Cultivated meat for human space exploration

2022 MELiSSA Conference
Toulouse, France

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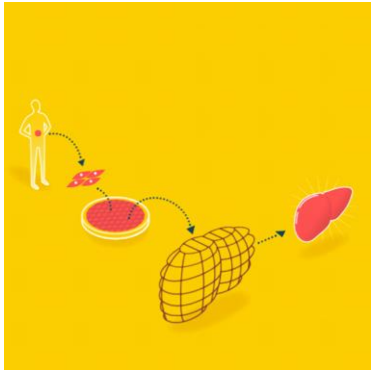
Future space food systems

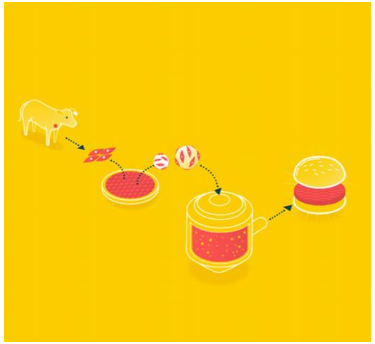
1- Plants & vegetables
- Different species have been tested so far (VEGGIE and APH platform)
- Potential for water filtering and CO2/O2 recycling

2- Microalgae and (ciano)bacteria
- Rapid biomass production and harvest index
- High protein content
- Potential for water filtering and CO2/O2 recycling

3- Cellular agriculture & cultivated meat

Cellular agriculture & cultivated meat





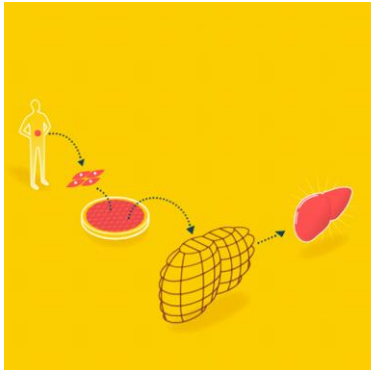
Cellular agriculture describes the process of using cells to produce commodities (meat, leather, milk)

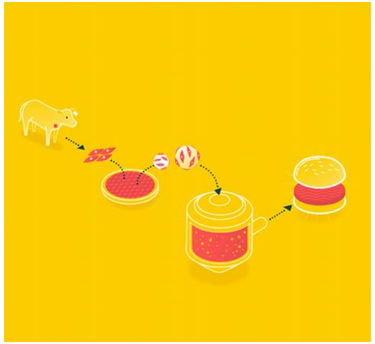
Cultured meat describes the process of growing animal tissues (i.e. muscle, fat) using animal cells:

- Core principles derived from **tissue engineering** and **regenerative medicine**
- It emerged as an alternative to conventional (and **unsustainable**) livestock farming
- Deemed to be **safer**, as there is total control of the production processes, reducing the likelihood of contamination and **foodborne illnesses**
- Requires less **land**, **energy** and **water** when compared to livestock farming

Source: New Harvest

Cellular agriculture & cultivated meat





Cellular agriculture describes the process of using cells to produce commodities (meat, leather, milk)

- **1932** – Winston Churchill mentions CM
- **1999** – 1st patent on CM
- **2001** – NASA-sponsored project to cultivate goldfish and turkey cells
- **2013** – Production and tasting of the 1st lab-grown burger
- **2020** – Singapore approves a CM chicken product
- **2022** – 2nd experiment onboard ISS

