Shrimply Delicious: A Decision Framework for Space Aquaculture Species Selection

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Key obstacles to future long duration space missions include the in-situ production of sufficient proteins and nutrients for crew health, as well as the yet-unsolved challenge of closing the waste and water life support loops. Bioregenerative architectures, such as ESA's MELiSSA, can effectively process human solid waste into clean water and nutrient effluent which is converted to microalgae biomass. Still, algae are undesirable as a primary food source and should instead be used as feed for aquaculture to meet nutritional and palatability needs and effectively close the loop. However, the strict constraints imposed on space aquaculture eliminate most common options, necessitating the consideration of less conventional species. This paper introduces a framework for comparing potential space aquaculture candidates across traits that are relevant to husbandry in the space environment, including the flexibility to optimize for specific mission scenarios by adjusting trait importance weighting. Applying this framework revealed two strong candidates for long duration missions: aquatic *Pomacea* snails and ephemeral shrimp of the *Artemia* genus.

Acronyms and Nomenclature

PCLSS	=	Physicochemical Life Support System
LEO	=	Low Earth Orbit
DLR	=	German Aerospace Center
CELSS	=	Closed/Controlled Ecological Life Support System
BLSS	=	Bioregenerative Life Support System
ESA	=	European Space Agency
NASA	=	National Aeronautics and Space Administration
MELiSSA	=	Micro-Ecological Life Support System Alternative
SWaP	=	Size, Weight, and Power

I. Introduction

WITH a few exceptions during the Apollo era, the entirety of human space exploration and habitation has occurred within the protected shallows of low-Earth orbit. This position, just a short jaunt away at a few hundred kilometers above the surface of the planet, offers generous radiation protection and an authentic microgravity environment in which living and working in space can be practiced.

The conventional approach to sustaining life in space has not substantially changed since the Apollo era. The effort of pioneering early space stations required many rocket launches to assemble modules, integrate subsystems, ferry crew, and resupply them with essential life support consumables and spare parts for repairs. This coincided with The Cold War, when the priority was to display technological superiority at any cost. This paradigm, which evolved out

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of necessity, was gradually established as the status quo due to the heavy preference for solutions with spaceflight heritage. Modern astronauts on the ISS are supported by a physicochemical life support system (PCLSS) that is not too dissimilar to those introduced 50 years ago.

However, as the New Space industry accelerates and more stakeholders look to establish a permanent foothold beyond LEO, the economics of frequent resupply rockets quickly become untenable. It's clear that a base on Mars must be a self-sufficient homestead: able to produce its own food and other necessary supplies and equipment to survive in the long term as any supply chain interruption would spell certain death otherwise. Without a local biosphere to exploit, settlers will need to live in a closed-loop system where all of their food, water, air, and waste are recycled indefinitely, supplemented with raw resources extracted from the local environment.

A. A Model Bioregenerative Architecture – MELiSSA

The solution to the above dilemma is an alternative life support strategy that relies on bioregenerative technologies, utilizing various plants, animals, and microbes to regenerate critical resources from complementary waste streams. The goal of a bioregenerative life support system (BLSS) is to reduce or eliminate the need for external resupplies by balancing synergies between organisms to facilitate the closure of various material loops - food, waste, water, etc.

Despite the dominance of conventional PCLSS, bioregenerative technologies have been thoroughly investigated by the USA (NASA - CELSS & BIOPLEX, Biosphere 2) and USSR (BIOS 1, 2 ,3), and more recently by ESA (MELiSSA Program) and China (Lunar Palace 1). However, few of the innovations in life support technologies from these facilities have made it to orbit. Yet, it will be necessary to employ at least some of them as the PCLSS status quo does not attempt to close critical life support loops of food production or solid waste recycling. The Water Recovery System on the ISS recovers 98% of water from urine[1], but merely bags feces to be evacuated and burned in the atmosphere. Likewise, it's possible to synthesize nutrition directly from chemical reagents or to cultivate plants and animals for consumption, but only experimental quantities of edible food have been grown aboard the ISS and the crew eats prepackaged food that is frequently replenished by resupply vehicles.

A prime example of a bioregenerative life support system to address these closure gaps is the European Space Agency's MELiSSA (Micro-Ecological Life Support System Alternative) program, which consists of a pilot plant in Barcelona and a consortium of research partners endeavoring to create a closed-loop ecosystem for recycling waste back into edible food.[2] The system is composed of four interconnected compartments, each with a specific function in the waste processing and regeneration cycle: Liquefying Compartment (C1), Photoheterotrophic Compartment (C2), Nitrifying Compartment (C3), Photoautotrophic Compartment (C4), and the crew compartment which should be considered the fifth element of the system.

However, a significant inefficiency exists in such an architecture. Each compartment expends energy to generate biomass as it converts waste into ever more available nutrients, and in a human-oriented system, all inedible biomass is another "waste" to be recycled again at the beginning of the loop. Only C4A and C4B generate human-appropriate food, but even the higher plants have inedible biomass and algae is generally not considered suitable for a consequential portion of the diet. While it's been demonstrated many times that algae are sufficiently nutritious to comprise most or all of a human's diet [3,4], this strategy has been roundly dismissed by everyone with good taste. If for no other reason than morale, a varied diet is a necessity. Therefore, to finish closing the food-waste-water loop, it's necessary to find a species which can effectively upcycle primarily algae, but also inedible higher plant biomass and potentially bacterial biomass, into a more palatable form while remaining within the constraints of a realistic early-stage space habitat where a system such as MELiSSA will be employed.

Given the outputs of clean-but-not-potable water and microalgae (phytoplankton), as well as assumed small volumes (< ~100L), raising aquatic animals for consumption is the obvious synergy - and indeed, aquaculture is a common fixture in hypothetical closed loop living systems.

B. Previous Investigations of Space Aquaculture Candidates

It has long been apparent that aquaculture will be the preferred choice for protein production in the space environment. Even before the early space biology experiments that showed fish can adapt to microgravity relatively easily, science fiction authors already imagined and disposed of the notion of trying to wrangle chickens or goats in zero-G.

