonstrate additional potentials [33]–[36]. In the perspective of missions beyond LEO, the role of the food sub-system needs to be re-considered and needs to clearly include its contribution to socio-medical aspects, which become paramount for the success of such mission. In addition, any future space food system will need to meet basic requirements in-line with the associated space mission concept: safety, stability (i.e. shelf-life), palatability, nutrition delivery, resource minimization, variety, reliability, usability, space-ready appliances [37]. Beyond Van Allen belts, crew will be exposed to higher radiation levels. The impact on the intestinal microbiota will have to be better understood before final requirements on the diet can be elaborated, and consequently on the potential food production too. The food production sub-system shall be included in the overall design of the life support system and its impact on the CO_2 and N_2 shall be evaluated.

When envisaging a MTM food system *in-situ* production, the ability to combine various ingredients into food items by additive manufacturing is also considered highly valuable to provide variety to the crew, while guaranteeing the nutritional value of the dishes. While not essential in an ISS context, development and proofing of such capability on the ISS will be invaluable to ensure availability of such technology in a MTM context. Food printing systems shall preserve the nutritional value of their constituents, while offering satisfactory sensory experience to the crew. To conclude on this potential (i.e. quantitative analysis, trade-offs and computation of the breakeven point), further studies and developments are needed to go from laboratory work to scaled technology. Non-edible biomass can be considered as a substrate for 3-D printing of mechanical spare parts, as already demonstrated (Ink from Organic Waste for Additive Manufacturing in Space, Blue Horizon, https://www.melissafoundation.org/download/737).

Waste management

On top of the human generated metabolic wastes (e.g. perspiration, CO_2, urine faeces), the average daily waste generated on ISS per crewmember is approximately 1.5 to 2 kg, which includes clothing, paper, foam packaging, wipes and other personal hygiene items, EVA supplies [4], [5], [12], [17], [30]. Yet, waste products are currently not recycled on-board ISS and are temporary stored according to waste categories (crew, hardware, payload and launch restraints) and loaded into visiting cargo modules for subsequent destruction upon re-entry. This waste management not only does not provide any significant volume reduction and stabilization, but it also hampers recovery of critical resources, such as water and carbon. Besides, it exposes the crew to (bio-)safety risks during the temporary storage period.

This ISS waste management concept is unviable for a MTM. Hence it is imperative that the commonly accepted mentality of “waste, trash, refuse” is replaced by “waste, trash, reuse”. In this respect, integration of new technologies to enable recycling, such as waste compactors to transform waste into tiles for radiation protection or into ink for 3D-printing are being developed (ESA internal communication). In addition, initiatives are on-going to re-define the selection of materials, choosing for biodegradable polymers, especially for food and beverages packaging that can become reusable source of carbon.

Clothing and hygiene management

Nowadays, clothing is worn as long as tolerable to the crew and launched incrementally to sustain crew needs. Commercially off-the shelf clothing is used and is mainly composed of cotton. Hygiene items include wipes, towels, shampoo, sanitary items, etc. and are not recycled either. It is estimated that each crew member requires 0.3 kg hygiene items on a daily basis [4], [5].

In the context of a MTM, new fabrics for crewmember clothing will be required, focusing on extending the life of a garment and thus minimizing the number of items required for the overall mission. This approach shall also consider fabrics that can be recycled into different tools such as ink for 3D-printing. Activities are being implemented to study innovative micro-fibres and textile materials, aiming to elongate the shelf life of the textile while focusing as well on the recycling aspects (ESA internal communication).

PRELIMINARY RECOMMENDATIONS FOR THE ELABORATION OF A MTM ECLSS

In light of the state-of-the-art presented in the previous section, some preliminary considerations can be formulated in the context of a MTM.

