

Review

Challenges for a Sustainable Food Production System on Board of the International Space Station: A Technical Review

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Abstract: The possibility of prolonging space missions—and consequently the permanence of humans in space—depends on the possibility of providing them with an adequate supply of fresh foods to meet their nutritional requirements. This would allow space travelers to mitigate health risks associated with exposure to space radiation, microgravity and psychological stress. In this review, we attempt to critically summarize existing studies with the aim of suggesting possible solutions to overcome the challenges to develop a bio-regenerative life support system (BLSS) that can contribute to life support, supplying food and O_2 , while removing CO_2 on the International Space Station (ISS). We describe the physical constraints and energy requirements for ISS farming in relation to space and energy resources, the problems related to lighting systems and criteria for selecting plants suitable for farming in space and microgravity. Clearly, the dimensions of a growth hardware that can be placed on ISS do not allow to produce enough fresh food to supplement the stored, packaged diet of astronauts; however, experimentation on ISS is pivotal for implementing plant growth systems and paves the way for the next long-duration space missions, including those in cis-lunar space and to the lunar surface.

Keywords: space farming; light-emitting diodes (LED); microgravity; bio- regenerative life support systems (BLSS); physical constrains; solar energy; photovoltaic cell modules; candidate crops; nutrient delivery system; VEGGIE

1. Introduction

"Space food" has been attracting discussions since 1926, when the Russian scientist Konstantin Tsiolkovsky wrote his "Plan of Space Exploration", a map for the colonization of the universe in 16 stages, in which he hypothesized the use of solar radiation to grow food in space [1]. Subsequently, Willy Ley in 1948 and Jack Myers and colleagues during the 1950s [2] understood that growing plants during long space travel would have been an alternative, not only to supply food but also oxygen. The first plants grown in space were leeks, onions and Chinese cabbage on board of Salyut 1 in the Oasis 1 device in 1971, while the first plants grown and eaten in space were onions in 1975 by cosmonauts Klimuk and Sevastianov, as detailed in Zabel et al. [3]. Notwithstanding, even nowadays, astronauts eat primarily freeze-dried or canned foods, since bringing or producing fresh food under space conditions is challenging for a variety of reasons [4,5]. A major concern for ISS astronauts



is that they cannot have a refrigerator on board to keep fresh food, because there is no room for it [6,7]. Moreover, due to the narrow spaces on the ISS, food could be stored in lockers close to electrical equipment, with temperatures even higher than the controlled ones of 21–23 °C reported by Thirsk et al. [8]. Consequently, fruits and vegetables can have only a very short post-harvest shelf-life and must be eaten in the first days/week of flight. Such constraints may force astronauts on ISS to eat dried food for months, with likely health and performance consequences during and after space flight, like weight loss, cytotoxic oxidative stress, impaired eye health and alterations of the central nervous system [3,7,9,10], despite the availability of fruit juices or dried fruits and multivitamin pharmaceutical products. Indeed, essential nutrients for humans are deficient in processed and prepackaged space foods (e.g., potassium, calcium, vitamin D and vitamin K) or they are more unstable, rapidly degrading during long-term missions (e.g., vitamins A, C, B_1 and B_6) [7,11,12]. Therefore, to supplement the diet of astronauts, ISS must receive supplies of fresh food by un-crewed cargo spaceflights like US Dragon and Cygnus and Russian Progress supply ships, which raises the costs of space missions [13]. However, for very long journeys packing or supplying enough food may not be a viable option. In fact, for a hypothetical human mission to Mars, where the average distance from Earth is approximately 225 million km, such a trip may take almost eight months. Adding the time spent on Mars and the return journey, the entire short stay mission could last at least 1.5 years, while long surface stays could last up to three years [14]. Hence, plant production in a fully functional space greenhouse is the only option able to provide fresh food to space travelers. This would guaranty them to be self-sufficient and having a proper dietary intake for months/years for short-duration missions, like low earth orbit (LEO), cis-lunar or lunar surface missions, as well as for long-duration and distance exploration missions, like missions to Mars [3,4,14–16]. Several environmental control and life-support systems (ECLSSs) were designed and tested for sustainable plant production in space [17] in order to provide the necessary food sources overcoming the need to rely on space cargos' resupply from Earth [14] and ensuring human survival during long-term space exploration [17]. Their main idea is to consider wastewater and CO_2 -rich cabin air as a resource for plant cultivation rather than wastes [18,19]. In fact, plant growth systems can be used to recycle exhaled CO_2 producing O_2 through the photosynthetic process, and to purify wastewater through its uptake and transpiration of water vapor that can be condensed in pure water [15,16,20–22]. Currently on the ISS, regenerative physico-chemical systems are used to recycle water and CO₂. Multi-filtration and vapor compression distillation (VCD) recycle water that is also used for water electrolysis to produce O_2 and H_2 [23]. O_2 is used for cabin air, while H_2 is used in the Sabatier reactor. CO_2 is removed from the cabin by a 4-bed molecular sieve (4BMS) carbon dioxide removal assembly (CDRA), and it is used together with H_2 for the Sabatier reaction as follows $4H_2$ + $CO_2 \rightarrow CH_4 + 2H_2O$ [24,25]. In this system however, there are some drawbacks. Apart from the low efficiency of the water electrolysis process that can supply only a portion of the required O_2 by the crew, the CDRA generates dust that contaminates the equipment on ISS and increases the pressure in the packed beds of 4BMS. In addition, a large amount of energy is required for recycling the CO_2 absorbent material [26].

