Dark Food: Feeding People In Space Without Photosynthesis

Michael Nord[1] and Scot Bryson[2]

[1]The Johns Hopkins University Applied Physics Laboratory
[2]Orbital Farm

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Abstract

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DARK FOOD: FEEDING PEOPLE IN SPACE WITHOUT PHOTOSYNTHESIS

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Michael Nord, Ph.D.
Principal Staff
The Johns Hopkins University
Applied Physics Laboratory
`Michael.Nord@jhuapl.edu`

Scot Bryson
Founder
Orbital Farm
`scot.bryson@orbital.farm`

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ABSTRACT

Production of food in space via photosynthetic crops similar to the ones we use on Earth requires profligate use of resources that will be in short supply in early long duration space missions. We demonstrate that production of bulk calories via chemotrophic single cell organisms is 2 to 3 orders of magnitude less expensive in terms of energy, volume, and water usage than via photosynthetic crops. In addition we survey the history and current state of the art in production of food from non-photosynthetic single cell organisms.

Keywords Space Resources · Single Cell Protein · Life Support Systems

1 Introduction

Food production in space is often visualized as a modification of present day Earth agricultural practices to the unique problems of space environments. As early as 1880, novelist Greg Percy had his protagonist bring plants along on his trip to Mars to help with waste recycling and food production (Percy, 1880). Konstantin Tsiolkovsky proposed the use of plants to make artificial atmospheres in spaceships (Tsiolkovsky, 1926). More recently we have Mark Whatney's famous potato plants (Weir, 2014) and even very recently, the subject of NASA's 2019 BIG Idea Challenge was to design a greenhouse for Mars. Plant agriculture has fed humans for the last 10,000 years. It seems obvious that this must continue into space.

The problem with this approach is that plant agriculture is terribly wasteful of energy, pressurized volume, water, human labor, and other resources that will be in short supply in early human space activity. To consider just energy, a human with a basal metabolic rate of about 100 watts (Dunford, 2007) and typical crops having 0.5 percent photon to food efficiency (Blankenship et al., 2011), suggest a physical minimum of 20,000 watts of photosynthetically active photons need to be continuously generated or harvested per person to generate sufficient calories. Considering light emitting diode inefficiencies, the need for pressurization, heating, pumps, etc., food for a single person could require on order of 50 kWe. Compare this against the 20 kWe total power consumption assumed for the crew phase of the NASA Mars Reference Mission 5 (Drake et al., 2010) and one begins to see the problem with photosynthesis as a basis for feeding people in space.

Earth's dark ecosystem (El Abbadi and Criddle, 2019) affords us an elegant solution. A variety of single cell organisms, often discovered in caves or deep undersea vents, can directly chemosynthesize an inorganic source of carbon and a source of chemical energy such as hydrogen or methane, into proteins, fats, carbohydrates, and a number of other useful organic compounds. NASA studied this extensively in the mid 1960s and early 1970s (Jagow, 1967) as an answer to food production and closed loop life support during long term space missions, and a number of commercial companies have used and are using the technology for food production on the Earth. In this work we will demonstrate that this approach is order of magnitude 100 times more energy efficient, 100 times more water efficient, 1000 times more volume efficient, and has startup times of hours instead of months. In addition, the very same organisms can be engineered to make pharmaceuticals, plastics, and a variety of other useful complex organic compounds.

2 What Is Dark Food?

When considering a food production system within limited and controlled environments like in a space habitat, the budget of energy, nutrients, water, and waste streams are of fundamental importance to the selection of what, how and which types of food are viable to produce. Large animals such as pigs, cattle, or chickens, are not well suited food sources for constrained environments for many reasons, for example, their inefficient feed conversion ratios. We will show in this work that multicellular photosynthetic crops have similar problems. However, the space environment is ideally suited for alternative sources of protein, such as growth of single celled organisms, cellular agriculture, and other biotechnology based foods.

