Food in space from hydrogen oxidizing bacteria

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Abstract: The cost of launching food into space is very high. An alternative is to make food during missions using methods such as artificial light photosynthesis, greenhouse, nonbiological synthesis of food, electric bacteria, and hydrogen oxidizing bacteria (HOB). This study compares prepackaged food, artificial light microalgae, and HOB. The dominant factor for each alternative is its relative mass due to high fuel cost needed to launch a payload into space. Thus, alternatives were evaluated using an equivalent system mass (ESM) technique developed by the National Aeronautics and Space Administration. Three distinct missions with a crew of 5 for a duration of 3 years were analyzed; including the International Space Station (ISS), the Moon, and Mars. The components of ESM considered were apparent mass, heat rejection, power, and pressurized volume. The selected power source for all systems was nuclear power. Electricity to biomass efficiencies were calculated for space to be 18% and 4.0% for HOB and microalgae, respectively. This study indicates that growing HOB is the least expensive alternative. The ESM of the HOB is on average a factor of 2.8 and 5.5 less than prepackaged food and microalgae, respectively. This alternative food study also relates to feeding Earth during a global agricultural catastrophe. Benefits of HOB include recycling wastes including CO_2 and producing O_2. Practical systems would involve a variety of food sources.

Keywords (6): Alternative Food; Sustainability; Single Cell Protein; Space; Global Catastrophic Risks; Existential Risks

1 Introduction

A food production method using hydrogen-oxidizing bacteria (HOB), a single cell protein (SCP) source, was first developed by microbiologists in 1965 [1] and soon after experimented for applications in space by the National Aeronautics and Space Administration (NASA) [2]. This technology is currently being developed for human and animal consumption [3–5]. The process typically involves electrolysis; using electricity to split water into oxygen and hydrogen and provide them to hydrogen-oxidizing bacteria for their growth. HOB, specifically *Cupriavidus necator*, have been experimentally found to contain ~50% protein content and 25% carbohydrates [6]. They have an amino acid composition similar to or better than algae or soybeans [7] and pasteurization and drying into a fine powder produces a texture comparable to dried milk [8]. According to Finnish food company, Solar Foods, their HOB SCP product called Solein looks and tastes like wheat flour [9]. Growth occurs inside a bioreactor similar to other fermentation processes and requires nutrients including ammonia, sulfates, and phosphates. Using current technology, the efficiency from electricity to calories from SCP is around 20% [10]. By contrast, the conversion of electricity into food via photosynthesis is around 3% [11]. This alternative food source would be valuable in space missions and in Earth catastrophes that disrupt agriculture, such as abrupt climate change or supervolcanic eruption. Concurrent research has been completed on the subject of feeding Earth during a crop-inhibiting global catastrophe, such as nuclear winter. The research investigates feeding Earth using HOB quickly and cost effectively [12]. Similar concepts could be applied for feeding people in refuges to repopulate the Earth, which could be in space, underground, or under water [13,14]. In either case, HOB would need to be supplemented with other foods to form a complete diet. In space or refuges, this could take the form of electroactive bacteria (EAB) SCP, nonbiologically synthesized food, photosynthetically produced food with artificial light or greenhouses (space only), or prepackaged food. In the case of global catastrophes, other alternative foods include cellulosic sugar, seaweed, greenhouses [15], methane SCP, EAB SCP, nonbiological synthesized food, or ruminants. Alternative foods differ in cost and scaling ability based on resource availability, however, they can potentially meet diverse nutritional needs [16].

This study compares the cost of current space food alternatives, including dry prepackaged food and photosynthetically grown microalgae SCP [17], to the cost of producing SCP from hydrogen using electrolysis. The cost to transport a payload, i.e. food, is proportional to the mass of that payload [18] and the fuel required increases exponentially with the velocity reached [19]; therefore, less mass launched means less cost for the mission. This project aims for the production of food for deep space and lunar exploration and increases the viable time in space through providing effectively produced food. Food is supplied to the International Space Station (ISS) in Low Earth Orbit (LEO) every 90 days [20], or approximately four times per year. These resupply missions could be significantly reduced by using a bioreactor system.

