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# Automated production of microalgae as an efficient food source for future manned missions to Mars

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## Abstract

One of the key issues for designing manned missions to Mars is providing food on the red planet. While for shorter missions, bringing sufficient food supplies for the entire duration may be manageable, producing fresh food on Mars is preferable for multiple reasons. First, food in long term storage gradually loses its nutritional value. Second, preparing fresh food, and consuming fresh ingredients is beneficial not only for nutrition but also for the mental health of the crew. Here we propose a compact, highly efficient food production unit designed for a Martian setting. A photobioreactor producing microalgae is an autonomous unit that requires minimal human intervention, and is able to cover the vitamin and micronutrient requirements for a crew almost completely, in a smaller volume than any plant-based solution. It is designed to run on Martian atmospheric CO2 in future iterations, therefore requiring only power between harvest cycles, and minimal nutrient replenishment after harvests. The bioreactor is using liquid medium containing the microalgae, and is illuminated by power-efficient LEDs. A pump system circulates gas to facilitate growth, while a feedback system monitors growth of the algal culture and adjusts operating conditions for optimal production. The system operates with minimal moving parts and simple electronics leading to a low mass and convenient storage and transport.

Harvesting is done simply by filtering the medium solution through a mesh which separates the algae from the medium. The medium can then be reused after the addition of liquid fertilizer, leading to a system more efficient for water use than any known plant cultivation method. The harvested algae are then washed, dried and are ready for consumption, with no additional processing required. Recommended dosing is 5-50g/day for crew members. It is advised to simply mix it into any meal, adding a lively green colour and significant nutritional value to it. A proof-of-concept unit to demonstrate the technology is being prepared for the Mars Desert Research Station in Utah, where it aims produce enough algae for a crew of 5 to cover their micronutrient requirements for a two week simulated Mars mission, using a bioreactor the size of a standard oil barrel.

**Keywords:** Mars, habitation, deep space, food production, algae, photobioreactor

## Acronyms/Abbreviations

| | |
|---|---|
| CO2 | Carbon dioxide |
| EIT | European Institute of Innovation and Technology |
| ESA | European Space Agency |
| KIC | Knowledge and Innovation Community |
| MOAR | Mars Oil-drum Algae Reactor |
| MDRS | Mars Desert Research Station |
| NASA | National Aeronautics and Space Administration |
| UAE | United Arab Emirates |

## 1. Introduction

Crewed missions to Mars remain one of the most ambitious goals humanity is set to fulfill. After the historic successes of human spaceflight in the 20th century, space agencies around the globe have now set their eyes on visiting the red planet. At the time of writing, the United States, Russia, China, and ESA are actively developing crewed missions to Mars, all of them expecting to launch in the next few decades. Other nations like India, Japan or the UAE are currently involved in unmanned missions, each considering more ambitious follow ups in the future.

From the list of emerging challenges needing to be tackled for sending people to Mars, here we address food production. Providing food for long term space missions is currently unsolved. Extended crewed missions at space stations in Low Earth Orbit currently rely on regular resupply that periodically bring fresh food and other supplies for the crew. Such a system is not considered for a future Mars mission due to the sheer cost of sending cargo to another planet. The other existing alternative - taking along enough preserved food for a long-term space mission - is equally problematic. Even the best preservation methods lead to a loss of nutritious compounds in pre-packaged meals stored for long periods of time. In addition, hauling enough food for years for the entire crew again leads to heavy and prohibitively expensive payloads.

Therefore every attempt needs to be made to develop systems that are able to use resources available on-site, and generate fresh food to supply the mission over long periods of time. Producing food through cultivation was a defining step in the history of humanity, and even today remains one of the main activities being carried out on a daily basis around the globe. The long history of agricultural research enabled us to collect a wealth of information on food production. However, most of our knowledge is focused on food production in fertile terrestrial environments, therefore feeding the first crewed mission to Mars requires rethinking food production in its entirety.

As an added benefit, developing novel solutions for food production in environments where traditional agriculture is not possible may have an enormous positive impact back on Earth as well. An increasing number of people are living in areas unsuitable for agriculture like deserts or large cities, while at the same time arable land is disappearing at an alarming rate. Furthermore, with the climate emergency looming large, more localised and effective nutrient production is vital for a sustainable future.