Well before photosynthesis emerged in cyanobacteria, life on Earth evolved in the early atmosphere which was composed of hydrogen, carbon dioxide, methane, and ammonia (Harold, 2014). This early environment harbored single cell organisms which evolved in many areas on Earth without light. This dark ecosystem existed in soils, at the bottom of lakes and oceans, and in caves. These terrestrial environments were a soup of warm waters from hydrothermal vents enriched with electron donors, such as H_2S, H_2, CH_4. These compounds along with water and organic materials that float to the ocean floor are what the dark ecosystems are built from. Chemoautotrophic bacteria use these nutrients to thrive and provide nutrients to an ecosystem of other organisms such as worms, mollusks, clams, mussels, snails etc. (El Abbadi and Criddle, 2019).

One example of such an organism is *Cupriavidus necator*. This is a hydrogen-oxidizing bacterium capable of growing at the interface of anaerobic and aerobic environments. It can easily adapt between heterotrophic and autotrophic lifestyles. Both organic compounds and hydrogen can be used as a source of energy and it consumes CO_2 as its carbon source.

Additionally, methane oxidizing bacteria (Methanotrophs) play a key role in most lake ecosystems. These organisms can account for up to 40% of the total bacterial biomass in some lakes (Sundh et al., 2005). These protein rich organisms are building blocks to thriving ecosystems and convert CH_4, O_2, NH_3 into amino acids, oils and biomass.

2.1 History

Humanity has a long history of using dark food chains for food, drinks and nutrition. Fermentation is a part of the dark ecosystem, has been used for thousands of years and might even predate agriculture. Certainly biologically speaking, fermentation was one of the earliest of biological processes of life on Earth even prior to the great oxygenation event. "In the first two billion years of life on Earth, bacteria - the only inhabitants - continuously transformed the planet's surface and atmosphere and invented all of life's essential, miniaturized chemical systems," (Margulis, 1997). "Bacterial fermentation processes have been part of the context for all life. Fermentation plays such a broad and vital role in nutrient cycling that all beings coevolved with it, ourselves included." (Katz, 2012).

Controlled fermentation is conducted in a bioreactor, which is a closed vessel that can range from <1 liter to millions of liters. Bioreactors allow control of aeration, agitation, temperature, pH regulation, as well as a drain or overflow vent to remove the biomass of cultured microorganisms and their outputs or products. Bioreactors are most commonly understood as the tanks used to produce wine or beer, but generally they enable a low value product to be utilized by living cells or enzymes to make a product of higher value.

During the late 1960's during the heart of the space race, NASA undertook efforts to develop planning for long duration crewed missions in space. This effort was considered essential planning for crews that would operate for durations exceeding one year without resupply. This included converting human and cabin waste products into useful products such as oxygen, food and potable water. Focused conferences, papers, prototypes, and mice/rat and human studies were conducted to determine ideal life support systems models which could effectively nourish astronauts in closed systems. These included utilization of existing resources which exist in the presence of humans: CO_2, urine, water from respiration and perspiration and feces. The systems proposed and evaluated included hydroponic systems for growing plants, yeasts, algae, and hydrogen bacterial systems. In this early research the use of microbial proteins gained prominent attention, gaining standardization from the term "petroprotein" to single-celled proteins (SCP) and starring in an MIT conference called "Single Celled Protein" in 1967 (Tannenbaum and Mateles, 1968).

During this period, NASA contracted studies of single-cell proteins from hydrogen bacterial fermentation systems. The feeding trials for both human and rat diets were found to be well tolerated, even in high concentrations (Waslien et al., 1969), however during human trials, intolerance to the high concentrations of nucleic acids present in the single-cell protein produced digestive issues in subjects. This seems to have caused a halt to further studies and efforts in single-celled proteins. It wouldn't be until 1974 that a patent would be awarded for the removal of nucleic acid content for single-cell protein (Akin and Chao, 1974) which simply involved heating the cells to 60°C with aqueous ethanolic mineral acid for 5 min.

These early studies identified hydrogen bacteria as a powerful tool for utilizing waste and producing food on long duration missions with applications on Earth. The main but very addressable challenges which were identified included digestive issues stated above, requirements to handle explosive gas mixtures, the post processing requirements, and supplementation to meet complete nutritional requirements. These challenges were far outweighed by the benefits of high protein concentration, waste utilization, minimum modification as a food source, less energy required than algae, simple automation capabilities, higher density than algae, and the fact that, unlike algae, the reserve bacterial cultures can be carried in a metabolically inactive freeze-dried state until required for use (Drake et al., 1967).

