Review

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Cultivation of Vitamin C-Rich Vegetables for Space Radiation Mitigation

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Simple Summary: Space exploration introduces astronauts to many challenges such as space radiation and microgravity. We have investigated vitamin C as a potential radiation mitigator and antioxidants for sustaining astronaut health. Cultivation of vitamin C-rich vegetables, which austronauts can eat after the being exposed to sudden large solar particle events, could help mitigating acute radition illness.

Abstract: Space exploration introduces astronauts to many challenges such as space radiation and microgravity. Researchers have investigated vitamin C as a potential radiation mitigator and antioxidants for sustaining astronaut health. Building on our own studies, which indicate vitamin C's life-saving radioprotective effects and its potential as a radiation mitigator, our research highlights its promise, even when administered 24 h post-exposure. This is particularly relevant in scenarios where astronauts may be exposed to sudden large solar particle events, potentially resulting in lethal doses of space radiation. The success of vegetable cultivation on the International Space Station using NASA's Veggie system offers fresh, vitamin C-rich food. While approved supplements address somatic function, further research is needed to optimize vitamin C's efficacy in humans and develop antioxidant cocktails for space missions. The variable vitamin C content in vegetables underscores the necessity for utilization of artificial intelligence (AI) to assist astronauts in selecting and cultivating vitamin C-rich vegetables that are best suited to combat high levels of space radiation and microgravity. Particularly, AI algorithms can be utilized in analyzing various factors such as nutritional content, growth patterns, and cultivation methods. In conclusion, vitamin C shows significant potential for mitigating space radiation, and ongoing research aims to enhance astronaut health through optimal dietary strategies.

Keywords: radiation; C-vitamin; solar particle event; SPE; antioxidants; radiation mitigator

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1. Introduction

Space exploration poses unique challenges to astronauts, including exposure to space radiation and microgravity [1]. To mitigate the detrimental effects of these stressors, researchers have investigated the potential of vitamin C as a radiation mitigator and explored the use of antioxidants in maintaining astronaut health [2]. Studies on rodents have shown that vitamin C can reduce radiation-induced chromosomal damage. Additionally, experiments with rats exposed to gamma radiation have demonstrated improved survival rates and cell viability when treated with vitamin C [3]. NASA has successfully tested vegetable cultivation aboard the International Space Station (ISS) using the Veggie system, providing fresh food and dietary variety for astronauts [4]. While vegetables high in vitamin C offer health benefits, limited research exists on their efficacy in coping with space radiation and microgravity. Moreover, the vitamin C content of these vegetables can vary, highlighting the need for further investigation. Supplements regulating somatic function have been approved for reducing the effects of space radiation, microgravity, and the hypo-magnetic environment in space [5]. Our team's studies have indicated that vitamin C has emerged as a prospective radiation mitigator, even when administered 24 hours after radiation exposure [2]. This is particularly relevant in scenarios where astronauts may be exposed to sudden large solar particle events (SPE), potentially resulting in lethal doses of space radiation. Furthermore, the development of an antioxidant cocktail is being considered as a strategy to counteract damage caused by reactive oxygen species (ROS) during space exploration [6]. In conclusion, vitamin C shows promising results as a radiation mitigator, while antioxidants hold potential for protecting against space-induced stressors. Further research is warranted to determine the effectiveness of vitamin C in humans and to optimize antioxidant formulations for maintaining astronaut health during space missions.

Understanding the Challenges of Space Radiation and Microgravity

Space radiation, consisting of high-energy particles from the sun and cosmic sources, poses a formidable threat to astronauts' health. Prolonged exposure to space radiation can damage DNA and weaken the immune system, making astronauts more susceptible to illnesses [7]. Additionally, microgravity, experienced on spacecraft and space stations, can lead to muscle atrophy [8], bone density loss [9], and compromised cardiovascular function [10], etc. Finding effective countermeasures is therefore crucial for successful long-duration space missions.

