PILOT STUDY ON THE IMPACT ASSESSMENT OF ESA EARLY R&D ACTIVITIES

Cellular Agriculture for Future Human Space Missions

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Our growing population needs a sustainable food supply …

Just as the human population on Earth is projected to grow, so is the human population in space. In both instances, renewable nutrient sources will be vital for ensuring the long-term sustainability and security of our food supply.

For future crewed space missions, where every gram of mass and drop of water counts, cultivated meat could be the key in ensuring astronauts' health and wellbeing on long duration journeys, helping to achieve sustained human presence in space. On Earth, cultivated meat represents a significant step towards food security, and could address the growing resource pressures and contribution to climate change associated with traditional animal agriculture.

… and a new system developed with ESA funding can produce renewable nutrient sources in space …

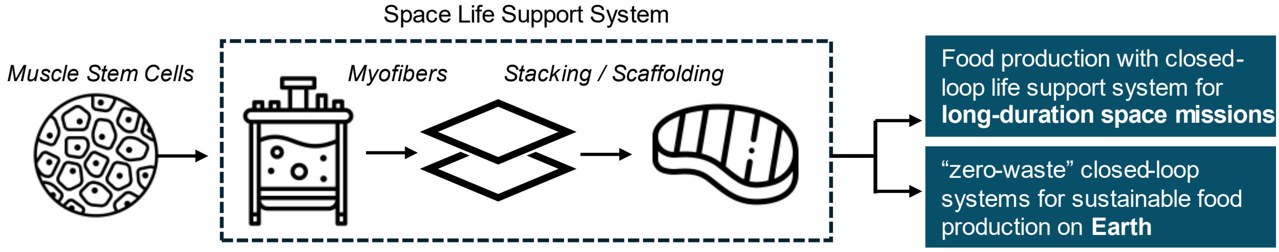
The *'Cellular Agriculture for Future Human Space Missions'* (BioCeMe) project worked toward developing food production *in situ* to reduce the long shelf-life food that needs to be transported from Earth for long-duration missions. This €100k feasibility study was funded by the European Space Agency (ESA) under the Discovery programme[1], and represents the first step towards developing a system able to produce reliable renewable nutrient sources in space. No system was expected to be developed at this stage, and theoretical questions still need to be addressed to ensure continued technological advancement.

The activity was led by Kayser Space (UK), an SME that conducts scientific research in microgravity, supported by two consortium partners. Cellular Agriculture (UK) is a startup which has developed an innovative hollow fibre membrane bioreactor technology platform enabling the industrial scaling of affordable cultivated protein. Campden BRI (UK) is a food & drink analysis company with expertise in food safety (i.e., hygiene, hazard) and nutrition. This activity represents the first collaboration with ESA for both sub-contractors.

[1] The Discovery programme, as part of ESA's innovation pipeline, explores new ideas and disruptive technologies by funding early-stage research and development in space technology. Through an open and competitive approach, it encourages risk-taking and collaboration with academia, industry, and innovative SMEs, aiming to identify game-changing concepts for future space missions.

The consortium's production process involves isolating stem cells from animal tissue, growing these cells in a nutrient-rich bioreactor, differentiating them into muscle fibres, and turning these into an edible product. In this Discovery-funded project, the project team assessed the viability of a space-based bioreactor for producing cultivated meat that meets nutritional requirements. The project assesses the concept of a 'closed loop' life support system for far-from-Earth missions, while also supporting development of the equivalent terrestrial system for sustainable food production.

Overview of the activity



Source: Kayser Space

The unique selling point of this solution is the hollow fibre bioreactor (HFB), which provides significant mass and volume advantages. It reduces resource demands such as atmosphere, water, media, and energy, and could achieve an order of magnitude higher cell density output compared to other systems. The highly efficient perfusion technology and localised, in vivo-like environment enable scaling without compromising performance. This makes it much more attractive than other solutions, such as fixed-beds or stirred tanks.

