

# Engineered Biopolymer Delivery Platforms for Space Nutrition: Food Encapsulation, Stability and Controlled Nutrient Release Strategies - A Review

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**Abstract:** Long duration space missions pose a special problem of ensuring the quality of nutritional value, safety, and stability of food systems because radiation, micro-gravity, and prolonged storage conditions are exposed. As a developing area of food, this review seeks to evaluate the promise of food grade biopolymers like proteins, polysaccharides (chitosan, alginate, pectin, cellulose) and pseudocereals as enhanced carriers of sensitive Nutrients like vitamins, probiotics and unsaturated fatty acids in harsh conditions of space nutrition systems. Current developments in food encapsulation technologies including nano-encapsulation technology, complex coacervation technology, hydrogel-based delivery systems and others are presented in terms of improvements in shelf life, oxidation prevention, and bioavailability enhancement. Also, the controlled release systems, such as pH-responsive and enzyme trigger responsive delivery systems, are discussed as the possible ways to enhance the efficiency of nutrient intake during the altered physiological conditions. Present due to food safety and scaling, material constraints issues are also brought into the limelight. The end of the review represents the future opportunities of developing functional and stable food systems to aid in feeding humanity during space exploration in the long-duration.

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## 1. Introduction

Future human space missions such as the lunar habitats and even future Mars mission will require the use of high quality, safe, and stable food systems that will ensure that nutritional value, safety, and bystand are not compromised by the long-duration space mission without resupply[1,2]. The space food systems that are currently present are mainly processed and shelf-stable foods which are preserved through freeze-dry process, thermal sterilization, and irradiation. Although these processes guarantee safety of microbes and longer shelf life, they can cause loss of heat labile and oxygen labile nutrients during processing and long periods of storage[2,3]. It has been found that long-term storage at ambient spacecraft factors can cause the loss of vitamins A, C and various B-complex vitamins by a very large margin, which questions the effectiveness of extended nutritional support of missions beyond low Earth orbit [2,3]. Preservation of functional nutrients is especially a challenge since astronauts undergo physiological alteration such as bone mineral density, muscle atrophy, immune dyssteadiness, and heightened oxidative stress [1]. The bioactive substances contained in nutritional countermeasures including antioxidants, probiotics, omega-3 fatty acids, and micronutrients are critical in the alleviation of these health risks [2,3,4] Nevertheless, most of these compounds are chemically impotent and prone to oxidation, radiations, and disintegration in long term storage [2,4,5]. Conventional methods, like direct fortification or dietary supplements are perhaps incapable of solving these drawbacks since isolated nutrients can be degraded as well, and maybe not

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have the same functional benefit as nutrients that are presented in protective food matrices [6]. Because of this, interest in the development of next-generation space foods as something that is no longer about an approach focused on shelf stability, but about more nutritionally and functionally optimized, and physiologically supportive food systems is increasing [6]. These might involve implementation of personalized nutrition strategies, introduction of functional ingredient delivery, and adoption of the advanced food processing technologies in the future. Sensitization of the environment can however be acquired such as radiation, microgravity and changes in temperature during spaceflight which may stimulate lipid oxidation, protein breakdown and loss of bioactive functionality [1,2]. These aspects raise the concern of the necessity to develop unique food engineering schemes that could enhance the protection of the nutrients with respect to their bioavailability [7,8]. Biopolymers that are food grade, specifically, naturally produced polysaccharide including chitosan, alginate, pectin, and cellulose have focused a lot of interest as a potential delivery component in food systems [7,9,10]. These products have desirable characteristics such as showing biocompatibility, biodegradability, capability of forming films and the ability to create structured delivery vehicles such as nanoparticles, hydrogels, emulsions and microcapsules [9,10,11]. This type of system has been shown to enhance stability of vitamins, probiotics and polyunsaturated fatty acids by inhibiting oxidation, enhancing dispersion, overcoming undesirable flavors and controlled release during digestion [7,9,10]. Improvements in the fields of encapsulation technologies such nano-encapsulation, complex coacervation, and hydrogel-based carrier further indicate the potential that such materials can provide in the context of improving stability and bioavailability of sensitive food constituents under adverse processing and storage environments