There is an obvious need to elaborate the ECLSS requirements for a MTM. The continuous trade-off, selection and integration steps will require to upgrade the level of understanding and characterization of a larger number of scientific and technical domains. Though this is not meant to be an elaborated list, priorities can be given to: radiation effect and protection; human microbiota; food elaboration; multi-phases processes; hygiene and microbial safety. As an example, the design, development, operations and maintenance of a complex circular system cannot be performed without a higher degree of characterization and understanding of multi-phases processes. Additionally, system tools to simulate, emulate and select the most appropriate ECLSS architecture will have to be deployed. The life and physical sciences and life support challenges will undoubtedly impose a multi-disciplinary approach. A few examples can be provided in this regard:

- All consumables of the mission shall be considered as a potential resource,
- All process energy and/or exergy shall be considered to reach the best energy balance,
- Food is not only a metabolic need but shall also be considered as a potential health and psychological issue,
- Water resources are not only additional mass but shall also be considered for radiation shielding,
- Microorganisms have not been included in ECLSS so far as they are often considered as a potential source of contamination. Yet, they could also be potentially involved in transformation processes,
- The human microbiota is a part of a circular ECLSS and shall be characterized as such,
- End-products which cannot be transformed into metabolic consumables could become material for spare parts,
- Fundamental sciences shall be looked at to support process characterization to reach higher levels of performance.

MELISSA DEVELOPMENTS IN THE CONTEXT OF A MTM

The preliminary recommendations formulated in the previous section are at the core of ESA's MELiSSA project. MELiSSA has been focusing for the last 30 years on enabling technology fields for the sustainable and long term presence of mankind in space as well as conducting direct liaison with the urgent need to facilitate a sustainable use of limited resources and associated risks in our terrestrial ecosystem [5], [7]–[11]. Based on a unique expertise of multiphase processes in reduced gravity, current on-going MELiSSA technology demonstrators aim at advancing Technology Readiness Level (TRL) of life-support systems and at demonstrating the functionalities, performances and basic operations of selected recycling processes in micro-gravity, among other, the following: *i)* ARTEMISS, characterizing the response of *Arthrospira sp.* PCC8005 to *in situ* spaceflight conditions, and its impact on the bioprocess in the photo-bioreactor [27]; *ii)* BIORAT, Flight demonstrator of a regenerative process for air loop closure, improved water loop closure (i.e. urine treatment), and food supplement production (i.e. protein rich biomass) [7], [27], [30], [38]; *iii)* URINISS, Investigation of the bacterial components and processes of biological urine treatment in space conditions focusing on metabolic conversion efficiencies and rates determination [31], [39]; *iv)* WAPS, Water Across Plants evaluates the effects of microgravity on morphological and physiological traits of plant organs with a specific reference to the water flow pathway across the whole plant [7].

In parallel, the MELiSSA project also puts emphasis on ground demonstrators to demonstrate the operability and relevance of technologies with humans in the loop and for long periods of time. MELiSSA Pilot Plant (MPP) [40], [41], Concordia base [42], Lunares and Spaceship.fr are some examples of facilities which include MELiSSA technology ground demonstrators.

Besides, MELiSSA is actively involved in the identification of material candidates and proof of concept of recycling and manufacturing as well as on improving waste handling and management approach implemented in crewed exploration missions, particularly focusing on aspects related to waste biosafety and encumbrance. Study of technological solutions to inhibit decomposition, compact and re-process selected wastes, which also make use of biodegradable packaging are being conducted as well. Over the last 50 years, many projects of circular life support systems have been created and later-on disappeared (e.g. CELSS, Bioplex, space activities in CEEF, C2-3A, etc.). The reasons can potentially be found in an undervaluation of the challenges, evolution of national strategies, followed by a drastic budget cut after a few years. Nowadays, the challenge of circular systems is not solely led by space challenges and synergies with terrestrial challenges are obvious. Although rarely involving biological processes, the space sector is used to studying and designing complex systems. Lessons learned from past experience, associated with a more multi-disciplinary approach, including terrestrial experts in science and technology, is highly recommended. As an example, the philosophy of the MELiSSA project enables spin-in and spin-off of relevant technologies, representing a gateway project to link space activities to terrestrial use and *vice versa (ezCOL BV, Hydrohm, SEMiLLA IPStar, SEMiLLA Health BV, SEMiLLA Sanitation BV, etc).*

CONCLUSION

The way ahead to make the desired extended space exploration beyond LEO possible relies on the development of multidisciplinary, synergistic and closed ECLSSs valorising consumables and wastes. In order to be successful, a comprehensive roadmap needs to be established following intermediate and sequential steps, starting from the definition of the requirements of a MTM ground based analogue test bed, with stepwise integration of the many subsystems in a realistic environment with humans in the loop with a focus on Advances ECLSSs, followed by defining the requirements for an inflight validation of subsystems on the ISS when possible.