This HFB system supports a compact, low-mass cellular agriculture production platform in space, comparable to existing ISS facilities in mass, volume, and power usage. A series of five reactors can produce enough cultured meat to meet the animal protein needs for crews of four to eight people at any given time (given this is a closed loop system), with specific requirements outlined in the table below.

Protein production vs. crew size and mission duration

Crew size	Persons	8	4	4	4
Mission duration	Days	90	650	950	1,200
Total protein production requirement	Kg	47.52	171.6	250.8	316.8

Source: Kayser Space

The same system design can also support longer mission durations (e.g. several months for Martian missions) by accommodating more raw material inputs and production batches while maintaining the same target batch mass. Additionally, its closed-loop nature is critical, with effective waste valorisation and resource recovery from lactate being vital to the model.

… supporting long-term space exploration and habitation far from Earth …

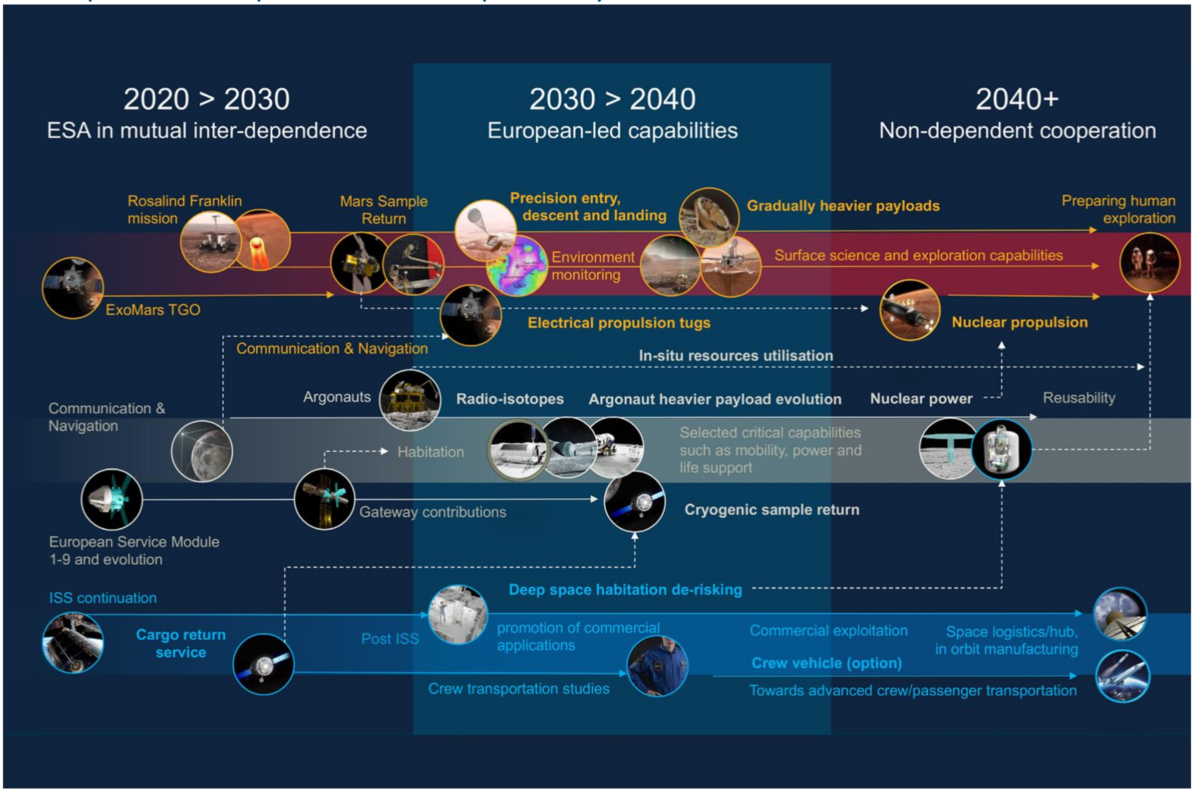
As part of the NASA-led Artemis programme, Europe will return to the Moon within the next decade. The Lunar Gateway, the first space station beyond low Earth orbit, will serve as a communication hub, science laboratory, and habitation module for astronauts exploring the Moon. The programme ultimately seeks to establish a permanent base on the Moon and to facilitate human missions to Mars. In the more distant future, there have also been concept studies for Martian long-term habitation systems.

