Energy reduction by using direct sunlight for a microalgae photobioreactor for a Mars habitat

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The usage of in situ resources to reduce (re-)supply mass demands for human spaceflight to surfaces of celestial bodies will be a key element in evaluating mission feasibility. Biological components on the Life Support Systems (LSS) can benefit from the use of in situ resources to reduce the required mass. A potential biological component, that would help reduce resupply mass for future missions, is a microalgae photobioreactor. By means of photosynthesis, microalgae use CO_2, water, light, and nutrients to provide oxygen and biomass, which can be used as a supplement food source for the astronauts. The Institute of Space Systems at the University of Stuttgart currently investigates microalgae-based biological components for LSS. Critical factors for the system mass of this kind of biological components are the large amount of required water, and the high energy demand, compared to physico-chemical systems. For biological systems in a Martian habitat, the overall required energy can be of higher relevance than the system volume, if water can be found on Mars near the landing site and can be made available. This paper investigates the possibility of using direct sunlight as energy source for such a system, first evaluating the boundary conditions for the system development. Simulations of the lighting concept and experimental data from microalgae cultivation under simulated Mars light conditions are used to model the system. Different illumination strategies, via combination of sunlight and artificial illumination, are analyzed, both in simulations and laboratory experiments.

Nomenclature

DSN = *Diluted Seawater Nitrogen Medium*
DW = Dry Weight
ESM = Equivalent System Mass
FLE = Flashing Light Effect
FPA = Flat Panel Airlift Bioreactor
IRS = Institute of Space Systems
ISRU = In Situ Resource Utilization
LED = Light Emitting Diode
LSS = Life Support System
PBR = Photo Bio Reactor
OD = Optical Density

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I. Introduction

Recent developments in the private space sector and the roadmaps of space agencies suggest that we will witness astronautic missions to Moon and Mars within the next decades, with the intention of establishing infrastructure for long-term presence. [1; 2; 3] A Life Support System (LSS) for such an endeavor must be as independent from Earth as possible due to the increased distance. Maintaining a constant resupply as we have it today on the ISS, especially in the context of permanently crewed Martian habitation will be difficult, if not impossible, to realize. To reduce the required resupply demand of surface bound habitats, the degree of closure of the LSS can be increased, and In-Situ resources can be harvested. During the development process of LSS components, one tool at hand to evaluate the effectiveness is calculating the Equivalent System Mass (ESM) or equivalent system costs (ESC).[4] For the ESM, the system start mass and the time dependent resupply mass are added. The start mass is calculated by adding the mass of the component under evaluation with equivalent masses for energy-, space-, crewtime- demands.[5] The required resupply mass is dependent from the degree of closure and the duration of the mission.

In the context of In-Situ Resource Utilization (ISRU) for LSS, other factors, such as sustainability, also must be considered. For example, using electrolysis to provide oxygen merely by splitting up H_2O that is gathered from in situ resources might result in a low ESM but would not be sustainable.[6] In terms of sustainability, biological components for LSS are being investigated due to the possibility of in situ food production, and the synergies with CO_2 reduction and O_2 production via photosynthesis, as well as waste-water processing. One potential candidate that could be used in such a system are microalgae. Microalgae can carry out photosynthesis, using CO_2, water, nutrients and light energy to produce biomass and oxygen. The advantages of microalgae are a higher harvest index (percentage of edible biomass), higher biomass productivity, more efficient light utilization, and lower water requirements.[7] However, microalgae alone cannot provide a balanced diet, so a Photobioreactor (PBR) alone cannot eliminate the necessity of supporting food production or resupply missions, but it could reduce the required frequency. A PBR system must be regarded and evaluated as one of many components within a LSS and would work together with other physicochemical and biological systems.

Over the past decade, the LSS-research group at the Institute of Space Systems (IRS) of the University of Stuttgart focused on research and development of such microalgae based components, resulting in an experiment on the ISS – Photobioreactor at Life Support Rack - PBR@LSR where, the capability to cultivate under µ-G was demonstrated. The chosen microalgae species for the investigation was *Chlorella vulgaris*, a spherical cell with a mean diameter of 6 µm. This species was selected due to its robustness towards fluctuations in temperature, pH, nutrient- and CO_2 concentrations. The capability of long term cultivation in a high performing flat panel airlift reactor (FPA) has been demonstrated.