Source: New Harvest

Several cultivated meat products are in development

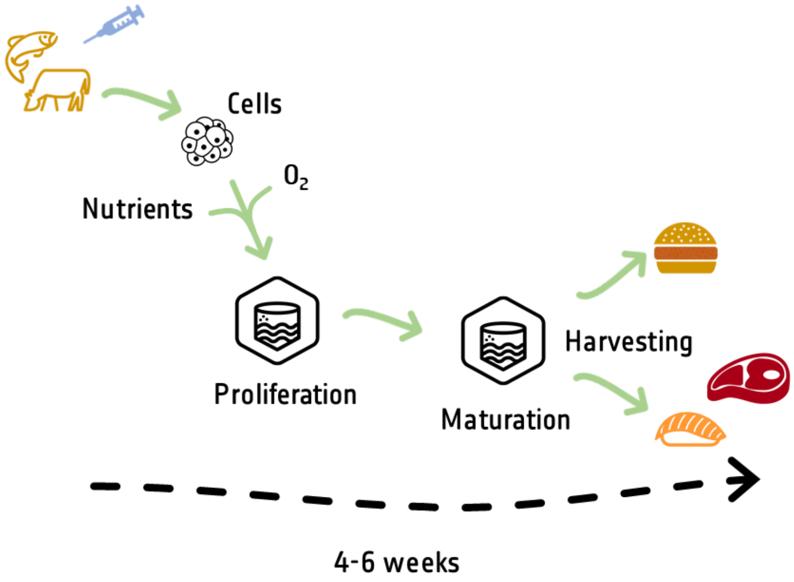


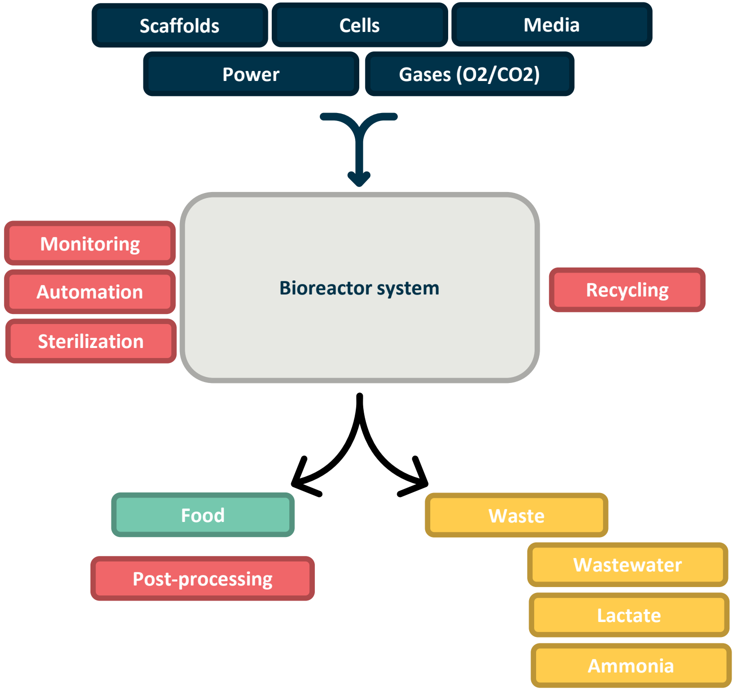




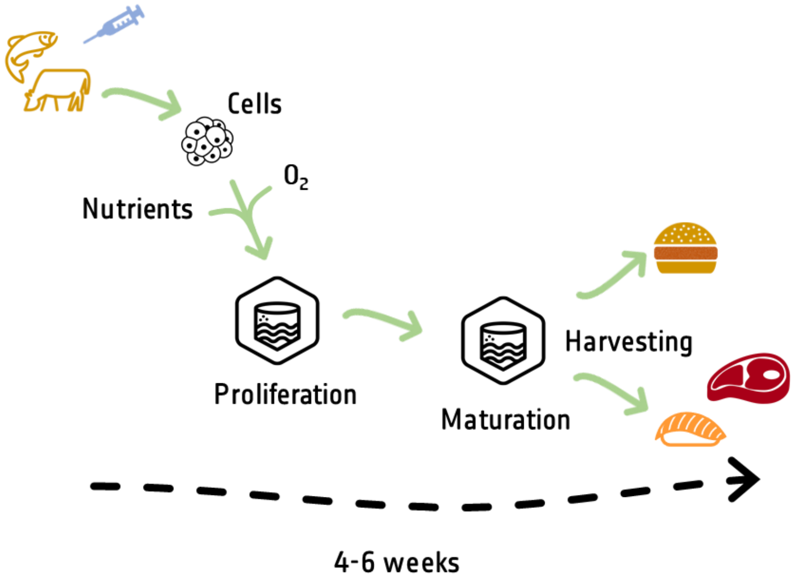
Sources: Aleph Farms, Meatable, Wildtype, Blue Nalu, Future Meat Technologies, Steakholder Foods