At present, research programs such as MELiSSA (micro-ecological life support system alternative) aim to create space growth chambers to contribute to astronauts' life support, through the supply of water, air and food for long space travels [16,21]. In this view, ground-based facilities for simulation of microgravity are valuable and cost-efficient systems for assessing space farming. However, true responses of plant crops to real microgravity and limited resources can be accurately measured only in real conditions. Therefore, experimentations on the ISS over the next few years may effectively help us understand how to reduce and/or overcome problems related to the impact of microgravity and the use efficiency of space and resources. In addition, it may be pivotal to validate all the experimentations carried out in ground-based simulators [27,28]. Indeed, ISS will only work for another eight years and there is little possibility of including a larger growth hardware in it. However, experiments conducted on ISS for implementing plant growth systems can provide the critical knowledge for the next long duration space missions including those in cis-lunar space and on lunar surface [29,30].

2. Physical Constraints and Energy Requirements for ISS Farming

Since ISS has an orbit with a height about 400 km above the Earth surface and a period around 90 min, it is somewhat protected from solar particles. Still, ISS can be exposed to high amounts of gamma rays, cosmic rays and other damaging radiation [31]. In case of danger, radiation monitors on ISS can reveal their increase (e.g., in case of solar storms), and the astronauts can stay for some time in strongly shielded sections of the ISS [27,32]. The BLSS may be not protected by these events and cultivated crops may be exposed to such solar flares. However, not all solar storms are strong enough to be dangerous and require this precaution, and/or directed towards the Earth/ISS [33]. Therefore, the main problems to cope with on ISS plant growth systems, can be related to limited resources and volume/space, microgravity, energy consumption, heat transfer and crew time associated with their maintenance [34–37].

The station is exposed directly to the sun for around 55 min, and is in the shadow for the remaining time exposed to the deep space, a blackbody at 3 K. Thus, the ISS external surface temperatures can vary between -120 °C (when in the dark) and +120 °C (when in sunlight) [37].

The electrical energy demands aboard for flight systems, life systems and all the experimental setups, are provided using solar energy captured by photovoltaic cell modules (PV). The four set of solar arrays cover an area of about 2500 square meters and produce 84–120 kW for the ISS [38]. The PV system can provide more electricity than ISS needs to maintain its systems and experiments, whose energy demand is around 75–90 kW [39], of which around 50 kW are for essential payload operations and 24 kW for research operations [40]. Therefore, in the period of light, some of the electricity generated by the PV is used to recharge the lithium-ion batteries of the ISS, while when the station is in the shadow period, the energy of the batteries is used [41].

The spectral distribution of solar irradiance outside the atmosphere (Air Mass Zero or AM0), given by a curve resembling that of a blackbody at 5800 K, and on the Earth's surface (Air Mass 1.5 or AM1.5) [42], produces the results reported by the blue and red curve of Figure 1, respectively.



Figure 1. Spectral distribution of sun energy at AM0 and AM1.5.

Therefore, AM1.5 is the reduced power of sunlight as it passes through the atmosphere, while, outside the atmosphere, AM0 represents the sunlight when essentially non attenuated. Since ISS is 400 km above the Earth surface, the total average annual solar irradiance at AM0 is around 1370 Wm^{-2} .

PV cells are semiconductor devices mainly made of silicon atoms Si. Si atoms are doped with gallium (Ga) or phosphorous (P) to arrange a p-n junction, which separates the electrons and the hole

carriers. When sufficient solar energy is absorbed by the PV cells, the electrons and the hole carriers start flowing in opposite directions producing electric current [43].