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REFERENCES

[1] E. Musk, “Making Humans a Multi-Planetary Species,” *New Sp.*, vol. 5, no. 2, pp. 46–61, 2017, doi: 10.1089/space.2017.29009.emu.

[2] E. Seedhouse, *Life Support Systems for Humans in Space*. 2020.

[3] B. Mattfeld, C. Stromgren, H. Shyface, D. R. Komar, W. Cirillo, and K. Goodliff, “Trades between opposition and conjunction class trajectories for early human missions to mars,” *AIAA Sp. 2014 Conf. Expo.*, pp. 1–17, 2014.

[4] J. L. Broyan *et al.*, “Exploration Mission Benefits From Logistics Reduction Technologies,” *AIAA 46th Int. Conf. Environ. Syst.*, no. July, 2016.

[5] M. K. Ewert and J. L. Broyan, “Mission benefits analysis of logistics reduction technologies,” *43rd Int. Conf. Environ. Syst.*, pp. 1–10, 2013, doi: 10.2514/6.2013-3383.

[6] I. I. Gitelson *et al.*, “Life support system with autonomous control employing plant photosynthesis,” *Acta Astronaut.*, vol. 3, no. 9–10, pp. 633–650, 1976, doi: 10.1016/0094-5765(76) 90103-X.

[7] C. Lasseur *et al.*, “Melissa: The European project of closed life support system,” *Gravitational Sp. Biol.*, vol. 23, no. 2, pp. 3–12, 2010.

[8] C. J. Savage, C. Lasseur, E. Control, L. S. Section, and T. Centre, “S0094-5765(01)00110-2,” vol. 49, no. 3, pp. 331–344, 2001.

[9] C. Lasseur, W. Verstraete, J. B. Gros, G. Dubertret, and F. Rogalla, “Melissa: A potential experiment for a precursor mission to the moon,” *Adv. Sp. Res.*, vol. 18, no. 11, pp. 111–117, 1996, doi: 10.1016/0273-1177(96)00097-X.

[10] C. Lasseur and D. Schmitt, “Biological Life Support within ESA past and future developments,” *SAE Tech. Pap.*, no. 724, 2000, doi: 10.4271/2000-01-2338.

[11] S. Paladini, K. Saha, and X. Pierron, “Sustainable space for a sustainable Earth? Circular economy insights from the space sector,” *J. Environ. Manage.*, vol. 289, no. January, p. 112511, 2021, doi: 10.1016/j.jenvman.2021.112511.

[12] S. S. Jahnke *et al.*, “Orbital Hub: a concept for human spaceflight beyond ISS operations,” *CEAS Sp. J.*, vol. 10, no. 3, pp. 355–379, 2018, doi: 10.1007/s12567-018-0203-y.

[13] P. Robotic and H. S. Exploration, “IAA Space Exploration Conference,” no. January, pp. 1–7, 2014.

[14] D. E. Williams, J. R. Dake, and G. J. Gentry, “International space station environmental control and life support system status: 2009 - 2010,”

40th Int. Conf. Environ. Syst. ICES 2010, no. 724, 2010, doi: 10.2514/6.2010-6180.

[15] G. J. Gentry, R. P. Reysa, and J. F. Lewis, "International Space Station (ISS) Environmental Control and Life Support (ECLS) system equipment failures, causes, and solutions February 2001 - February 2002," *SAE Tech. Pap.*, no. 724, 2002, doi: 10.4271/2002-01-2495.

[16] D. E. Williams, J. F. Lewis, and G. Gentry, "Control and Life Support System Status : 2002 – 2003," no. 724, 2003.