[7,9]. Food biopolymer delivery systems have proven useful in the context of space nutrition despite the recent advances, but the exact application is quite unexplored [1]. Much of the literature relating to space food development has been dominated by preservation technologies (e.g., freeze-drying), packaging advances (e.g., oxygen barriers), or crop production regimen (e.g., bioregenerative life support) and a relatively lower level of attention has been paid to encapsulation-based nutrient protection systems adapted to space environments [1,2]. Equally, there is a substantial body of literature regarding nano-delivery systems in earth functional foods; however, there are very limited studies on the application of these technologies in overcoming the combined issues related to radiation exposure, altered gravity, and extended storage of space missions [8,12]. This shows that there exists a research gap in the convergence of developed food delivery systems and space nutrient needs. Thus, this review is going to critically analyze the potential of food-grade polysaccharide biopolymers, in particular, chitosan, alginate, pectin, and cellulose, as high-tech delivery platforms to enhance nutrient stability and functionality of space food systems. The review gives a first description of the main nutritional and technological issues unique of the long-duration missions. It then reviews the recent event in food encapsulation technologies that interest the enhancement of the stability and delivery of bioactive compounds. Controlled release strategies such as pH-sensitive or enzyme-sensitive delivery systems are also explained in terms of their possibilities to enhance the nutrient utilization in various physiological conditions that are not normal [10]. Lastly the existing constraints in food safety, scalability, regulation considerations and material performance are also mentioned with future research directions of creating stable, functional, and nutritionally effective food systems that will aid human health in extended space exploration [13].

## **2.Space environmental stressors and nutritional needs.**

### **2.1 Space environmental stressors**

The stressors that are applied to food and nutrient delivery systems change as transitioning to deep space trajectories in contrast to responses in low Earth orbit. The most important ones are ionizing radiation, microgravity and altered cabin atmosphere all of which may pose some problems with nutrient stability and bioavailability. [14,15,16]

#### **Ionizing radiation**

Reactive oxygen species (ROS) have been produced through radiolysis of water and other foods components causes oxidation of lipids and breakdown of labile vitamins like vitamin C, thiamine and fat-soluble vitamins by galactic cosmic rays and solar particle activity [14,17,18]. These reactions may decrease the nutritional and shelf life of space foods.

#### **Microgravity**

Microgravity causes changes in the distribution of fluids, gastrointestinal motility and potential processes of intestinal transport, which can have effects on digestion and absorption of nutrients [15,19,20]. Such alterations

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can be of specific interest to hydrophobic nutrients and encapsulated bio actives that are meant to be released gradually.

### **Cabin atmosphere**

Cabins of spacecraft normally have a high carbon dioxide concentration, which may influence systemic acid-base homeostasis and indirectly mineral metabolic rhythm and bone, health [15,19,20]. In the case of pH sensitive delivery systems, dissolution and release behavior of the carriers based on biopolymer would be altered due to variation in luminal pH.

### **2.2 Functional nutritional requirements**

It is connected with long duration spaceflight, affecting bone, muscle atrophy, oxidative stress, immune changes and alteration in microbiota, the countermeasures of dieting are necessary[18,21,22]

### **Bone Mineral Density (BMD)**

Astronauts lose bone at a rate of 1.0-1.5% every month[20,23,24].In response to this, the delivery systems need to bypass the acid environment of the gastric tract and deliver a response of Calcium and Vitamin D3 in an environment with a pH of 3.0, specifically in the ileal area. By taking naturally mineral rich biopolymer bases like Amaranth (Rajgira), this has been doubly advantageous since besides a high-protein protective framework, a bioavailable source of Calcium (up to 700 mg/100 g) and Iron which are crucial in skeletal maintenance is obtained.

### **Radiation and oxidative stress**

Space radiation, microgravity augment production of ROS that leads to skeletal and systemic damages [14,18,25,26].Potential solutions to these effects include antioxidant functional foods (e.g. polyphenols, omega 3 fats, vitamin C and E) and possibly radioprotective matrices .

### **Iron and redox balance**

Spaceflight is able to disrupt iron homeostasis and facilitate oxidative damage of bone and muscle through Fenton chemistry . The nutritional interventions involve strict regulation of iron as well as eating antioxidant or chelator foods to maintain redox equilibrium.[18,24,26]

### **Gut microbiota and immunity**

Dysbiosis can be caused by microgravity and radiation and diet and can result in the augmentation of intestinal permeability, which has an effect on immunity and inflammation. Functional ingredients such as fermentable fiber and oligosaccharides, which are known as prebiotic and probiotics, are hence of interest as ingredients in space foods[14,16,19,27]

## **3. Biopolymer Selection for Space-Adapted Food Delivery Systems**

### **3.1 Key Biopolymers and Their Functional Properties**

The advanced food delivery systems based on biopolymers should have a high potential of film forming, protection of nutrients, controlled release behavior and stability in long-term storage. Polysaccharides and proteins based on natural sources are of great interest, as these can be biodegraded, and they are non-toxic and can be incorporated into the food system. They are also crucial in ensuring that sensitive nutrients like probiotics, vitamins and polyunsaturated fatty acids are not damaged due to degradation.