During the formative years of NASA in the 1960s, human spaceflight accounted for over half of the budget in most years and nearly two-thirds of the budget in 1965. After the Apollo Program's accomplishments, and after Apollo 17's last manned Moon landing in 1972, NASA shifted its budgets to other programs and human spaceflight was no longer an individual priority after 1975 (Statista, 2019). To date, there hasn't been a need for missions longer than one year, however as plans for sustainable development on lunar and Mars missions continue, the need for bioregenerative life support systems has increased. In addition, here on Earth, there is a great need to develop more climate friendly, cost effective foods with minimum impact on the natural environment and our climate. Dark food technologies are extremely well positioned to supply these needs.

2.2 State Of The Art

Globally, the demand for protein to feed the growing human population and animal agriculture systems have been driving innovation, investment, and interest in alternative sources of nutrition from more advanced food production technologies. Within the coming 29 years, we will see an additional 1-2 billion people inhabiting the Earth, resulting in a total population of 9-10 billion people. This has driven ecological and efficiency concerns about scaling the existing food system and an interest in an ecosystem of single-celled protein companies which have emerged around the world. These companies are producing single-celled proteins using a variety of technologies which utilize low value products which are fermented to produce higher value products. Specializing in algae to fungi, yeast, and bacteria, the companies come in large to small sizes and have a few locations near global manufacturing facilities.

There are a number of companies that are working with dark food organisms that are mainly focused on producing alternative proteins for the animal feed markets and a few are now moving to produce products for direct human consumption. Companies like Calysta, String Bio, Unibio that are focused on methane consuming bacteria are all making animal feed products. Companies such as Kiverdi, Novonutrients, White Dog Labs, Deep Branch, and Solar Foods are working with hydrogen consuming bacteria and are producing animal feeds, polymers, oils, and human food products. Others like Arbiom are utilizing low cost feedstocks such as wood waste; iCell, which utilizes leftover sugars in waste water to produce animal feeds; and companies such as Lanzatech, which use syngas to biomanufacture liquid fuels.

These technologies and companies have been in development mostly since the early 2000's and are at different stages of commercialization but all have gained market interest and traction. This developing ecosystem has led to an increase in scientific knowledge of growing systems, organisms and products. The resulting increase in capabilities in this field by orders of magnitude can play a role in providing nutrition for those on Earth today and has the potential to impact people in space tomorrow.

While these companies are growing and scaling their technologies, there is a considerable amount of work to be done to understand how these technologies will function in the space environment. Challenges include micro or partial gravity; closed systems; and interconnection with a wider food production, life support systems and energy systems on Earth and in space. Companies such as Orbital Farm are working to understand these challenges today with the development of new manufacturing facilities and generation of the long term application of the technology for use in life support systems in space.

3 Efficiencies

To demonstrate some of orders of magnitude increases in efficiencies of dark food over plant agriculture, we perform the following order of magnitude calculations:

3.1 Energy

We will bound the energy analysis by following only the flow of primary energy. Energy used in pumps, to pressurize and heat volumes, to mine and refine water, etc. will be ignored, as they should be secondary and similar for both photosynthetic and Dark Food systems. We'll assume we start with electricity, water, carbon dioxide, a source of fixed nitrogen (from processed astronaut urine, or through the Haber-Bosch process), and micronutrients such as iron, zinc, etc. These inputs are essentially identical for both systems and are thought to be readily available on Mars.

For photosynthesis, the calculation is simple. Maximum efficacy (watts per watt) of LEDs varies across the photosynthetically active regime from about 40% to 90% (Kusuma et al., 2020). We assume on the high end at 80%. Photon to food efficiency for typical photosynthetic crops is about 0.5% (Blankenship et al., 2011), for a total efficiency of approximately 4×10^{-3} joules of food energy per joule of electricity.

For methanotrophic bacteria, the process starts with electrolysis of water. Disassociating a mole of water (at 25C) takes 237 kJ of electricity and 48.6 kJ of heat (Harrison et al., 2010). State of the art electrolysers are between 56 and 75% efficient (Ivy, 2004). Choosing 70% leads to a value of 57 KWh/kg of electricity per kilogram of hydrogen. Conversion to methane via the Sabatier reaction is exothermic and results in a mass gain for a resultant cost of 14 KWh per kilogram of methane. Batch cultivation of of methanotrophs have experimentally measured yields in grams of cells produced per gram of methane consumed in the range of 0.8 to 1.2 (Lamb and Garver, 1980; Leak and Dalton, 1986; Park et al., 1991, 1992). Choosing a value of 1.0 results in an energy cost of 11 KWh of electricity per kilogram of dry cell mass.