2 Methods

This study was completed from a synthesis of literature on emerging HOB technology, establishing the procedure for evaluating alternatives for space, and leveraging other investigations on alternative foods. For equitable comparison, each food alternative was treated as the exclusive food source for its mission. In practice, a variety of food sources should be used in space to provide nutritional diversity. Since protein from the SCP sources and carbohydrates from dry prepackaged food have similar energy density, 4 kcal/g dry [21,22], all three alternatives are considered equal in energy provision to astronauts. Conservative estimates were used suitably to give an advantage to prepackaged food and microalgae SCP alternatives.

2.1 Calculation of equivalent system mass

Using NASA's equivalent system mass (ESM) method [18], the aggregate mass of each alternative was calculated for three distinct missions: the ISS, the Moon, and Mars. The equation for the ESM of a subsystem during a segment of the mission, with the applied location factor L_{eq}, is:

$$L_{eq} \,.\, [(M_I \,.\, SF_I) + (V_I \,.\, V_{eq}) + (P \,.\, P_{eq}) + (C \,.\, C_{eq}) + (CT \,.\, D \,.\, CT_{eq}) + (M_{TD} \,.\, D \,.\, SF_{TD}) + (V_{TD} \,.\, D \,.\, V_{eq})] \quad \text{(Eq. 1)}$$

The essential parameters, explained by [18], include mass, power, cooling (or in this study, heat rejection), and crew time. The ESM of a subsystem is the sum of the mass equivalencies of these parameters. Variables of a subsystem include initial (or apparent) mass M_I, initial mass stowage factor SF_I, initial pressurized volume V_I, power P, heat rejection C, crew time CT, mission segment duration D, time- or event-dependent mass M_{TD}, mass stowage factor SF_{TD}, and pressurized volume V_{TD}, and mass equivalency factors for pressurized volume V_{eq}, power P_{eq}, heat rejection C_{eq}, and crew time CT_{eq}. Certain mission specifications are held the same for each mission to support comparability. The selected mission duration for each mission was 3 years with a crew of 5, similar to current proposed manned Mars missions (Ansdell et al. 2011).

Mass equivalency factors for pressurized volume, power, and heat rejection were collected from NASA's Baseline Values and Assumptions Document (BVAD) [23], unless otherwise specified. Mass equivalency factors for pressurized volume were obtained for a shielded aerodynamic crew capsule; 66.7 kg/m^3 for ISS missions, 80.8 kg/m^3 for Moon missions, and 215.5 kg/m^3 for Mars missions. The mass equivalency factor for powering the bioreactor systems, 76 kg/kW$_{electrical}$, was collected from a Brayton cycle nuclear reactor producing 20 kW$_{electrical}$. The same value was used for the prepackaged food alternative. Mass equivalency factors for heat rejection for Moon and Mars missions were obtained as 65 and 60 kg/kW$_{thermal}$, respectively. This value on ISS missions was calculated based on the ISS Heat Rejection System (HRS), which weighs 6,736 kg and has a capability of rejecting 70 kW [24]. Heat rejection from the nuclear reactor was not considered since, in practice, its heat would be rejected into space [23]; in addition, the selected nuclear reactor from the BVAD contains a heat rejection system and is included in the power requirement. Heat rejection for the bioreactors was considered the same as the power requirement since all power would end up as heat from growing food and human metabolism. Similarly, the power input to the ECLSS was considered to be rejected as heat. In reality, heat would be released by astronauts' metabolism, but energy is contained in the jettisoned methane, so we estimate that these effects counteract.

Missions were divided into segments to account for changing propulsion and changing ESM. A segmented approach was considered for this study to involve the progressively decreasing apparent mass of prepackaged food. Single factors that sum each mission's segments were estimated for simplicity. Location factors were found for different segments of Moon and Mars missions, summarized in Table 3.18 of the BVAD [23]. A reference of 1.0 was used for launching a payload to LEO. Six distinct segments for Moon and Mars missions involving fuel consumption include Earth's surface to LEO, LEO to a celestial body's orbit, orbit to surface, surface back to orbit, orbit to LEO, and LEO to Earth's surface. These segments were combined into one trip by applying known location factors from Table 3.18, involving: (1) the reference from Earth's surface to LEO, (2) LEO to the celestial body's orbit, (3) LEO to the celestial body's surface then back to the celestial body's orbit, and (4) LEO to the celestial body's orbit then back to LEO and down to Earth. Different vehicles were involved in developing the values in Table 3.18; however, the comparison between different food options is insensitive to these values as the same values are applied to all foods. One location factor, adding the six accelerations, was derived with the following arithmetic using the above notation: (1) + (2) + [(3) - (2)] + [(4) - (2)]. LEO to Earth's surface was considered to use negligible fuel. The location factors were estimated to be 1.0 for ISS missions, 16.6 for Moon missions, and 14.1 for Mars missions.