### **Chitosan and its derivatives**

Chitosan is a significant polysaccharide derived based on chitin and commonly applied in encapsulation of food substances because of its antimicrobial attributes, biocompatibility and excellent film forming attributes[28,29,30]. Reactive amino functional groups allow the chemical conjugate to be modified to enhance solubility, encapsulation efficiency and controlled release behavior. Nanoparticles of chitosan have already shown to have a higher structural stability and protection efficiency than the traditional liquid delivery systems and are a substance that holds promise to be used in advanced applications in food[30,31] .

### **Alginate and pectin as encapsulation matrices**

Pectin and alginate are natural anionic polysaccharides which are generally employed in the encapsulation of bioactive compounds and probiotics[28,29,32]. These polymers are hydrogels that are cross linked by ionic cross-

linking to enable mild encapsulation conditions that are appropriate with sensitive food ingredients. They can be used in functional food delivery use due to their capability to form a stable gel matrix. Nevertheless, they can be too sensitive to moisture, so they might need to be mixed with proteins or lipids to increase storage stability[33,34].

### Casein and Whey protein isolate

Whey protein isolate and casein are milk proteins, which greatly apply in encapsulation due to their qualities of emulsifying, forming gels and their quality of blocking oxygen and preventing rancidity.[2,31,32].Cross-linking procedures enhance both their mechanical properties and minimize oxygen permeability hence preserving nutrients that are vulnerable to oxidation. These properties render milk proteins useful ingredients when it comes to the creation of structured functional foods and encapsulated nutrient systems[35].

### Plant proteins like amaranth

Plant proteins are getting more attention as viable biopolymer to be used. Amaranth (*Amaranthus* spp.) is a well-balanced nutritionally significant pseudocereal that has a protein concentration ranging about 13-18% with a well-balanced amino acid composition especially lysine in comparison to other traditional cereals source of protein, amaranth also contains dietary fiber, iron and bioactive compounds that improve nutritional value of developed food products. Research on amaranth food products have shown enhancement in protein levels, mineral availability and sensory acceptability, that emphasized its possible use as a functional constituent in food products with high nutritional values [37]. These properties lead to the idea that it can be used as a structural and nutritional component of advanced food delivery frameworks since it is a plant-based product. [35,36].

### Lignocellulosic materials and nanocellulose

Cellulose materials are extensively explored as they have mechanical sturdiness, biodegradability and structural stability. Lignin is a natural polymer containing phenol and is an antioxidant polymer with potential to facilitate oxidative degradation protection of composite-based products in case it is introduced into composite matrices. The use of a fiber-based system is under investigation to enhance structural stability of food grade materials and protective capacity[31,36].

### Protein-based microcapsule systems

Protein based microcapsule formed by using whey protein isolate and soy protein isolate are used extensively since they can be produced and shaped to give dense forms of gel by thermal or enzymatic cross-linking. These systems help in the enhancement of nutrient stability, a better encapsulation capability and controlled delivery of bioactive substances to the gut[2,4,35]. These characteristics enter them as optimal sources of the production of functional and fortified foods[7,38,39].

**Table1: Different types of Biopolymers**

Biopolymer	Source	Functional properties	Food/Delivery applications	Advantages	References
Chitosan	Chitin (crustacean shells)	Antimicrobial activity, film forming ability, biocompatibility, controlled release capability	Encapsulation of probiotics, vitamins and bioactive	Improves shelf life and microbial stability	(Khubiev et al., 2023)
Alginate	Brown seaweed	Gel forming ability, biocompatibility, mild encapsulation conditions	Probiotic encapsulation, vitamin delivery systems	Protects sensitive nutrients during storage	(X. Wang et al., 2022)
Pectin	Plant cell walls (fruits)	Hydrogel formation, pH responsive behavior	Functional food encapsulation	Suitable for controlled nutrient release	(Said et al., 2023)
Whey Protein Isolate	Milk	Oxygen barrier property, gel	Microencapsulation of lipids and fat-soluble vitamins	Prevents oxidative degradation	(Said et al., 2023)



		formation, emulsification			
Casein	Milk	Stable micelle structure, good binding properties	Nutrient delivery matrices	Improves stability of bioactive compounds	(Fan et al., 2023)
Soy Protein Isolate	Soybean	Gel forming ability, emulsification, film formation	Plant based encapsulation systems	Sustainable plant protein alternative	(Fan et al., 2023)
Amaranth protein	Amaranthus spp.	High protein quality, lysine rich amino acid profile, mineral content	Functional food formulations and nutrient enrichment	Improves nutritional quality and protein content	(Puliani & Bhavana, 2025)
Cellulose/Nanocellulose	Plant fibers	High mechanical strength, structural stability	Composite food packaging and delivery systems	Biodegradable structural material	(S. Kumar et al., 2020)

### 3.2 Selection Criteria for Biopolymers in Advanced Food Delivery Applications

The choice of appropriate biopolymers relies on its physicochemical characteristics, effectiveness and capability to provide protection against food systems, and compatibility. The criteria are usually important as the following one.