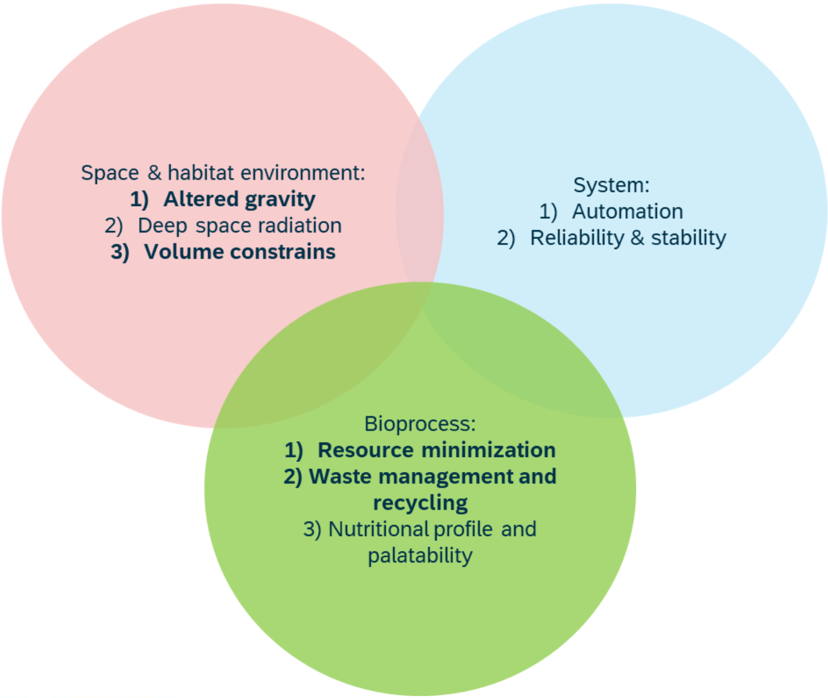
Cultivated meat





MELiSSA Cultivated meat - From Earth to Space





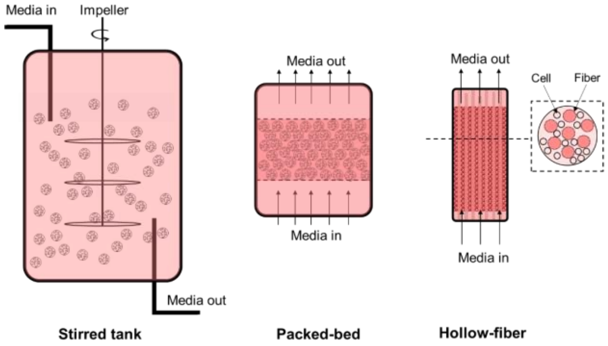
Sources and cell types

Parameter	Mammalian & avian cells	Fish & crustacean cells
Temperature (°C)	37	10-30
Oxygen (pO_2)	1-5% or 21%	<1-21%
Carbon dioxide (CO_2)	5 %	5 %
pH	7.4	7.4, possibly resisting higher variations

Water species might be more convenient as they are more resistant to variation in environment conditions and can be cultured at lower temperatures

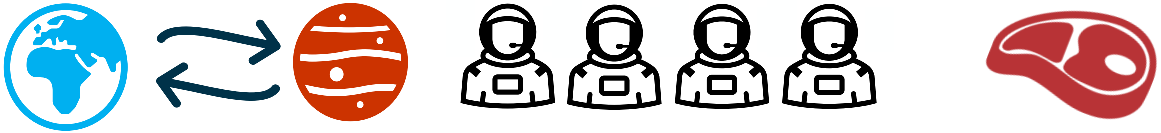
	Cell type	
	Muscle-resident cells/progenitor cells	**Pluripotent stem cells**
Examples	• Satellite cells • Fibro-adipogenic progenitor cells • Mesenchymal stem cells	• Induced pluripotent stem cells (iPSCs) • Embryonic stem cells (ESCs)
Cons	• Limited proliferation capacity • Long doubling times (>30h)	• Difficult to (re)program cells • Might require genetic engineering strategies • Ethical concerns (ESCs) • Can be difficult to obtain
Pros	• Easy to isolate • Differentiation protocols are faster and easier	• “Unlimited” proliferation capacity • Can differentiate into multiple tissues • Short doubling times (<24h)

Bioreactors



Characteristic	Bioreactor		
	STR	PBB	HFB
Max cell density (cells/ml)	$1x10^5$ - $1x10^7$	$1x10^6$ – $1x10^7$	$1x10^7$ - $1x10^8$
Operation in microgravity	Possible, but mixing of media and cells will need to be optimized	Suitable, since cells are attached to a substrate and media is perfused	Suitable, since cells are attached to a substrate and media is perfused
Reusability	Yes	Yes, but further development needed (edible microcarriers or efficient dissociation methods)	Yes, but further development needed (edible fibers or efficient dissociation methods)
Major limitations	• Shear stress on cells • Control aggregate formation/size • Not suitable for differentiation stage	• Scalability • Mass transfer • Cell harvesting • Reusability	• Cell harvesting • Reusability