The development of a PBR and its components for an application in µ-G on a space station focuses on minimizing ESM via optimization of the volumetric efficiency, since the required water is part of the system mass that needs to be transported. This might not necessarily be the case for a LSS in the context of a Martian habitat. Recent findings suggest that water could be found on Mars in a form where harvesting it might be feasible. Roadmaps and space exploration visions suggest, that finding, harvesting and using Martian water could be a key goal of future Mars missions.[8–10] Using this water in biological components would not only reduce the required mass that needs to be transported, but also influence the design and optimization parameters. Optimizing energetic efficiency, redundancies and reducing crew time demand is now of increased importance. One way to reduce the power demand on the illumination system is directly using sunlight as light source.

This paper presents the investigation into PBR design to utilize sunlight and optimize energetic efficiency for microalgae based biological components in the context of a Martian habitat. The investigation is conducted under the assumption that water is available from in situ harvesting and that the mission design allows it to be used in a PBR system.

II. Reactor Concept and Test Infrastructure

A. Reactor Geometry

One of the most critical system design parameter for any PBR is the reactor geometry, which has an influence on physical and biological properties of the PBR. Since the feasibility of an illumination with Martian daylight depends on the reactor geometry, the first task is to investigate which geometry would be most suitable for this purpose. Previous studies at the Institute of Space Systems (IRS) have shown, that tubular PBR geometry seems to have many advantages for surface applications, including the illumination profile.[11] Tubes are robust, easy to produce and allow varying illumination angles.[12; 13] Additionally, the positioning is versatile (e.g. on the ground, on roofs, at walls, free standing) and the biofilm formation is at minimum which reduces maintenance effort. On Mars, the in situ production of the PBR tubes from raw material could drastically reduce the volume during transport and allow flexibility in reactor design. Tubular reactors are more efficient in terms of varying entrance angles of light compared to e.g. a flat panel reactor[13]. Tubular reactors can be designed in a closed manner and are insensitive to pressure, which would be an advantage under the thin atmosphere of Mars. Hence, tubular PBRs seem to be a promising candidate for cultivation on Mars and are therefore object of this study. Figure. 1 shows the result of a simulation to compare the light distribution in tubular and FPA reactors. The simulation is based on the Lambert Beer law of absorption. A closer description of the simulation can be found in Martin *et al*. (2020).[14]

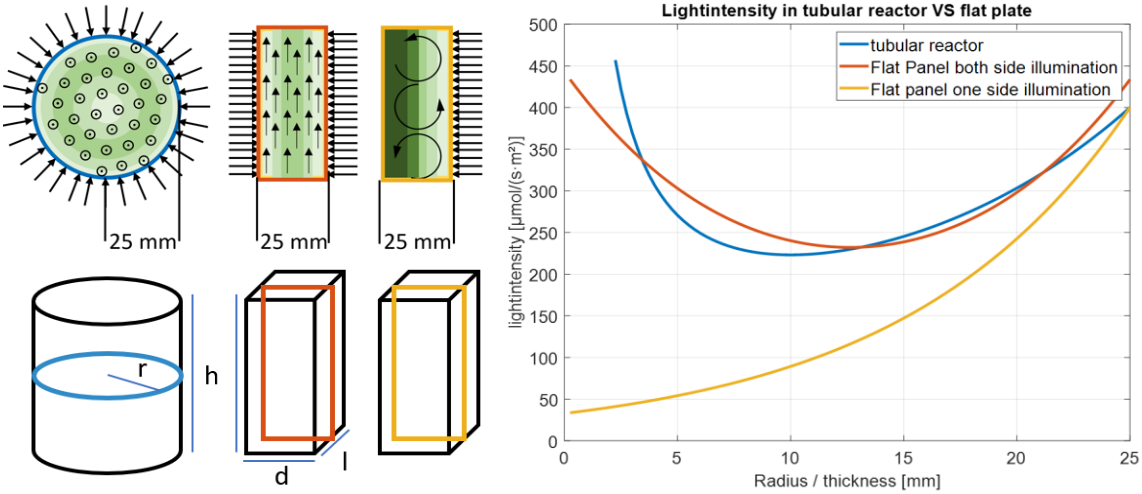


Figure 1. Simulated light distribution in tubular- and flat panel airlift reactors. Simulation along one line orthognal to the surface through the reactor. (Radius of tube: 25mm, Thickness of flat panel: 25mm)

