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Review Article

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Sowing Health Beyond Earth: The Scope of Microgreens as Space Food for Astronauts

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Abstract

The need for substantial food production for astronauts in space has significantly increased due to prolonged space exploration missions. Microgreens, the miniature version of a mature plant, have a short production cycle, with young and tender shoots, gaining attention due to their vibrant color and unique taste. Due to their quick growth, they allow for crop rotation, which fulfills the requirement of fresh food for astronauts and helps in alleviating space-induced fatigue as well as offering psychological benefits. They are an ideal option for substituting packaged food, as they offer abundant nutrients, palatability, variety, and safety to astronauts. Besides advantages, there are several challenges that need to be considered for growing microgreens, like growth conditions, microgravity, ionizing radiation, and lightning conditions. The intake of microgreens can prevent several space-induced diseases, as they are the richest source of vitamins, antioxidants, and minerals. This review article explores the scope and suitability of microgreens for astronauts in improving their diet as well as overall health status.

Keywords

Space foods, Microgreens, Phytonutrients, Health effects, Growth challenges

Introduction

New world exploration by migrating to the planetary world by astronauts has initiated a new chapter regarding nutrition for human existence in space [1]. Over the past few decades, astronauts have contributed to spaceflight short-term and long-term manned missions, with food and nutrition being a major hindrance to their goals. Therefore, it has become very important to develop good quality, highly nutritious, and palatable food products that closely resemble the Earth's food [2]. To bring advancement in space foods, the Indian Space Research Organization has spent almost 10,000 crores. Moreover, the National Aeronautics and Space Administration (NASA) has also spent 22.6 billion dollars on research to develop space foods. Researchers at Hawaii Space Exploration Analog and Simulation have implemented various new strategies and technologies to formulate food in accordance with the space environment for the sake of providing adequate nutrition to astronauts during long-term missions [1]. Long-term missions from Earth to the Moon have been projected to last between 20 to 30 days whereas, from Mars and Venus, it has been anticipated to be between 800 to 1100 days. In short-term missions, astronauts take their food along with them from Earth, but they need to make other arrangements to fulfill their nutritional requirements during the long-term missions [2].

Astronauts have very limited food choices due to inadequate resources for the preparation of food. They often consume pre-packed preserved food, that is dehydrated, frozen, irradiated, and thermostabilized [3]. Recent studies showcase that different food preservation methods have been adopted during the missions such as dehydrated foods used for the Apollo missions to reduce weight as well as the volume of food, whereas in the Skylab mission, a menu of approximately 72 foods was planned based on the 6-day cycle where they used to refrigerate, frozen and food warmers [3, 4]. The pre-packaged food offered to crew members has a low shelf life which further raises the issue of food decay, spoilage, as well as poor quality food. Thus, NASA has been researching the ideal food variety for crew members which must have a good shelf life, be ready to eat, and can sustain in microgravity [5, 6]. They discovered an alternative crop other than green leafy vegetables for space life i.e., "Microgreen" that can be easily harvested and freshly consumed. It has captured a high interest because of its short production cycle and prominent nutritional profile [7].

Microgreens originate from vegetables and are commonly known as vegetable confetti, aromatic herbs, and micro herbs [8, 9]. These microplants consist of three different parts, a fully-grown central stem, sensitive cotyledon leaves, and a set of true leaves that are partially extended [9-11]. The developed cotyledons and the emergence of true leaves indicate that these immature greens are ready to harvest, and the optimum duration for harvesting is between 7-14 days [12, 13]. Microgreens possess significant characteristics, unique colors, odor, relishing flavor, and texture. Moreover, it is packed with abundant phytonutrients which vary by the category of seed chosen to grow microgreens [11]. This review highlights the scope of microgreens as a practical, sustainable food source for astronauts who encounter space-induced challenges. The review discusses the composition and potential health benefits of microgreens in relation to the astronaut's health. Moreover, it focuses on the suitability of microgreens to be grown in confined environments and their sustainability for long-term missions.

Understanding Microgreens

In the 1980s, in San Francisco, California microgreens were seen for the first time on the menu of chefs, and later in the 1990s, they were harvested in the southern part of California due to their popularity in that region [14]. In restaurant kitchens, they are considered culinary specialists, increasingly popular for human food consumption [13]. Among all salad crop categories, the youngest and smallest ones are sprouts, with heights ranging from 5-8 cm, and are composed of seedlings and embryo portions. In contrast, microgreens are 3 to 10 cm in height and moderately older and larger than sprouts. In addition to this, baby greens are 10-15 cm in height yet considered the oldest among microgreens and sprouts, with precise root and shoot systems [12, 13].