2.2 Design of alternatives

The mass of the prepackaged food would include the dry food mass and the equivalent mass of the Environmental Control Life Support System (ECLSS). A balanced diet of astronaut's meals [25] were assembled for the prepackaged food alternative that could calorically sustain a crew of five for three years. The mass of prepackaged food for each mission was calculated from a daily nutrition plan of 2,800 kcal per person [23]. For protein comparison, 2-3 servings of meat and 2-3 servings of dairy are suggested daily [25]. Considering 30 g and 10 g of protein per serving of meat and dairy, respectively, this equates to 80-120 g of protein daily, which aligns with the recommended protein intake for athletes [21], and would be about 15% of daily energy intake. For comparison, the protein content of microalgae SCP, specifically *Spirulina spp.*, is about 60% [26], and *C. neactor* is 50% [6]. The HOB system has an estimated efficiency of electrical to chemical energy of 15% to 21% and the microalgae system has an efficiency of 1% to 8%. For HOB, the energy efficiency was estimated by calculating the energy requirements of each step in the process per unit of SCP produced. The mid-range value 18% was used in further calculations for a conservative estimate. The energy efficiency of microalgae was estimated mainly on the expected efficiency of each step, and the mid-range value of the expected range of efficiency was used (4%). Design and specifications for the microalgae setup were gathered from current literature [27,28]. The mass of HOB and microalgae systems includes the apparent mass of the bioreactor setup and the mass equivalent of the power generation system. The HOB setup includes the tank, fluids (essentially H_2O), microbial broth/media, electrolyzer, centrifuge, dryer, pumps, pipes, and connectors. By combining the mass, the mass of the setup would be approximately a factor of 3 heavier than the mass of the HOB fluids. The mass of the microalgae setup was calculated by adding two times the mass of the HOB fluids to the mass of the photobioreactor.

2.3 Microbial energy efficiencies

The energy efficiency of HOB, more specifically *Cupriavidus necator*, was estimated by considering the electricity consumption of the five steps involved in the process: water electrolysis, CO_2 capture, HOB fermentation, centrifugation, and spray drying. On the ISS the electrolyzer has a thermodynamic efficiency of 80% [29]; the specific energy of hydrogen, 39.4 kWh/kg [30] and a requirement of 0.394 kg H_2/kg SCP [31] translates to an electrolysis energy requirement of 19.4 kWh/kg SCP produced. The fermentation energy consumption is 1.5 kWh for industrial scale [32]; allowing for a penalty of 3 times as much to account for the uncertainty of bacterial growth in space yields 4.5 kWh/kg for the high energy end. For CO_2 capture, current NASA equipment operates at a thermodynamic efficiency of 20% [33]. The thermodynamic minimum for the representative concentration and gas efficiency is approximately 21 kJ/mol CO_2 [34]. For a CO_2 requirement of 2.2 kg CO_2/kg SCP produced [31] the energy required is 1.45 kWh/kg SCP produced. For the water removal steps (centrifugation and drying), a range of values was considered to account for the uncertainty of performing the process in space. The range of solids content at the outlet of the bioreactor is 1%-3% of solids, which means between 0.03-0.10 m^3 water/kg SCP has to be separated. Considering a power consumption of centrifugation between 0.7 kWh/m^3 [35] and 8 kWh/m^3 [36] the energy required for the centrifugation step is in the range of 0.02-0.76 kWh/kg SCP for a solids concentration in the outlet of 22%. The energy requirements of spray drying are between 4,500-11,500 kJ/kg water [37]. This translates to a requirement of 4.4-10.3 kWh/kg SCP. Adding the consumption of all steps yields 26.8-37.5 kWh/kg SCP. An energy content of 5.56 kWh/kg SCP [38] translates to an efficiency of 14.8-20.7% for HOB.