The Mars example



1200 days

4 CM (4x82 kg)

59.04 g protein/CM/day

The Mars example

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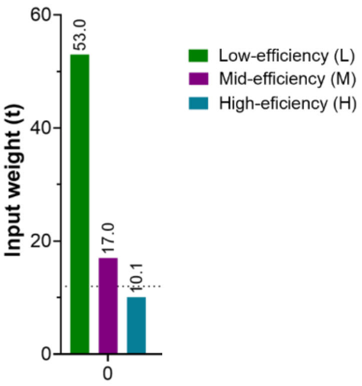
59.04 g protein/CM/day

	kg media per kg cultivated meat
Low-efficiency	41
Mid-efficiency	23
High-efficiency	6

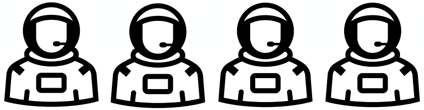
Roughly 1300 kg of cultivated meat over a period of 1200 days

> 97% of media is water



The Mars example - Recycling will be crucial

1200 days



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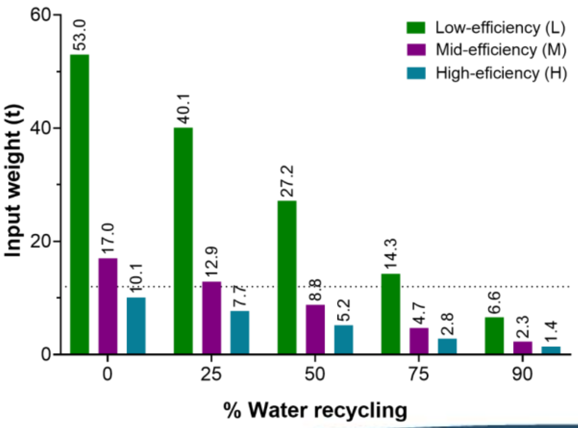
Wastewater

Lactate

Ammonia



Possibility for integration with water reclamation systems with recovering efficiencies >75%

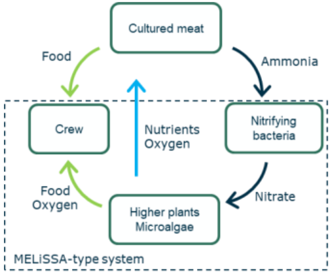
The Mars example - Recycling will be crucial

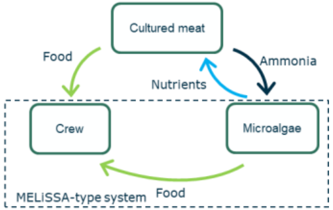
Wastewater

Lactate

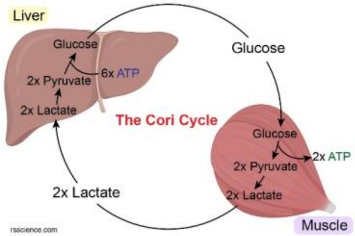
Ammonia

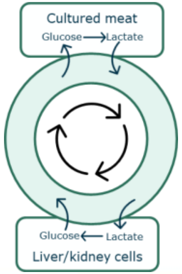
Bacteria and microalgae can metabolize ammonia





Certain mammalian cell types convert lactate into glucose





MERMADE
PREMIUM CELL-BASED SEAFOOD

seawith

ORIGINAL PAPER

A circular cell culture system using microalgae and mammalian myoblasts for the production of sustainable cultured meat

Yuji Haraguchi · Yuta Okamoto · Tatsuya Shimizu

BIOTECHNOLOGY PROGRESS

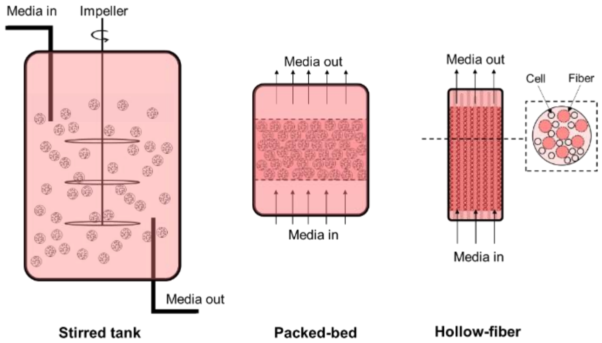
RESEARCH ARTICLE

Proliferation and differentiation of primary bovine myoblasts using *Chlorella vulgaris* extract for sustainable production of cultured meat