#### Barrier properties

Good systems of delivery need low oxygen and moisture permeability rates to avoid oxidation and degradation of delicate nutrients. More crystalline materials tend to have better barrier qualities as they tend to have lower molecular diffusion [1,40,41].

#### Mechanical and structural stability

During processing, storage and handling, biopolymers have to be structurally intact. Several composite systems that are created by binding proteins and polysaccharide can also be found to be stronger and more stable than the individual polymers themselves [31,42,43].

#### Encapsulation efficiency

The perfect type of delivery material would be the one that can accommodate large amounts of nutrients and remain structurally intact. Effective encapsulation helps in the prevention of sensitive nutrients, as well as the functional performance of the created foods [29,44,45].

#### Biodegradability and sustainability

Biodegradability and natural biocompatibility are the reasons why natural biopolymers are better. The interest to use plant proteins, microbial polymers and food processing by-products as the sources of sustainable materials is growing [1,46].

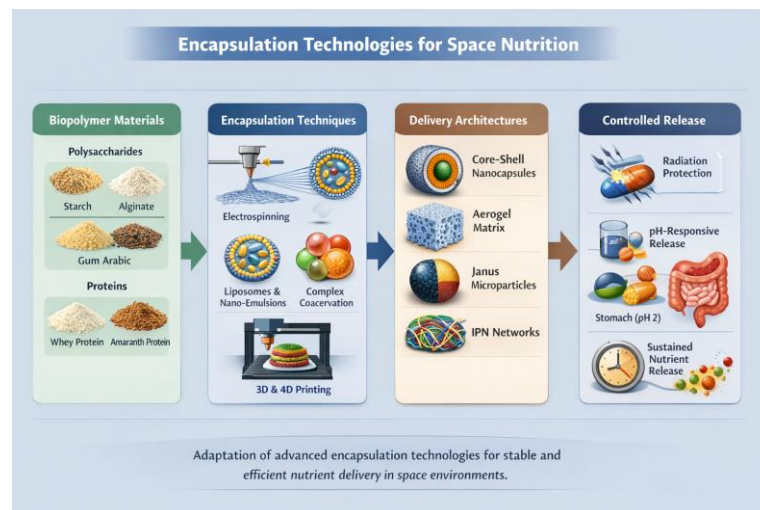
#### Controlled release characteristics

Releasing nutrients in the gastrointestinal conditions should be possible through effective delivery system. Several protein and polysaccharide structures adapt to the alterations in pH and digestive enzymes that allow slow release of nutrients and better access [44,47,48].

### 4. Advanced Encapsulation and Fabrication Techniques

The need to develop assurance technology in the development of food systems that can sustain space missions of long duration is due to the fact that, the technology should be able to ensure that nutrients are not destroyed, yet, they must be delivered efficiently in the human body. Space foods are subjected to various stressors such as long storage period, oxidation, vibration during launching and radiation. Unless protective measures are therefore

implemented, the factors can decrease the quality of nutrition. More elaborate encapsulation technologies should thus be influential in nutrient stability, better bioavailability and controlled release of nutrients[49,50,51,52]. Modern science is concerned not only with preservation, but with the development of the systems of delivering, which would incorporate protection, structural balance, and the ability to control digestion[53,54]. The encapsulation materials which are made in biopolymers are most appropriate because they are biodegradable, functional and capable of integration into food systems[3,55,56].



**Figure 1: Encapsulation Technologies for Space Nutrition**

#### 4.1 Nano and Micro-encapsulation Strategies

Micro and nano-encapsulation methods are being actively researched on enhancing their efficiency in relation to nutrient preservation and facilitating delivery[3,57,58,59]. Reduction of the particle size enhances the contact between the surface and the dispersion of nutrients which may be utilized to augment absorption effectiveness. This would be significant in space missions where there is the possibility of physiological modifications in the digestive and metabolic systems[3,12].

Electrospinning is a developing encapsulation method that can provide ultrafine-sized fibers that have the ability to entrap vitamin, antioxidants and probiotic cultures. The process does not involve the use of high temperature implying that it can be applied to heat sensitive compounds[3,55]. There is also the nanofiber structure that enhances the rehydration behavior, which is useful in case of dehydrated foods that are common in space food[60]. Carriers made of lipids e.g. liposomes and nano-emulsions are handy in delivery of fat-soluble vitamins. They are better dispersing systems, which preserve hydrophobic nutrients and mitigate their oxidation. They can be used to assist in enhancing the provision of vitamins and fatty acids that are essential in the health of astronauts[3,59]. Complex coacervation in which the proteins and polysaccharides interact is also an effective encapsulation strategy. Such systems create coatings with a protective effect against exposure to oxygen and exposure to moisture. This kind of protection is significant in the stability of the micronutrients in extended storage[56].