But there are many concrete advantages of rearing aquatic organisms for food as well. Fish as a rule have significantly better feed conversion rates than common terrestrial livestock due to their poikilothermic metabolism requiring less energy to maintain homeostasis. For all extended-duration missions, particularly those that venture outside of Earth's protective magnetic field, prolonged radiation exposure poses serious danger. Conveniently, water is an effective barrier to radiation[5], and many aquaculture candidates have fairly short lifespans anyway, so concerns around the accumulation of radiation are well-addressed. Equally convenient is water's tendency for being a homogeneous solution - even with very limited diffusion caused by the lack of convection in microgravity, substances are (eventually) distributed evenly throughout the system.[6] This vastly simplifies aspects of livestock husbandry, particularly food and waste management.

While vegetarian diets are commonly considered for space crew due to logistical rather than ethical reasons, there are a few vital nutrients and minerals that cannot reasonably be sourced from an all-plant diet, notably vitamin B12 (cobalamin) and long chain omega 3 fatty acids. While these deficiencies can be covered in the short term by vitamin supplements, studies show that the space environment causes multivitamins to lose much of their potency within several years[7], illustrating a critical need for in-situ vitamin production. Coincidentally, these essential nutrients are commonly abundant in seafood.

Given the compelling case for space aquaculture, there have been a number of projects working directly and indirectly towards this goal:

- **CEBAS** - The Closed-Equilibrated Biological Aquatic System (CEBAS) developed in Germany by Blüm and DLR in the 90s is likely the closest we have collectively come to space aquaculture thus far.[8] CEBAS was a multi chambered aquarium with separate compartments for swordtail fish (*Xiphophorus hellerii*), ram's horn snails (*Biomphalaria glabata*), hornwort (*Ceratophyllum dermersum*), and aquatic microorganisms. Several iterations of the system were constructed and flown, as well as larger ground-based models that focused on optimizing biomass production for eventual aquaculture use. Despite having separate compartments, CEBAS is particularly interesting as one of very few multitrophic ecosystems flown in space. Ancillary mechanical systems such as the water filter and heater supplemented a functional, closed-loop ecosystem which makes this experiment perhaps the first example of a hybrid physicochemical-closed ecological life support system in space.
- **CERAS** - In Japan, Takeuchi led the ambitious Closed Ecological Recirculating Aquaculture System (CERAS) project through the early 2000s which investigated an earth-bound closed loop aquaculture system.[9] They conducted an exhaustive investigation of food production and optimization in closed multitrophic systems, including tracking mass balances, monitoring atmosphere and pressure dynamics, waste recycling methods, photoperiod effects, and testing different fresh and saltwater ecosystem compositions of fish/microalgae/zooplankton. During the course of the experiments, they looked at quite a few fish candidates for aquaculture, including the ubiquitous Nile tilapia (*Oreochromis niloticus*), red sea bream (*Pagrus major*), striped knifejaw (*Oplegnathus fasciatus*), tiger puffer (*Takifugu rubripes*), Japanese flounder (*Paralichthys olivaceus*), and the longtooth grouper (*Epinephelus bruneus*). They even developed a transgenic tilapia strain optimized for closed recirculating aquaculture that was remarkably efficient compared to its natural counterparts. While CERAS was never intended for operation in space, it established methods and quantified performance of multitrophic recirculating intensive aquaculture systems which will no doubt inform the development of future space systems.
- **Lunar Hatch Program -** Since 2019, Cyrille Przybyla of IFREMER (French Research Institute for Exploitation of the Sea) has led the development of the Lunar Hatch program.[10] The objective of Lunar Hatch is to solve the technological, logistical, and biological challenges of implementing a closed loop fish aquaculture system on the lunar surface. The conceptual food production system is sized to provide two servings of fish per week to the crew, though it requires egg resupplies from Earth on a 6 month cadence. The current focus of investigation at Lunar Hatch revolves around the successful launch of fertilized sea bass eggs and subsequent embryonic development in the context of reduced/microgravity. Sophisticated ground experiments recreating the microgravity impact and vibration profile of launch have shown the eggs to be very resilient to stressors they will likely encounter on their journey to the moon.

II. Methods

The primary offering of this manuscript is a "House of Quality" matrix that quantifies and compares the suitability of aquaculture candidates. Using the accompanying rubric, organisms are scored on 9 relevant traits or "consideration factors". Of course, those traits that are most valuable can vary significantly as mission parameters change. An aquaculture facility on Mars is less concerned about adaptations to reduced gravity than a space station in LEO; similarly, the storage potential of a candidate is critical for outposts that are unmanned for months or years at a time and relatively unimportant in continuously inhabited facilities. To accommodate different scenarios, an adjustable, subjective "importance weight" multiplier is applied to each of the consideration factors.

In order to fill the House of Quality matrix, a literature review (located in the appendix) was conducted to garner data about the potential of several functional groups of aquatic organisms. Keep in mind that several of these species are not currently common aquaculture species and therefore do not have a wealth of literature examining those traits relevant to aquaculture, such as feed conversion ratio or nutritional profile. The data which does exist was taken indiscriminately from earth aquaculture approaches, both intensive and extensive. Yields are based on harvest frequency, not normalized to a general unit of time. Therefore, the comparison presented should be used to set relative, rather than absolute, expectations for performance.

Note that mass measurements are inclusive of the whole animal, not just the edible part, though this mostly impacts shelled mollusks. Where appropriate, data is interpolated linearly from closely related species or scaled proportionally based on relative sizes. These estimations are marked with an asterisk. Cells were left blank if no relevant data was available.

Lastly, a rubric for scoring species based on each of these metrics was formulated to quantify their performance in each of the consideration factors (Table 1). It attempts to quantify and encompass a range of traits, but it must acknowledged that some of them (such as palatability) are inherently subjective.

