BioCeMe

Cellular Agriculture in Space Feasibility Study

Executive Summary Report

Issue 1.0

Date: *29th March 2023*

Ref.: KS-AGR-RP-012

ESA contract no. 4000137210/22/NL/GLC

KAYSER SPACE

Cellular Agriculture

Campden BRI
food and drink innovation

Project name:	**Cellular Agriculture**
Document title:	**Executive Summary Report**
Reference no.:	**KS-AGR-RP-012**
Issue date:	**29/03/2023**
Issue and revision:	**1.0**
ESA contract no.:	**4000137210/22/NL/GLC**
Organization:	Kayser Space UK Ltd, Harwell Campus Building R104, Fermi Avenue Didcot, Oxfordshire, OX11 0QX

	Name	Company or Institute	Signature
Prepared by	Ramón Nartallo	Kayser Space Ltd	
Reviewed by	Gianluca Neri	Kayser Space Ltd	
Distribution list	Paolo Corradi (TO) Christel Paille Leopold Summerer	ESA/ESTEC ESA/ESTEC ESA/ESTEC	

EUROPEAN SPACE AGENCY

CONTRACT REPORT

The work described in this report was done under ESA contract.

Responsibility for the contents resides in the author or organisation that prepared it.

Executive Summary Report

The provision of food is obviously important to the wellbeing of astronauts. Space travel has advanced over the years from 'short' space missions to the moon to longer stays in the International Space Station (ISS), where astronauts are supplied with shelf-stable, single-serving food products, either in their natural form or preserved (e.g. by dehydration, freeze-dried, retort thermo-stabilization or irradiation). However, due to limited physical space, additional services and associated loads required, future long-duration manned space missions or planetary outposts (e.g. on the Moon or Mars) will need solutions for producing food in-situ with a view to:

- Limit the amount of long shelf-life food (and associated waste material) to be transported.
- Provide an alternative fresher source for essential nutrients.
- Provide a higher level of self-sustainability.
- Reduce reliance on costly resupplies from Earth.

A feasibility study on *Cellular Agriculture for Future Human Space Missions* was carried out by an industrial consortium comprising Kayser Space Ltd., Cellular Agriculture Ltd. and Campden BRI. The study was staged over three phases covering:

- Mission analysis, Mission requirements and Technologies assessment.
- System conceptual design and Performance analysis.
- Knowledge Gaps and road-mapping, Development plan and Regulatory outlook.

Two long duration deep space mission scenarios were analysed in terms of astronaut nutrition and food safety requirements. The key space environments considered are: a) the long duration transit phase to Mars, where the technology would be required to operate in a microgravity environment, and b) Lunar and Martian outposts with reduced gravity with respect to Earth. In both cases there are additional issues related to potential space radiation effects, shelf-life and waste management and re-cycling. There are also engineering budgets and performance factors to consider: mass, power and volume, as well as input/output efficiency.

Preliminary driving requirements and derived technical requirements were defined against these operational scenarios, and also informed by nutritional and logistics considerations derived from discussions with experts in an ESA organised workshop.

In terms of the nutritional requirements of astronauts, particular focus was placed on protein amino acids. Meat is considered to provide the optimum combination of properties overall, and meat cells will be utilised in the future as the starting material for the cell culture process. A detailed review of published literature identified a wide range of potential protein sources - from insects to cyanobacteria and algae – considered their properties, and assessed associated technologies providing an estimate of technology readiness level for terrestrial applications.

The production of cultured meat follows similar techniques and processes to those used in tissue engineering. Bioreactors replicate *in vivo* conditions most closely, and are typically used to achieve higher density cell cultures than are obtainable, for example, in standard tissue culture flasks. They typically consist of: a central module which is provided with a liquid nutrient medium to facilitate the expansion of a resident cell population; a reservoir where the medium can be stored externally to the module; pumps that facilitate flow of the medium around the system; an oxygenation system (internal or external to the module); sensors for on/offline monitoring of e.g. temperature, pressure, dissolved oxygen and other elements concentration; temperature control (e.g. heating and cooling jacket); filtration units for waste valorisation; a means of agitating or mixing the contents of the module to achieve homogeneity of both waste outputs and nutrient inputs within the media. A general system approach would constitute a series of reactors, often termed the ‘seed train’, which function to expand cells to a quantity sufficient for seeding of the final ‘production’ reactor vessel.

