Food production in space from CO_2 using microbial electrosynthesis

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Abstract (248 words): Human space survival requires sustainable food production methods. The current food method in space is launching prepackaged food which is costly, wasteful, and unsustainable. Alternatives include growing crops and microalgae single cell protein (SCP) using artificial light photosynthesis, which are also costly and inefficient. Prepackaged food and SCP food growing solutions were compared to microbial electrosynthesis of acetic acid (MES-AA) using electroactive bacteria. The analysis employed an equivalent system mass (ESM) technique customarily used by the National Aeronautics and Space Administration to compare and select from alternative systems. Since the dominant cost of a space mission is the cost of launching mass, components of a system are converted to an equivalent mass, including power, heat rejection, and volume. Distinct three-year roundtrip manned missions were evaluated for the International Space Station, the Moon, and Mars. The average ESM of MES-AA is 1.38x and 2.84x lower than prepackaged food and microalgae SCP, respectively. The alternative food with the lowest average ESM in space, SCP from hydrogen-oxidizing bacteria (HOB), is 1.86x lower than MES-AA. The expected electricity-to-calorie energy conversion efficiency of MES is 19.8%; consuming 3.45 kW to fully feed five astronauts with AA (diets would realistically compose multiple foods). MES-AA has a higher energy efficiency than any currently investigated alternative food in space. The most promising food source is HOB, having the lowest ESM and highest nutritional quality. However, MES can provide diet diversity at a lower cost than customarily storing prepackaged food or growing crops in space.

Keywords (6): Equivalent system mass; Alternative food; Microbial electrosynthesis; Space food; Global catastrophic risk; Existential risk

1 Introduction

The cost of providing food in space is excessively [1] high [2]. There is a need to develop a sustainable and affordable food growing solution for environments in which it is difficult to grow food. Such environments include the Earth's orbit, the Moon, or Mars, and even on the Earth in a sun-obscuring global catastrophe, such as a supervolcanic eruption or a nuclear war causing cities to burn and the smoke inducing a nuclear winter. Existing space food technologies are expensive, not scalable, and not suitable for long duration missions. This article investigates the use of electroactive bacteria (EAB) as a resilient food production source for personnel in space. The goal was to characterize the potential of a food production method from CO_2 and compare it to relevant technologies, in order to mitigate certain restrictions of a manned space mission.

A number of challenges make agriculture in space a difficult premise, including lack of gravity, ionizing radiation, limited on-board space, and contaminants [3]. There is a limit to greenhouse efficiency due to the infrastructure required to protect from cosmic radiation. Current space foods are prepackaged food and fresh food shipped to space after being grown on the Earth [4], neither of which are sustainable for long term space missions. One alternative growing method to conventional agriculture is growing crops with artificial light, which is not economically feasible for feeding a large population even on the Earth [5]. In addition, artificial light infrastructure consumes large amounts of electrical energy, since phototrophic organisms (such as crop plants and microbes) have low light to chemical energy conversion efficiency [6]. Since the dominant cost of a space mission is fuel [7], minimizing the elements needed for food production in space is essential for reducing costs. Other potential solutions not including plants of algae are foods from bacteria, which provide direct sources of nutrients needed by human beings. EAB can release or retrieve electrons from solid state electron donors or acceptors using extracellular electron transfer (EET) mechanisms. This allows them to use a wide range of electron donors/acceptors meaning that they can survive in different environments [8]. There are several genera of EAB that grow under a variety of conditions on Earth, from moderate to extreme environments, making them an ideal candidate for being grown in space. EAB are also found naturally and widely spread across microbial communities, from wastewater systems to the human gastrointestinal tract. Auto-lithotrophs, including some EAB, do not require organic molecules (such as sugar) or valuable oxygen in order to grow. As far as we know, their environmental adaptability could give them added benefit as a direct source of food if they are found to be edible like many other bacteria.

Bioelectrochemical systems (BES) are emergent technologies that convert organic and inorganic material into electricity and/or chemical products through reduction and oxidation reactions [9]. BES can be divided based on their applications; microbial fuel cells for the oxidation of organic/inorganic matter to the production of electricity, and microbial electrosynthesis (MES) and microbial electrolysis cells, which reverse the microbial fuel cell process, to product synthesis by applying an electric current [10]. BES results in a wide range of applications spanning from energy production, waste recovery, bioremediation to food/nutrient production. The recent advancements of BES are promising for assessing their use in manned space missions for the generation of electricity from human wastes and the use of electricity for the synthesis of useful chemicals [11,12], moreover contributing to biologically sustained life support. Such an adaptable design would allow the manned space missions to cut down the mass of shipped products as they would be synthesized on board by MES. The use of MES in space for food and nutrient production has not been explored yet. The advantages of a bioelectrochemical system in space are apparent by their efficiency when compared to photosynthesis, the supply of electricity compared to energy from light, and the electrode surface area to microbial cell surface area [13]. A study investigated the utilization of MES to produce food on the Earth to obviate the use of additional stored food and artificial light photosynthesis during a global catastrophe [14]. While MES is currently not a competitive food alternative for the Earth during a global catastrophe, the high caloric efficiencies of this system may significantly reduce the equivalent system mass (ESM) for space food production. Thus, MES could compete with conventional space food, prepackaged food, and be more energy efficient than a competing alternative space food, microalgae SCP, specifically *Spirulina platensis*. *Spirulina platensis* [15] was selected to be grown in space using artificial light photosynthesis because it is among the most productive photosynthetic microorganisms. This study is similar to [1] which investigated the use of hydrogen-oxidizing bacteria (HOB) single cell protein (SCP) as food in space. The current study assesses the economic feasibility of using MES with a mixed microbial community in space for acetic acid (AA) production. AA is a product of fermentation; when diluted 4-6% by volume, is vinegar. On the Earth, AA is commercially used in the manufacture of vitamins, antibiotics, hormones, organic chemicals, and as a food additive [16].