Table 1. Consideration factors rubric

Characteristic	Metric	1	2	3	4	5
Palatability	Holistic metric that includes subjective flavor profile, mouthfeel/texture, psychological appeal, and ease of preparation. Subtract 1 point if the candidate is not already considered a culinary ingredient.	Repulsive to eat in most forms (ex: algae)	Unsavory but still edible (ex: medicine)	Unoffensive taste (ex: oatmeal)	Flavorful and enjoyable to consume (ex: fruit)	Actively desirable and delicious food (ex: ice cream)
Nutrition	The macronutrient profile should favor protein production; the micronutrient profile should include those difficult to source from plant-diets (B12, omega 3 fatty acids).	Less than 50% protein AND lacks nutrients of concern.	Has either less than 50% protein OR lacks nutrients of concern	50%-59% protein; contains nutrients of concern	60%-69% protein; rich nutrients of concern	70%+ protein; rich in nutrients of concern
Productivity	Expected productivity as determined by feed conversion ratio (FCR) and time to harvest.	FCR > 3 OR Time to Harvest > 4 months	FCR ≤ 3 OR Time to Harvest ≤ 4 months	FCR ≤ 2 AND Time to Harvest ≤ 4 months	FCR ≤ 2 AND Time to Harvest ≤ 2 months	FCR ≤ 1 AND Time to Harvest ≤ 2 months
Diet	For loop closure, candidates should readily accept the output of at least one other process (ex: inedible biomass from higher plant cultivation, microalgae from waste recycling). Ideally, inefficient protein supplementation and live food requirements are avoided.	Requires significant protein supplements AND live food	Requires significant protein supplements OR live food	Satisfied by waste stream from another process AND supplemental feeding	Satisfied by waste stream from another process	Satisified by waste streams from another 2+ processes
Reproductive Potential	Aquaculture candidates are ideally rapidly reproducing R-selected species that reach reproductive maturity quickly and do not require synchronized or batch breeding (ex: spawning season).	K-Selected Species OR Reaches sexual maturity > 6 months AND no continuous reproduction	R-Selected Species AND Reaches sexual maturity < 6 months OR no continuous reproduction	R-Selected Species AND reaches sexual maturity < 3 months OR continuous reproduction	R-Selected Species AND reaches sexual maturity < 3 months AND continuous reproduction	R-Selected Species AND Reaches sexual maturity < 1 month AND Continuous Reproduction
Storage Potential	Capacity for long duration storage of a breeding population (eggs, dormant adults, etc), including any necessary maintenance and storage requirements (energy, technology, or crew time resources).	Cannot be stored in an inactive state for any duration	Can be stored for limited periods (days to weeks) OR storage incurs significant costs	Can be stored for long periods (months to years) AND storage incurs significant costs	Can be stored for long periods (months to years) with minimal resources	Can be stored indefinitely with minimal resources
Waste & Byproducts	The difficulty of addressing waste or other byproducts of cultivation. Includes potentially beneficial secondary products	Produces waste that is difficult to collect AND treat OR reuse	Produces waste that is difficult to collect OR treat OR reuse	Produces waste that is difficult to collect OR treat OR reuse; AND produces 1 or more useful byproducts	Produces virtually no problematic waste	Produces virtually no problematic waste AND produces 1 or more useful secondary products

Lifecycle Complexity	How many different operational modes (procedures/processes) are required to successfully advance the lifecycle until harvest? For example, if eggs need to be collected and moved to a hatching chamber temporarily, that is an additional operational mode. If larvae have different diet or water parameter requirements that require special care, that is another operational mode.	Organism requires 3+ operational modes for lifecycle completion.	Organism can complete its lifecycle within 2 operational modes at reduced efficiency (ex: cannibalization of some young)	Organism can complete its lifecycle within 2 operational modes	Organism can complete its lifecycle with one operational mode at reduced efficiency (ex: cannibalization of some young)	Organism can complete its lifecycle comfortably with one operational mode.
Adaptation to Reduced Gravity	How suitable an organism is for being reared in reduced gravity conditions, based on flight heritage (within the taxonomic order) and anticipated issues with gravitropism or proprioception.	Organism is known to be intolerant of altered gravities	Organism has not been validated in a reduced gravity environment or simulation.	Order has some previous flight experience that did not reveal significant issues with reduced gravity adaptation.	Species has some previous flight experience that did not reveal significant issues with reduced gravity adaptation OR order has been validated through its full lifecycle in real reduced gravity	Species has been validated through its full lifecycle in real reduced gravity.

III. Results

To explore how the optimal aquaculture candidate differs based on the needs of the mission, the importance weights of the House of Quality can be adjusted to describe different scenarios. To ensure that each scenario weighting is equivalent, the average of all consideration factors should equal one.

A. Early Planetary Outpost with a Bioregenerative Architecture

Currently, only a few space powers have publicly declared their intent to establish permanent bases on the Moon in the foreseeable future. This scenario assumes one similar to China's International Lunar Research Station, which will support a small crew most of the time and be a testbed for technologies similar to MELiSSA. It will still receive regular resupplies, but at a lower cadence than LEO facilities due to the increased cost of shipping, so attempts are made to recycle as much as possible.

It can be assumed that these early attempts will be similar in scope and scale to existing space facilities. Pressurized space will be at a premium and life support functions should be as automated as possible to avoid wasting precious crew time. The results show that brine shrimp followed by apple snails are most appropriate at this scale, as the consideration factors are tuned for simple, reliable food production that does not distract the crew from other tasks. Other options, such as fish or shellfish, are less suitable because their strengths of being widely palatable and having valuable waste/byproducts are less valued in this scenario where the comfort is deprioritized and loop closure is not complete.

B. Orbital Space Station with Frequent Resupplies

This scenario is meant to emulate the near-future commercialization of cislunar space, in which a multitude of commercial and government entities are quickly expanding their activities in one of several near-Earth orbits. This assumes a continuation of the status quo of using primarily physicochemical life support systems in combination with frequent resupply vehicles from Earth.

While the ISS has averaged 7 crew members in recent years, publicly announced commercial LEO destinations such as Blue Origin's Orbital Reef or Vast's Haven-1 plan to quickly scale to being continuously inhabited by tens of crew. We can expect these multi-purpose facilities to support a range of research, manufacturing, and tourism.