Chemical Stability of Ascorbic Acid

Vitamin C is a sensitive compound that degrades when exposed to factors such as light, heat, oxygen, metal ions (Cu2+, Fe2+, Zn2+), and an alkaline pH. It can even denature at temperatures as low as 30 ° C, making it vulnerable during cooking. In a dry state, it remains stable, but in a solution, it rapidly oxidizes. To address this challenge, researchers are developing methods to encapsulate vitamin C for protection. Techniques like microfluidic, melt extrusion, spray drying, and chilling have been employed, primarily producing microscale particles. In specific conditions, nanoscale encapsulation can be achieved through ion gelation of chitosan or complex coacervation with anionic polymers. Low-molecular-weight bioactive compounds can also shield vitamin C by neutralizing factors causing degradation in the solution [11].

Protective role of vitamin C against ionizing and non-ionizing radiation

Over the past decade, Mortazavi et al. have conducted several studies on the protective role of vitamin C against ionizing and non-ionizing radiations. One study found that even high doses of vitamin C can show life-saving radioprotective effects [12]. Another study investigated the potential radiation mitigation effect of vitamin C and found that it can serve as an antioxidant to protect DNA damage caused by exposure to ionizing radiation [13]. They have also explored the possible applications of vitamin C in manned deep space missions, where it could be used as a radiation mitigator to protect astronauts from the harmful effects of radiation [13]. These studies suggest that

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vitamin C has potential as a promising radioprotective agent and could be useful in protecting against the harmful effects of radiation.

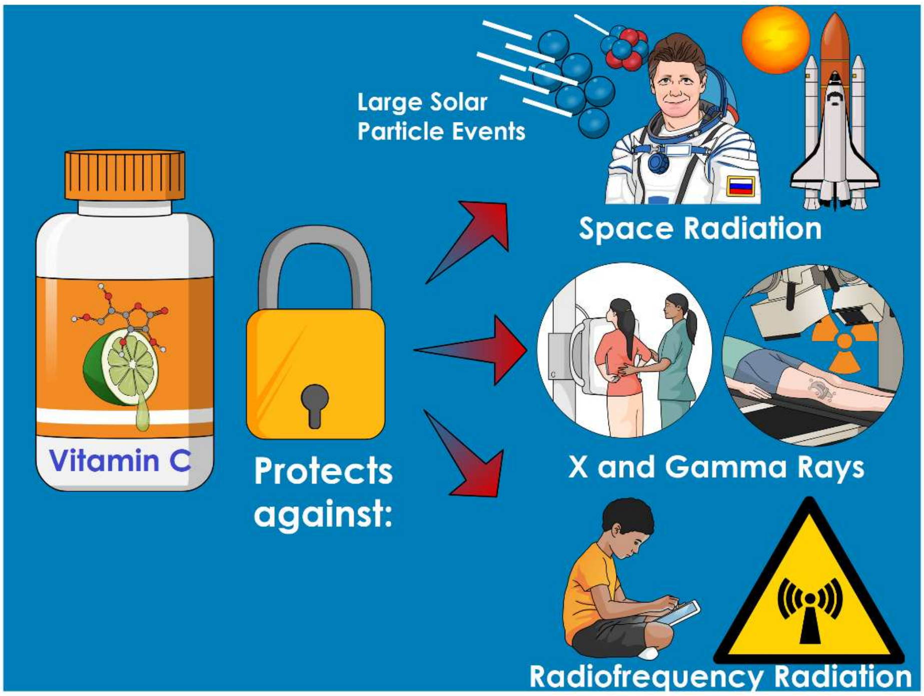

Figure 1. Protective role of vitamin C against both ionizing and non-ionizing radiationsis confirmed in several studies. Figure produced based on the reference [5,13,14].

Why do we need fresh sources of vitamin C in space?

When astronauts are in space, they tend to build up too many ROS because of the effects of microgravity and radiation. To counteract this, providing antioxidants could be beneficial in promoting astronaut well-being by reducing this occurrence [6]. Excessive increase in ROS levels may require the use of exogenous antioxidants like vitamin A, vitamin C, vitamin E, carotenoids, and polyphenols [15]. ROS can negatively impact a range of processes, including redox regulation, cell signaling, promotion of proliferation, immunity, apoptosis, autophagy, and necrosis [16].