EAB have an advantage over other organisms because of their ability to utilize electrons from the electrode surface on which they grow and transfer those electrons across their biofilm via extracellular electron transfer (EET). A diagram of the MES process [14] is depicted in **Figure 1**, for which the overall chemical reaction is described by **Equation 1**, based on partial reactions from literature [17]. Since fuel is the dominant cost of a space mission, and fuel consumption is directly proportional to payload mass, the economic feasibility of MES in space was addressed by using an ESM technique [18], established by the National Aeronautics and Space Administration (NASA).

2 Methods

The ESM results were used to select between competing subsystems. In this study, the ESM of MES is calculated and compared to the ESM of prepackaged food, microalgae SCP, and HOB SCP, calculated in a previous study [1]. An International Space Station (ISS) mission, a Moon mission, and a Mars mission were assessed, each consisting of 5 crew members (CM) for a duration of 3 years. Currently, more EAB research is needed to make sufficiently accurate assumptions [19], but sufficient information exists to achieve the goals of this work, which is to make a comparison to relevant space food technologies to inform prioritization of developments in the field. Values need to be consistent with each other to evaluate the technology for the purpose of food production. MES-AA is treated as the sole calorie source for this study to form an equitable comparison to other food production methods. In addition, this food production method can be used as a resilient food for sun-blocking global catastrophic risk (GCR) scenarios in accordance with its ability to use feedstocks not directly dependent on agriculture and sunlight, such as water and industrial or atmospheric CO_2 [14]. Both CO_2 capture [20] and utilization [21] are rapidly expanding areas of research, containing value in sustainable chemical energy production and energy integration. MES as a CO_2 utilization method currently faces significant challenges such as low titers, high operating costs, and the achievement of industrially relevant production rates at an acceptable energy efficiency [22]. However, MES holds significant potential for production of value-added chemicals independent of fossil resources, which would contribute towards a circular carbon economy [19].