Challenges for Growing Plants in Space

Growing microgreens in outer space might be very challenging compared to Earth because different environmental constraints like temperature, humidity, and light intensity have been observed in space for growing crops [9]. A few challenges including temperature and humidity can be overcome by astronauts whereas microgravity and radiation cannot be easily handled.

Microgravity

Microgravity affects plant growth in many ways like improper nutrient distribution to roots, and accumulation of CO_2 and waste products near the cells due to reduced diffusion which further causes alteration in cell metabolism. Moreover, it also slows down sedimentation rates, hydrostatic pressure, and gas exchanges, thereby affecting nutrient uptake [15]. Modification of gene expression has been observed in plant cells during long-term missions which are further responsible for altering the cytoskeleton formation, and plant hormone metabolism. Alternatively, microgreens can be easily grown in shallow hydroponic systems (plants receive nutrients and water through methods such as misting, immersion, and flooding) [16]. Also, they can be easily grown without any nutrient supplementation as they receive most of the energy from seeds for their growth. The veggie chamber in microgravity employs a root pillow and arcillite growth substrate to provide water and nutrients to the roots [8, 16].

Lighting

To control the performance and quality of microgreens in space, light modulation is the best tool. Different types of light sources are used during space missions like metal halide, fluorescent, light-emitting diode (LED), and high-pressure sodium lamps. Among all, the most efficient is LED because it reduces the power demand of the growing area and consists of spectral quality of 450, 660, and 730 nm which provides surety of even distribution of light [17]. It has been reported that modulation in light intensity, photoperiod, and wavelength is done to enhance the antioxidant value of microgreens. A study conducted by Al-Shrouf [18] revealed that the levels of antioxidant activity were increased in soybean microgreens when they were treated with blue light or UV-A, in comparison to white light. Although the photo-inhibition mechanism and photosystem can be affected due to exposure to excess light, its further results in the formation of peculiar plant structures and alters the profile of photosynthetic pigments [17]. Orbital Technologies Corporation had explored 'Veggie' a suitable system for the space environment to grow plants [14]. It is a type of space garden specially designed for the ISS consisting of various properties such as low mass, low energy unit, useful in the production of palatable and safe food for astronauts. Moreover, this system uses LED light of less than 90 W which is useful in maintaining flexible wavelengths [18, 19].

Radiation

The influence of ionizing radiation on plant morphology has not been completely revealed because there are many factors that act as discriminators such as the type of ionizing radiation, dose, exposure time, type of tissue exposed, species, and phenological stage [17]. Commonly, genetic mutations in plants have been observed when exposed to a high dose of light energy transfer. Hence, with an increase in dose the chances of radiation-induced damage increase [19].

Crop selection

The selection of crops in space is the biggest challenge because certain criteria must be followed to grow crops in space such as (i) the requirement of crop-like tools to harvest like processing units, and planting material; (ii) the efficiency of the crop-like growth cycle, volume; and (iii) production yield (water and oxygen production) [20]. Microgreens that are explored for space environments belong to different families like Asteraceae, Brassicaceae, Chenopodiaceae, Lamiaceae, Amaranthceae, Amarillydaceae, and Cucurbitaceae (Figure 1) [20, 21].

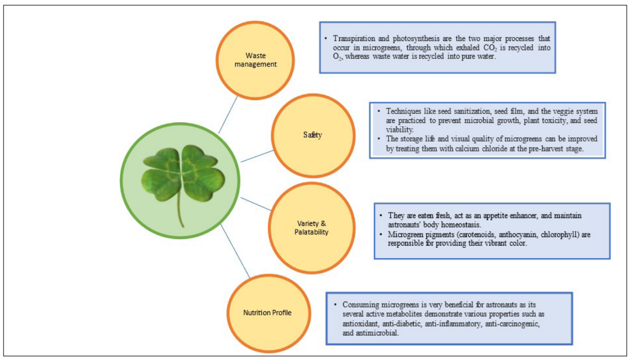

Figure 1: Suitability of microgreens for space environment.