The typical electrical characteristics of a PV cell are displayed in Figure 2, where the usual curve, current–voltage (I–V) and power–voltage (P–V) are shown.



Figure 2. Electrical characteristics current–voltage (I–V) and power–voltage (P–V) of a Si cell. Modified from [44].

Efficiency of PV cells is defined as the fraction of incident power converted to electricity and is measured as:

$$\eta_{cell} = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{IA_{cell}} \tag{1}$$

where *I* is the irradiance on the PV surface, P_{out} the critical power generated by the cell and A_{cell} the surface area of the cell. PV cells employed on the Earth can attain efficiency values at most around 20% [45].

Since the environment in space differs from that on Earth as far as the solar spectrum (AM0), the absence of atmosphere and the presence of very low temperatures not compatible with Earth conditions, different PV cells have been developed for their use in space [46]. In particular, multi-junction (MJ) solar cells are employed, and they are made of several sub-cells stacked on top of each other, as reported in Figure 3.



Figure 3. Sketch section of a triple-junction solar cell made of GaInP/GaAs/Ge.

The MJ cells made of gallium arsenide and similar materials resist degradation better than silicon and are the most efficient cells, with energy conversion efficiencies up to 40% [47,48].

In order to understand if the energy delivered by PV cells may be sufficient to support a space farm on ISS, VEGGIE was considered; a deployable plant growth system developed by Orbital Technologies Corporation (now Sierra Nevada Corporation, SNC, Madison, WI, USA) [49,50]. It is conceived as a modular low mass and low energy unit, with the possibility to grow different horticultural crops as well as flowers designed for the International Space Station (ISS) (Massa et al. 2017). Its peculiarity is being the first plant growth system designed for producing food and not only for microgravity plant growth experiments. VEGGIE thermal control is provided from an ISS in-cabin system and the carbon dioxide source is the ambient air aboard ISS, while the light is provided by LEDs. The system consumes no more than 90 W of power and its LEDs can support adjustable wavelengths, light levels and day and night cycles to match the biologic needs of the plants [51]. Initially, during plant germination the energy required is low, then the requirement of energy grows. However, electrical energy consumption required by VEGGIE is very low compared with the power that the PV solar array of the ISS can supply, so even if the number of VEGGIEs increases (space wise not feasible), the management of power supply may be not a major concern on the ISS, since as specified above, the energy demand on the ISS is on average lower than the energy supply [48].

Thus, the temporal availability of electrical power on ISS may allow the operation of a growth chamber more energy consuming than a VEGGIE unit and up to 1 kW, or even more, if there would be sufficient room for it. For this reason, numerical simulations should be carried out to evaluate the balance among the electrical energy supplied by the PV arrays that largely varies during the orbit around the Earth, the ion-lithium battery capacities during the excess production period and its power during the discharge period, the energy demand of VEGGIE and the ISS as a function of the time.

3. Light Sources for Space Farming on ISS

Light conditions (photoperiod, intensity and spectral quality) and its use efficiency, are among the most important factors determining plant growth and development. Since space is a limited resource on ISS, there is no room for spare lamps. Cold and long-lasting light sources, like light emitting diodes (LEDs), are actually considered the best option for BLSS growth facilities [52,53]. There are solid state lights that are difficult to damage with physical shocks and resistant to extreme temperature changes than fluorescent lamps; for this reason, they are also easily integrated into digital control systems. Instead, fluorescent bulbs are particularly fragile; more important, since they contain hazardous materials like mercury (about 4 mg), they require special handling and disposal when broken [54]. LEDs can be regulated using, if necessary, from 100% of the light to 0.5%, through LED dimming functions by either lowering the forward current or modulating the pulse duration [55–57].

Many experiments have demonstrated the feasibility of growing different species/cultivars of plant crops under LEDs in BLSS [52] Currently, the VEGGIE flight hardware light cap includes red (630 nm), blue, (455 nm) and green (530 nm) LEDs [53]. Instead, fluorescent lighting systems produce primarily UV radiation, and then thanks to the fact that the bulb is coated with a layer of phosphor, the UV radiation in contact with phosphor glows, emitting visible light. Fluorescent lamps spectral quality mainly reflects the needs of plants in terms of photosynthesis and photomorphogenesis [58,59]. In Figure 4, the spectral output of commercial fluorescent and LED lamps vs. that of sunlight are presented.