$$2CO_2 + 2H_2O \rightarrow CH_3COOH + 2O_2 \qquad \textit{(Equation 1)}$$

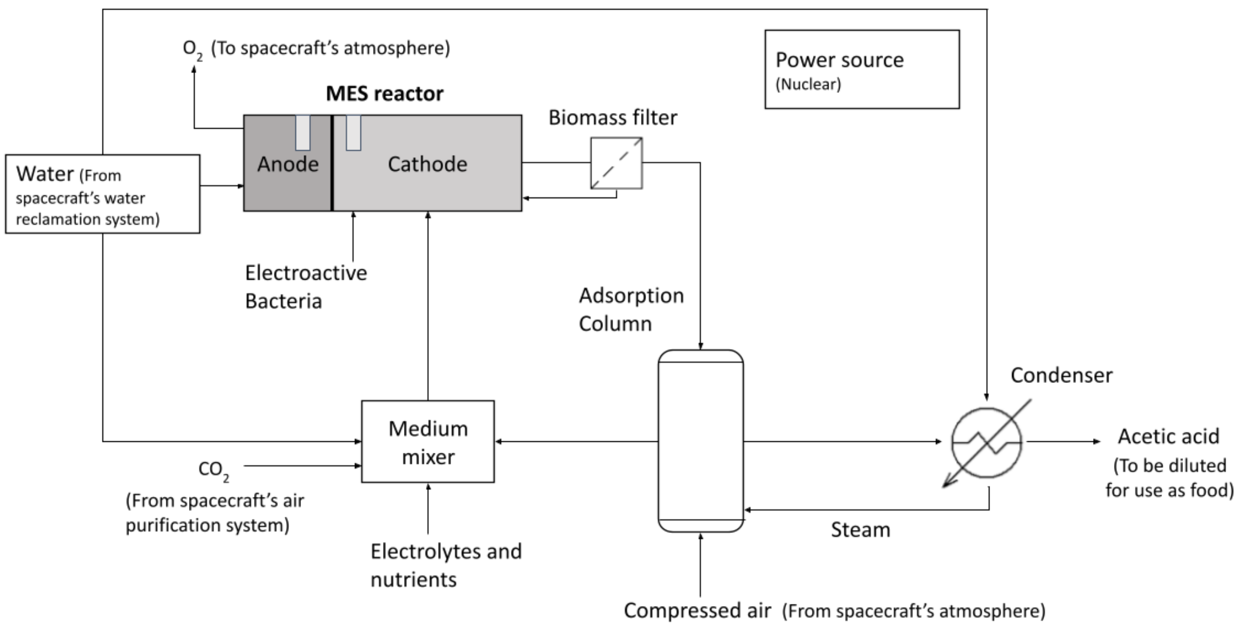

***Figure 1**. Process flow diagram of the MES-AA system adapted from [14]. The cathode compartment has a 3:1 volume compared to the anode.*

2.1 MES system design and operation

MES technology has not yet been attempted in space applications for food/chemical production, however, EAB are known to survive in different environments using different substrates, which suggests potential suitability for microgravity environments. The design for the MES system is based on the most promising experimental lab-scale research ([23]). **Figure 1** illustrates a flow diagram of the MES food production concept which includes all major equipment, excluding storage tanks. Liquid reaction medium and CO_2 from the spacecraft's air purification system are mixed prior to their entry to the cathode and fixed at 32 ºC. The cathode compartment includes the EAB, electrodes, and membranes needed for the MES reaction to occur. The reaction medium in both cathode and anode compartments contains trace elements and synthetic nutrient solution ([23]). The anolyte composition is optimized with decreased pH to favor proton crossing through the membrane. The inoculum used for EAB is considered to be a mixed microbial consortium enriched with bacterial populations such as *Proteobacteria*, *Firmicutes*, *Bacteroidete*s and *Actinobacteria* [24–26]. Experimental evidence suggests the use of aggregated forms of cells as a potential way to improve the survivability of a microbial population in high-radiation microgravity environments and allow biofilms to thrive [27]. The EAB biofilm could be grown, optimized, and stabilized prior to the launch of the spacecraft to aid its adaptation in space conditions. The reaction starts by applying a specific potential, -0.85 V vs standard hydrogen electrode (SHE), to achieve AA production. The liquid mixture is then moved to an EAB separator (biomass filter) where any remaining EAB are filtered and collected to be recycled to the cathode compartment, followed by product separation through an absorption column. Any byproduct production such as O_2 and H_2O can be recycled within the MES system or used for the needs of the spacecraft.

2.2 Equivalent system mass

ESM equates all components of a subsystem with a unit mass for analog comparison using mass equivalencies, derived by the NASA Life Support Baseline Values and Assumptions Document (BVAD) [28]. The relevant equation for this study, originally from the BVAD [18] and adapted [1] to fit a time-independent study, is indicated by **Equation 2**. From **Equation 2**, initial (apparent) mass M_I comprises the initially launched mass and ancillary components required for food production; power consumption P is the electrical power demand of each system; cooling (or heat rejection) C is the thermal demand for rejecting heat developed by the system (since it is a closed system, $C = P$); and initial (on-board) volume requirement V_I is the volume occupied by the food system at launch. Mass equivalency factors P_{eq}, C_{eq}, and V_{eq} convert non-mass components to mass equivalencies and are determined by the design and cost of infrastructure. For example, the mass equivalency factor for power P_{eq} relates the quantity of mass and cost of installation and components per rate of power delivered, so that the product of P ($kW_{electrical}$) and P_{eq} ($kg/kW_{electrical}$) is unit mass (kg). The location factor L_{eq} is dependent on the spacecraft infrastructure and the destination in reference to the acceleration needed to travel from the Earth's surface to Low Earth Orbit (LEO) [28].

$$ESM = L_{eq} * [(M_I) + (P * P_{eq}) + (C * C_{eq}) + (V_I * V_{eq})] \qquad \textbf{\textit{(Equation 2)}}$$

2.2.1 Apparent mass and volume

The apparent mass of the MES-AA food production system includes the mass of the reactor medium and the equipment. The MES equipment includes a reactor, separation equipment (adsorption column, sorbent, water boiler), support equipment (pumps, pipes, frames, control equipment), and the power source. The medium mass is the largest constituent of the setup mass and depends on the volumetric productivity of the system. The MES key performance parameters used in this study to estimate system mass and energy usage are based on the system characterized by the most promising lab-scale research [23]. Although other studies have shown somewhat higher production rates, the reference study has better overall performance provided by the maximum production rate (11.55 ± 0.15 kg/m^3 catholyte/d), product titer (8.2 ± 0.4 kg/m^3 catholyte), and electron recovery (91 ± 9%) [23]. However, the AA production rates that have been sustained in prolonged operation over hundreds of days are lower than the maximum at around 5-9 kg/m^3 catholyte/d [23], so this study conservatively uses this range as a basis. The associated catholyte volume ($m^3_{catholyte}$), which is the portion of electrolyte solution in the cathode compartment, is calculated as the ratio of production rate requirement (kg/d) and volumetric productivity (kg/m^3_{medium}/d). **Figure 1** indicates that 75% of the volume is in the cathode [23]; the reactor volume is calculated by dividing the associated catholyte volume by this percentage. The corresponding values of volumetric productivity in terms of medium volume are then (3.75-6.75 kg/m^3_{medium}/d). The total setup mass was estimated as the average value obtained from the low end and high end of the volumetric productivity range, as described in the Supplementary Material. The reactor volume is estimated using volumetric productivity and required mass flow rate, then multiplied by 1.5x to account for the volume occupancy of the units around the reactor and ancillary equipment. The total system volume is estimated to be 1.26 m^3.