IntegriCulture

FORK&GOODE

The Mars example – bioreactor sizing



Assuming a batch production cycle of 4 weeks:

34 kg meat ≈ $1x10^{13}$ cells

	STR	PBR	HFB	Units
Max cell density bioreactor	$1x10^7$	$1x10^7$	$1x10^8$	cells/ml
Internal volume	0.34	0.34	0.034 (0.068)*	m^3

*in HFBs fibers account for 50% of the total volume

Bioreactors that achieve higher cell densities will likely be preferred due to volume and mass limitations

Other considerations

Scaffolding

(edible or reusable)

Sensing and monitoring capabilities

(biochemical, chemical and physical parameters)

Sterilization methods

(heat, radiation or chemical methods)

Post-processing

(Product formulation, storage, cooking)

Microgravity leads to muscle loss

J Physiol 588.18 (2010) pp 3567–3592 3567

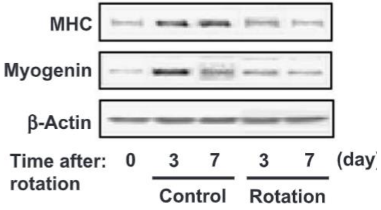
Prolonged space flight-induced alterations in the structure and function of human skeletal muscle fibres

R. H. Fitts[1], S. W. Trappe[2], D. L. Costill[2], P. M. Gallagher[2], A. C. Creer[2], P. A. Colloton[1], J. R. Peters[1], J. G. Romatowski[1], J. L. Bain[3] and D. A. Riley[3]

Clinorotation prevents differentiation of rat myoblastic L6 cells in association with reduced NF-κB signaling

Katsuya Hirasaka[a], Takeshi Nikawa[a,*], Louis Yuge[b], Ibuki Ishihara[a], Akira Higashibata[c], Noriaki Ishioka[c], Atsuko Okubo[b], Takashi Miyashita[b], Naoto Suzue[d], Takayuki Ogawa[d], Motoko Oarada[e], Kyoichi Kishi[a]

Reduced myogenin and myosin heavy chain production in *simulated* microgravity



Space travel directly induces skeletal muscle atrophy

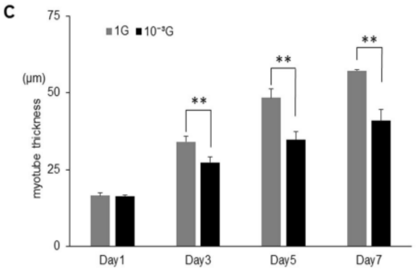
HERMAN VANDENBURGH,*,†,1 JOSEPH CHROMIAK,* JANET SHANSKY,* MICHAEL DEL TATTO,* AND JULIE LEMAIRE*
*Department of Pathology, Brown University School of Medicine and The Miriam Hospital, Providence, Rhode Island 02906, USA; and †Department of Molecular Pharmacology, Physiology, and Biotechnology, Brown University, Providence, RI 02912, USA

npj | Microgravity
www.nature.com/npjmgrav
Corrected: Author correction
ARTICLE OPEN

Simulated microgravity attenuates myogenic differentiation via epigenetic regulations