Harvesting

Astronauts face food insecurity due to microgravity because some food items like salt and pepper clog into air vents or may get stuck into astronauts' mouths, ears, or noses. It can also lead to equipment contamination [22]. Due to microgravity, microgreen stems float in spacecraft and it becomes very difficult to collect them. Moreover, microbial safety is another major concern during space missions because plant roots use water and fertilizers to grow which further results in microbial contamination. Thus, astronauts consume only shoots to prevent harmful effects. To combat this issue, they developed a growth chamber where both roots and shoots were harvested separately. Different methods of harvesting including scissors, sliding blades, and pepper grinding were tested. A glove box was created to monitor the growth of microgreens which included a camera to record the growth and an accelerometer to observe the microgravity level [8, 19].

Suitability of Microgreen to be Used as Space Food

In space agriculture, there are various challenges such as microgravity, high CO_2 levels, ionizing radiation, and low atmospheric pressure that can impede plant growth. As a result, it is essential to minimize the use of energy, mass, and volume to make the most of available resources such as water and light for the cultivation system [23]. Microgreens are edible crops or seedlings of about 5 to 10 centimetres that possess favourable characteristics for the space environment (8). These favourable factors include (i) a short production cycle, (ii) minimum investment, (iii) limited resources, (iv) chamber cultivation, (v) less space required (vi) wholesomeness (vii) access to preferable seeds, and (viii) homogenous nature. Moreover, there is no need for nutrient supplementation to grow microgreens as they are dependent on seeds' energy for their growth [10, 22, 23]. They are valued for their unique color and flavor, and for providing astronauts with phytonutrient content. Microgreens not only fulfil the nutritional profile of astronauts but also ensure freshness and good quality.

Waste management

The demand for water is very high during long-term spacecraft missions compared to other human necessities. To fulfil the water requirements, wastewater in the form of urine, sweat, and respiration is recycled for cultivating plants in spacecraft. Transpiration and photosynthesis are the two major processes that occur in microgreens, through which exhaled CO_2 is recycled into O2, whereas wastewater is recycled into pure water [20]. Transpiration and gas exchange in leaves is induced by a LED and vapor pressure deficit levels. LED acts as a source of artificial lighting to enhance photosynthesis and plant growth in microgreens, while vapor pressure deficit levels are is responsible for transpiration. It affects the physiological and biochemical processes of crops, thus resulting in modifications in crop gas exchange and water use [24, 25].

Nutrient profile

The World Health Organization has set up some nutritional requirements for space crew members. Their diet must include essential nutrients including, water-soluble vitamins (ascorbic acid, B-complex vitamins), fat-soluble vitamins (tocopherol, cholecalciferol, retinol), minerals (calcium, iron, magnesium, potassium, zinc), and macronutrients (protein, lipids, carbohydrates) [1]. It is evident from research studies that microgreens have an abundance of bioactive compounds like vitamins, minerals, polyphenols, carotenoids, and glucosinolates. Consuming microgreens is very beneficial for astronauts as its several active metabolites demonstrate various properties such as antioxidant, anti-diabetic, anti-inflammatory, anti-carcinogenic, and antimicrobial [19]. There is a huge difference between the chemical composition of microgreens and that of fully grown plants. Several studies have reported that microgreens possess a higher number of phytonutrients as compared to their mature counterparts. For instance, fenugreek and roselle contain higher levels of vitamin E than mature plants [10, 25].

Variety and palatability

International Space Station (ISS) revealed that Mizuna microgreens have unique nutritional properties and the potential to grow in space environments. Mizuna is a hydroponic crop that belongs to the mustard family and consists of nutrients like vitamins (C, K), and antioxidants. In addition to this, its other features like colour and unique taste (neutral, bitter, spicy) further add to its high acceptability [22]. They are eaten fresh, act as an appetite enhancer, and maintain astronauts' body homeostasis [10]. Microgreens consist of three pigments that are responsible for providing their vibrant colour (i) anthocyanin, (ii) carotenoids, and (iii) chlorophyll [26]. Anthocyanin not only contributes to health benefits like anti-inflammatory and antioxidants; it also adds to sensory traits like astringency and bitterness. Chlorophyll, on the other hand, imparts green colour to plants and serves as a precursor for tocopherol.

Safety

Numerous parameters affect the storage and handling of microgreens, such as a high surface area-to-volume ratio, delicate leaves, rapid post-harvest deterioration, and loss of exudate nutrition [27]. However, the storage life and visual quality of microgreens can be improved by treating them with calcium chloride at the pre-harvest stage [28]. In various studies, it has been revealed that many precautionary measures regarding microgreens safety have been adopted to prevent the growth of pathogenic bacteria which further ensures the safety and access to hygienic food for astronauts [10, 28]. Techniques like seed sanitization, seed film, and the veggie system are practiced preventing microbial growth, plant toxicity, and seed viability [28].