2.2.2 Caloric energy conversion and electrical power requirement

A nuclear reactor was the selected power source for this study considering it has less equivalent mass than a solar powered system for these particular missions and produces steady power [1]. The electrical power demand depends on the electrical-to-caloric energy efficiency of the system, or in other words, the electricity input required to obtain a calorie in food. The electrical power requirement of the MES setup is calculated using **Equation 3**. From **Equation 3**, $\dot{m}_{AA}$(kg/d AA) is AA mass flow rate required to feed 5 CM exclusively with MES-AA, V (Volts) is voltage, F is the Faraday constant (96,485 coulombs/mol), n_{e-} is number of electrons required per unit of AA produced, FE is Faradaic efficiency, and X_{AA} is the fraction of acetate in the product distribution. Contributors to energy consumption of the system were considered: (1) energy requirement of MES, or the energy required to make the bacteria produce the required amount of AA, (2) energy requirement of separation, in this case to separate AA from the reactor medium, and (3) energy requirement of CO_2 capture needed as starting material for AA production. All values applied to calculate energy consumption are compiled in **Table 1**. Values were gathered from experimental literature [29], considered as representative of current state of science MES systems. The proposed AA recovery system via adsorption requires energy mainly to produce the steam used to desorb the AA from the sorbent, with an expected requirement of 5 units of steam per unit of AA recovered [30]. A typical water boiler efficiency of 80% is used. Regarding CO_2 capture, the system at the ISS is used as a reference with 20% thermodynamic efficiency [31]. An overall CO_2 utilization of 95% was used, close to single pass conversion values reported in literature [32,33], which could be increased even further from recycling unconverted CO_2.

$$P = V \cdot F \cdot n_{e}- / (FE \cdot X_{AA}) \cdot \dot{m}_{AA} \qquad \textit{(Equation 3)}$$

Table 1. *Basis of calculation for the energy analysis.*

Variable	Value	Unit	Basis for
Faradaic efficiency into products	70%		MES-AA from CO_2
Cell voltage	3	V	MES-AA from CO_2
Share of acetate in product distribution	100%		MES-AA from CO_2
Electrons required	8	mol e-/mol AA	MES-AA from CO_2
Steam requirement of desorption	0.2	kg AA/kg steam	Separation of AA from reactor medium
Latent heat of water	2,256	kJ/kg steam	Separation of AA from reactor medium
Boiler efficiency	80%		Separation of AA from reactor medium
Overall CO_2 utilization	95%		CO_2 capture
ISS CO_2 capture system efficiency	20%		CO_2 capture
Minimum CO_2 capture energy requirement	21	kJ/mol CO_2	CO_2 capture

2.2.3 Location factors

A location factor is needed for each acceleration during a mission to account for time-dependent changes in mass. Since this study is independent of time, one location factor was derived for each mission using values from the BVAD [28]. There are six acceleration steps that are relevant to this study, including (1) Earth's surface to LEO, (2) LEO to the mission body's orbit, (3) mission orbit to mission surface, (4) mission surface back to mission orbit after completing the mission objective, (5) mission orbit to LEO, and (6) LEO to the Earth's surface. The ISS mission would only involve the reference location factor of the Earth's surface to Low Earth Orbit (LEO), where $L_{eq,(1)}$ = 1.0.

3 Results

Volumetric productivity of the MES system corresponds to a volume requirement of 0.6-1.1 m^3_{medium} for the desired AA production capacity. The corresponding medium mass would be 0.6-1.1 tonnes, with the accompanying equipment mass estimated to be much lower in comparison (**Table 2**), and mass of the nuclear reactor equaling 79 kg from an infrastructure penalty of 23 kg/$kW_{electrical}$ [28]. Feeding 5 CM for 3 years would require 15.5 million kcal.

Since AA energy density is 3.49 kcal/g [34] and astronaut food requirement is 2,820 kcal/d/CM [28], then the equivalent mass flow rate $\dot{m}_{AA}$ would be ~4 kg/d of AA production. The estimated power requirement to produce the AA calorie-equivalent of feeding 5 CM is 3.45 kW, with an overall electricity-to-calorie efficiency of 19.8%. Nearly 80% of the power demand is required by AA electrosynthesis.