[17] M. Jernigan, R. Gatens, J. Joshi, and J. Perry, "The Next Steps for Environmental Control and Life Support Systems Development for Deep Space Exploration," *48th Int. Conf. Environ. Syst.*, no. July, pp. 1–8, 2018.

[18] E. Hodgson, D. Converse, G. Gentry, and M. Duggan, "Flexible path environmental control and life support technology-possible first steps to move beyond LEO," *42nd Int. Conf. Environ. Syst. 2012, ICES 2012*, no. July, pp. 1–18, 2012, doi: 10.2514/6.2012-3443.

[19] L. Carter *et al.*, "Status of ISS water management and recovery," *41st Int. Conf. Environ. Syst. 2017, ICES 2017*, no. July, pp. 1–17, 2017.

[20] M. M. French, "Water Recovery Trades for Long-Duration Space Missions," no. July, pp. 1–16, 2019.

[21] S. H. Vijapur, T. D. Hall, E. J. Taylor, D. Liu, and S. Snyder, "Loop Living," no. July, 2021.

[22] L. K. Kelsey *et al.*, "Closing the Water Loop for Exploration : Status of the Brine Processor Assembly," no. July, pp. 2020–2021, 2017.

[23] R. Reysa, M. Russell, and J. Knox, "International Space Station (ISS) United States Carbon Dioxide Removal Assembly blower anomaly resolution," *SAE Tech. Pap.*, no. 724, 2001, doi: 10.4271/2001-01-2416.

[24] R. Kay, "International Space Station (ISS) Carbon Dioxide Removal Assembly (CDRA) protoflight performance testing," *SAE Tech. Pap.*, no. 724, 1998, doi: 10.4271/981622.

[25] R. P. Reysa, J. P. Lumpkin, D. El Sherif, R. Kay, and D. E. Williams, "International space station (ISS) carbon dioxide removal assembly (CDRA) desiccant/adsorbent bed (DAB) orbital replacement unit (ORU) redesign," *SAE Tech. Pap.*, no. 724, 2007, doi: 10.4271/2007-01-3181.

[26] H. W. Jones, "Using the International Space Station (ISS) Oxygen Generation Assembly (OGA) Is Not Feasible for Mars Transit," no. July, 2016.

[27] D. Chapuis *et al.*, "Oxygen Regeneration by Algae Cultivation in Photo-Bioreactor for ISS Cabin Technology Demonstrator," *Int. Conf. Environ. Syst.*, pp. 1–12, 2020.

[28] L. A. Shaw *et al.*, "International Space Station as a Testbed for Exploration Environmental Control and Life Support Systems-2020 Status," pp. 1–12, 2020.

[29] D. J. Leonard, "International space station (ISS) nitrogen and oxygen logistics; Predictions verses actuals," *SAE Tech. Pap.*, no. 724, 2005, doi: 10.4271/2005-01-2896.

[30] P. Clauwaert *et al.*, "Nitrogen cycling in Bioregenerative Life Support Systems: Challenges for waste refinery and food production processes," *Prog. Aerosp. Sci.*, vol. 91, no. February 2017, pp. 87–98, 2017, doi: 10.1016/j.paerosci.2017.04.002.

[31] J. De Paepe *et al.*, "Refinery and concentration of nutrients from urine with electrodialysis enabled by upstream precipitation and nitrification," *Water Res.*, vol. 144, pp. 76–86, 2018, doi: 10.1016/j.watres.2018.07.016.

[32] K. M. Udert and M. Wächter, "Complete nutrient recovery from source-separated urine by nitrification and distillation," *Water Res.*, vol. 46, no. 2, pp. 453–464, 2012, doi: 10.1016/j.watres.2011.11.020.

[33] M. Cooper, M. Perchonok, and G. L. Douglas, "Initial assessment of the nutritional quality of the space food system over three years of ambient storage," *npj Microgravity*, vol. 3, no. 1, pp. 1–4, 2017, doi: 10.1038/s41526-017-0022-z.

[34] M. H. Perchonok and G. L. Douglas, *The spaceflight food system: A case study in long duration preservation*, vol. 3. Elsevier, 2018.