Hence, as part of this study, we propose an innovative, automated food production system that is extremely efficient at using resources, produces food faster than most traditional crops, and requires no soil. Our proposed photobioreactor grows microalgae in liquid culture, creating vitamin rich, easy-to-prepare algae-based foods for human consumption. The unit outlined here is expected to make its debut on a simulated Mars mission at the Mars Desert Research Station in Utah.

## 2. Overview of algal growth experiments for space applications

Microalgae have been considered as a means of producing oxygen in closed systems even before the space age, since they produce more of it than any other cultivated crop, are easy to grow an handle, yield most nutrients per unit mass (see Table 1 below) and are a source of vitamins and minerals (Clarens et al, 2010; Tredici et al, 2015).

Table 1 – Comparison between algae and crop plants and greens in nutrition/energy per unit mass and growth area.

| | **Crop plants** | **Leafy greens** | **Algae** |
|---|---|---|---|
| % edible | 25% | 90% | 95%+ |
| Land use (ha/317GJ) | 1.3 | 39 | 0.4 |
| Protein content | 13% | 2% | 40% |

The US navy successfully experimented with using *Chlorella* to replenish oxygen on submarines already in the early sixties (Hannan et al, 1963). During the space race, more extensive testing was performed and the first habitats were constructed to model crewed space missions. The BIOS-3 experimental closed ecosystem featured both bioreactors growing algae, and “phytotrons” growing plants and vegetables. This Soviet-built unit was capable of providing oxygen to a crew of three for up to 180 days, and recycled 85% of water in the process (Salisbury et al 1997).

Europe also developed interests for microalgae-based life support systems. The MELiSSA project operated by ESA aims to go a step further and not only uses algae as a food and oxygen source, but it is developing a system to fully recycle human waste and use it for food production. The multi-stage digester, alga bioreactor, and plant growth chamber has been in development since 1989 (Mergeay et al, 1988, Lasseur et al, 1996).

Despite such successes, few experiments have demonstrated the feasibility of alga production in space. In 2017, the Artemiss project was the first to fly a strain of *Limnospira indica* to ISS and demonstrate that both oxygen and biomass production is possible with microalgae in microgravity (Garcia-Gragera et al, 2021). The NASA Veggie module employed *Chlamydomonas reinhardtii* and *Haemataococcus pluvialis* to show that the production of antioxidants, and thus possibly other high value organic compounds can be performed on the ISS similar to terrestrial systems (Zhang et al, 2020).

Specific planning for Martian alga production was explored only recently. This showed that in a test environment algae flourished in a low pressure, Mars analogue atmosphere and could even take advantage of simulated Martian regolith as a nutrient source (Verseux et al, 2016, Verseux et al, 2021).

## 3. Considerations for species selection

While the logistical prospects of algae growing on Mars is currently under theoretical exploration, the idea is conceptually very promising. Requirements for growing algae include the provision of light, and optimal levels of pH, temperature, pressure, water, carbon dioxide, and other supplemented nutrients, the level of all of these factors being specific to the organism being grown. Mars has inherent properties that could promote the growth of algae. For example, water could be obtained from the atmosphere (~0.3%), from hydrated materials, from martian ice caps, or from subsurface ice (Verseux et al., 2016; Williams 2020). From the martian atmosphere $CO_2$ is present at 95.32% and $N_2$ at 2.7%, making carbon fixation feasible for autotrophic organisms while nitrogen fixers would have access to martian nitrogen (Williams, 2020). Micronutrients such as Ca, Fe, K, Mg, Mn, Na, Ni, and Zn would be hypothetically available in the Martian regolith (Cockell, 2014). Additionally, in order to limit the complexity of the algal growth system, it would be ideal to grow algae under the naturally low pressure of the martian atmosphere. A small variety of algae have been tested for growth under low pressure but *Chloromas brevispina* and *Chlorella vulgaris* have been found to grow under pressures as low as 80 mbar (Cycil et al. 2021). Once humans are able to establish themselves at a martian base one can assume that light intensity and temperature of an algal growth chamber or room could be feasibly controlleable.