With frequent crew rotations and cargo rockets, there is less emphasis on long-term nutritional needs and efficient production. LEO stations will likely remain continuously inhabited as the ISS has, and aquaculture will be supplementary rather than essential. Furthermore, this is the only scenario that takes place in microgravity, which has many downstream effects on both animal physiology and husbandry. Here, snails are most suitable, in part because of their diet which consists mostly of waste streams from other processes (as opposed to delivering fresh meat or, worse, living meat accompanied by the necessary protein-rich foods to finish growth). Brine shrimp fall out of favor because they probably won't be appealing to the average space tourist.

C. Established Planetary Settlers

Consider a time in the future some decades hence when cislunar commercialization efforts have succeeded and built confidence in the ability to not just survive, but thrive off-Earth. Mars may be host to a smattering of outposts and larger colonies with permanent and growing populations using primarily local resources. While these will still be engaged in practical pursuits of research or mining, the tone will be that of homesteading rather than expedition.

Those settlers will spend years at minimum in such a colony and each vehicle to the red planet will spend a similar amount of time in transit. The settlers will have to maintain a high degree of self-sufficiency but should have comparatively more time to pursue it. They can afford some luxuries that would be infeasible in the other scenarios, and have many more options in terms of technologies and available resources to pursue them.

Again, apple snails are ranked highly with ephemeral shrimp species trailing. It’s hard to beat the combination of excellent nutritional profile, ease of rearing, and flexible diets with useful byproducts. However, in this scenario of a stable, thriving community, there is sufficient resource buffer to indulge in inefficiencies, and the tilapia that has been hovering just outside of the top 3 in each scenario becomes an attractive option.

Table 2. House of Quality matrix for Early Planetary Outpost with a Bioregenerative Architecture

	Scenario A: Early Planetary Outpost with a Bioregenerative Architecture	Consideration Factors										
		Palatability	Nutrition	Productivity	Diet	Reproductive Potential	Storage Potential	Waste & Byproducts	Lifecycle Complexity	Adaptation to Reduced Gravity		
	Importance Weight	1	1.1	1	0.9	0.8	1.2	0.8	1.2	0.9		
Category	**Species**										**Score**	**Rank**
Commercial Marine Shrimp	Pacific White Shrimp	4	4	2	2	2	1	4	2	3	23.3	9
	Black Tiger Shrimp	4	4	2	2	2	1	4	2	3	23.3	9
Ephemeral Shrimp	Brine Shrimp	2	4	5	4	5	5	4	5	4	37.8	1
	Fairy Shrimp	2	3	5	4	5	5	4	5	3	35.8	4
Filter Feeding Shrimp	Bamboo Shrimp	3	4	2	4	2	1	4	3	3	25.3	5
	African Giant Fan Shrimp	3	4	1	4	2	1	4	3	3	24.3	7
Apple Snails	Golden Apple Snail	3	5	3	5	4	4	5	5	4	37.6	2
	Golden Mystery Snail	3	5	3	5	4	4	5	5	4	37.6	2
Commercial Clams	Quahog Clam	4	3	1	4	1	2	5	2	3	24.2	8
	Portuguese Oyster	4	3	2	4	1	2	5	2	3	25.2	6
Mostly Herbivorous Aquaculture Fish	Nile Tilapia	4	5	1	3	3	2	4	4	4	29.6	5
	Grass Carp	4	5	1	3	1	1	4	2	3	23.5	10
								Average			29.0	
								St. dev			6.3	

Table 3. House of Quality matrix for Orbital Space Station with Frequent Resupplies

Category	Scenario B: Orbital Space Station with Frequent Resupplies	Palatability	Nutrition	Productivity	Diet	Reproductive Potential	Storage Potential	Waste & Byproducts	Lifecycle Complexity	Adaptation to Reduced Gravity	Score	Rank
	Importance Weight	1.4	0.8	0.7	1.3	0.9	0.5	0.8	1.1	1.5		
Category	**Species**										**Score**	**Rank**
Commercial Marine Shrimp	Pacific White Shrimp	4	4	2	2	2	1	4	2	3	25	11
	Black Tiger Shrimp	4	4	2	2	2	1	4	2	3	25	11
Ephemeral Shrimp	Brine Shrimp	2	4	5	4	5	5	4	5	4	36.4	3
	Fairy Shrimp	2	3	5	4	5	5	4	5	3	34.1	4
Filter Feeding Shrimp	Bamboo Shrimp	3	4	2	4	2	1	4	3	3	27.3	6
	African Giant Fan Shrimp	3	4	1	4	2	1	4	3	3	26.6	8
Apple Snails	Golden Apple Snail	3	5	3	5	4	4	5	5	4	37.9	1
	Golden Mystery Snail	3	5	3	5	4	4	5	5	4	37.9	1
Commercial Clams	Quahog Clam	4	3	1	4	1	2	5	2	3	26.5	9
	Portuguese Oyster	4	3	2	4	1	2	5	2	3	27.2	7
Mostly Herbivorous Aquaculture Fish	Nile Tilapia	4	5	1	3	3	2	4	4	4	31.5	5
	Grass Carp	4	5	1	3	1	1	4	2	3	25.5	10
									Average		30.1	
									St. dev		5.2	