It is known that space radiation can have an impact on the structure and function of various drugs, including but not limited to epinephrine. Space radiation can cause ionization and fragmentation of the molecules in drugs such as epinephrine, leading to changes in their chemical structure and potentially affecting their effectiveness. Some examples of other drugs that may be affected by space radiation include antibiotics, anticancer drugs, and painkillers [17]. The extent of the impact can vary depending on factors such as the specific drug and the duration and intensity of exposure to radiation [18]. Given this consideration, as scientists cannot fully protect drugs such as vitamin C from space radiation during long-term space missions such as Mars journeys or beyond, access to fresh and rich sources of vitamin C would be crucial.

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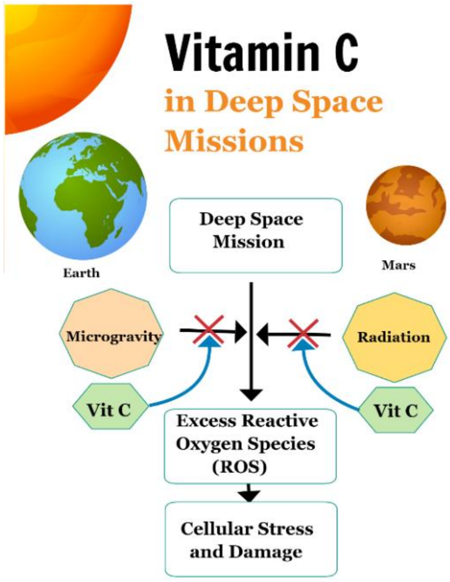

Figure 1. The accumulation of excess ROS in space by astronauts, caused by microgravity and radiation, can potentially be reduced by administering antioxidants such as vitamin C. This could potentially improve the health of astronauts. Figure produced based on the reference (6).

The history of microgreens for cultivation in space

While growing vegetables in space presents challenges, NASA has successfully tested growing a variety of vegetables aboard the ISS using Veggie [19]. Growing food in space has several benefits, including providing fresh food and variety in astronaut diets. NASA has been growing fresh vegetables on the ISS using the Veggie system since 2014 [20]. Astronauts have grown eight different types of leafy greens, including red and green romaine lettuce, Chinese cabbage, mustard, and Russian kale [21]. While consuming vegetables high in vitamin C can provide several health benefits, including immune system support [22], there is limited research on whether it can help astronauts better cope with the problems associated with space radiation and microgravity, the two key stressors in space environment. It is important to note that the vitamin C content of vegetables can vary depending on factors such as the variety, ripeness, and cooking method.

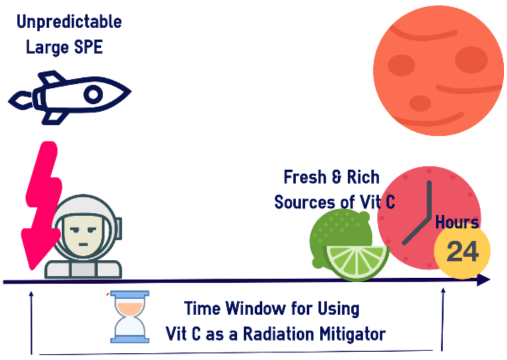

Figure 1. Time window for using Vitamin C as a Radiation Mitigator.

Astronauts aboard the ISS have been successfully cultivating kale and other vegetables as part of their ongoing efforts to sustain themselves during long-duration space missions. This

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groundbreaking initiative aims to provide fresh and nutritious food for the crew while also studying the potential for sustainable agriculture in space [23].

Inside the ISS, a designated area called the "Veggie Plant Growth System" has been set up to facilitate the growth of various plants. This system utilizes LED lights to provide the necessary light spectrum for photosynthesis, while a carefully controlled environment ensures optimal temperature, humidity, and nutrient levels [24].

Kale, a leafy green vegetable rich in vitamins and minerals, has been a popular choice for cultivation due to its hardiness and nutritional value [25]. The astronauts carefully tend to the plants, monitoring their growth and ensuring they receive the right amount of water and nutrients.