To fulfil the derived protein intake requirements, different terrestrial bioreactor technologies used for culturing artificial meat and their potential adaptability to the space environment (microgravity, radiation, consumables and waste management) were assessed. The goal was to define a suitable architecture concept that addresses the outcome of the mission analysis and model its performance. While some bioreactor technologies were judged to be not well suited for scaling up or operating within the space environment, the Hollow Fibre Bioreactor (HFB) in particular, was found to be comparable with those utilised traditionally in microgravity conditions on the ISS in terms of its perfusion flow and buoyant neutral operation. It is therefore considered highly feasible that the HFB can be adapted as a cellular agriculture system for use in space with limited modification.

A system architecture based on HFB technology was proposed for operation in space environments and its performance modelled in terms of input /output parameters and engineering budgets, aimed at sizing an HFB design that satisfies the protein requirements of the mission. An assessment of the toxicity of concentrated culture medium components was also considered from a safety point of view.

The HFB systems modelled provide the potential for a compact low mass cellular agriculture production platform in space. A five-reactor series at two sets of scales - small seed reactors followed by larger proliferation and differentiation reactors - are estimated to be capable of producing enough cultured meat to satisfy the animal protein requirements for a crew of up to eight persons. The system derived is comparable in size and complexity to existing microgravity facilities onboard the ISS in terms of mass, volume and power budgets. High scalability in stepping up from seed train to production scale with high density cell culture, mean the core inputs and utility duties are dominated by the final proliferation and differentiation reactors, with the smaller seed reactors requiring comparatively very little material input.

While mission duration does not affect the size of the system required (as this is designed according to crew size) it obviously impacts the raw material inputs, which are the key criticality identified and quantified in this study. In particular, glucose and oxygen are the most highly consumed media components, with glucose required in the order of thousands of kilograms in all system scenarios considered. Waste valorisation is another key criticality derived from the model – with over a thousand kilograms of lactate produced in a crew of four, 1200 days scenario; thus, resource recovery is vital.

Science and engineering questions still remain in the development of an efficient HFB closed loop system for space. The output products of a cellular agriculture system can become core resources to other systems (including life support) and therefore significantly improve the efficiency of the ‘closed loop concept’. Identifying these challenges requires further research and development in the cellular agriculture field and in closed loop systems in general.

Knowledge gaps identified in the current technology and its operational implementation in the space environment include detailed knowledge of the nutritional content of cultured cells and the optimisation of cellular growth and culture media, as well as its storage and shelf life. Optimisation of the HFB technology and system modelling, hollow fibre material, sterilant, cell attachment and release and rate of fibre biofouling also require further development. Other aspects to advance include life support and system recycling, culture medium filtration, and in-situ glucose production and valorisation of waste metabolites (Lactate). In addition to space qualification of future bioreactor systems, potential effects of the space environment need further knowledge, including effects to radiation exposure and the impact of operating in microgravity.

Cultured meat is a recent technology and, as such, there are currently several regulatory considerations and challenges facing the development and legal commercialisation of cultured meat. The study includes a report on the regulatory outlook for artificially cultured meat in Europe, the UK, the US and globally, including pre-market plans for certification, harmonisation, labelling, environmental protection and safety and quality standards. A brief report is also given of the significant interest and many outstanding questions around cultured meat within the mainstream food and drink industry. The driver that justifies the involvement of most legacy food manufacturers in this new industry is sustainability, which has emerged as the most significant driver of diet changes in the past 5 years and has resulted in a significant number of consumers moving to a more plant-based diet. Research has shown that cultured meat is seen as an important innovation due to the “importance of meat” and “a consumer’s perception of cultured meat as a realistic alternative to regular meat”. It appears clear from the movement of large food manufacturers investing in cultured meat that the industry is prepared to explore the technology, however significant barriers, across cultural, ethical and technological areas remain.

In summary, cultured meat offers an exciting potential food production platform for long-term space missions. To achieve this goal small steps and breakthroughs in the field need to be taken before the end goal can be realised. Understanding the behaviour of muscle cells that will go on to form the cultured meat product is vital to refining the process by which they are grown. A roadmap to address this and other gaps in the required technology and processes has been proposed in terms of a development plan with specific short, medium and long terms goals aimed at the full development of a space compatible cellular agriculture system. In the short term, a miniaturised ISS demonstrator is proposed to understand the behaviour of the HFB in microgravity. In the medium term the scaling up of the technology needs to be achieved for viable terrestrial commercial systems; this will then translate into a space system capable of producing a sufficient amount of cultured product to enable full nutritional and food safety analysis. A ‘life support’ class system, capable of producing enough food to support a crew of eight on a long duration space mission, is the long-term goal.