[35] M. C. Kyriacou, S. De Pascale, A. Kyratzis, and Y. Rouphael, "Microgreens as a component of space life support systems: A cornucopia of functional food," *Front. Plant Sci.*, vol. 8, no. September, pp. 8–11, 2017, doi: 10.3389/fpls.2017.01587.

[36] C. Gupta, "Prebiotic Efficiency of Blue Green Algae on Probiotics Microorganisms," *J. Microbiol. Exp.*, vol. 4, no. 4, pp. 4–7, 2017, doi: 10.15406/jmen.2017.04.00120.

[37] A. J. Hanford, M. S. Anderson, M. K. Ewert, and I. Stambaugh, "Potential Evolution of Crop Production in Space Using Veggie," *48th Int. Conf. Environ. Syst.*, no. July, 2018.

[38] D. Demey, V. Hermans, J. F. Cornet, J. J. Leclercq, C. Lasseur, and A. Delahaye, "BIORAT: Preliminary evaluation of biological life support in space environment," *SAE Tech. Pap.*, no. 724, 2000, doi: 10.4271/2000-01-2384.

[39] C. Ilgrande, R. E. F. Lindeboom, F. Mastroleo, M. E. R. Christiaens, X. Sun, and T. Defoirdt, “Nitrogen recovery from urine in Space : a case for nitrification,” no. 3, pp. 5–6, 2017.

[40] F. Gòdia *et al.*, “The MELISSA pilot plant facility as an integration test-bed for advanced life support systems,” *Adv. Sp. Res.*, vol. 34, no. 7 SPEC. ISS., pp. 1483–1493, 2004, doi: 10.1016/j.asr.2003.08.038.

[41] L. Poughon, B. Farges, C. G. Dussap, F. Godia, and C. Lasseur, “Simulation of the MELiSSA closed loop system as a tool to define its integration strategy,” *Adv. Sp. Res.*, vol. 44, no. 12, pp. 1392–1403, 2009, doi: 10.1016/j.asr.2009.07.021.

[42] A. Van Ombergen, A. Rossiter, and T. J. Ngo-Anh, “‘White Mars’ – nearly two decades of biomedical research at the Antarctic Concordia station,” *Exp. Physiol.*, vol. 106, no. 1, pp. 6–17, 2021, doi: 10.1113/EP088352.

[43] Z. W. Greenwood *et al.*, “State of NASA Oxygen Recovery,” *48th Int. Conf. Environ. Syst.*, no. July, p. ICES-2018-48, 2018.

[44] M. S. Anderson *et al.*, “NASA Environmental Control and Life Support Technology Development and Maturation for Exploration: 2018 to 2019 Overview,” *49th Int. Conf. Environ. Syst.*, no. July, pp. 7–11, 2019, [Online]. Available: https://ttu-ir.tdl.org/handle/2346/64419.

[45] D. L. Linne, B. A. Palaszewski, S. Gokoglu, C. A. Gallo, R. Balasubramaniam, and U. G. Hegde, “Waste management options for long-duration space missions: When to reject, reuse, or recycle,” *7th Symp. Sp. Resour. Util.*, no. January, pp. 1–9, 2014, doi: 10.2514/6.2014-0497.

[46] P. Lopez, E. Schultz, B. Mattfeld, C. Stromgren, and K. Goodliff, “Logistics needs for potential deep space mission scenarios post Asteroid Redirect crewed Mission,” *IEEE Aerosp. Conf. Proc.*, vol. 2015-June, 2015, doi: 10.1109/AERO.2015.7119161.

[47] M. Simon *et al.*, “NASA’s advanced exploration systems Mars transit habitat refinement point of departure design,” *IEEE Aerosp. Conf. Proc.*, 2017, doi: 10.1109/AERO.2017.7943662.

[48] M. S. Anderson, M. K. Ewert, J. F. Keener, and S. A. Wagner, “Life Support Baseline Values and Assumptions Document,” *Nasa/Tp-2015-218570*, no. March, pp. 1–220, 2015.

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