Regular supply of food from Earth would be too costly and inflexible for long-duration human missions far from Earth. Developing a 'renewable' nutrient source for astronauts is a key enabler to achieving ESA and international ambitions on the Moon and Mars.

Once fully developed, the HFB system could enable food production *in situ* to support future long-term crewed space endeavours far from Earth: spacecraft-based missions, planetary outposts and habitation systems. Contractors anticipate that the system will require another decade of development before it is ready to be used for space applications, and that further research funding is essential.

The development of innovative enabling solutions, such as the one examined in this case study, is an integral part of the long-term space exploration and habitation roadmap (see below), and thus requires early funding, such as through ESA's Discovery programme, to ensure timely technological and industrial readiness.

ESA Explore2040 capabilities roadmap and beyond for Terrae Novae with notional timelines



Source: ESA 2024[i]

… with potential technology transfer to enhance food sustainability on Earth …

There are growing concerns about the environmental impact of meat production, with the livestock industry accounting for 12-18% of total greenhouse gas (GHG) emissions, on top of its negative influence on water footprint, water pollution and water scarcity[ii].

Compared to conventionally produced European meat, cultured meat has 7–45% lower energy use, 78–96% lower GHG emissions, 99% lower land use, and 82–96% lower water use[iii]. Additionally, animal welfare and zoonotic disease outbreaks concerns are also drivers for the growing shift towards diets with a lower dependency on animal proteins.

Prominent agri-food companies including ADM, Nestlé, and Tyson Foods are investing in the development of cultured meat technology, and the global cultured meat market is anticipated to experience significant growth in the next decade, reaching €6bn in 2033 (from €92m in 2023),[iv] with the fastest growth forecast in Europe.

The HFB system is designed to minimise resource requirements (i.e. atmosphere, water, media, energy, physical space), and its technologies could contribute to sustainable terrestrial food production. If the terrestrial technology is scaled up, it could increase access to food and significantly reduce agricultural greenhouse gas emissions. In turn, the technology could contribute to addressing global challenges, such as eradicating world hunger and mitigating climate change.

… delivering potentially valuable socio-economic benefits

This technology is at an early stage of R&D, and needs to be further developed to be deployed and unlock the most significant benefits. However, **some important human capital and knowledge benefits have already been realised** at this early stage through the feasibility study.

Promoting spin-in to the space sector

The two sub-contractors of this activity have never been involved in the space sector until they joined the consortium led by Kayser Space, and both highlighted their keenness to continue work in this 'exciting' industry in the future.

Before this project, Kayser Space, Cellular Agriculture, and Campden BRI had never collaborated together. The two subcontractors are experts in their fields but had never worked on space applications before.

All three organisations saw this new partnership as promising and have the ambition to further pursue common activities leveraging their ESA Discovery-funded work. The two non-space contractors were particularly keen to continue their work in space, having found this project particularly interesting and inspiring. This was an opportunity for them to enter the space sector (initially with a space industry partner), opening new market segments and future revenue opportunities. Overall, contractors are pursuing collaborations, both as a full consortium and bilaterally, resulting in a total of three new partnerships established.

Fostering new commercial revenue

The work done in this ESA-funded activity can be leveraged to develop commercial products for the terrestrial food market, leading to new commercial revenue.

Cellular Agriculture, one of the two sub-contractors of this activity, highlighted that they would be able to commercially deploy a product for ground applications that leverages the work done in this ESA early R&D funded activity with another 18-24 months of further technology maturation. The company would sell the product to food manufacturers who would then supply it to mass retailers in countries with supportive novel food regulations (e.g., Singapore, United States, Israel) after approval of the product by authorities.

Indicative revenues for Cellular Agriculture would initially range between €59k (£50k) per unit for R&D-scale systems to €1.2m (£1m) for a pilot-scale factory, though the opportunity could be much larger given the significant projected market growth in the next decade.