However, fluorescent lamps loose at least 15% of the emissions due to energy dissipation and heat; in particular, they emit heat that is absorbed by the ballast and/or lost to the environment. Moreover, although most of the UV radiation remains in the bulb, the ones that escape into the environment can be potentially dangerous. Fluorescent lamps are still used in the Lada plant chamber housed in the Russian module of the ISS, which provides about 0.034 m² of growing area with fluorescent lighting. The growth chamber is open to the cabin atmosphere and uses cabin air to maintain canopy ventilation and to cool the light bank [3,54,60]. In five experimental cultivations carried out from March 2003 to

April 2005 in the Lada chamber on ISS, Line 131 dwarf pea plants were grown over the full ontogenetic cycle (from seed to seed), showing no differences with ground control plants and maintaining their capability to yield viable seeds [61].



Figure 4. Spectral output of sunlight vs. different artificial lighting systems. Modified from [59].

The LADA light bank may be outfitted also with LEDs [62,63]. LEDs produce significantly less heat than conventional gas discharge lights, and do not produce or emit UV [59,64]. LEDs source efficiency ranges between 0.62 and 2 μ mol J⁻¹, with an effective average value that gets the target area at 0.83 μ mol J⁻¹. Fluorescent lights (including compact fluorescent lights) are considered comparable to LEDs (0.83–1.67 μ mol J⁻¹ source efficiency). However, while fluorescent lights emit light over 360 degrees (omnidirectional output around the bulb/lamp) loosing light that must be redirected to the target area, LEDs, emitting over 180 degrees, are directly orientated over the target area [65].

Xin et al. [66] grew lettuce plants (cv. Ziwei) under 150, 200, 250 and 300 μ mol m⁻² s⁻¹ provided by fluorescent lamps with a R:B of 1.8 and LED lamps with a R:B of 1.2 and 2.2, in combination with photoperiods of 12 h and 16 h. No differences in leaf fresh weight (FW), nitrate, soluble sugars and ascorbic acid were found between plants grown under 250 and 300 μ mol m⁻² s⁻¹ with photoperiod of 16 h, regardless of light quality. Net photosynthetic rate of lettuce leaves before harvest, was higher in plants grown under 250 μ mol m⁻² s⁻¹ than that under 300 μ mol m⁻² s⁻¹. They concluded, according to the results concerning growth, photosynthesis, quality and energy consumption, that LED light of 250 μ mol m⁻² s⁻¹ with a photoperiod of 16 h and a R:B of 2.2, was the best condition for maximum growth and high quality of lettuce plants under indoor controlled environment. Accordingly, Dueck et al. [4] underlined that the same attention paid to light intensity should be paid to light spectrum, because a light source with the proper spectrum can influence the production of secondary metabolites like phenolic compounds, ascorbic acid and anthocyanins and growth performance.

For this reason, if necessary, the narrow spectra of LEDs may be conveniently widened using different phosphor blends, which allow to add any light spectrum in the visible range, in addition to ultraviolet and infrared radiations [67]. The green leaves of plants typically contain high levels of β -carotene and lutein, but usually very low levels of zeaxanthin, which together with the other two carotenoids, are essential for vision, protectors against age-related blindness (age-related macular degeneration, AMD) and other eye chronic diseases like cataracts, knowing that the latter's risk is increased by low space radiations [31]. Extreme conditions like cool temperature and very high light

trigger strong retention of zeaxanthin in green leaves, together with growth retardation [68]. These are the conditions to consider in order to enrich the nutraceutical content of leafy vegetables in BLSS [69].

However, some plants like spinach, tomato, pepper and cucumber require higher light intensities ranging between 300 and 600 μ mol m⁻² s⁻¹. A major problem of LED systems, is that even if the voltages are increased above 3.5 V, the emission intensity remains quite constant, independently of the applied voltage [70]. It is due to the fact that other light systems follow the Ohm's law and have an increase of current proportional to that of voltage as long as the resistor's value stays the same, whereas LEDs behave as a diode with a characteristic I–V curve [71].