Dry cells are approximately 70% protein and 10% lipids (Øverland et al., 2010). The remaining 20% contains valuable micronutrients and some carbohydrates that are digestible, but we will ignore this here. Using the standard nutritional values of 4 calories per gram of protein, and 9 calories per gram of lipids results in a food energy value of 3,700 calories per kilogram of dry cells, which required 11 KWh to produce, for a total electric energy to food energy efficiency of 0.39. This value is two orders of magnitude higher than the 4×10^{-3} value for photoautotrophic crops derived above.

A full lifecycle analysis for food production from hydrogenotrophs that includes power for machinery, pumps, drying, as well as other environmental impacts was performed by Järviö et al. (2021). They conclude an energy requirement of 15 KWh per kilogram of dry cell mass. This is in line with the 11 KWh derived above, and demonstrates that the majority of the energy requirements is in the biological pathway, not in associated equipment.

We note that it would be possible to lower the energy requirement for photosynthetic food by using sunlight directly, but sufficient photons may not be available. For example on Mars, the average photosynthetic flux is only 25 mol m^{-2}, which is only marginally adequate for plant growth before 50%-70% transmission losses from greenhouse materials are taken into account (Cannon and Britt, 2019). Photon flux will also be significantly reduced during months-long dust storms. On the Moon, adequate flux exists, but may only be available for 14 days at a time, which is insufficient for growth of many crop foods. Very small regions of the Lunar poles do exist where sunlight is available for $\sim$250 days straight.

3.2 Volume

Staple crops such as wheat, potatoes, and sweet potatoes grown hydroponically in Mars analog greenhouse experiments produce on average 20-60 g of dry edible food per m^2 per day, averaged over several months (Drysdale et al., 2003). These crops are mostly carbohydrates, which at 4 grams per calorie, and assuming the hydroponic chamber is one meter tall, results in a volume rate of 80 to 240 calories per cubic meter, per day.

Methylotrophic yeasts in bioreactors have demonstrated a productivity of 10 grams of dry cell weight per liter per hour (Johnson, 2013). Extrapolating (while noting that scaling bioreactors up is notoriously difficult) to one cubic meter (1000 liters) over a 24 hour period would then produce 240 kilograms of cells in the same volume in the same time. Using the 3,700 calories per kilogram number used above results in 880,000 calories per cubic meter per day, a value between 3,700 and 11,100 times that of the crop plants, on order three to four orders of magnitude more productive.

This productivity has been demonstrated at scale for protein production on earth. The 1,500 cubic meter Pruteen bioreactor(Vasey and Powell, 1984) used methylotrophic microbes to produce protein for livestock consumption. The reported real-world productivity was 50 to 60 thousand dry mass tons per year (Westlake, 1986). Assuming the same caloric value as before, this converts to 14,000 to 17,000 cal m^{-3} hr^{-1} - well short of the extrapolated value of 880,000 cal m^{-3} hr^{-1} above, but still a demonstrated 70-200 times increase over the volume efficiency demonstrated for hydroponic crops.