Capturing follow-on funding

Contractors are highly motivated to build on the work undertaken during this activity, applying for and securing follow-on funding to ensure readiness for the eventual high value commercial contracts in the future.

The consortium has won and will apply for further funding to progress their technology, with the ultimate goal of winning large contracts to supply renewable nutrient source solutions for lunar and Martian endeavours.

Kayser Space and Cellular Agriculture have secured matched funding from the UK's Science and Technology Facilities Council (STFC) to build a prototype of the HFB system and test it terrestrially, with STFC and the consortium each providing €35k (£30k), for a total of €71k (£60k). This funding brought the technology from a nascent concept to TRL1-2. ESA's early R&D funding was essential in securing this follow-on support by starting to 'de-risk' the technology. The consortium had initially been unsuccessful for the STFC funding, but resubmitted an application after completing the ESA-funded project which was successful.

The consortium has also applied for the UK Space Agency (UKSA) and Axiom Space's call for proposal for science experiments and technology demonstrators that could be flown on the International Space Station in late 2025. While unsuccessful, the three companies will seek alternative funding under UKSA's National Space Innovation Programme.

Additionally, Cellular Agriculture and Camden BRI have initiated a new, separate, collaboration following the ESA early R&D activity. They have secured €1.8m (£1.5m) from Innovate UK and the Biotechnology and Biological Sciences Research Council (BBSRC) to optimise, test and validate the scalability of hollow-fibre bioreactors to produce cultivated meat products for terrestrial use.

Improving business and technical skills

All employees involved in this activity developed new technical and business skills, which is particularly valuable for the several early career individuals involved. This contributes to reinforcing the skilled talent pipeline essential to deliver space sector growth.

The organisations involved in the activity have developed technical skills, due to the project's innovative and cross-sectoral nature. The consortium unlocked access to ESA experts, with whom it had discussions around mission parameters, focusing on topics like astronaut diet and the impact of radiation exposure on cell cultivation. Cellular Agriculture also reported developing skills in design system layout, software development, and chemical engineering. Overall, the activity helped contractors develop background knowledge of space requirements, which will also support future space projects. This technical learning opportunity is particularly valuable for the young professionals and students involved in the project (~5), contributing to building a highly skilled workforce in the space sector.

Additionally, the activity was an opportunity for Kayser Space to further strengthen its project management skills. Cellular Agriculture also reported similar benefits, on top of enhanced skills in partner relationship management and ESA proposal development. Campden BRI highlighted during a consultation that the platform provided by this activity led to its involvement in a regulatory sandbox for novel food.

Triggering new IP creation

This activity enabled contractors to develop knowledge that can be leveraged in other projects, whether in space or terrestrial sectors.

This ESA-funded early R&D activity has enabled all consortium partners to develop background IP, which they can reuse in other projects or commercial products/services. In the case of Cellular Agriculture, this first involvement in a space project has triggered a change in approach for their terrestrial technologies. The constraints and stringent requirements of space have forced the project team to adapt to a closed-loop secular system, which is likely to have terrestrial applications. This new approach has led to the filing of a patent in mid-2024. Specifically, the requirements in space for miniaturised components (i.e., pumps), and the use of media bags instead of reservoirs were described by the project team as "eye opening", resulting in spillover innovations on the company's terrestrial technologies.

Enhancing reputation

Involvement in this activity generates significant credibility for all contractors, benefiting from an 'ESA stamp of approval', which can help secure follow-on funding and innovative collaborations.

A key benefit of this activity is the considerable positive impact it has had on the contractors' reputation. Involvement with ESA enhances consortium members' credibility, who benefit from an 'ESA stamp of approval', having demonstrated that they can successfully fulfil stringent requirements. This can help increase trust in the contractors' capabilities and reliability, attracting partners and customers in space and beyond. This is particularly valuable, as all consortium partners are SMEs or startups with emerging reputations and growing heritage. While Kayser Space had already worked with ESA, this activity was an opportunity to further increase its heritage with the Agency.