Few years ago, the LED lamp YUJILEDS[®] VTC series full spectrum, with phosphor coating producing white light that is highly like sunlight, was produced by Yuji LED. It uses a blue light for exciting the phosphor and producing white light similarly to how fluorescent bulbs function. However, even if it almost overlaps the total solar spectrum, it does not guarantee an excellent performance because the system procuring white light decreases its efficiency. In fact, when blue light is converted to other colors, part of the energy is lost in the conversion process [72]. Thus, these white phosphor coating LEDs produce less light than traditional LEDs. However, the same company has just completed the evaluation of the NEW Sunlight LED AP(Apollo)-2835 @ 5600 K with ultra-smooth spectrum by using 420 nm blue chip. It is a new full-spectrum LED able to fill all spectral gaps of the YUJILEDS[®] VTC series full spectrum enhancing the radiant power at 420 nm. Moreover, it will have an efficacy of 100 lm/W (Figure 5). Some experiments are ongoing to check the efficiency of these full spectrum LEDs on plant growth (F. Apelt unpublished results).





4. Criteria for the Selection of Potential Candidate Crops for ISS Farming

When designing a food production system for ISS, the selection criteria for choosing the crop or species/cultivars candidates to grow, is a very important matter. Various species such as cereals, fruits, tubers and leafy vegetables have been tested as potential candidates for food production in space [19]. The main selection criteria for these species were their adaptability based on environmental constraints; therefore, plant size, light requirements, harvest index, as well as nutritional value are considered fundamental aspects for the crop selection [1,4,5,21,73]. However, as reported by Wheeler [19] and Dueck et al. [4], an appropriate choice of crops to be grown in space can not only serve for producing nourishing foods, but also biologically active components that deliver benefits beyond basic nutrition, particularly related to health promotion, disease prevention and psychological health.

As early as 1962, during a symposium held at Wright Patterson Air Force Base, thinking of specific criteria like the need of low light intensities, compact size, high productivity and tolerance to osmotic stress, some species were selected as suitable for space farming. They included lettuce,

Chinese cabbage, cabbage, cauliflower, kale, turnip, Swiss chard, endive, dandelion, radish, New Zealand spinach, tampala and sweet potato [74]. However, only starting from 1965 BIOS projects in Krasnoyarsk Siberia and from 1980 NASA's Controlled Ecological Life Support (CELSS) and Advanced Life Support (ALS) Program activities, focused on studying higher plant crops for life support in space programs. In the test of Biosphere 2 for food production from 1991 to 1993, crops like rice, sweet potato and beets were found growing well in this system [75]. However, in the following years it has become clear that plant species suitable for space farming should have had particular features, in particular being dwarf species, with a high harvest index, high light use efficiency (LUE) and water use efficiency (WUE), short growing cycle, high plant density and high nutritional values, like dwarf wheat, soybean, potato, rice, sweet potato, lettuce and peanut [1,21,76], with a particular preference for vegetables

The dwarf wheat USU-Apogee was selected for cultivation in space systems, after a 12-year selection over a thousand of wheat genotypes, by hybridization and breeding by Bugbee and Koerner [78]. It was grown in the Bulgarian/Russian growth chamber Svet on the space station Mir through two generations and—although the seed yield was low—the seeds were viable [79,80]. However, the production of wheat, just like other staple crops, is more cost effective for near term future missions and it will be probably adopted in Lunar and Martian greenhouse modules for long-duration exploration missions and not likely on ISS [76,81,82].

requiring little or no preparation, i.e., ready to eat [4,5,77].

The high nutritional values (proteins, vitamins, minerals, phenolics etc.) and fast growth rates (5–7 days) make herbaceous crop sprouts, like soybean, alfalfa, broccoli and rocket (*Eruca sativa* Mill.), an interesting opportunity to offer high-quality fresh food to astronauts [73], even if as negative trait, they have a very high oxygen consumption until the expansion of true leaves [83]. In particular, Rivera et al. [84] showed that simulated microgravity (ASI project 'Morphologic and Physiological response of seedlings to a low-gravity environment') increased the content of phytochemicals (e.g., carotenoids, chlorophyll, ascorbic acid) and dry mass in rocket seedlings. However, Colla et al. [73] showed that real microgravity conditions (ENEIDE mission—SEEDLINGS project on the International Space Station, ISS) affected the chlorophyll, triglycerides and carotenoids content of rocket seedlings, probably also due to a very low light intensity (50 µmol m⁻² s⁻¹) that negatively affected photosynthesis. As evidenced by De Micco et al. [83], microgravity may affect rocket germination, it caused only some degree of negative gravitropism in a small number of roots on Earth-grown and space-grown seedlings [85] and thinner seedlings with closed cotyledons in space-grown seedlings [73], but no morphologic anomalies [84].