The energy efficiency of microalgae, more specifically *Spirulina platensis* M2 strain [17], is derived from the electricity produced by the power source which is converted to light with lamps, part of which is absorbed by the microorganisms for photosynthesis. The microorganisms are then centrifuged, which consumes 8 kWh/m^3 for centrifugation to concentrate from 0.4% solid mass [36] to 22%, resulting in 2.0 kWh/kg SCP. Finally, they are dried to a powder. CO_2 capture and spray drying are accounted for using the same values as HOB. The conversion efficiency of sunlight to microalgae biomass is expected to be 3%-9% [39] and the photosynthetically active radiation (PAR) of sunlight is about 50% [40], which means the expected value of photosynthetically active light to biomass is within the range of 6-18%. The PAR of the lamp that would be used is expected to be between that of an HID lamp (40%) and a state of the art LED lamp (80%) [41]. These values translate to a light to biomass efficiency range of 2.4%-14.4%. The expected energy efficiency of conversion from electricity to light, or wall-plug efficiency, is between 41.4% [42] and 81% [43], from which an electricity to biomass efficiency of 1.0-11.7% can be obtained. Including the energy for water removal and CO_2 capture, the overall efficiency of electricity to microalgae SCP biomass is between 1.0%-7.7%. The lower bound of the photosynthetically active light to biomass value is in agreement with that of an integrated algae production and life support system, known as the Micro Ecological Life Support System Alternative (MELISSA) [44]. MELISSA uses halogen lamps with a notably inefficient expected PAR of 15% and wall-plug efficiency of 5%, to obtain 25.3 g dry/day with an energy use of 7 kW [45], which results in electricity to biomass efficiency of 0.05%. From these, a value of photosynthetically active light to biomass of approximately 6.8% can be back calculated, very close to the expected lower bound of 6%.

2.4 Power generation methods

The prepackaged food alternative requires full use of the ECLSS, which operates at 5.1 kW [23] for 9 ISS crew members [46]. HOB and microalgae require an alternative power system than prepackaged food for providing chemical energy and to power the bioreactor systems, such as for the electrolyzer. Two possible power sources are solar power and nuclear power. Solar power is limited in that it requires sunlight. The ISS, Moon, and Mars are eclipsed for 50% of time. Additionally, Mars experiences sun-blocking dust storms occurring up to several weeks [47], and would have lower solar intensity being further from the sun. Setups could operate in stasis during times when no solar energy is collected to conserve energy and minimize power storage requirements. In view of this, a solar powered setup would require a freezer, batteries, additional solar panels, and a larger setup. Alternatively, nuclear power does not require sunlight to operate; however, it requires more heat rejection per unit mass. The predicted dominant cost was the ESM of each food system, as opposed to the cost of the individual materials. Ancillary equipment for powering the bioreactors was selected by considering the lowest ESM. Mass equivalency factors convert heat rejection ($W_{thermal}$), power ($W_{electrical}$), and pressurized volume (m^3) to unit mass (kg); derived by dividing the mass of the infrastructure by the unit of resource used in the mission scenario [18]. A nuclear reactor was the selected power source for this study considering it has less equivalent mass than a solar powered system.

3 Results

A crew of five would require 15.5 million kcal for a three-year mission. The initial mass of prepackaged food would be 3,690 kg. This mass would be reduced as the mission progressed; the apparent mass therefore changes with each segment of the mission. The pressurized volume of prepackaged food was calculated considering the ordinary density of dehydrated food is 1,400 kg/m^3 [48]. The pressurized volume for the bioreactor system is the volume of the setup. The power source was considered to be outside of the pressurized capsule. Further specifications for each bioreactor are listed in Table 1. The energy density for HOB was calculated after removal of nucleic acid content [38].

Table 1: Specifications of the HOB bioreactor and the microalgae photobioreactor.

	HOB	Microalgae
Volumetric productivity (kg dry/m^3/day)	48	3
Energy density (kcal/g)	4.78	2.86
Bioreactor volume (L)	62	1,780
Setup mass (kg)	184	1,520
Electrical efficiency to dry food	17.8%	4.0%
Chemical energy requirement of food (kW)	0.684	0.684
Required power for product (kW)	3.8	17.1

For a conservative analysis with respect to HOB, the crew would begin with exactly enough prepackaged food for a three-year mission which would be depleted (zero mass) upon landing back on

Earth. Since these missions are round trips, the apparent mass for prepackaged food was averaged for the entire mission as 1,840 kg. More practically, redundant prepackaged food supply would be carried for the mission. Table 2 summarizes the components of this ESM study.