B. Illumination System

The illumination system plays a key role in microalgae cultivation as light is the main energy source for photosynthesis. Thus, it is of major interest to optimize light availability for the algae while at the same time energy and material investments should remain as low as possible. When the suspension flow in the PBR is generated passively via air flow, the illumination system represents the main energy consumer of the system. To reduce energy consumption, the usage of sunlight as in situ resource comes to focus. Concerning intensity, spectrum and radiation, algae cells are adapted to Earth conditions. Sunlight on Mars is less intense than on Earth because of the greater distance to the sun and has a differing spectrum. A Sunlight intensity increase could effectively be achieved via mirrors. Since static mirrors reflect light of a moving sun with unsatisfactory efficiency, movable mirrors should be considered. The necessity of mirrors can easily be used to additionally address other problems of outdoor algae cultivation from Mars. A surrounding envelope of mirrors would serve as insulation against low temperatures at night and high radiation peaks caused by solar storms. By day the envelop could open and reveal light collecting mirrors adapting their position to the sun and enabling near-circular illumination. Small LEDs on or between the mirrors would ensure light supply for the algae e.g. during sand storms. Figure. 2 shows a scheme of this system. In this scenario, the PBR is placed in a small furrow on the Mars surface and covered by glass. This positioning guarantees protection

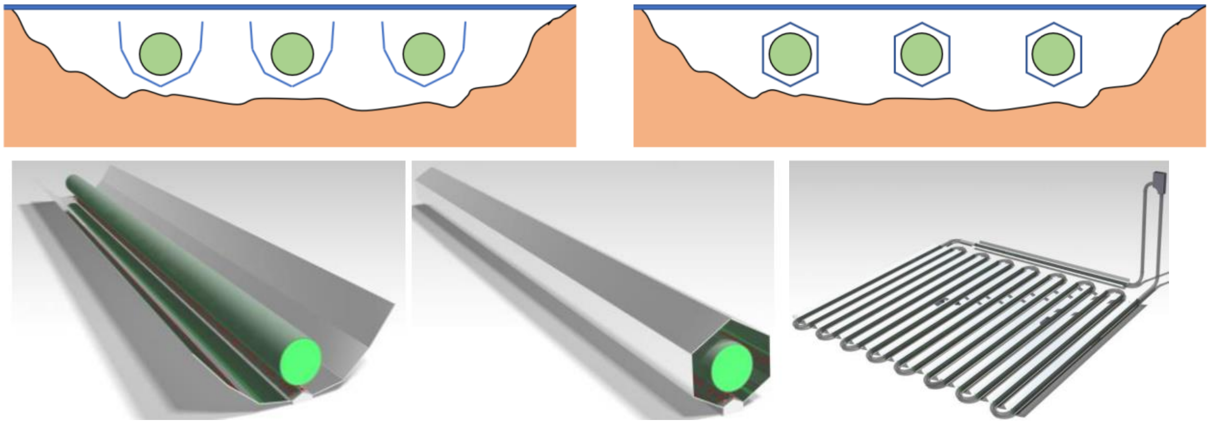
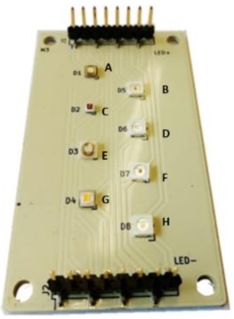


Figure 2. Scematic of sunlight collectors that can function as isolators

from dust, which could otherwise cause technical defects on the mirror engines or simply cover mirrors and PBR in dirt. The glass cover, on the other hand, should easily be cleanable.

As cultivation experiments on the Mars surface seem to be in a far future, the first approach is the implementation of Mars like cultivation conditions in the lab. Our aim was the adjustable simulation of Mars light. At the Institute of Space Systems a modular LED-unit has been developed, including 8 LEDs of various wavelengths and a LED-driver. Complete controllability of each LED allows free adjustability of light intensity and spectrum, e.g. to mimic Mars lighting in the laboratory. Additionally, the modular construction enables linear scalability. Figure.3 shows one chip that consists of 8 LEDs of different wavelength. The illumination unit of the PBR consists of several single chips connected in series. The control unit can control the intensity of every wavelength individually. As light conditions on Mars are not constant, an accurate simulation needs to include the day and night cycle including dawn.