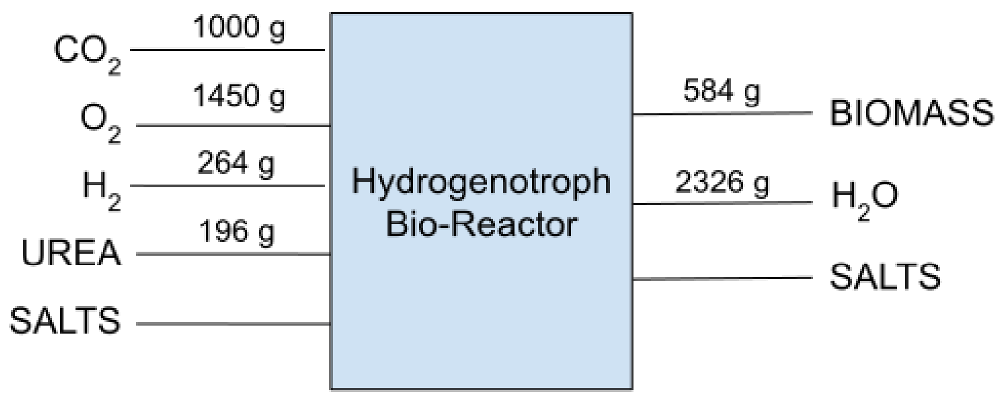

Figure 1: Mass Balance of a Hydrogenotroph bioreactor. Adapted from Drake et al. (1967). Note that more mass of water results than mass of hydrogen and oxygen supplied.

3.3 Start Up Time

Crops have long start up times, and provide calories in large amounts only during harvest. This means a wait of 3-4 months (Drysdale et al., 1994) for a typical hydroponic staple first crop, and can mean that human labor input required is very variable. This can also mean that a failed crop can cause months of productivity loss. Bioreactors, on the other hand, taking advantage of exponential growth, can begin producing in a matter of hours (Luperini-Enciso et al., 2010). A failed crop or contaminated bioreactor can be emptied, sterilized, and producing again in hours instead of months. Human labor inputs should also be more evenly distributed as the bioreactor produces calories consistently, not in large periodic harvests.

3.4 Water

The energy for production of biomass from inorganic carbon in these species of chemotrophs is mainly provided by the oxidation of hydrogen into water. Considering only the reaction chamber itself, A typical dark food reactor such as in Figure 1 is a net producer of water with 35% more mass in water resulting than mass of hydrogen and oxygen supplied. This water will need to be removed from the reaction chamber and can be supplied back to the electrolysers. Hydrogen atoms supplied are ending up in biomass, so eventually more hydrogen in the form of water will be required. Hydrogen by weight in dry biomass is about 6%, suggesting as little as 35 grams of hydrogen (315 grams of water) would be required to produce 2,100 calories (one human-day or 584 grams) of food.

Water usage in an enclosed greenhouse or hydroponics system is difficult to estimate as it depends highly on the efficiency and complexity of the water recovery systems. As a point of comparison, The BEAVER Martian hydroponics system design (Babakhanova et al., 2019) calls for 62.5 kilograms of water per day as an input in order to feed 4 people, which is approximately 50 times more water per person per day required than the dark food bioreactor.

3.5 Additional Products

On Earth, bioreactors are very rarely used for direct food production, though that may be changing. Typical Earth-based applications use engineered organisms to produce antibiotics, insulin, plastics, feedstock for cellular agriculture, and a wide variety of other valuable organic compounds. This leads to the possibility of dual use bioreactors producing valuable organic compounds with the cell mass then being harvested for food.

4 Conclusions

We have demonstrated the potential for chemotrophic bioreactors to provide calories for humans in (semi) closed systems in space. Compared to the plant-based methods which have long been considered the way we will feed ourselves off-world, chemotrophs have the potential to be two to three orders of magnitude more efficient in energy, volume, and water. Reduced human labor inputs, reduced startup times, and the creation of valuable vitamins, amino acids, growth factors, plastics and pharmaceuticals are additional potential benefits of the technology.

The technology was widely studied and shown to be viable by NASA in the 1960s-70s, and though mostly ignored in the decades since, commercial companies are beginning to work with the technology again.

No doubt, photosynthesis will have its place in bio support systems for humans, particularly for production of phytonutrients and the positive morale effects of working with and consuming fresh plants. However, for bulk production of calories, chemotrophic organisms have enormous efficiencies over production with staple crops which will be nearly impossible to ignore for mission designers.

5 Declarations

The authors acknowledge that Dr. Michael Nord works under contract for NASA's Space Technology Mission Directorate on matters of space in-situ resource utilization. Dr. Nord did not perform this work under the NASA contract.

The authors acknowledge that the author Scot Bryson is the founder and a shareholder of Orbital Farm, which has interests in developing technologies and projects that use some of the approaches discussed in this paper. All details cited or discussed in this paper are from publicly available information and no references are made to any work related to Orbital Farm. There is no financial compensation, grants for anything related to the writing or publication of this article.

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