The benefits of cultivating vegetables in space are manifold. Firstly, it provides astronauts with a fresh food source, reducing their reliance on pre-packaged meals and increasing their overall well-being. Fresh produce not only improves the crew's morale but also contributes to their physical health by providing essential nutrients [26]. Moreover, growing plants in space has broader implications for future space exploration and colonization. It helps scientists understand the potential for sustainable agriculture in environments with limited resources, such as on other planets or in space habitats. By studying how plants adapt and thrive in microgravity, researchers can develop innovative techniques to support long-duration missions and establish self-sustaining colonies in space [27].

The cultivation of kale and other vegetables inside the ISS represents a significant milestone in the quest for sustainable space exploration. It showcases the ingenuity and resourcefulness of astronauts and scientists working together to overcome the challenges of living and thriving in the harsh environment of space. As we continue to push the boundaries of human exploration, the ability to grow fresh food in space will undoubtedly play a crucial role in our journey to the stars.

Why choosing the best microgreens for cultivation in space is a big challenge?

Microgreens are small, fast-growing crops that are valued for their color, flavor-enhancing properties, and rich phytonutrient content. A recent study has focuses on the selection of microgreens for cultivation in space [28]. The researchers developed an algorithm to compare different genotypes of microgreens based on various parameters related to growth, phytonutrients, and mineral elements. The selection process consisted of two phases. In the first phase, the researchers used literature data to generate a ranking list of microgreens. This list was based on 25 parameters, including growth characteristics and the presence of phytonutrients such as tocopherol, phylloquinone, ascorbic acid, polyphenols, lutein, carotenoids, and violaxanthin. In the second phase, germination and cultivation tests were conducted on the top six species identified in the first ranking list. Based on the results, radish and savoy cabbage were ranked highest in terms of productivity and phytonutrient profile. The algorithm and selection method used in this study provide an objective way to compare and rank candidate species for cultivation in space. This approach can also be adapted for new species or specific selection purposes by modifying the parameters or prioritization criteria [28].

Why do astronauts need biological protection against space radiation?

The occurrence of a large SPE that leads to exposure of astronauts to lethal doses of space radiation is considered to be a low probability event [29]. However, it is important to note that space radiation and its effects are still areas of active research, and our understanding of them continues to evolve.

SPE are caused by the release of highly energetic particles, primarily protons and occasionally heavier ions, from the Sun during solar flares or coronal mass ejections. These particles can pose a significant radiation hazard to astronauts and can penetrate spacecraft shielding, potentially exposing astronauts to elevated radiation levels [29].

While SPEs can be detected and monitored, accurately predicting their occurrence and magnitude with a high degree of certainty is challenging. However, advances in space weather forecasting have improved our ability to provide early warnings of potential SPEs. Monitoring

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systems on spacecraft and satellites, as well as ground-based observatories, continuously observe the Sun and its activity to detect and track solar events that could lead to SPEs [30].

The magnitude of an SPE refers to the intensity of the particle flux, which is the number of particles per unit area per unit time. The magnitude of an SPE can vary significantly, ranging from minor events with relatively low particle fluxes to major events with high particle fluxes. Predicting the exact magnitude of an SPE is also challenging, as it depends on various factors, including the energy and direction of the particles emitted during the solar event and the characteristics of the interplanetary space through which these particles travel [31].

To mitigate the risks associated with SPEs, space agencies employ measures such as active monitoring, early warning systems, and spacecraft shielding. Astronauts are also provided with dosimeters to monitor their radiation exposure during space missions. Additionally, mission planners aim to schedule extravehicular activities (EVAs) and critical operations during periods of lower solar activity to minimize the potential for high radiation exposure [32]. Therefore, while SPEs can pose a risk to astronauts in space, the space agencies and researchers are actively working to improve our understanding, monitoring capabilities, and mitigation strategies to ensure astronaut safety.

Why diet extremely matters in space

As humans venture farther into the cosmos, it becomes increasingly important to address the physiological challenges associated with extended space missions. Among these challenges, the impact of space radiation and microgravity on human health has emerged as a significant concern [33]. Researchers and space agencies are exploring innovative strategies to mitigate these effects and improve astronauts' resilience. One such approach involves harnessing the power of artificial intelligence to guide the selection and cultivation of vitamin C-rich vegetables, offering a promising solution to bolstering astronaut health.