Table 4. House of Quality matrix for Established Planetary Settlers

Category	Scenario C: Established Planetary Settlers	Palatability	Nutrition	Productivity	Diet	Reproductive Potential	Storage Potential	Waste & Byproducts	Lifecycle Complexity	Adaptation to Reduced Gravity	Score	Rank
	Importance Weight	1.4	1.2	1.1	1	1.1	0.8	1	0.7	0.7		
Category	**Species**										**Score**	**Rank**
Commercial Marine Shrimp	Pacific White Shrimp	4	4	2	2	2	1	4	2	3	25.1	11
	Black Tiger Shrimp	4	4	2	2	2	1	4	2	3	25.1	11
Ephemeral Shrimp	Brine Shrimp	2	4	5	4	5	5	4	5	4	36.9	3
	Fairy Shrimp	2	3	5	4	5	5	4	5	3	35	4
Filter Feeding Shrimp	Bamboo Shrimp	3	4	2	4	2	1	4	3	3	26.4	7
	African Giant Fan Shrimp	3	4	1	4	2	1	4	3	3	25.3	9
Apple Snails	Golden Apple Snail	3	5	3	5	4	4	5	5	4	37.4	1
	Golden Mystery Snail	3	5	3	5	4	4	5	5	4	37.4	1
Commercial Clams	Quahog Clam	4	3	1	4	1	2	5	2	3	25.5	8
	Portuguese Oyster	4	3	2	4	1	2	5	2	3	26.6	6
Mostly Herbivorous Aquaculture Fish	Nile Tilapia	4	5	1	3	3	2	4	4	4	30.2	5
	Grass Carp	4	5	1	3	1	1	4	2	3	25.1	10
									Average		29.7	
									St. dev		5.4	

IV. Discussion

At first glance, the results of the different scenarios appear to be fairly similar with the same groups of species consistently showing better results. While this is in part due to the relative paucity of quality data to differentiate related species, a larger portion of this effect can be ascribed to the general similarity of aquatic species. *This decision matrix can be applied equally to terrestrial animals,* but the scope was limited to aquaculture due to the context in which this paper was written (i.e. what's the best way to convert microalgae to protein and essential nutrients?).

The remaining sections will be written from the perspective of Scenario A - Early Planetary Outpost with a Bioregenerative Architecture. When establishing an early base on the moon or Mars, the primary constraints on the aquaculture system are the small volume and the requirement of microalgae as the primary feedstock. These factors work against one another - species that can thrive on algae alone will typically require more than this system is sized to provide, as in the case of bivalves and herbivorous crabs. Traditional commercial shrimp aquaculture species were also considered but quickly dismissed. For them, the biggest obstacle to integration is the inability to scale efficient production down to a 100 L volume. Industry best practices demand multiple grow out tanks for different age cohorts for efficient production.[11] Even if that was sacrificed, the need for substantial protein supplements defeats the purpose of raising them to supplement the crew's diet.[12] Furthermore, a surprising proportion of current and potential aquaculture species are diadromous, requiring alternating between fresh and saltwater at different life stages. The hassle of sorting adults and young into containers of different salinities excludes those options.

Aquaculture operations can be broadly split into two categories: extensive and intensive. Extensive aquaculture relies on natural water bodies and minimizes external inputs such as feed and aeration, encouraging organisms to grow at their natural pace for a low-maintenance, low-yield system. Intensive aquaculture utilizes multiple controlled environments optimized for each life stage of the organism, using significant feed, pharmaceutical, and labor resources to maximize yield in a constrained footprint.

This theoretical space aquaculture unit will necessarily be an intensive culture due to volume limitations, but borrowing strategies from extensive methods could improve yield while reducing maintenance. For example, cultivating a closed ecological system rather than attempting to maintain an axenic culture should facilitate the growth of zooplankton and bacterial flocs that are important dietary supplements for even those organisms considered herbivores. Not only could this reduce or eliminate the need for supplementing specific nutrients[13], but diverse systems are shown to cycle nutrients more efficiently.[14] Incredibly, intensive recirculating brine shrimp cultures can even achieve a feed conversion ratio of less than 1 using this method, producing more biomass than they are fed by consuming microbial biomass incidentally generated in the container.[15] Maintenance of such a system could be as simple as occasionally siphoning detritus from the tank and feeding it back into the bioregenerative architecture.

Of the functional groups considered, two stand out as potentially feasible microgravity aquaculture candidates in the framework of a bioregenerative architecture - brine shrimp and apple snails.

A. *Artemia & Anostraca*

Brine shrimp (*Artemia spp.*) are an attractive option for many reasons. They can tolerate a wide range of salinities, from just barely brackish to hypersaline, making them an excellent option for recycling brine waste from other processes. This salinity range could be manipulated to serve as a biosecurity measure against pathogens. Furthermore, they are one of the rare crustaceans that have a diet that consists almost entirely of phytoplankton. While they can be fortified with easily sourced yeast or bacterial flocs to improve their nutritional value, they are sated by a wide range of microalgae that are commonly grown in photobioreactors.[15]

Furthermore, brine shrimp have flexible reproduction. In favorable conditions, they reproduce asexually via parthenogenesis, with females producing hundreds of genetically identical offspring every few weeks. They may choose sexual reproduction in less-than-ideal circumstances as well. When the environment becomes hostile, such as in anoxic or hypersaline conditions, they produce resilient "cysts" instead of eggs. The cysts are extremely hardy to environmental conditions such as desiccation and extreme temperatures and have even shown remarkable resistance to radiation on the Apollo 16 mission.[16] The cysts are shelf stable for years, though techniques for harvesting them will need to be adapted to microgravity. The tendency to produce cysts when the environmental conditions tend towards lethal makes this an incredibly resilient food source. The enclosure could be engineered in such a way that mechanical failures, such as power outages, induce cyst formation - effectively preserving the culture with high reliability, allowing crew to restart it quickly and easily when it's convenient. The ease of starting and stopping the culture makes it an excellent option for those facilities that expect to be dormant for months or years, such as the Artemis Lunar Gateway.

Where many aquaculture options require the young to be separated out and multiple tanks with differently sized cohorts, brine shrimp can be grown in a continuous culture without concern for cannibalism or age-related dietary differences. This dramatically reduces the size, weight, and power (SWaP) costs and the crew time necessary to maintain productivity. Looking forward, juvenile brine shrimp are the zooplankton supplement of choice for most vertebrate aquaculture operations. Juvenile fish especially tend to require live food for proper development. Incorporating brine shrimp into the loop now would solve a large part of the future challenge of including fish aquaculture in space food systems.

Fairy shrimp (*Anostraca spp.*) are very similar to brine shrimp in their life history strategy and potential advantages as a candidate species for space shrimp aquaculture. The primary difference is that they are a (relatively) much larger freshwater species, which might make them more palatable but reduces the potential stocking density and yield. These should be investigated in parallel.