Table 2*. Average expected MES setup mass.*

System part	Mass (kg)
Nuclear Reactor	79
Reactor Medium	839
Empty reactor mass	60
Adsorption column + adsorbent mass	10
Boiler mass	10
Support equipment (pipes, pumps, frames, instrumentation, etc.)	80
Total setup mass	1,078

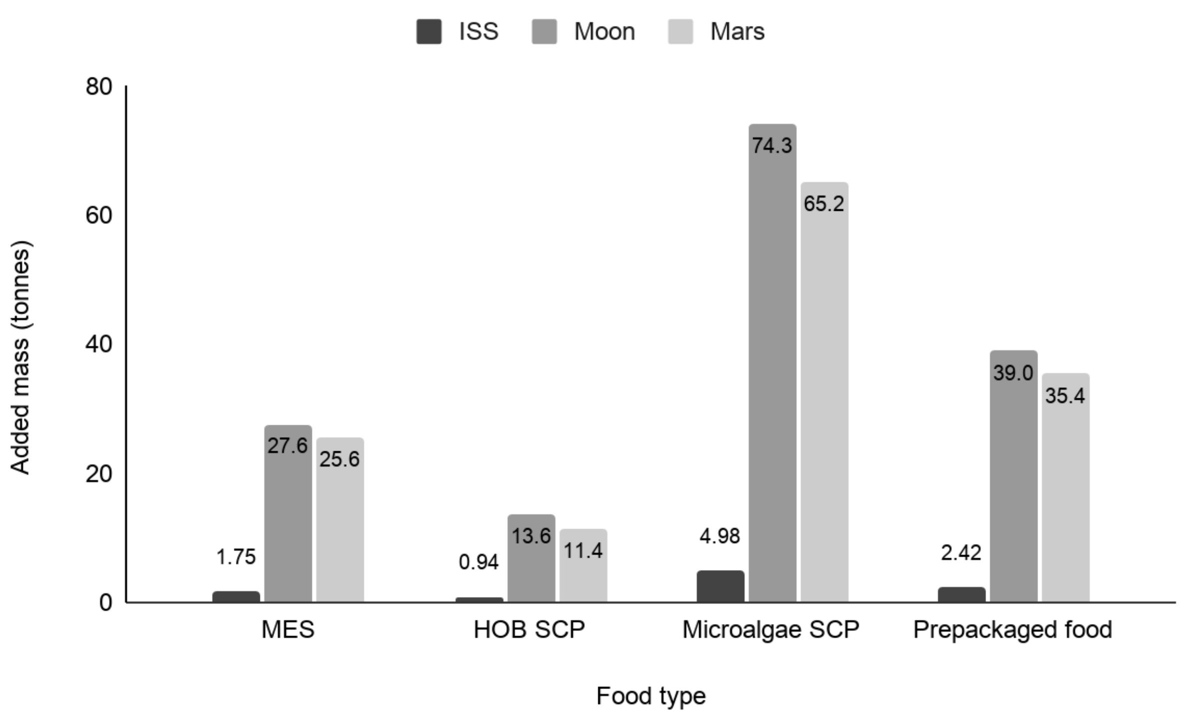

Figure 2*. The ESM of the alternative space food systems for each mission. Values are represented as added mass (in tonnes) to the mission.*

Table 3. *Components of each food alternative (ordered from largest ESM food to smallest), in kilograms, after applying mass equivalency factors to non-mass units and before applying location factor (which acts as a mission scalar). This may be used for comparison within each mission scenario, not for comparison between missions.*

	Apparent mass	Power	Heat rejection	Volume
Microalgae SCP				
ISS	1,918	1,300	1,642	119
Moon	1,918	1,300	1,112	144
Mars	1,918	1,300	1,026	384
Prepackaged food				
ISS	1,842	215	272	88
Moon	1,842	215	184	107
Mars	1,842	215	170	284
MES				
ISS	1,078	262	331	84
Moon	1,078	262	224	102
Mars	1,078	262	207	271
HOB SCP				
ISS	273	293	371	4
Moon	273	293	251	5
Mars	273	293	232	13