In the quest for extended space missions and interplanetary travel, ensuring the health and well-being of astronauts is paramount. One of the key challenges faced by astronauts in space is the detrimental impact of high levels of space radiation and microgravity on their overall health, particularly their immune systems [34]. To counteract these effects, researchers are turning to artificial intelligence (AI) to assist astronauts in selecting and cultivating vitamin C-rich vegetables. This innovative approach not only contributes to better resistance against the harsh space environment but also enhances the nutritional quality of astronauts' diets.

The Role of Vitamin C in Astronaut Health

Vitamin C, renowned for its antioxidant properties and immune-boosting effects, plays a pivotal role in maintaining astronaut health. Adequate vitamin C intake can help mitigate oxidative stress caused by space radiation and enhance the body's ability to repair DNA damage. Furthermore, vitamin C supports collagen production, critical for maintaining healthy skin, blood vessels, and connective tissues, which are susceptible to deterioration in microgravity conditions [6].

Rich sources of Vitamin C

Radish [35] and savoy cabbage [36] are indeed good sources of vitamin C, but they may not be considered the richest fresh vegetables in terms of vitamin C content. While radishes and savoy cabbage contain moderate amounts of vitamin C, there are several other vegetables that are higher in this nutrient. For instance, bell peppers (particularly red and yellow varieties), kale, broccoli, Brussels sprouts, and cauliflower are generally recognized as vegetables with higher vitamin C content compared to radishes and savoy cabbage [37]. Citrus fruits like oranges and grapefruits are also well-known for their high vitamin C content [38]. It's worth noting that the vitamin C content can vary depending on factors such as the vegetable's freshness, growing conditions [39], and storage methods [40]. To maximize the vitamin C content in vegetables, it's recommended to consume them when they are fresh and not overcook them, as vitamin C is sensitive to heat and can be lost during cooking [41].

Our experience on Vitamin C as a mitigator of Space Radiation

Vitamin C has been proposed as a potential radiation mitigator for astronauts exposed to space radiation. Studies have shown that vitamin C can decrease radiation-induced chromosomal damage in rodents, but further investigation is needed to determine its effectiveness in humans [3]. In one study, rats treated with a single dose of vitamin C up to 24 hours after exposure to gamma radiation showed improved survival rates and cell viability [2]. Simulated microgravity, which is experienced during spaceflight, has been found to increase heavy ion radiation-induced cell apoptosis in human B lymphoblasts. However, antioxidants such as N-acetyl cysteine (NAC) and quercetin have been shown to reverse this effect, suggesting their potential as protective agents for astronauts [42]. Developing an antioxidant cocktail to prevent or mitigate reactive oxygen species (ROS) damage during space exploration is also being considered as a strategy to maintain astronaut health [6].

Based on this background, supplements that benefit regulating the somatic function have been approved to reduce the influence caused by cosmic radiation, microgravity, and hypo-magnetic environment in space [5]. Vitamin C is a prospective safe and available radiation mitigator several hours after exposure to radiation [2,43] Recently, vitamin C has also been reported to have a role as radioprotector [2,44,45], thus in a space mission context, can help neutralizing free radicals and protecting cells from damage induced by ionizing radiation [6].

Conclusion

Vitamin C emerges as a promising candidate for mitigating space radiation's effects, offering potential benefits even when administered after exposure. The success of vegetable cultivation on the ISS indicates the feasibility of providing fresh, vitamin C-rich food for astronauts. However, challenges like the variable vitamin C content in vegetables and the need for stable formulations in space conditions persist. The protective role of vitamin C against both ionizing and non-ionizing radiations underscores its significance in safeguarding astronaut health. As researchers explore the potential of microgreens for space cultivation, selecting optimal varieties becomes critical. Integrating artificial intelligence in vegetable selection and cultivation may enhance astronaut diets and resilience. While the threat of Solar Particle Events remains, ongoing advancements in monitoring and mitigation strategies demonstrate a commitment to astronaut safety. As we venture into extended space missions, understanding the crucial role of vitamin C and maintaining a balanced diet becomes imperative for astronaut health and well-being.

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