#### 4.2 Macro-structured Delivery Platforms and Food Fabrication

Advanced space nutrition studies are also adopting macro-level structuring of foods. There are emerging technologies like 3D food printing which enable production of foods with predetermined structure based on printable biopolymer recipes. Alginate, starch, gelatin and plant proteins are the materials that are frequently utilized as they possess the appropriate flow and gel forming characteristics[51,60]. Another great benefit of 3D food printing is the capability of the control of internal structure. Porosity and density can be modified in order to control hydration behavior and mechanical breakdown. This internal regulation enables a slow release of nutrients which can enable certain stability in nutrient availability on a slow encoding rather than a high rate of digestion[5,60]. 4D food printing is a build on the idea, with materials that can be altered in structure upon exposure to aspects like moisture or temperature. Such systems can enable the dehydrated foods of small size to



develop into edible forms following hydration. This transformation can help to increase efficiency in storing and minimize volume of transportation needs[5,60].

### 4.3 Structural Design of Encapsulation Systems

The orchestration composition of encapsulation systems has a significant role in defining efficiency of protection. Single layer encapsulation has lower stability that multilayer systems have. The reason why core-shell structures are usually adopted is that sensitive nutrients are concealed by covering them with protective shells. Such buildings are able to cut off environmental stressors and inhibit degradation responses[56,57]. Interpenetrating polymer networks offers better mechanical strength due to the formation of dense interconnected net structure by a number of polymer systems. These networks enhance resistance to penetration of oxygen and to mechanical dyes which can enhance storage stability. Other matrices under exploration are aerogel-based with its low density and high porosity. With these structures, the incorporation of nutrients into lightweight matrices is made possible, and this is favorable when the mass of transportation is to be reduced. Their thermal insulating can also be used to ensure that they are stable with change in temperature[56]. Another new form that is developing is compartmentalized particles which are the physical separation of incompatible nutrients. Such a coating avoids any undesirable chemical interaction during store timely and yet facilitated joint delivery during digestion[56]. Stimuli-responsible polymers also have potential of being delivery systems that can release nutrients based on environmental conditions like pH. These systems could enhance the use of nutrients as they can be released at the right levels of digestion[56].

### 4.4 Integration of Plant-Based Nutrient Sources into Delivery Systems

Plant nutrients have been increasingly gaining popularity in the field of space nutrition due to their sustainability and good density of nutrients. Microgreens are one such promising food source because of richness in vitamins, minerals, antioxidant food compounds and very short growth time. Studies done on fenugreek microgreens have indicated that the drying process largely affects retention of nutrients with freeze drying in preserving more micronutrients as opposed to usual drying[61]. These results indicate that using optimization of drying methods with encapsulation methods can help to enhance nutrient stability to prolonged storage. Microgreens also can be used to solve micronutrient deficiencies as they are rich in iron and antioxidants. Adding microgreen powders into encapsulated delivery system could thus offer stable plant-based nutrient food supplements to be used in space diets[61]. Amaranth is the other relevant source of plant as well because it is a good source of protein and amino acids. Such functional properties of amaranth proteins as emulsification and film formation can enable the use of amaranth proteins as encapsulation materials. They have potential dual structural material and nutrient source and can be considered the future space food systems of the future. It is believed that in the future research, incorporation of plant proteins, microgreen nutrients and smart delivery matrices into multifunctional systems that can include protection, delivery and nutritional benefits will be introduced. These integrated systems can help to create effective and sustainable nutrition platforms in the case of long-human space missions[62].

**Table 2: Biopolymer based delivery technologies and their functional relevance in space nutrition systems**

Technology approach	Material system	Functional benefit	Relevance to space nutrition
Electrospinning	Biopolymer nanofibers	Protection of sensitive nutrients	Long-term nutrient stability
Liposomal delivery	Lipid vesicles	Improved bioavailability	Efficient nutrient absorption
Complex coacervation	Protein-polysaccharide systems	Oxidative protection	Micronutrient preservation
Freeze drying + encapsulation	Microgreen powders	Nutrient retention	Stable plant nutrient source
3D food printing	Hydrogel biomaterials	Structured nutrient delivery	Personalized astronaut diets
Core-shell encapsulation	Multilayer polymers	Environmental protection	Stability of sensitive nutrients
Aerogel matrices	Porous biomaterials	Lightweight storage	Payload efficiency
Smart hydrogels	Responsive polymers	Controlled nutrient release	Improved digestion efficiency
Amaranth protein systems	Plant protein matrices	Nutrient carrier + protein source	Sustainable protein delivery

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## 5. Longterm stability of encapsulated nutrients under spacelike storage

For long duration missions, nutrient delivery systems must remain safe, palatable and nutritionally adequate over several years. Work on space foods and encapsulation offers guidance that can be translated into dairy and functional food formulations.