Table 2: Component summary for each mission and food alternative.

	Heat rejection, *C* ($kW_{thermal}$)	Heat rejection equivalency, C_{eq} (kg/ $kW_{thermal}$)	Apparent mass, *M* (kg)	Power, *P* ($kW_{electrical}$)	Power equivalency, P_{eq} (kg/ $kW_{electrical}$)	Pressurized volume, *V* (m^3)	Pressurized volume equivalency, V_{eq} (kg/m^3)	Location factor, L_{eq} (kg/kg)
HOB system								
ISS	3.8	96	273	3.8	76	0.06	66.7	1.0
Moon	3.8	65	273	3.8	76	0.06	80.8	16.6
Mars	3.8	60	273	3.8	76	0.06	215.5	14.1
Microalgae system								
ISS	17.1	96	1,920	17.1	76	1.78	66.7	1.0
Moon	17.1	65	1,920	17.1	76	1.78	80.8	16.6
Mars	17.1	60	1,920	17.1	76	1.78	215.5	14.1
Prepackaged food								
ISS	2.8	96	1,840	2.8	76	1.32	66.7	1.0
Moon	2.8	65	1,840	2.8	76	1.32	80.8	16.6
Mars	2.8	60	1,840	2.8	76	1.32	215.5	14.1

A table of data similar to Table 2 was assembled to calculate the ESM results, displayed in Table 3. Prepackaged food was found to be 2.6, 2.9, and 3.1 times greater in mass than the HOB alternative for ISS, Moon, and Mars missions, respectively; or on average a factor of 2.8. Similarly, the microalgae alternative was found to be 5.3, 5.5, and 5.7 times greater in mass than HOB for each respective mission; or on average a factor of 5.5.

Table 3: ESM results (in kg) for each food alternative averaged for three distinct missions.

	HOB	Microalgae	Prepackaged food
ISS	939	4,980	2,150
Moon	13,600	74,200	39,000
Mars	11,400	65,300	35,400

4 Discussion

4.1 Life support considerations

Table 4 summarizes the considerations made for certain life support components. A net reaction for HOB (Ishizaki and Tanaka 1990) was used for considering the nutrient and other growing requirements. The net reaction could be reduced (Eq. 2) for the overall system if ideal nutrient recycling occurred and ammonia was the nitrogen source.

$$0.76\ NH_3 + 2.66\ H_2O + 4.09\ C \rightarrow C_{4.09}H_{7.13}O_{1.89}N_{0.76} + 0.38\ O_2 \quad \text{(Eq. 2)}$$

The ammonia can be recycled from urine. The water consumption can be provided by the water production in astronauts' metabolism of the SCP. Life support subsystems for air, water, and waste are currently used to minimally improve resource recovery and recycling [23]. Moreover, if total recycling efficiency of CO_2 is achieved, then the carbon in CO_2 produced by the astronauts' metabolism is consumed by the HOB. The net SCP production can be stable with complete carbon recycling; only a small amount of raw materials would need to be included at the start of a mission. CO_2 and water may also be available from local mission sources, particularly on Mars. All three systems require CO_2 capture to maintain life support, and microalgae is the only system that does not require water electrolysis since the microorganisms directly produce oxygen from water via photosynthesis. The prepackaged food option additionally requires a CO_2 reduction system. The system used by NASA is a Sabatier reactor that combines the CO_2 produced by the crew with H_2 to make CH_4 waste and recycle the oxygen via electrolysis of the water product [49].

Table 4: Considerations for components that may add equivalent mass to a food alternative.