Significant Benefits of Microgreens for Astronauts

The cellular structure of humans relies on nutrition for their functioning, but maintaining health during long-term and short-term missions might be very challenging for astronauts. Muscles, bones, and the cardiovascular system decline as we grow older. However, these changes occur ten times faster during space missions due to environment-induced physiological changes. The stressful circumstances they face can be either environmental (microgravity, radiation) or social (isolation, anxiety, fatigue, sleep disturbance) [29-31].

During the initial phase of long-term missions, when astronauts try to adapt themselves to stressful circumstances, they face muscle loss because the body uses limited force which causes the degeneration of muscle. Hence, the efficiency of muscle is reduced. Alternatively, calcium homeostasis becomes abnormal as the activity of bone-forming cells osteoclast and osteoblast alters which causes calcium loss and enhances the chance for kidney stone formation [28]. Moreover, 40 to 60% of astronauts from the international space station and 25% from Space Transportation Systems suffer from visual impairment during long-term missions [32]. Canadian Space Agency showcased that microgravity affects cardiovascular health by causing a disturbance in cardiac electrical rhythm, arterial stiffness, and changes in blood parameters, likewise, it also alters fluid homeostasis from the thorax to the head. In 2023, Green et al. [33] reported that the levels of white blood cells rise by 17% in the blood sample of crew members taken by the ISS. Similarly, the level of red blood cells level was reduced by 10% which might affect the functioning of the immune system. However, the levels increased in some other cells like T-cells, B-cells, and neutrophils, as well as a reduction in levels of natural killer cells was also observed in microgravity.

All space-induced diseases can be prevented by supplementing the astronaut's diet with food rich in bioactive compounds as they possess positive responses toward psychological health [18]. Microgreens are suitable for maintaining health and homeostasis in the space environment as compared to

Table 1: Health benefits of microgreens.

Microgreens family	Health benefits	Ref.
Amaranthaceae (amaranth, beet, quinoa, spinach, buckwheat chard)	1. Betalanins, β-cyanins, and β-xanthin are natural pigments found in amaranth. and red beet. These pigments are helpful in preventing chronic diseases such as skin disease, aging, and cardiovascular disease moreover, it also curbs hemolytic anemia and thalassemia. 2. Quinoa has the potential to prevent hypertension and diabetes. 3. Ascorbic acid present in spinach shows antioxidant properties, it also performs various functions such as lipid-lowering, antimicrobial, antioxidant, anti-inflammatory, and preventing cancer by performing anti-carcinogenic properties. 4. Buckwheat is a gluten-free microgreen and is a good source of protein which helps prevent malnutrition.	[30] [34] [21] [15] [32]
Apiaceae (parsley, carrot, fennel, celery, dill, chervil, cilantro, coriander)	1. Fennel shows scavenging activity because it consists of high phenolic and flavonoid content. 2. A 3-fold higher concentration of β-carotene is found in coriander microgreens. 3. Celery prevents cardiovascular disease and maintains blood homeostasis. 4. Coriander is the richest source of polyphenols (5920 mg/g).	[15] [20]
Asteraceae (lettuce, chicory)	1. Lettuce contains various health-promoting phytochemicals, including vitamins and phenolic compounds with antioxidant properties.	[15]
Brassicaceae (radish, watercress, arugula, broccoli, cauliflower cabbage, chicory, wild rocket, red cabbage)	1. Broccoli microgreens had the highest content of isothiocyanates, known for their cancer-preventing abilities. 2. Brassicaceae microgreens are used to prevent noncommunicable diseases such as diabetes, cancer, obesity, and chronic heart failure. 3. Cabbage prevents liver lipid metabolism. 4. Radish and mustard are good sources of bioactive compounds. 5. Radish microgreens are a good source of glucosinolates which helps in the prevention of cancer. 6. Red cabbage microgreen helps to lower hepatic cholesterol ester, low-density lipoprotein, and expression of inflammatory cytokines in the liver.	[20] [31] [34] [35]
Poaceae (corn, lemongrass)	1. Corn is a good source of vitamin A. 2. Boost immunity. 3. Rich source of calcium, magnesium, and antioxidants.	[16]
Lamiaceae (chia)	1. Rich in chlorophyll and carotenoid.	[27]
Leguminosae (chickpea)	1. Chickpea microgreens aid in weight management. 2. Fenugreek microgreens are rich in vitamin C, and A and also have various medicinal properties. 3. Alfalfa microgreens are a good source of unsaturated fatty acids such as linoleic and oleic acid.	[31] [34]

pre-packaged food provided to astronauts. The various health benefits associated with the consumption of microgreens are presented in table 1.