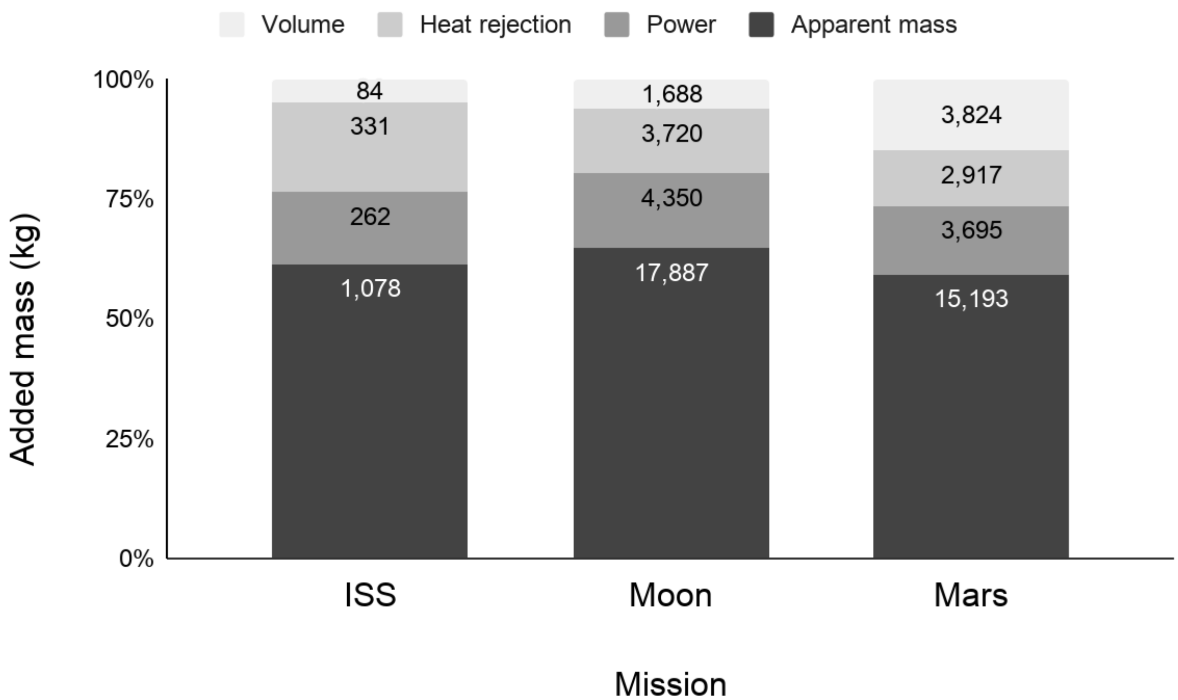

Figure 3. *Component contributions to the ESM of MES for each mission before summing them as a mission ESM and after applying mission location factors and mass equivalency factors to power, heat rejection, and volume. Values on bars are in kilograms (kg).*

4 Discussion

The methodology still requires further development and testing in space conditions before implementing. Improvements to EAB studies and related fields are currently advancing [35–37]. Before this production method is sufficiently advanced for the proposed application, there are several technical challenges relating to its reliability as a food production method. The appropriate cathode material should be identified to enhance the electrocatalytic activity and microbial cell adherence to the cathode. The appropriate bacterial strain or community should be identified specific to its food production employment, i.e. for AA production; perhaps genetically modified to improve production rates. Condition monitoring should be performed to optimize energy consumption, biofilm formation time, biofilm stability, and byproduct production rates. Studies performed on microorganisms in microgravity confirmed the increased production of viable cells, biofilm biomass, and thickness compared to normal gravity [38]. These promising results are an advantage to BES since a healthier biofilm formation will drive better EET and therefore higher efficiency rates (synthesis). Additionally, the effects of spaceflight on the physiology of EAB, specifically *Shewanella oneidensis* manganese-reducing strain (MR-1), have been examined during transfer to the ISS [11]. Potential impacts of a space environment have been thought to be an increase in cellular stress, which could negatively impact growth performance, and a decrease in biofilm development, which could negatively impact growth and byproduct formation. However, studies including electroactive cultures must be performed under space conditions to verify this behavior. Field experiments in microgravity conditions with an MES food production system are required to establish feasibility for manned space missions.

4.1 Alternatives comparison

This analysis indicates that the ESM of MES is lower than prepackaged food and microalgae (**Figure 3**). The ESM of HOB remains the lowest alternative, and therefore lower cost compared to each food system. The mean ESM of MES is 2.84x lower than microalgae, 1.38x lower than prepackaged food, and 1.86x higher than HOB SCP. The apparent mass is the dominant contribution to the total ESM of MES for each mission; whereas on-board volume is relatively insignificant for ISS and Moon missions (**Figure 4**). ESM results are higher in value for the Moon mission than for Mars (**Figures 3-4**) due to location factors. This is because the Moon and Mars missions have different shuttles, propulsion types, and transportation history (i.e. whether payloads are jettisoned during travel). ESM is not the exclusive metric for a comparison study since it lacks considering reliability, safety, and palatability [39]. However, it is pivotal for evaluating cost. The location factor is multiplied as the endcap of the analysis to magnify the propulsion requirement. As MES productivity advances, MES-AA would become more competitive as a food source in space. As the technology of MES advances and volumetric productivity and faradaic efficiency are improved, the apparent mass of an MES setup will reduce and could come closer to (or optimistically pass lower than) the ESM of HOB. Based on current, long-term sustained literature values for MES (volumetric productivity of 6.75 $kg/m^3_{medium}/d$ and faradaic efficiency of 90%) the ESM of HOB is more favorable than for MES. In order to make MES competitive with HOB in terms of ESM (for the expected faradaic efficiency of 70%), volumetric productivity equal to 25 $kg/m^3_{medium}/d$ or higher would be needed. High volumetric productivities have been achieved [40]; however, they were not used in this analysis because it is not the exclusive key parameter; this system had much lower titers and overall lower energy efficiency. Another advantage to the system used as a basis in this study is that it was tested in long-term operation (hundreds of days). The electricity-to-calorie efficiency for MES-AA was calculated as 19.8% which is more favorable than the two competing microorganisms. The same conversion is 4.4% efficient for microalgae SCP and 17.7% efficient for HOB SCP [1]. It is worth mentioning that the range of 50-90% faradaic efficiency translates to 15.2-20.8% overall electricity-to-calorie efficiency, but the average expected value of 70% faradaic efficiency corresponds to the 19.8% electricity-to-calorie efficiency value.