Which algal species would be optimal for growing on Mars remains an open question. The ideal algal candidate would be, first and foremost viable for human consumption and nutritious. Furthermore, rapid growth rates with no need for highly specific growth additives, a diazotrophic life cycle, and ease of purification would be ideal. An ability to grow under more extreme pressure, temperature, and microgravity conditions would be a bonus. A variety of algal taxa are being utilized in the health foods market including Chlorophytes like *Chlorella*, and *Chlamydomonas*; Euglenozoans with *Euglena*; and Cyanobacteria like *Nostoc*, *Arthrospira*, and *Anabaena*, to name only a few. *Arthrospira* and *Chlorella* are two of the most widely available algae mass produced for human consumption in part due to their high nutritional value. *Chlorella* is 55-67% protein, and has been associated with a number of health benefits. However, cultivation of *Chlorella* can easily become contaminated by bacteria and if not processed correctly, *Chlorella* consumption can cause gastrointestinal issues (Bishop & Zubeck, 2012). *Arthrospira* contains 60-70% protein and is rich with B vitamins and other nutrients making this alga a promising taxa. Yet, on earth this taxon has been shown prone to contamination by toxic algae (Bishop & Zubeck, 2012). While at the forefront of nutritious algae on Earth, neither *Arthrospira* nor *Chlorella* are diazotrophs. Mass production of a diazotroph like *Anabaena*, which is under exploration as a potential biofertilizer and as feed for animals as well as human consumption (Rosales-Loaiza et al. 2017, Chittora et al. 2020, Fadla et al. 2020), may be prefered. *Anabaena* is composed of ~40% protein and is easy to purify, but can produce toxins and has not been extensively tested for human consumption yet (Rosales-Loaiza et al. 2017). In addition to these species familiar in the literature, there remains a wealth of unexplored algae, one of which could be the perfect candidate to grow on Mars.

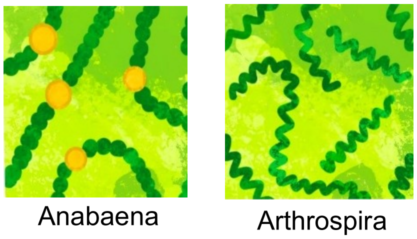

Fig. 1 – Illustration of the most promising combination of a diazotroph and non-diazotroph alage species.

Observing the current knowledge of edible algae, there are obvious tradeoffs to any species selected. Along with the variety of naturally available algae, genetic modification of an existing edible algae strain could be explored for the purpose of growing on Mars as a strategy to offset some of the tradeoffs. Genetic engineering would be beneficial in enhancing nitrogen fixation as was the demonstrated in Liberton et al. (2019) where nitrogenase activity in *Cyanothece* 51142 was enhanced by modification of a single gene; or the engineering of a non-diazotroph species to enable N fixation as was performed in Lui et al. (2018), modifying *Synechocystis 680*3 with genes from *Cyanothece* 51142. The engineering of enhanced nitrogen fixation and the ability to create diazotrophs from non-diazotrophic oxygenic photosynthesizers would be of benefit not just to prospective Mars missions but also to industry where the chemical fixation of nitrogen for use in fertilizers is very energetically costly. Additionally, it has been found that some genes for nitrogen fixation and heterocyte maturation remain conserved in the non-diazotrophic Arthrospira genome, suggesting this genus may be viable for manipulation (Fujisawa et al. 2010). Genetic engineering also opens the possibility of tailoring the specific nutrients synthesized by an organism and the halting of toxin productions, making non-edible strains edible.

Lastly, the idea of growing algae or microbial consortia should also be considered. The nutrient ratios required for directly sustaining human life are different from the nutrient requirements of crops in need of fertilizing. Thus, one strain could be grown purely for human consumption and another for the fixation of nitrogen for the purpose of extracting ammonium/use as fertilizer. In summary, there is extensive potential for natural and/or genetically modified algae to be grown on Mars for nutritional and other functional purposes.

## 4. Overview of the design of the MOAR unit

Apart from choosing the best strain of algae, it is also important to design appropriate machinery to perform the cultivation. While on Earth open ponds are often employed on industrial-scale algae farms, photobioreactors are also used, in particular for better control of growing conditions. These units contain a liquid culture of algae, and control main environmental parameters like lighting, agitation or nutrient supplies while measuring key culture performance, like the production of chlorophyll and oxygen.

Operating photobioreactors is similar to industrial fermentors, the main difference being algae requiring a light source for phototrophic growth. Employing photobioreactors is also advantageous as unlike plant-based agriculture which may require copious amounts of human labour, the reactors are often programmable and can perform the cultivation without direct human intervention, allowing safe, automated handling of the food supply and remote control of the cultivation units. This is a particularly useful trait for crewed missions to extreme environments, where crew members are expected to undertake a plethora of tasks, and therefore easing their workload is of considerable benefit.