However, it must be noted that neither brine nor fairy shrimp are not commonly consumed by humans, though they do have an excellent nutritional profile.

B. Artemia Palatability

Given the rapid life cycle of Artemia and the low cost and labor of establishing a culture, it was little effort to grow out a brine shrimp cohort during the writing of this manuscript. The purpose of this pilot is to produce preliminary answers for some of the culinary questions that arise from the use of unorthodox cuisine.

The brine shrimp culture was cultivated for 2 months before harvest, meaning that all of the shrimp consumed were subsequent generations born in-situ. The operation was extraordinarily simple - a 4L container of brine aerated with a 5v air pump, rehydrated Spirulina powder fed every other day, and detritus siphoned out once a week. Adult brine shrimp were "purged" of waste by moving them to a nearly freshwater environment without food for 24 hours before being harvested via straining. The brine shrimp were then separated into equal portions and prepared 5 different ways: raw, dried with and without seasoning, and sauteed in vegetable oil with and without seasoning.

Table 5. *Artemia* palatability test set up.

Method	Preparation	Result
Raw	None	Very slightly crunchy saltwater flavor, similar to caviar/roe.
Oven-dried	1. Unseasoned 2. Seasoned with Old Bay.	Dehydrated into almost nothing, but the flavor was inoffensive.
Sautee	1. Unseasoned 2. Seasoned with salt, black pepper, garlic powder, and sauteed in vegetable oil.	Remarkably similar to ground beef in texture and taste. Not fishy tasting.

The results were surprising. Brine shrimp were fairly palatable in every case, and even tasty when sauteed in the manner of a minced meat. It bears further (culinary) experimentation to see if they can be used similarly to other micro-shrimp species for products such as shrimp paste or dried shrimp flakes or processed further into a substance similar to imitation crab meat.

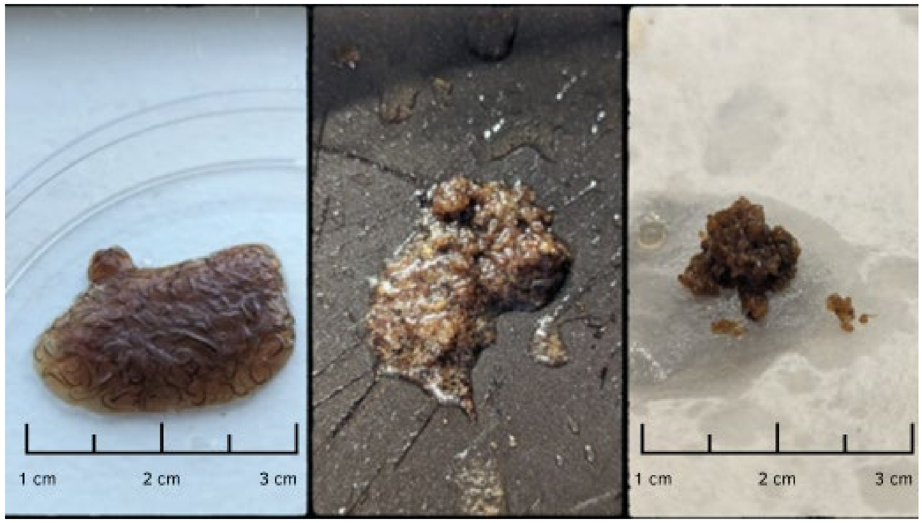

Figure 1. Left: About a tablespoon of strained, living brine shrimp. Center: Seasoned brine shrimp sautee. Right: Product of sautee - savory brine shrimp nugget.

C. Pomacea

On the other hand, apple snails (*Pomacea*) are commonly consumed in parts of the world and offer a more conventional culinary profile. They can thrive on a diet of benthic microalgae like diatoms, although this would necessitate a shift from the current photobioreactor system designed for planktonic algae. Most snails are unable to filter feed and would have a hard time accessing the planktonic algae unless it is pelletized or flocculated. Unlike brine shrimp, the snails are an excellent "garbage disposal" for inedible biomass, such as from a higher plant growth unit. Using them in this way will increase the maintenance needed, but it is a very efficient upcycling of biomass compared to conventional solutions for inedible biomass (pyrolysis, etc.). With sufficient food, there's little risk of cannibalism and snails may be grown in continuous culture.[17] Juveniles and adults have essentially the same diet.

Apple snails are not hermaphrodites like many snails, but manage to reproduce rapidly nonetheless. Eggs are typically laid in bunches of several hundred a handful of centimeters above the water line. They hatch within a week or two when kept moist and exposed to oxygen. While some snail species have eggs edible as "snail caviar", recent research suggests that some *Pomacea* species' eggs are poisonous when ingested, including *P. canaliculata*.[18] Apple snails aren't as readily stored as brine shrimp, but they do possess the ability to go dormant in cool, moist conditions for months up to years.[19] They or their eggs may be good candidates for cryopreservation, but that needs to be validated. A byproduct of apple snail production will be a significant mass of discarded snail shells, which can be ground and returned to the system or collected to harvest calcium carbonate, easily converted to calcium oxide (quicklime) for agriculture, steel production, or construction.

Recalcitrant materials from anaerobic digesters may be edible for snails. But that may incur the risk of pathogen transfer, and it should be noted that some apple snails are intermediate hosts for roundworm species that parasitize humans, such as lungworm. However, standard biosecurity protocols and proper food safety and preparation can eliminate the threat.

D. *Pomacea* Palatability

While the familiar "escargot" typically refers to a cuisine composed of terrestrial snails, aquatic snails such as *Pomacea* are faithful substitutions for any dish that calls for snails. They're a common fixture in many parts of Southeast Asia in sauces, curries, and soups.

The snails pictured below are "Mystery Snails" or *Pomacea bridgesii*, commonly available at pet stores for keeping in aquariums. They were kept in the author's planted freshwater tank where they were fed no specific diet and grazed on algae and detritus for 2 months before harvest. They were prepared according to the following table.