4.2 Life support considerations

Food is a category of life support and can be supplied via MES using resource recycling. Life support subsystems are currently in place to improve air and water recovery and waste recycling but have low effectiveness [41]**. Table 4** compares each component of MES to prepackaged food and microalgae; of which the microorganisms display higher effectiveness with resource recovery and recycling. Ammonia, providing the nitrogen for EAB, can be recycled from urine. Water, consumed in electrolysis and microbial growth, can be supplied by the water production in astronauts' metabolism (mostly urine, perspiration, and exhalation); oxygen as a product of electrolysis can be used for astronauts to breathe. The carbon in CO_2 produced by the astronauts' metabolism is consumed by microbial growth and MES. Net MES activity (food production) can be stable with complete carbon recycling; meaning less expected amounts of raw materials would be needed at the beginning of a mission leaving the Earth. These would include specific nutrients for the bacterial culture, and the amounts required are small enough to be negligible in terms of mass at launch. Resources such as CO_2 and water may also be available from mission locations, particularly on Mars. The prepackaged food option additionally requires operation of a Sabatier reactor that combines CO_2 produced by astronauts with H_2 to yield methane waste and water; oxygen is recycled via electrolysis of the water product [42]. The methane and excess water wastes add mass to the system and must be ejected. Although MES contributes to biologically sustained life support, the pressure and atmospheric conditions would still need to be controlled. In comparison with the current prepackaged food standard, the MES-based life support system substitutes for the Environmental Control and Life Support System (ECLSS) equipment, but both systems would incorporate an identical set of equipment (Sabatier, etc) as a backup. Thus, the backup does not need to be accounted for in either option, but the ECLSS system needs to be accounted for as an ESM contribution of the prepackaged food option. Frozen EAB starter cultures may be carried in the spacecraft for increased resilience of the MES life support system, but this was not accounted for in terms of mass.

Table 4. *Considerations for components that may add equivalent mass to a food alternative [1].*

Component	**MES**	**Prepackaged food**	**Microalgae**	**HOB**
H_2O (liquid)	Consumed in the MES process	Consumed in drinking, electrolysis, and rehydrating food, and product of crew metabolism	Consumed by microbial growth	Consumed in electrolysis and microbial growth
CO_2	Consumed for microorganism growth and food production	Product of crew metabolism, converted to methane waste via the Sabatier system and ejected	Consumed for growing microorganisms for food	Consumed for growing microorganisms for food
O_2	Product of MES	Produced via electrolysis	Product of microbial growth	Product of electrolysis
Food	Vinegar	Prepackaged food	*Spirulina platensis* powder	Microbial protein
Additional infrastructure	MES setup, power supply	ECLSS	Microalgae setup, power supply	HOB setup, power supply
Additional power requirements	Bioreactor, separation, processing of AA	ECLSS	Bioreactor, drying, processing of SCP	Bioreactor
Additional thermal control	Bioreactor cooling, heat exchangers, power supply cooling	ECLSS	Bioreactor cooling, heat exchangers, power supply cooling	Bioreactor cooling, heat exchangers, power supply cooling
Crew time	Operating, maintenance, cleaning (neglected)	Maintenance, cleaning (neglected)	Operating, maintenance, cleaning (neglected)	Operating, maintenance, cleaning (neglected)
Waste	Non recyclable waste from spent media (if any)	Food packaging, human waste and contaminants, methane gas, excess water	Non recyclable waste from spent media (if any)	Non recyclable waste from spent media (if any)

4.3 Nutrient diversity and future work

This study explored MES-AA as the exclusive calorie source. A proper nutrition plan may consist of significant portions of MES-AA but since this source does not provide all of the nutritional needs of a human, it would need to be complimented by food sources that provide vitamins, minerals, fats, carbohydrates, and proteins. These needs may be met in combination with other alternative foods such as prepackaged food, microalgae, HOB SCP [1] or non-biologically synthesized carbohydrates from CO_2 (García Martínez et al. to be published). The latter is the last work on the current series of publications on alternative foods for space missions and contains a more holistic comparison of the five food options mentioned above. Further research can be derived from this, moreover, combining low-cost alternative foods for a mission. MES has been studied as an alternative food production method to feed humanity during a global catastrophe inhibiting conventional agriculture, constituting a global catastrophic risk [14]. Such a catastrophe could potentially provoke or lead to existential risk, threatening the survival or future potential of humanity.