For a space mission in particular, additional design criteria are the ease of use, as it is expected to be operated by astronauts who are not experts in chemical engineering or microbiology, and ruggedness as the reactor has to withstand the extreme conditions experienced during space travel.

Working towards developing such a unit, Algacraft Ltd has been designing the Mars Oil-drum Alga Reactor (MOAR), see Fig. 2 below. MOAR is a demonstration unit aiming to showcase how algae can be cultivated during a simulated Mars mission. It consists of two standard sized oil barrels: a reactor and a processing unit.

The reactor is housed in a converted 220L steel oil drum (see Fig. 2a). The barrel ensures a rigid, safe enclosure that can be transported with ease, while also being robust enough to hold 200L liquid without significant deformation. In addition, the barrel has a food-grade coating on the inside that is also smooth, which enables safe production of edible biomass while also being resistant to biofilm formation.

Outside of the barrel is the power supply. As pumps, lights and electronics need to operate inside the barrel in a wet environment, for safety high voltage is kept outside and converted to 12V before entering the barrel. Once the converted 12V electricity enters the barrel via a socket near the top, it is distributed to all components needing power.

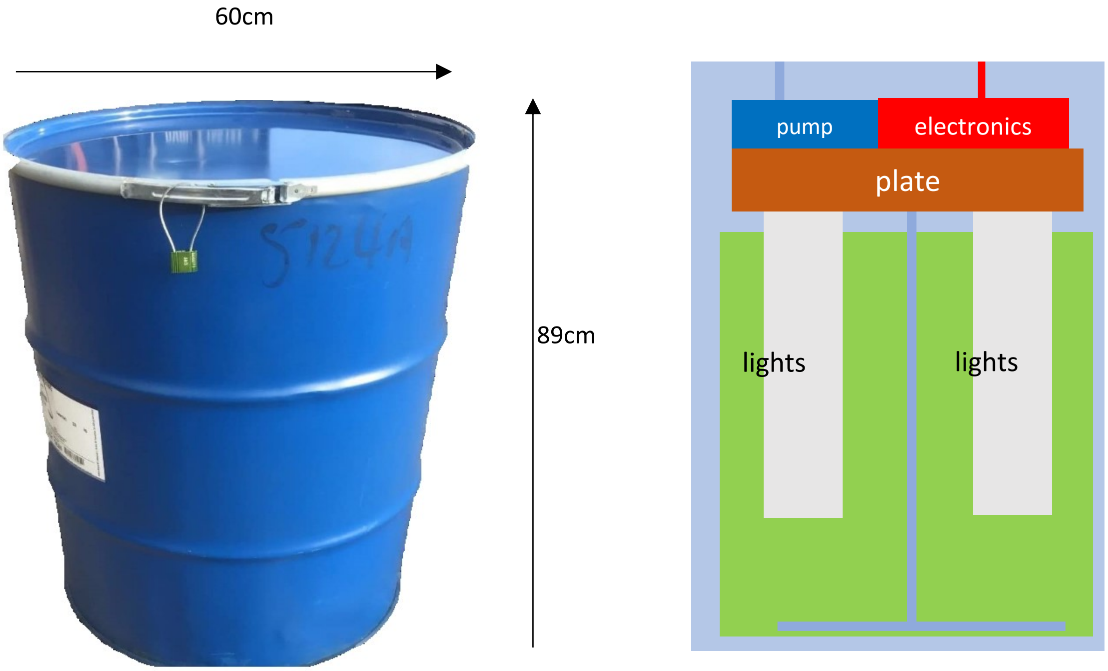

Fig. 2 – MOAR unit's a) exterior (left) and b) schematic representation of reactor design (right).

Inside the barrel (see Fig. 2b) most of the space is taken up by the alga culture itself, consisting of 200L of medium inoculated with a culture of *Arthrospira* microalgae. Above the water level an acrylic plate is suspended, which houses all the electronics. As the plate is kept above the water level it is easy to access for maintenance, while at the same time keeping all the electronics physically separated from the liquid phase.

The plate contains the air pumps that agitate the culture and enable gas exchange within the reactor. The pumps push air through a central column through the liquid to the bubblers located at the bottom of the barrel. The bubblers create a uniform upwelling of air through the liquid body, allowing gas exchange while at the same time creating a gentle circulation in the liquid, which prevents sedimentation and ensures algae are uniformly exposed to fresh nutrients and light over prolonged periods of time.