### 5.1 Behavior of vitamins during prolonged ambient storage

Studies on current space foods stored for up to three years at ~21–22 °C show that many micronutrients decline over time, with water-soluble vitamins being particularly vulnerable [63,64]. In a survey of 109 items, vitamins A, C, B<sub>1</sub> and B<sub>6</sub> decreased during three years of ambient storage, and thiamin and vitamin C could fall below target levels within one and three years, respectively [63]. A scoping review similarly reports substantial losses of folate, thiamine, vitamins A, C and K after 880 days, with vitamin A and C reductions of 10–35 % even in fortified multivitamins [64].

Low moisture, carefully formulated products can substantially improve retention. In fortified, low water activity bars and powdered beverages designed for NASA, encapsulated vitamins A, B<sub>1</sub>, B<sub>9</sub>, C and E were retained at 70–95 % of initial values after three years at 21 °C; all remained above spaceflight requirements. Susceptibility followed the order B<sub>9</sub> > A > B<sub>1</sub> > C > E, and vitamin A and C were most sensitive to higher temperature (38 °C). Matrix composition and lipid level also affected stability [63,65].

### 5.2 Role of encapsulation and packaging

Encapsulation in carbohydrate or lipid coatings, and incorporation into dense, low oxygen matrices (e.g. compressed bars, powders) slow oxidative and thermal degradation [65,66]. In mashed potato, encapsulated vitamin C showed no processing losses and lower storage losses than free vitamin C, while vitamins A and E (ester forms) remained stable over 90 days when combined with suitable barrier films [66]. Reviews on vitamin and carotenoid encapsulation confirm that micro and nano systems can maintain >70–80 % stability for vitamin C and A and improve bio-accessibility of fat-soluble vitamins and carotenoids during storage and digestion [35,67,68,69].

Packaging and storage conditions are critical. Vacuum or modified atmosphere packaging in high barrier films, together with low water activity, limit oxygen ingress and delay vitamin C and lipid oxidation [63,65,66]. Refrigerated storage further improves vitamin stability and limits lipid oxidation in high moisture food bars, although ambient storage for up to 18–27 months can still meet minimum requirements when formulations are optimized [70]. Reviews emphasize that, beyond microbial safety, chemical and oxidative stability must be addressed through gentle processing (e.g. microwave assisted thermal stabilization, high-pressure technologies), protective packaging and antioxidant use to achieve multiyear shelf life [54,71,72].

### 5.3 Implications for Dairy and Composite Functional Food Systems

The findings from stability studies of encapsulated nutrients have important implications for dairy-based and plant-dairy composite food systems. Dairy proteins such as whey protein and casein possess excellent encapsulation properties due to their emulsification capacity and gel forming ability. These proteins can therefore serve as both structural carriers and nutritional components in encapsulated delivery systems.

Low moisture dairy formats such as milk powders and protein concentrates may provide suitable matrices for incorporating encapsulated micronutrients. Similarly, composite systems combining dairy proteins with plant materials such as amaranth or cereal proteins may improve nutritional diversity while maintaining structural stability [63,65,72].

The inclusion of polysaccharides such as alginate or pectin together with milk proteins may further improve encapsulation efficiency by forming protein–polysaccharide complexes [68,69,73]. These systems can improve stability of lipophilic nutrients such as carotenoids and essential fatty acids. In addition, incorporation of natural antioxidants from plant sources such as microgreens may provide additional protection against oxidative degradation. Such integration of plant bioactive with dairy encapsulation systems may represent a promising strategy for developing nutritionally balanced foods suitable for long-duration storage conditions [65].

Overall, the combination of encapsulation technologies, suitable dairy and plant matrices, and protective packaging strategies may significantly improve the long-term stability of functional foods designed for extreme environments including space missions [65,74].