Table 6. *Pomacea* palatability test set up.

<table>
<tr><td colspan="3">Method: Traditional Escargot</td></tr>
<tr><td>Preparation: 1. Snails were "purged" by keeping them in a separate container of clean water for several days without food, periodically removing their waste until its production stopped.</td><td>2. They were humanely euthanized by chilling them in a refrigerator to put them into torpor before adding them to a heavily salted and boiling saucepan.</td><td>3. After 5 minutes, the snails were removed from the boiling water and the meat was plucked from the shells. It was returned to another saucepan to be sauteed in vegetable oil seasoned with salt, black pepper, and fresh garlic.</td></tr>
<tr><td colspan="3">Result: The resulting escargot was quite similar in both taste and texture to fried shellfish like oyster or clam.</td></tr>
</table>

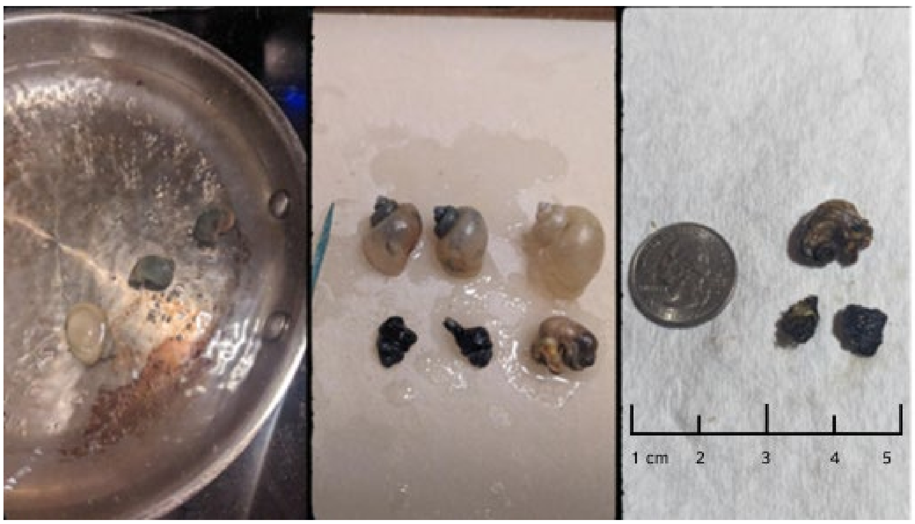

Figure 3. Left: Boiling purged snails. Center: Snail meat removed from shell after boil, the two darker snails tore during extraction and left their tails in the shell. Right: Sauteed snail meat compared to a US quarter.

V. Conclusion

The potential for space aquaculture is an oft-courted notion that is hampered by the steep mass costs of building and maintaining an aqueous environment for the livestock. However, in-situ production of animal protein is highly desirable for morale and nutritional reasons, and the need scales with increasing mission duration. To be prepared for future long duration missions, or to conduct more sustainable cislunar operations, this manuscript established a decision framework in which to consider candidate species and demonstrated the viability of non-traditional options.

Ephemeral shrimp including *Artemia* and *Anostraca* are unorthodox food options, but are very attractive as an efficient, low-maintenance, and resilient food source. It's not clear if they will be commonly accepted as palatable, but the pilot test was promising and the potential advantages demand a thorough investigation. Alternatively, several species of the *Pomacea* genus of apple snails are a strong option due to their versatile diets and established use in several global cuisines. Supplying benthic instead of planktonic algae as a primary food source will require either crew time or innovative engineering, but the ability to supplement with inedible biomass is an attractive use of that waste stream.

In any case, the solution of using aquatic invertebrates in a bioregenerative architecture such as ESA's MELiSSA resolves two major obstacles blocking future long duration space missions - closure of the human waste loop and in-situ production of essential macro and micronutrients. The authors recommend preliminary pilot tests to establish baseline expectations for intensive recirculating micro-aquaculture before integrating it into a full bioregenerative water purification architecture to facilitate TRL advancement at a timely pace.

Appendix

The tables below contain data mined from literature in the bibliography and were used as quantitative data points to score each species for the HOQ. Values for fish were converted to dry weight to be comparable to other species. Carbohydrates are not typically measured in fish as the amount is negligible, so the data was omitted. The citations are removed due to length restrictions but are available upon request.

Species Overview							
Category	**Name**	**Summary**	**Size**	**Mass**	**Nutritional Profile**	**Culinary Products**	**Commonly Eaten?**
Commercial Marine Shrimp	Pacific white shrimp (*Litopenaeus vannamei*)	Most common commercial marine shrimp.	20 - 23 cm	30g	P: 60% L: 32% C: 5% Ash: 2%	shrimp meat, shrimp paste	Yes
	Black Tiger Shrimp (*Penaeus monodon*)	Biggest marine aquaculture shrimp.	20 - 30 cm	175g	P: 60%* L: 32%* C: 5%* Ash: 2%*	shrimp meat, shrimp paste	Yes
Ephemeral Shrimp	Brine Shrimp (*Artemia franciscana*)	Largest brine shrimp species	1.5 cm	4-5 mg	P:50-69% L: 2-19% C:9-17% Ash:9-29%	shrimp paste, shrimp flakes	No, piloted in this study
	Fairy Shrimp (*Streptocephalus dichotomus*)	Essentially a large freshwater brine shrimp.	2-4 cm	250mg*	P:55% L: 9% C:19% Ash:10%	shrimp meat, shrimp paste, shrimp flakes	No
Filter Feeding Shrimp	Bamboo Shrimp (*Atyopsis moluccensis*)	Mid-size fan shrimp that is fairly hardy.	8 - 10 cm	15g*	P: 60%* L: 32%* C: 5%* Ash: 2%*	shrimp meat, shrimp paste	No
	African Giant Fan Shrimp (*Atya gabonensis*)	Large armored fan shrimp, similar to crayfish.	8 - 18 cm	40g*	P: 60%* L: 32%* C: 5%* Ash: 2%*	shrimp meat, shrimp paste	No
Apple Snails	Golden Apple Snail (*Pomacea canaliculata*)	Large, adaptable aquatic snail that's easily farmed.	15 cm	150g	P: 71% L: 3% C: 13% Ash: 12%	snail meat, snail caviar	Yes
	Golden Mystery Snail (*Pomacea bridgesii*)	Golfball-sized aquarium pet and prolific breeder.	6.5 cm	20g*	P: 71%* L: 3%* C: 13%* Ash: 12%*	snail meat, snail caviar	No, piloted in this study
Commercial Clams	Quahog clam (*Mercenaria mercenaria*)	Commonly harvested atlantic clam.	10 - 13 cm	40g	P: 55% L: 15% C: 22% Ash: 8%	clam meat, clam condiment	Yes
	Portuguese oyster (*Crassostrea angulata*)	Commonly harvested atlantic clam.	10 - 13 cm	40g	P: 55%* L: 15%* C: 22%* Ash: 8%*	clam meat, clam condiment	Yes
Mostly Herbivorous Aquaculture Fish	Nile Tilapia (*Oreochromis niloticus*)	Common aquaculture fish that is omnivorous and easy to culture	15-40 cm	400g - 800g	P: 92% L: 4-5% C: Ash: 4-5%	fish meat	Yes
	Grass Carp (Ctenopharyngodon idellus)	One of the few herbivorous aquaculture fish	60-100cm	1 - 2kg	P: 76% L: 16% C: Ash: 4-5%	fish meat	Yes