Non-space contractors (i.e. Cellular Agriculture and Campden BRI) also benefit from the 'wow factor' associated with space activities, which they can leverage for marketing purposes to stand-out and initiate prospective discussions with potential partners and customers in their respective sectors.

Increasing visibility

This activity enhanced the visibility of all contractors within and beyond their respective sectors, laying the foundations for potential new collaborations in the future.

All contractors expanded their network within the UK cultured meat and space ecosystems. For example, they presented their work at conferences, reaching audiences in the food & drink industry and the microgravity community. Campden BRI has also participated in a panel discussion organised by the UK Students for the Exploration and Development of Space (UKSEDS) organisation, presented during a Member Interest Group online seminar to 30-100 companies in the food industry, published social media posts, and developed a brief case study on their website. Cellular Agriculture is currently working with London's Science Museum on an exhibition day, which will feature their ESA-funded work.

This increased visibility can foster new collaborations in the future. In this case, given it is involving non-space organisations, it could also result in knowledge and technology transfers, boosting innovation. Contractors' activity to disseminate their work to student and general public audiences could also inspire careers in STEM and/or space, helping build tomorrow's talent pipeline in the sector.

Would these benefits have been realised without ESA?

All three contractors agreed that this work would have likely not been undertaken had it not been for ESA's early R&D support through the Discovery Programme, as this is not an area where they were particularly active in before. ESA's invitation to tender was a trigger, which directly led to the collaboration between the consortium members to develop this technology. The benefits outlined in this case study would have thus been unlikely to occur without ESA, with the exception of those related to the separate new collaboration between Cellular Agriculture and Campden BRI, who had already been in contact with each other (though were yet to find an opportunity to collaborate).

> *"This work was triggered by the ESA invitation to tender as, while the topic of cultured meat was new to us, the activity fell precisely within our area of expertise - Dr. Ramón Nartallo, Kayser Space*

ESA Discovery funding was also highlighted as a critical enabler for the work undertaken and the associated benefits. Stakeholders emphasised that early R&D funding is very challenging to secure, given the risks involved and distant monetary returns on investment. ESA funding provided structure and resources for the consortium to explore this technology, which it otherwise would have likely not had the opportunity to do.

Next steps: Further development, further benefits

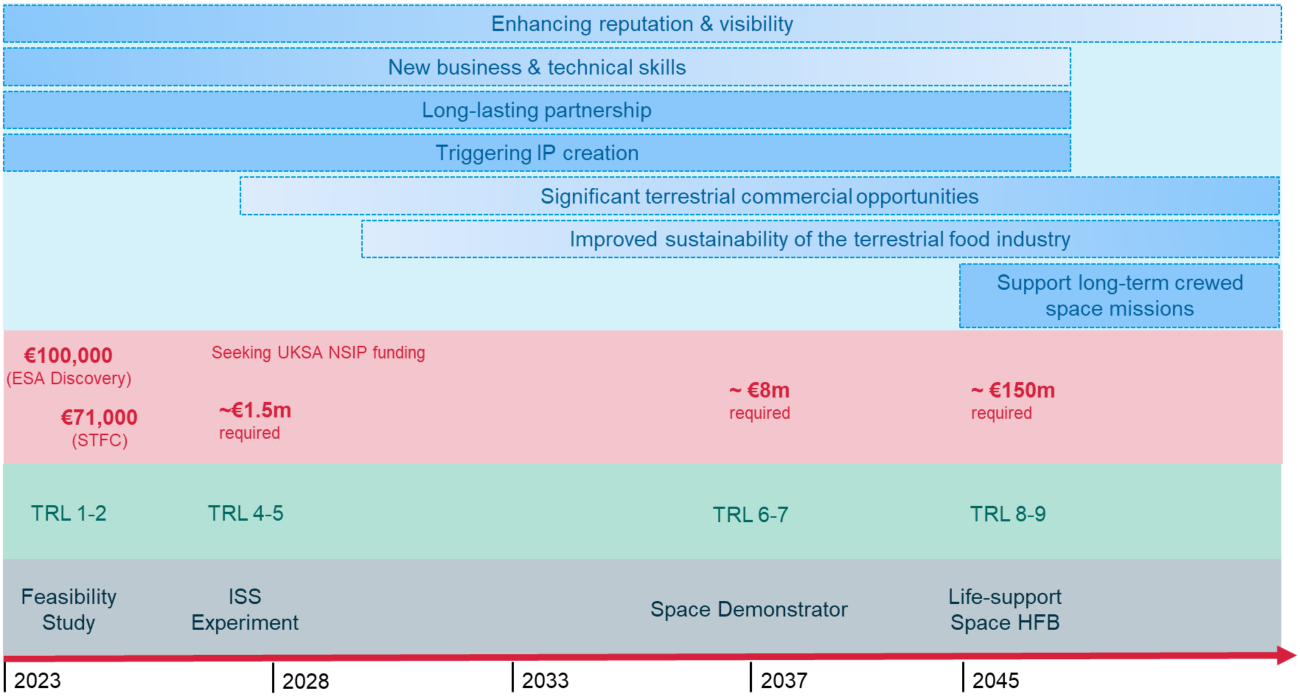
Kayser Space has planned future stages of the project, including initial trials on the International Space Station (growth trials, material refinement and performance, etc) by 2028, scaling up to a space demonstrator by 2037, and mass production by 2045. Given the technology is still at concept stage (with theoretical questions still needing to be addressed), these plans will naturally require further funding to be implemented (especially time sensitive for the trials on the ISS), which the consortium is actively exploring.