A	OSLON Signal LV CQBP	505nm
B	Luxeon Sunplus 20 Line	665 nm
C	SEOUL SZN05A0B	412nm
D	OSLON Signal LCY CLBP	590nm
E	LUXEON SunPlus	620nm
F	LUXEON SunPlus	455nm
G	OSLON Square GH CSSRM2.24	660nm
H	LUXEON SunPlus	480nm

Figure 3. Modulare LED chip with 8 different wavelength

C. Lab Scale Cultivation System

To verify the concept of using mars daylight, a lab scale test stand has been developed. The PBR of this test stand consists of a single tubular, upright column with aeration via a porous stone at the base of the column (“bubble column PBR”), including adjustable CO_2 concentrations. Figure. 4 shows a test setup. In contrast to a tubular PBR with a closed loop, where turbulence is caused by mass flow of the suspension in columns, a chaotic mixture of the suspension is generated by the uprising bubbles. This simple setup allows small scale cultivation of microalgae in parallel experiments with up to1 liter suspension volume each. *Chlorella vulgaris* has previously been selected for non-axenic cultivation for its robustness, productivity, tolerance and food suitability.[7;15] The suspension is illuminated from one side with a driver controlled LED panel. In this study, two initial experimental setups have been investigated:

- The cultivation of *C. vulgaris* under a Mars daylight scenario using DSN medium (a standard *C. vulgaris* medium) or C.R.O.P (filtrated wastewater produced by the DLR C.R.O.P (Combined Regenerative Organic food Production) system) [16; 17].
- Cultivation of *C. vulgaris* in DSN under lighting scenarios (Mars daylight & night illumination (see III.).

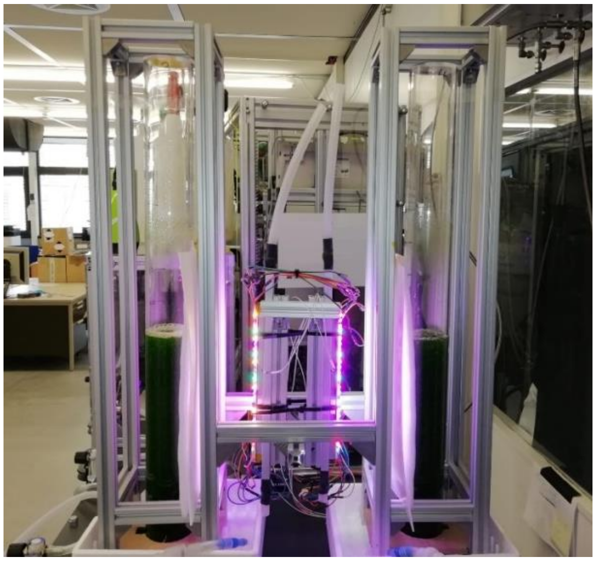


Figure 4. Modulare Lab scale *C. vulgaris* cultivation in a bubble column photobioreactor. A total of 6 PBRs was used for parallel cultivation.

D. Data Collection

Observation of algae growth is performed by spectrophotometric analysis. This technique allows determination of the absorbance at specific wavelengths (optical density). The absorbance at 680 nm (maxima of Chlorophyll)[18] is correlated to the increase of algae biomass. Previous studies at the IRS determined the exact correlation factor shown in equation 1.

$$DW\ [g\ l^{-1}] = 0{,}2123\ \cdot OD_{680} \qquad (1)$$

Additional wavelengths are tracked to investigate biological culture conditions. Absorbance changes at 454 nm can be caused by varying pigment ratios (e.g. carotenoids) and can indicate cell stress. Sudden absorbance increase at 850 nm can indicate the growth of photosynthetic bacteria.

Further parameters of interest are the macronutrient uptake rates for nitrate (NO_3^-) and phosphate (PO_4^{3-}). Nitrate and phosphate are two of the main bioavailable contaminants in wastewater and valuable compounds for every closed-loop economy.