Component	Prepackaged food	HOB	Microalgae
H_2O (liquid)	Consumed in drinking and rehydrating food	Consumed in electrolysis and microbial growth	Consumed by microbial growth
CO_2	Product of crew metabolism, converted to CH_4 waste via the Sabatier system and ejected	Consumed for growing microorganisms for food	Consumed for growing microorganisms for food
O_2	Produced via electrolysis	Product of electrolysis	Product of microbial growth
Food	Prepackaged food	Microbial protein	Microbial protein
Additional infrastructure	-	HOB setup, power supply	Microalgae setup, power supply
Additional power requirements	ECLSS	Bioreactor	Bioreactor
Additional thermal control	ECLSS	Bioreactor cooling, heat exchangers, power supply cooling	Bioreactor cooling, heat exchangers, power supply cooling
Crew time	-	Operating, maintenance, cleaning (neglected)	Operating, maintenance, cleaning (neglected)
Waste	Food packaging, human waste and contaminants, methane gas	Non recyclable waste from spent media (if any)	Non recyclable waste from spent media (if any)

4.2 Equivalent system mass contributions

Parameters that did not impact results of the equivalent mass system calculations (Eq 1) were the time- or event-dependent mass M_{TD}, volume V_{TD}, and mass stowage factor SF_{TD} (such as rack structure needed for the subsystem), and crew time CT and mass equivalency factor CT_{eq}. This is because there would be no time or event-dependent mass produced since all waste would be jettisoned periodically (which makes the estimate of the advantage of the HOB conservative compared to the scenario of retaining some waste). Additionally, crew time requirements were ignored since the crew would have excess time during long duration missions [23]; or because a mission's segment length was negligible. Thus, the contributing variables were apparent mass M_I, mass stowage factor SF_I (for known documented masses, SF_I is 1.0), pressurized volume V_I and mass equivalency factor V_{eq}, power P and mass equivalency factor P_{eq}, heat rejection C and mass equivalency factor C_{eq}. Mass equivalency factors vary with each mission and are derived from factors such as the resource used, location, infrastructure, processing, installation [23].

4.3 Alternatives comparison

Growing microalgae has been discussed for developing an ecological life support system for space missions [17]. A significant benefit of growing HOB is its electricity to energy efficiency. Calculated for space, this efficiency is more than three times higher than that of microalgae, which itself has higher photosynthetic efficiency than crops [11]. Since this is a comparison study, the accuracy of individual location factors does not have a significant impact on the results because they are consistent between food alternatives. Location factors, and therefore ESM results, are lower in value for the Moon mission than for Mars. This is because the ESM results are added mass as opposed to overall mission mass. The location factors for Moon and Mars are based on separate shuttles, propulsion types, and transportation history (i.e. whether payloads are jettisoned during travel). ESM is rarely the exclusive metric for a tradeoff study since it lacks considerations of reliability, safety, and performance, however it is pivotal as a cost metric [18]. Figure 1 illustrates the equivalent mass penalties for each alternative food for a Moon mission. ISS and Mars missions appear similar. The apparent mass of prepackaged food is the most significant penalty in comparison; meaning the other penalties are small for that food alternative. Likewise, the HOB and microalgae systems have relatively high heat rejection and power requirements, similar to the apparent mass penalty, and a small pressurized volume requirement.