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Delivery system	Biopolymer/material	Space-related condition evaluated	Main findings	Limitation identified
Chitosan nanoparticles	Chitosan	Simulated gastrointestinal changes under microgravity	Improved protection and controlled release of bioactives	Limited long-term storage validation
Alginate microcapsules	Alginate	Extended ambient storage relevant to space foods	Improved probiotic and vitamin stability	Sensitive to moisture and mechanical stress
Protein-polysaccharide complexes	Whey protein + pectin/alginate	Oxidative and storage stress	Higher encapsulation efficiency and oxidative protection	Limited industrial-scale studies
Liposomal delivery systems	Lipid vesicles	Oxidative degradation during prolonged storage	Enhanced bioavailability of fat-soluble nutrients	Stability affected by temperature fluctuations
Smart hydrogels	Chitosan/polysaccharide hydrogels	pH-responsive nutrient release under altered GI conditions	Controlled intestinal release behavior	Few in vivo or spaceflight validations
Encapsulated vitamin systems	Carbohydrate/lipid coatings	Long-duration storage and radiation-associated degradation	Improved retention of vitamins A, C and E	Nutrient losses still occur during multiyear storage
Aerogel-based matrices	Porous polysaccharide structures	Lightweight storage systems for space missions	Reduced payload weight and improved insulation	Structural fragility during handling
Amaranth protein-based systems	Plant protein matrices	Nutrient delivery for sustainable space nutrition	Dual role as nutrient source and carrier matrix	Limited experimental validation in space-like conditions
Irradiated food stability systems	Encapsulated food matrices	Gamma/neutron radiation exposure	Encapsulation reduced oxidative degradation compared to free nutrients	Data on bioavailability after radiation remains limited

## 6. Controlled and stimuli responsive nutrient release in functional and space foods

These controlled release strategies are particularly relevant for space foods, where altered gastrointestinal physiology and extended storage conditions may influence nutrient stability and bioavailability

### 6.1 Stimuli responsive release mechanisms

#### pH responsive system

Natural polysaccharides (alginate, pectin, starch derivatives) are widely used; ionizable groups change charge and swelling with pH, keeping nutrients protected in gastric acid and releasing them in the intestine, improving bioaccessibility of vitamins and lipophilic nutraceuticals. responsive microgels, nanoparticles and emulsions can maintain vitamin C or A stability in the stomach and promote intestinal release [29,75,76].

#### Enzyme / microbiome responsive systems

Colon targeted delivery exploits polysaccharides (e.g., pectin, guar type gums, inulin) that resist upper gut digestion but are degraded by colonic microbiota, enabling targeted release of probiotics, prebiotics and polyphenols in the lower gut. Microbiome responsive hydrogels and nanogels are engineered to respond to microbial enzymes and fermentation products for site-specific nutraceutical delivery [77,78].

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## Thermo and multistimuli systems

Temperature responsive carbohydrate-based hydrogels (often combined with pH sensitive components) alter hydration and porosity with temperature, allowing dual pH/thermal control of release, as shown in chitosan-based hydrogels that restrict release at gastric pH and promote it at intestinal pH and 37 °C . Reviews highlight emerging multistimuli platforms (pH, temperature, enzymes, redox, humidity) for precision release in foods and packaging [75,76].

### 6.2 Evaluation of controlled release performance

Invitro gastrointestinal models are standard to assess release profile, stability and bioaccessibility of encapsulated nutrients[79] . Encapsulation consistently increases invitro bioaccessibility versus free forms, e.g., vitamin D nanosystems reaching 75–88 % bioaccessibility and liposomal astaxanthin showing markedly higher bioaccessibility than free astaxanthin [67] . Pickering emulsions and liposomes protect curcumin or astaxanthin in gastric conditions and enhance intestinal micellization and cellular uptake.

Key performance metrics include encapsulation efficiency, loading capacity, release kinetics and storage stability; nano and microencapsulation can maintain >70–80 % vitamin stability under stressed conditions . Accelerated storage tests (elevated temperature/humidity) are used to predict long term nutrient retention and robustness of functional food formulations[80].

## 7.Challenges and Future Perspectives

Biopolymer-based encapsulation systems show significant potential for improving nutrient stability, bioavailability, and controlled delivery in functional foods and space nutrition[29,32,81,82]. However, their practical translation into real food systems remains limited by challenges related to large-scale processing, stability during storage, safety validation, and material performance trade-offs. Addressing these constraints is essential for successful industrial adoption and future application in extreme environments[32].

### 7.1 Scalability and Processing Constraints

Advanced methods (nanoencapsulation, electrospinning, microfluidics) offer precise control but are costly, low throughput, and difficult to scale consistently . Variability in encapsulation efficiency and particle size complicates industrial formulation and demands extensive optimization . Reviews emphasize the need to adapt encapsulates to mainstream operations such as spray drying, extrusion and coacervation, and to simplify processes and reduce cost for industrial uptake[29,32,83].

### 7.2 Stability in Processing and Storage

Many current systems fail under realistic thermal, mechanical, and oxidative stresses; none fully satisfy simultaneous criteria of processing stability, digestibility and safety for vitamins and other labile nutrients. Crosslinking and optimized nanosizes improve robustness but can also promote aggregation or alter release. Longterm storage, especially under fluctuating temperature and humidity, remains a major uncertainty, highlighting the need for systematic accelerated stability and Realtime shelf-life studies[89,90,91,92].