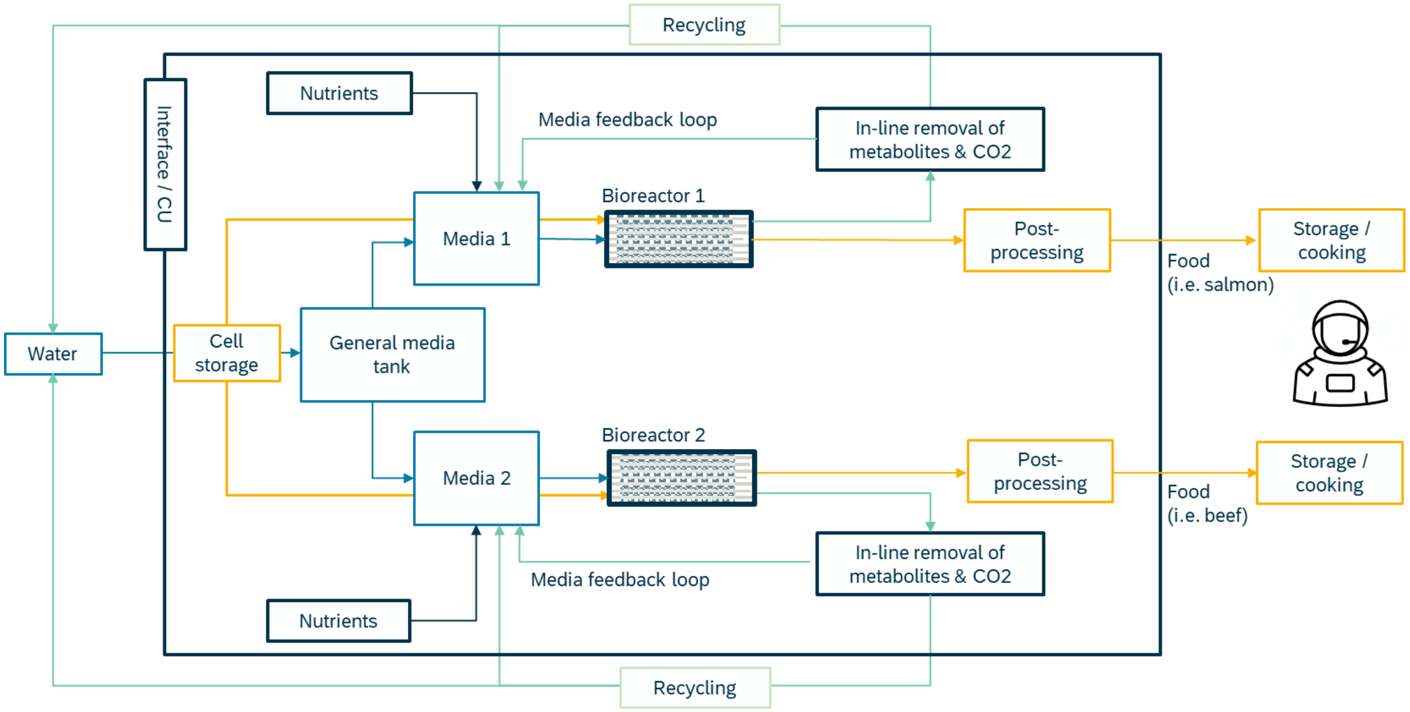
Takuma Furukawa[1], Keiji Tanimoto[2], Takahiro Fukazawa[3], Takeshi Imura[1], Yumi Kawahara[4] and Louis Yuge[1,4]

Lower expression of myogenic markers and reduced myotubule thickness



Countermeasure strategies are likely necessary for stimulating cells into forming muscle tissue

MELiSSA Concept



Future work

1) Studies on how cultured meat cells behave in space environment conditions
    1) Altered gravity
    2) Radiation

Potential countermeasure strategies to eliminate the effects of microgravity and radiation

2) Filtering and recycling strategies
    1) Filtering of wastewater, lactate and ammonia
    2) Possibility for integration with other life support systems

Take home message

1) The current space food system is **not suitable** for future long-term & long-distance exploration missions

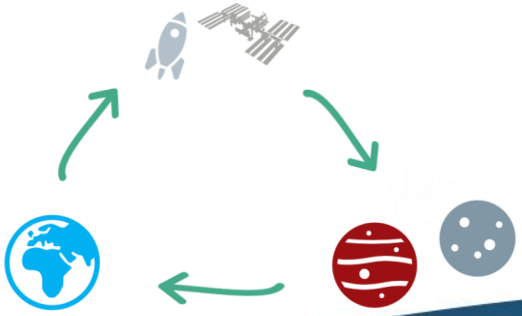
2) **Cultured meat** has the potential to deliver **highly nutritious** and **fresh** food products

3) Limitations include **launch volume** and **mass**, **recycling strategies,** and **cell behaviour in microgravity**

   1) Bioreactors that achieve higher cell densities will likely be preferred due to volume and mass limitations

   2) Recycling strategies (namely water) will be crucial for making cultured meat a viable food source in future human spaceflight

   3) Integration with existing life support systems will render the cultured meat systems viable for space exploration



Development and implementation of cultured meat systems for space will improve ground systems, and potentially contribute for a more secure and safe global food system.

MELiSSA

MICRO-ECOLOGICAL LIFE SUPPORT SYSTEM ALTERNATIVE

What is cultured meat?

Life cycle analysis of cultured meat

ESA's presentation @ CMS Astro

ESA's article on cultured meat

THANK YOU.

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