E. Gas Rate Calculation

A critical design parameter of LSS on Mars will be the CO_2 absorbance rate, because CO_2 recycling will be the foundation for successful implementation of space habitats. In small scale experiments, the air flow is relatively high compared to the biomass production rate to ensure not only abundance of dissolved CO_2, but sufficient suspension mixture. It is therefore difficult to detect the resulting small CO_2 concentration differences. An alternative approach is the calculation of the amount of absorbed CO_2 using the biomass equation (equation 2) published by Perdue [19] and adapted by Keppler [20] and shown in eq.2.

$$106\ CO_2 + 13\ H_2O + 16\ NO_3^- + H_3PO_4 + 144\ H^+ \rightarrow C_{106}H_{173}O_{65}N_{16}P + 106\ O_2 \qquad (2)$$

Given that the determined biomass concentration in the PBR is correct, the amount of CO_2 necessary to build this biomass can be calculated. But as the biomass composition is depending of various abiotic factors, like nutrient composition, light intensity and spectrum etc., it is possible that equation (2) does not represent the biomass composition of *C. vulgaris* under the conditions of this experiment. An easy and quick approach to evaluate the accuracy of the equation is by calculating the nitrate absorbance rate and compare the results to the empiric determined absorbance rates during cultivation. This calculation indicates an accuracy of more than 98% concerning *C. vulgaris* biomass, hence, this model seems suitable for the calculation of CO_2 absorbance

III. Test Campaign

A. Medium Studies

Cultivation media are complex solutions to provide all nutrients for optimal growth of algae or other microorganisms. Additionally, abiotic factors like pH and salinity are to a large extend given by medium composition. Human wastewaters contain valuable nutrients, and recycling of water and nutrients is of great interest in Earth and space applications. The DLR has developed a regenerative filtration system for the treatment of sewage and other nutrient rich wastes to produce bioavailable nutrient solutions.[17] In this study, the C.R.O.P. solution will be compared to diluted seawater nitrogen medium (DSN), a standard complex medium for *C. vulgaris* cultivation (see Table 1).[16] These two media were chosen due to the relevance of the C.R.O.P solution in the context of LSS and the available expertise on DSN as benchmark. In Both media, NO_3 is the source of nitrogen and PO_4 the source of phosphate.

Table 1: Cultivation media

	Concentration [mg/l]	
	DSN[a]	**CROP[b]**
Chloride	2980	396
Sodium	1459	828
Potassium	944	277
Phosphate	200	162
Nitrate	500	2727
Sulphate	0,143	278
Calcium	0	5405
Magnesium	0	404
Manganese	0,222	N.D.
Zinc	0,046	N.D.
Cobalt	0,042	N.D.
Molybdenum	0,079	N.D.
Copper	0,005	N.D.
Iron	0,003	N.D.

[a] values calculated from recipe
[b] values determined by chromatography prior to delivery

B. Experiment Setups

To evaluate energy efficient illumination scenarios for potential Mars cultivation of microalgae, it is necessary to design representable, Mars-like cultivation systems here on Earth. Mars atmosphere contains large amounts of CO_2. To ensure maximum photosynthetic efficiency, it is beneficial to ensure optimal availability of dissolved CO_2 by increasing CO_2 concentration in the air flow up to 5-10%. The volumetric flow rate of CO_2 enriched air was 0.5 $l*min^{-1}$.

Algae mainly absorb light in the red and blue parts of the spectrum (the remaining green light gives the typical color). In a first step, the LED illumination system (see II) has been adjusted to the Mars spectrum (Figure 5). Additionally, the programmable LED driver controls a day-night rhythm including twilight. In this study, algae cultivation with Mars light was compared to illumination scenarios where the efficiency of supporting synthetic light in the light phase was evaluated. It was differentiated between a constant and flashing illumination at night time. Flashing light is known to increase energy efficiency concerning biomass productivity compared to constant illumination.

Increasing cell density during cultivation results in increased light absorbance and reduced light penetration depth, respectively. This is described by the Lambert-Beer Law. To better understand this behaviour of light absorbance in tubular reactors, we used a scalar quantum sensor (Walz, Germany). Scalar quantum sensors allow a near 360° photon detection and therefore include the scattering light resulting from refraction at the reactor surface and enable an encompassing determination of light absorbance (Figure 6). This analysis will allow to best understand complex lighting scenarios including sunlight, mirror and LEDs operating from various angles and therefore be of great influence in the further development of the illumination system.