### 7.3 Safety, Digestibility, and Regulation

Regulatory and toxicological gaps are prominent for nanostructured and hybrid systems. Small size and novel materials (e.g., 2D nanomaterials, inorganic or hybrid carriers) raise questions about GI fate, accumulation and long-term safety . Reviews call for standardized digestion models, metabolic fate studies, and clear differentiation between food ingredients, additives and processing aids to support regulatory approval and consumer trust [29,84,85].

### 7.4 Material Design Tradeoffs

Dense, highly crosslinked matrices provide strong protection but can impede release and digestibility, leading to incomplete bioactive release in the GI tract . Conversely, highly degradable walls enhance release but compromise storage stability and processing resistance . Future designs are moving toward tunable architectures (e.g., protein–polysaccharide complexes, smart stimuli responsive systems) that better balance protection with controlled release [48,83,90].

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**Table 3: Challenges ,Current limitations and future research needs in biopolymer-based space nutrition delivery systems**

Challenge	Current Limitation	Research Need
Scalability	Low production throughput and high cost	Development of industrially scalable fabrication methods
Processing stability	Structural damage during heat and mechanical processing	Improved polymer network design
Storage stability	Nutrient degradation during long storage	Accelerated shelf-life validation studies
Safety	Limited nano-toxicity and digestion data	Long-term safety and bioavailability studies
Regulatory approval	Lack of clear classification frameworks	Standardized safety documentation
Material design	Protection vs bioavailability conflict	Tunable and stimuli-responsive polymers
Sustainability	Limited use of renewable materials	Development of biodegradable food-grade polymers

## 8. Discussion

An ability to match the bioactive compound with the delivery system to vehicle is a major factor to consider when designing a biopolymer delivery system. In general, proteins like whey protein and casein have strong interactions with hydrophobic bioactive compounds while polysaccharides like alginate and pectin have improved tolerance to environmental and processing stresses. Pomperma et al. have recently reported composite systems combining proteins and polysaccharides systems as superior in terms of encapsulation efficiency, structural integrity and release control properties when compared to single component systems.

Despite these developments, most of the studies published so far report rate measurements on laboratory scale products. A limited number of investigations examine encapsulated bioactives under actual food processing/storing conditions. The stability, bioavailability and release rate profile of encapsulated compounds can be greatly influenced by the conditions they are exposed to during the thermal treatment process, including pH changes, exposure to oxygen and storage time. This establishes a niche between experimental results and industrial food processes, highlighting the crucial need for industrial validation.

Stable nutrient delivery technologies are increasing in significance as a result of their rising popularity in programs sponsored by National Aeronautics and Space Administration and European Space Agency in the area of functional and space-ready foods. The high nutrient retention, long term food stability and little breakdown of nutrients during storage, along with controlled release of nutrients during extreme environmental conditions are demanded for space food systems. In long duration missions, therefore, the protection of sensitive nutrients, antioxidants, probiotics, and omega-3 fatty acids via technologies using biopolymers increasingly have been considered. Nevertheless, there is a lack of long-term stability and scalability studies on such demanding conditions presenting the current research.

A further drawback is the compromise between technology and industrialisation. For controlled release of nutrients, advanced techniques, like nano-structuring and multi-layer encapsulations, give good control of nutrient release but have limits in industrial applications because of their high production cost, process complexity and the scalability issues. Encapsulation techniques thus require further development so as to create commercially viable, food friendly and scalable systems that guarantee adequate protection and efficient release of nutrients from the capsule during digestion and use.

## 9. Conclusion

Quality of nutritional value in long period space missions is still a sensitive issue because nutrients are destroyed due to prolonged storage, radiation and other factors that alter the physiology of astronauts which influence their nutrient uptake. Encapsulation systems using biopolymers provide a viable solution to enhance the stability, protection, and release of nutrients whereby, in simulated conditions, alginate, chitosan, starch derivatives, and whey proteins have been shown to have a higher retention capacity of vitamins, antioxidants and probiotics. Nevertheless, the majority of systems are still laboratory scale and have few or no tests that validate them under real spaceflight environments, especially in terms of radiation stability, multi-year storage functionality and scale of manufacturability. Also, delivering materials should strike that niche between structural stability and mass

lowness, space food processing compatibility and predictable release behavior, to which current systems cannot attain in full. Thus, the future studies should emphasize simple, food-grade, and scalable encapsulation systems tested in the challenging conditions of both space and environment to allow using them in future space nutrition systems.

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## 11. Conclusion

No supplementary resources are associated with this article.

## 12. References

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The author declares no competing conflict of interest.

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