The other main component on the top plate is the light system. This features six columns of red and blue LED lights that reach down from the plate into the liquid phase using circular acrylic tubes. The six tubes provide sufficient illumination for the entire volume of the barrel even for denser algae cultures, forgoing the need for thin containers commonly used in bioreactors that prevent self shadowing of the algae.

The second barrel is used for harvesting and maintenance. It contains spare parts, portioned liquid and powder stocks for the alga medium, and equipment for dewatering and processing the harvested algae.

Harvesting is done by using a self-priming liquid pump that transfers the medium from the reactor barrel to the harvesting barrel. Before the liquid enters the harvesting barrel, it is passed through a mesh which filters out the filamentous algae, only allowing through residual single cells and the used culture medium into the second barrel. The harvested algae are retained on the top of the mesh of the harvest barrel, allowing easy access for processing. Processing is done by a simple wash with clean drinking water, which removes the salts in the medium, leading to a clean, ready to eat fresh algae paste that can be moved directly to a food prep area. The medium that was separated from the algae can be pumped back from the harvesting barrel, topped up with nutrients and the culture restarted. After the harvest is complete and a new growth cycle is started in the reactor, all the tools needed for harvesting and maintenance can be stored in the harvest barrel until further use.

## 6. (Future) field test

To demonstrate the effectiveness of MOAR we are deploying it to a simulated Mars mission at the Mars Desert Research Station (MDRS) in Utah. MDRS is operated by the Mars Society, and it is the biggest and longest running Mars simulation system today. During the two week mission, the astronauts are planning to take the two barrels to the site, set it up in the greenhab module of the research station, and grow sufficient algae with it to cover the vitamin requirements of the five person crew. Specifically, the aim is to grow sufficient algae in a single unit to cover the recommended daily intake of protein, vitamins B1, B2, B3, B5 and at least 20% of the recommended daily intake of vitamin C, E, K, B6, B9 and all micronutrients for the entire crew.

Apart from a two hour initial setup, maintaining the alga culture and harvesting weekly is expected to take no more than two work hours a week for the entire mission. Decommissioning the unit at the end of the mission is expected to require an additional two work hours. We are also planning a remote monitoring and partial control system, so that the reactor can be looked after from inside the habitat module, as well as from the MOAR HQ in Edinburgh via the internet.

The mission was originally scheduled to take place in December 2021, however due to the COVID19 pandemic, it has been postponed to 2022.

## 8. Outlook

The current prototype reactor expected to debut at MDRS in 2022 only incorporates part of the full feature list, but it does aim to demonstrate the working principle of the unit. Future iterations will feature more advanced electronics, where multiple sensors collect culture parameters and a small on-board computer regulates a feedback loop for optimal production. Such a unit shall be able to regulate CO2 intake, lighting intensity, and may even signal the operator if a harvest is due, while also sending back data to mission control where the reactor can be constantly monitored without sacrificing astronaut work hours. An even further, Mars-ready iteration is expected to operate by taking in (simulated) Martian atmosphere compressing and heating the gas before pumping it in for the algae thereby demonstrating in-situ resource utilisation.

The unit shall also be available for Earth-based applications. Remote locations or areas where traditional agriculture is not possible may greatly benefit from a ready available fresh source of protein and vitamins. From polar research stations through settlements in the desert, small-scale circular economy solutions, down to even household use, several potential terrestrial applications shall be explored.

Despite the various advantages proposed by an automated alga bioreactor, the unit is not intended as a sole food source. A large part of feeding long term space missions is the psychological aspect of eating meals. Astronauts do expect a pleasurable experience associated with food, which algal biomass is not able to provide due to its low perceived palatability.

Therefore, similar to the initial MDRS test, it is advised to use the algae not as a food source, but as a food supplement. Mixing in a few grams of algae powder into other meals fortifies them with fresh vitamins, protein and micronutrients, greatly enhancing their nutritional properties. Another issue that the current unit is not expected to tackle is the sourcing of fertilizer. Water soluble nitrates, phosphates and micronutrients are supplied as part of the growing kit, but they are only available in a limited supply which needs to be replenished periodically via chemical synthesis. A truly circular system is expected to reuse human waste, or be able to process regolith into the required fertilizer components, however incorporation of fertilizer generation is beyond the scope of the current project.

In conclusion, we aim to show that automated cultivation of algae is a viable, and desirable food production system due to its efficiency, yield, and nutritional value. The MOAR project hopes to be the first to demonstrate in practice the advantages of such cultures for future crewed missions to Mars.

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