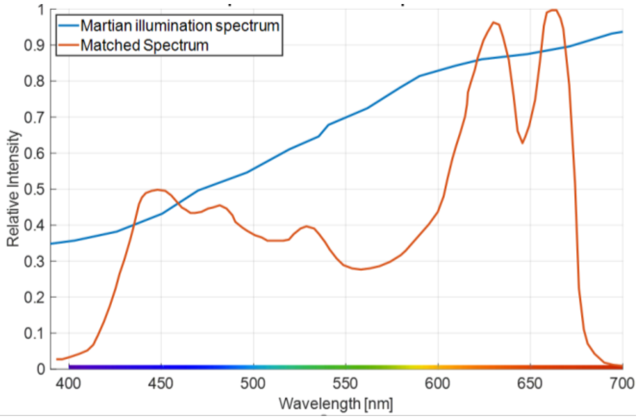


Figure 5: Martian Illumination spectrum [21] and matched spectrum of illumination unit.

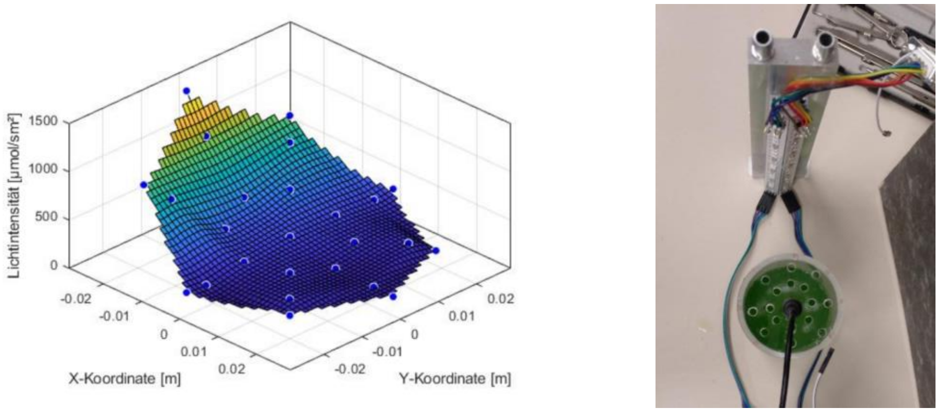


Figure 6: Photon flux density decrease in a tubular PBR containing microalgae (OD_{680} = 0.8). The picture on the right shows the experimental structure including the inlets for the scalar quantum sensor

C. Experiment Results

Overall, successful cultivation of *C. vulgaris* in bubble column reactors using simulated Mars light was demonstrated. The system seems suitable for small scale experiments in large numbers, meaning that larger reactors of an LSS might encounter some scale up effects that are not included in the 1-l reactors results. Yet, having smaller reactors allows to have many experiments in parallel for lower costs. Nevertheless, the reactor design includes a weakness at the connection between reactor tube and aeration inlet, that resulted in leakage. Careful workmanship during lab work inhibits these inconveniences. To connect the reactor-tubes to the air inlets, a glue had to be found with enough strength to support handling and without negative influence on the microalgae growth. The first attempt was a food approved silicone. After the leakage occurred, this silicone was replaced by a epoxy resin.

Figure 7 shows cultivation of *C. vulgaris* under a synthetic Mars daylight scenario in the standard DSN medium as well as medium from C.R.O.P.. C.R.O.P. seems to enable slightly higher growth rates in this experimental setup than DSN. This effect can be caused by the overall high availability of nutrients and especially by ammonium, which is (compared to nitrate) the more energy efficient nitrogen source for plants.

Supporting the simulated Mars daylight with continuous or flashing illumination by night did not result in major differences of the growth rate (Figure 7). For final statistical evidence the experiment should be repeated with increased sample size and verified in a scaled up PBR.