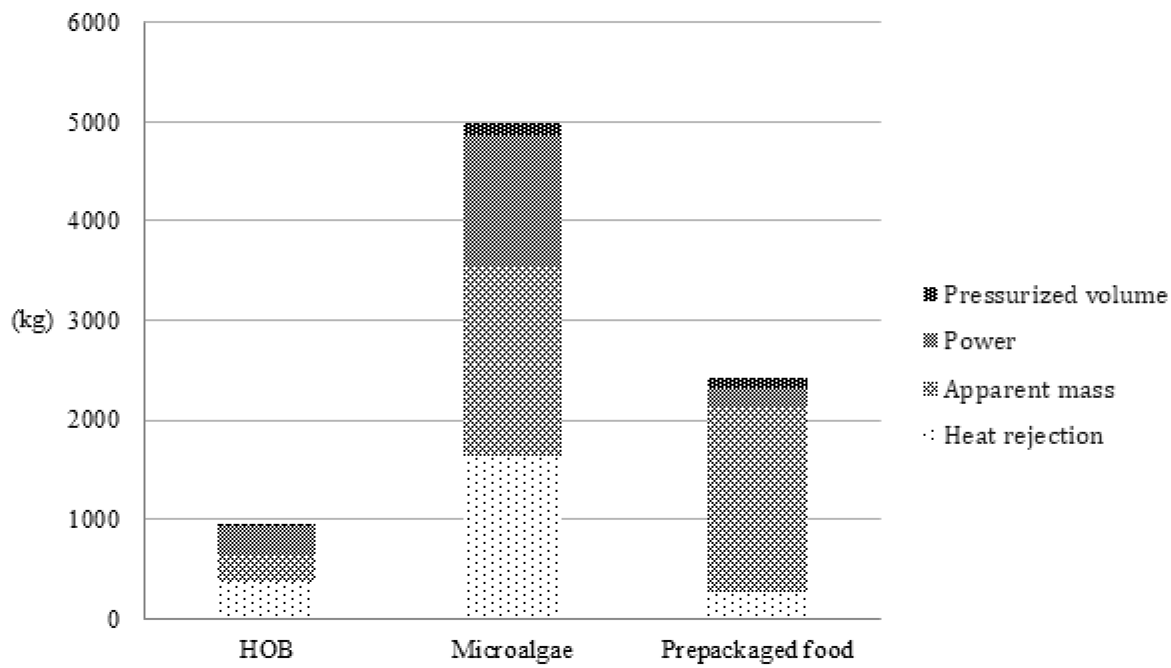

Figure 1: Overall comparison of equivalent mass penalties for a Moon mission.

Although there would theoretically not need to be a chemical ECLSS with either of the bioreactors [17], the infrastructure was kept to ensure a reliable life support system. The mass of the Sabatier reactor could be added but would be negligible in comparison; adding about a 14 mL reactor to a 4-crew unit [49]. All systems would also have a backup chemical ECLSS, including spare parts and smaller or associated systems to substitute its operation during repair, but since the ESMs would be the same, they are not included. The pressure and atmospheric composition of the spacecraft still needs to be controlled. A benefit of the HOB alternative is the recycling of nutrients and waste products. However, the technology for achieving this for these missions needs future work. Additional work should explore feeding a colony of people for a longer period. The growing process for HOB is gaining maturity on Earth for mass production [3–5] and rapid scalability has been investigated [12]. Existential risks that this research might apply to include scenarios that interrupt global food production, such as abrupt or extreme climate change [8,50], simultaneous extreme weather incidents resulting in multiple breadbasket failures [51], eradicative crop pathogens [52], super weeds [53], super crop pests [54], or super bacteria [55]. Common solutions to these risks are artificial light photosynthesis of crops and storage of food. For catastrophes that last several years, a small fraction of people would survive exclusively on the current amount of stored food [56]. Storing sufficient food for the world ahead of time would take years and would be expensive [57]. Artificial light photosynthesis is inherently expensive and energy intensive, and would therefore not be capable of feeding the world [15]. Alternative foods are investigated based on their potential to supply edible biomass; in other words, having low production cost and low energy and resource requirements. Nutrient diversity is also being explored to determine the extent for which the alternative foods should be produced [22].

5 Conclusions

The ESM analysis demonstrates that growing HOB as a food source during manned space missions has less equivalent mass, and therefore less cost, than prepackaged food by an average factor of 2.8, as well as growing microalgae by an average factor of 5.5. The electrical to biomass efficiency of HOB in space was calculated to be at least 15%, whereas the highest calculated efficiency for microalgae is 7.0%. It was anticipated that the cost of growing HOB, more specifically *Cupriavidus necator*, would be less than prepackaged food because of the recycling benefits of HOB. Furthermore, it was anticipated that growing HOB would be significantly less expensive than using electricity to grow food with photosynthesis, more specifically from *Spirulina platensis* M2 strain, given the much higher efficiency of HOB. A nuclear reactor was selected to power the bioreactor setups for providing lower equivalent mass than a solar powered system, especially because storage would not be required. The apparent mass of prepackaged food was found to be significantly high in comparison to the ESM penalties for that alternative as well as in comparison to other food alternatives. Similar alternative food studies are being conducted that relate to feeding people on Earth and in space using (i) EAB, wherein direct electricity is used as the energy source to feed bacteria, and (ii) non-biologically synthesized food, wherein food is chemically constructed without the use of living components. These studies will be compared to the results of this HOB study. Benefits of growing bacteria as a food source include its waste recycling, relatively high electrical to chemical efficiency, and reduced need for life support systems such as environmental control. Thus, HOB should be given consideration on future space missions as an important nutritional component.

Declarations

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