Alternative foods inherently produce food at lower relative cost or energy consumption than the most apparent solutions: stored food and crops grown with artificial light photosynthesis. This is analogous to prepackaged food and artificial light-grown microalgae. Refuges have been considered for reducing existential risk to humanity by increasing the likelihood of recovery from a global catastrophe or for self-sufficiency [43]. The small scale MES food solution may relate to a refuge or small community on Earth during a sun-inhibiting global catastrophe, similar to a refuge in space. Furthermore, this may apply to off-grid communities, such as those in rural Alaska [44], in which the cost of energy and product delivery is very high (analogous to current prepackaged food delivery to the ISS).

An additional option for food production from BES could be consumption of the EAB as a form of SCP, similar to the HOB SCP produced from H_2 gas described in the first article of this series [1]. This option was ultimately not developed here since producing SCP from EAB as a space food would likely be worse in terms of ESM than SCP from HOB. It is unlikely that a different electron donor (namely cathode electricity rather than H_2) would increase the metabolic rate of CO_2 fixation. The reason is that the same metabolic pathways are used once the electrons get into the cells [45], which means the cell growth rate will almost certainly be lower than that of HOB using external H_2. This would result in a lower production rate and thus higher ESM.

Researching the cultivation of EAB for SCP production and its composition could be useful on the grounds of nutrient diversity. Even though EAB SCP has higher ESM than HOB SCP, it could still be useful in combination if it could provide useful nutrients not found in the HOB SCP. However, no nutritional analysis of EAB SCP can be found currently in literature. Bacteria in general have high protein content (30–60% of dry weight) and some have high lipid content (50-70% of total biomass dry weight) [46]. In addition, different types of bacteria contain vastly different micronutrient profiles, potentially including essential fatty acids [46], while generally having a high average calorific content (over 5 kcal/g dry) [47]. Producing a variety of microbial foods could contribute to efficiently achieving a balanced diet in space missions.

Even though the use of MES seems promising, further research needs to be performed to ensure the ability and efficiency for food production in space. The survivability of EAB in space will directly affect the operation of the BES and therefore the production rates. To the best of our knowledge, no studies have been performed to test the long-term survivability of EAB in space during BES operation, with the longest one lasting only 4 days [11]. However, results from non-EAB studies showed that certain bacteria not only can endure extreme environments and survive in space conditions but also demonstrated improved growth and activity rates [27,48]. *Pseudomonas aeruginosa* has shown that spaceflight promotes biofilm formation and increases the numbers of viable cells, biomass, and thickness of biofilms [38]. Although these studies showed promising results, cellular stress, fluid, proton exchange membrane longevity, and gas distribution and separation must be studied prior to the application of BES in space [49]. Furthermore, a food production reactor based on MES is yet to be developed but nevertheless space food production is an additional potential application for this technology. Laboratory scale experiments consisting of a targeted species of EAB have been difficult to manage [50]; however, a mixed culture of acetogenic EAB is more robust to contamination by non-electrochemical microorganisms. Although the MES method discussed here is potentially viable, this study is based on a theoretical process that has yet to be performed at this scale [29]; therefore, key performance values may vary.

5 Conclusions

This analysis determined that MES-AA is a cost-reducing food substitution in space compared to conventional prepackaged food and using artificial light photosynthesis to grow microalgae, which is among the most productive photosynthetic organisms. Food produced via MES-AA would be at least one order of magnitude less cost than growing conventional crops in space with artificial light, and significantly more energy efficient. The conversion efficiency of electricity to caloric energy for MES-AA was calculated to be 19.8%. Fulfilling the caloric needs of a 5-crew mission, this would draw 3.45 kW from the system, all of which would eventually need to be rejected as heat. In view of this favorable conversion efficiency, the electrical and thermal demands on MES-AA is lower than every alternative food system considered in this study. However, the apparent mass is still relatively high due to low values of MES volumetric productivity, which could potentially be improved via further research in MES for AA production. For the latter reason, the ESM of HOB SCP, which leads the competition of food in space, is 1.86x lower than MES. However, the final ESM of MES is on average 1.42x lower than prepackaged food and 2.84x lower than microalgae SCP, and therefore the cost is proportionally lower. Although MES in space (and on the Earth) has significantly lower cost and energy consumption than these alternatives, it must be complemented with other foods. This MES food solution contributes to a biologically sustainable life support system by recycling CO_2 into useful (edible) compounds and recycling human contaminants, conducive to closed systems for manned space missions.

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