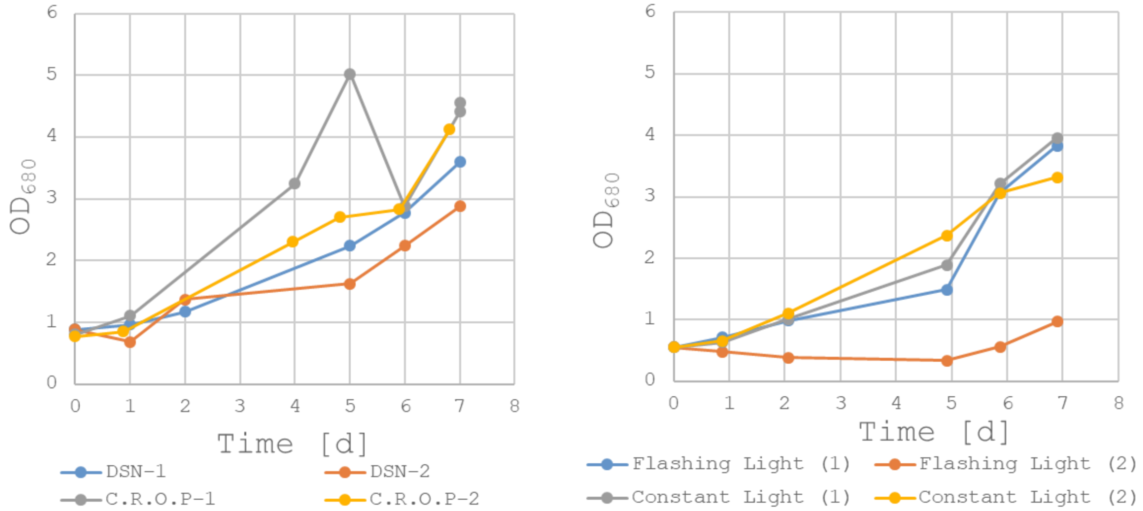


Figure 7: Growth of *C. vulgaris* in bubble column PBRs using different media (left) (Duplicates with DSN and CROP medium at same light-settings)or light settings (right) (Duplicates with DSN for constant and flashing light).

IV. Discussion of Results and Further Analysis of Concept

The usage of Martian daylight for microalgae cultivation can offer great possibilities and challenges. Our first results show that we are able to cultivate *C. vulgaris* in parallel experiments under simulated Mars light and increased CO_2 atmosphere. Our findings indicate, that in terms of illumination the reduced intensity and shifted spectrum of sunlight at Mars would allow algae cultivation without additional energy input for synthetic light. Nevertheless, the usability of a PBR in LSS depends on the overall productivity. Reduced photon availability results in low growth rates, making PBRs inefficient. This effect can be compensated by (1) additional illumination or (2) increased volume of the cultivation system or (3) a combination of both approaches.

Additional synthetic illumination could be integrated in a mechanical envelope structure as described in section II. This would allow adaptable, needs-oriented usage of light, e.g. during night. During phases of high energy availability (low demand of other consumers or peak production of solar panels) a supportive illumination during day could be used to increase biomass production and decrease energy loss.

As surface area can be considered available unlimitedly, the increase of overall volume of the PBR is mainly limited by two factors: water and material. Large PBRs need a large amount of water for cultivation and maintenance. Operating such a LSS is only relevant when water is abundant as in situ resource on Mars, e.g. near polar regions. The polymer for the construction of the reactor will most likely be produced on Earth and transported to Mars. To minimize transport volume, e.g. thermoplastic formation of the reactor tube could be performed on Mars. The development and the usage of a tubular microalgae system such as described in this paper could only make a contribution to a Martian mission under certain conditions: The availability of water and the possibility of harvesting it at the planned destination, the intention of long-term / permanent stays, and the commitment to sustainable usage of harvested water.

V. Conclusion and Outlook

Microalgae photobioreactors have the potential to reduce ESM in the development of future LSS. Nevertheless, PBRs will not be able to solitary enable human life on Mars but be part of a complex LSS. Not only can PBRs optimize the recycling of crucial elements like C, N, O and P but it will also be part of water and gas processing and even food production. These redundancies further support the usage of PBRs as system failures in other parts of life support might be compensated for a short time. It is now the time to fully develop the great potential of microalgae PBRs for Mars application by further studies, like the synergy of algae cultivation with insect or crop production and the accuracy of simulated Mars cultivation on Earth.

The usage of Martian daylight for a Mars habitat will reduce the energy consumption of the system. Most likely additional synthetic lights will be necessary to ensure oxygen production of the microalgae during long dark periods caused by sandstorms covering the PBR. But, as the reactor is equipped with a synthetic light source, it might be beneficial to use them to improve cultivation productivity as long as energy is abundant.

Acknowledgments

The implementation of the technology transfer project was made possible by a grant from DLR Space Management. Project number 50RP1925. This work was also partially financed by the Friedrich und Elisabeth BOYSEN - Stiftung [BOY-139].

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