The intake of microgreens can help prevent malnutrition and other chronic diseases as they are densely packed with nutrients [28]. Microgreens contain carbohydrates in the form of soluble sugars and dietary fiber. The primary element found in microgreens is polyphenols, as an aglycone they make connections with carbohydrates (monosaccharides, oligosaccharides) to form glycosides. Likewise, they can also bind with other compounds like lipids, amines, phenols, organic acids, and carboxylic acids to form various essential biomolecules [35]. Kaempferol, quercetin, and apigenin are some derivatives of polyphenols that are responsible for maintaining gut integrity by modulating the gut microbiome.

Vitamin C, also known as ascorbic acid, is typically a water-soluble vitamin that is considered an antioxidant. Studies have reported that microgreens that belong to the Brassicaceae family (mustard, broccoli, and kale) contain vitamin C in ample amounts i.e., 31-56 mg/100 g. Thus, microgreens are helpful in maintaining the immune system and collagen synthesis. Gupta et al. [14] observed that the concentration of vitamin C changes during plant growth, for instance, it is low in sprouts, and baby greens as compared to microgreens. Moreover, growing media also affects the concentration of vitamin C as microgreens grown hydroponically have more vitamin C than those grown in soil. Furthermore, cardiovascular health can be improved by the intake of microgreens as they consist of various antioxidants, and glucosinolates [32]. The level of glucosinolates in red cabbage microgreens is higher (17.15 μmol/g) than in mature cabbage [15, 33].

β-carotene, also known as provitamin A, performs various physiological functions in the body such as growth, and acts as an antioxidant by preventing cellular damage. The highest concentration of β-carotene was found in red sorrel (12.1 mg/100 g), whereas golden pea and popcorn shoots had the lowest concentration 0.6 mg/100 g [36]. The concentration of β-carotene is 260 times higher in red cabbage (11.5 mg/100 g), and 3 times higher in cilantro (11.7 mg/100 g) as compared to the mature greens [37]. Broccoli microgreens are also a good source of minerals including potassium, phosphorous, magnesium, zinc, iron, calcium, sodium, and copper. As noted, yellow light exposure to broccoli and mizuna with a wavelength of 595 nm increases the amount of carbohydrates. It has been observed that during germination, there is an extensive breakdown of components present in seeds which results in the synthesis of various amino acids and other cellular components [38]. Phylloquinone present in microgreens shows immunosuppressive and anti-cancer effects, besides, they also help in maintaining healthy bone tissue and blood coagulation [38, 39]. The color of vegetables helps in assessing the presence of nutrients. For instance, vegetables that are dark green, and bright red, show a higher concentration of vitamin K whereas yellow vegetables contain a lower concentration [40]. Thus, the health benefits make microgreens a suitable contender to be utilized as a safe and functional food ingredient for maintaining the overall health and well-being of astronauts.

Conclusion

Exploration of microgreens holds great promise as a space food for astronauts. They are considered a viable option due to their exceptional nutrient density, short growth cycle, unique taste, and vibrant color. Also, they can be easily cultivated in confined spaces of spacecraft owing to their small size and minimal space requirement. Microgreens, which contain abundant amounts of vitamins, minerals, and antioxidants, are helpful in preventing space-induced health problems. Although they cannot be considered as a sole food due to their less caloric content, they can be best utilized as supplements for enhancing nutritional content and energy sources. During space missions, there are many challenges to address, and incorporating a microgreen shows overall success as it proves to be a promising avenue for fulfilling the objective and sustainability of future space missions. Ultimately, microgreens are the best solution for exploring them as space food as they are improving life quality even beyond the earth. Thus, it is a wise strategy for new frontiers as it unlocks the secret of healthy space food. All the complications in the space environment need to be understood not only for crew members' existence in spacecraft but also for plants due to their ability to provide oxygen and nutrients under a sustainable life support system in space.

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Conflict of Interest

None.

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