Productivity						
Category	**Name**	**Diet**	**Density (#/L)**	**Feed Conversion Ratio**	**Theoretical Yield (kg/m3)**	**Time to Harvest**
Commercial Marine Shrimp	Pacific white shrimp (*Litopenaeus vannamei*)	protein supplements (fish meal), detritus	0.1 - 0.5	1.8 - 2.4*	3kg	2-6 months
	Black Tiger Shrimp (*Penaeus monodon*)	protein supplements (fish meal), detritus	0- 0.5	1.8 - 2.4	1.3kg	2-6 months
Ephemeral Shrimp	Brine Shrimp (*Artemia franciscana*)	various phytoplankton, yeast	200-2000	0.25 - 5.6	2-25kg*	14 days
	Fairy Shrimp (*Streptocephalus dichotomus*)	wide variety of phytoplankton, zooplankton as adults	50	0.25 - 5.6*	2.6kg	14-28 days
Filter Feeding Shrimp	Bamboo Shrimp (*Atyopsis moluccensis*)	suspended particles (phytoplankton, DOM, biofloc)	0.5 - 2			6 months
	African Giant Fan Shrimp (*Atya gabonensis*)	suspended particles (phytoplankton, DOM, biofloc)	0.25 - 1			6-12 months
Apple Snails	Golden Apple Snail (*Pomacea canaliculata*)	benthic algae, inedible biomass, live higher plants	1-10	2.1	6.3kg	2-6 months
	Golden Mystery Snail (*Pomacea bridgesii*)	benthic algae, inedible biomass	5-15	2.1*	6.3kg*	2-6 months
Commercial Clams	Quahog clam (*Mercenaria mercenaria*)	suspended particles (phytoplankton, DOM, biofloc)	0-2			12-18 months
	Portuguese oyster (*Crassostrea angulata*)	suspended particles (phytoplankton, DOM, biofloc)	0-2			6-12 months
Mostly Herbivorous Aquaculture Fish	Nile Tilapia (*Oreochromis niloticus*)	periphyton, algae, protein supplements, inedible vegetable biomass	0 - 0.02	1.4 - 2	0.01kg	5-12 months
	Grass Carp (*Ctenopharyngodon idellus*)	grasses, cereals, protein supplements, periphyton	0 - 0.0027	1.5 - 2.5	0 - 0.005kg	12-24 months

Husbandry						
Category	**Name**	**Sexual Maturity**	**Reproductive Potential**	**Continous Culture?**	**Long-Term Storage**	**Water**
Commercial Marine Shrimp	Pacific white shrimp (*Litopenaeus vannamei*)	4-6 months	10k-100k eggs about every month	N	No	marine
	Black Tiger Shrimp (*Penaeus monodon*)	4-6 months	10k-100k eggs about every month	N	No	marine
Ephemeral Shrimp	Brine Shrimp (*Artemia franciscana*)	7 days	100-300 eggs every 140 hours	Y	Cysts shelf stable for 2-10 years	brackish to hypersaline
	Fairy Shrimp (*Streptocephalus dichotomus*)	~2 months	40-200 eggs/cysts, 3-7 spawns per lifespan	Y	Cysts shelf stable for 2+ years	freshwater
Filter Feeding Shrimp	Bamboo Shrimp (*Atyopsis moluccensis*)	3-6 months	100s of eggs every few months	N	No	Adult - Freshwater Juvenile - Saltwater
	African Giant Fan Shrimp (*Atya gabonensis*)	3-6 months	800-12000 eggs (possibly) seasonally	N	No	Adult - Freshwater Juvenile - Saltwater
Apple Snails	Golden Apple Snail (*Pomacea canaliculata*)	2-6 months	100-200 eggs every 2-3 weeks	Y	potentially dormancy for 1-2 years	freshwater
	Golden Mystery Snail (*Pomacea bridgesii*)	2-6 months	100-200 eggs every 2-3 weeks	Y	potentially dormancy for 1-2 years	freshwater
Commercial Clams	Quahog clam (*Mercenaria mercenaria*)	2-10 years	millions of eggs per seasonal spawning event	N	No	marine
	Portuguese oyster (*Crassostrea angulata*)	1 year	millions of eggs per seasonal spawning event	N	No	marine
Mostly Herbivorous Aquaculture Fish	Nile Tilapia (*Oreochromis niloticus*)	3 months	100-1000 mouthbrooding	Y	No	freshwater
	Grass Carp (*Ctenopharyngodon idellus*)	4-7 years	up to millions of eggs, but require specific environmental parameters to induce spawning	N	no	freshwater

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