These technology development activities and the eventual deployment in space of the solution are expected to lead to a plethora of socio-economic benefits. By advancing bioreactor technology for producing cultivated meat in space, this project not only enhances self-sufficiency for deep space missions, but also aligns with the rapidly growing terrestrial cultivated meat sector, which is forecast to experience substantial growth.

This growth presents significant opportunities for job creation, increased revenue, and export potential, particularly for countries at the forefront of this technology. The innovations developed through this project could position the UK as a leader in the global cultivated meat industry, driving economic growth while contributing to more sustainable and secure food production systems. As this sector expands, the technology could generate high-value jobs and foster new industries, further reinforcing the economic benefits alongside its critical role in supporting future space exploration.

A preliminary overview of the timeline of the overall BioCeMe project, the magnitude of investment required, and the associated potential benefits of the activities is provided below. These next steps and their impact are entirely dependent on the availability and timeliness of funding.

Overview of the timeline of the overall BioCeMe project, the magnitude of investment required, and the potential associated benefits of the activities



Source: know.space based on Kayser Space data

Key priority indicators

Programme	Discovery
Country	United Kingdom (UK)
Activity cost	€100,000
Duration	12 months
Lead contractor	Kayser Space
Sub-contractors	Cellular Agriculture, Campden BRI
TRL progression	N/A
Spin-in into the space sector	2 (both sub-contractors)
Jobs supported	8-9 people involved, equivalent to 1.5 FTE
New collaboration with ESA	Both sub-contractors
Partnerships created	3

Follow-on funding applied/secured	• €71k secured from STFC to further mature this technology • €1.8m secured from Innovate UK and BBSRC for a separate project (leveraging a partnership formed in this activity) • UKSA-Axiom Space funding: unsuccessful • UKSA NSIP: intend to apply

[i] ESA (2024). Explore 2040: The European Exploration Strategy. Available from: https://esamultimedia.esa.int/docs/HRE/Explore_2040.pdf

[ii] González, et al. (2020). Meat consumption: Which are the current global risks? A review of recent (2010–2020) evidences. Food Research International; 137: 109341. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7256495/

[iii] Tuomisto & Teixeira de Mattos (2011). Environmental impacts of cultured meat production. Environmental Science Technology; 45 (14): 6117-23. Doi: 10.1021/es200130u. Available from: https://pubmed.ncbi.nlm.nih.gov/21682287/

[iv] Allied Market Research (2024). *Cultured Meat Market*. Available from: https://www.alliedmarketresearch.com/cultured-meat-market-A06670