In an experiment conducted with the same growth system as the one used by Rivera et al. [84], which is a clinorotation plus Porous Tube Plant Nutrient Delivery System (PTPNDS), Colla et al. [85] showed that Micro-Tom dwarf tomato plants were negatively affected by microgravity, which reduced nutrient assimilation and therefore plant growth, yield and fruit quality parameters. However, they succeeded in completing ontogenesis with no loss in pollen fertility with only limited effects on the new seeds germination. This experiment proved that while ontogenesis depended on environmental constraints imposed by microgravity, plant sexual reproduction did not depend on it [83].

In all crop lists suggested or studied for life support systems [1,4,21,76], and in several experiments [12,35,69,84,86,87], lettuce has been considered as a good model crop for space cultivation. Mainly, because it is an edible model crop characterized by high harvest index, low water uptake/transpiration ratio, light/energy use efficiency, short growing cycle, valuable qualitative aspects and little crew attention to be grown [4,5]. However, during a 40-day experiment carried out in the frame of the ASI Space Green House Project, Rivera et al. [84] found a great yield variability among lettuce cultivars under simulated microgravity obtained with a horizontal uniaxial clinostat and PTPNDS, suggesting the importance of a careful selection not only of the species, but also of the genotype/cultivar [21] for space farming. Clinorotation affected weight, shoot:root ratio and qualitative parameters (chlorophyll, total carbohydrates and ascorbic acid) of lettuce plants, but to a lesser extent in the cultivar 'Mortadella di primavera', which was suggested as the most suitable for space farming.

The different amounts of bioactive compounds can also vary among lettuce genotypes according to pigmentation [69]. In addition, El-Nakhel et al. [87] found that the red Salanova salad cultured in a closed soilless system (nutrient film technique) exhibited at harvest a 22% higher biomass, 2-fold higher amounts of lipophilic antioxidant activity and total phenols and 6-fold higher total ascorbic acid levels than green Salanova. These features allow red Salanova to cope better with oxidative stress improving the efficiency of photosynthesis and yield compared to green Salanova and to deliver higher amounts of natural antioxidants for human diet on BLSS.

In a review of Kyriacou et al. [5], it was suggested that microgreens are optimal candidates for BLSS for their color, flavor and richer phytonutrient content compared to their mature-leaf counterparts. In particular, the coloring pigments (i.e., carotenoids, phenols, anthocyanins and betalains) can be considered as an indicator of the antioxidant properties of edible plants, where red and dark green colored leafy vegetables are richer in antioxidant metabolites than lighter colored vegetables [88,89]. Albeit microgreens have a very short growth cycle of 1–3 weeks, they contain higher levels of ascorbic acid, β -carotene, α -tocopherol, phylloquinone, minerals (Ca, Mg, Fe, Mn, Zn, Se and Mo) and lower levels of the antinutrient nitrate [90,91].

Rouphael et al. [35] studied six lettuce cultivars (baby Romaine, green Salanova, Lollo verde, Lollo rossa, red oak leaf and red Salanova) of different types and pigmentations under optimal and suboptimal light intensity in order to identify the most promising salad crop candidates for BLSSs. Under suboptimal light intensity, baby Romaine was able to use light more efficiently (i.e., higher light use efficiency) and grow better than the rest of the tested cultivars demonstrating a more efficient light-harvesting mechanism, while red oak leaf showed the highest content in chicoric acid and total hydroxycinnamic acids. On the contrary, red butterhead Salanova exhibited the highest hydroxycinnamic derivatives profile under optimal light conditions. These experiments proved that cultivation of assorted lettuce cultivars should be the preferred system for space farming.

Moreover, as evidenced in EDEN ISS project [3,77], species like red mustard and chives, although producing relatively small amounts of biomass, have important qualities like short growth, spicy and pungent taste that must be taken into account when choosing crops for fresh food aboard the ISS because of the reported inhibited sense of smell in space missions [92].

Finally, Khodadad et al. [12] have recently reported VEGGIE tests on ISS in order to evaluate leafy greens microbial safety. Next Generation Sequencing (NGS) technology was used to characterize the microbiome (bacteria and fungi) and/or screening for specific pathogens in three different plantings of red romaine lettuce cv. Outredgeous. The diverse microbial communities were identified as potentially non-pathogenic to humans, proving that leafy greens cultured on-board can provide a safe supplement to the diet of astronauts.

5. Hydroponics for Space Farming on ISS

Reduced gravity and microgravity affect water and nutrients delivery to plants, being critical in particular for root functions and growth. The main effect of microgravity is a reduction in gravitational body forces, which decreases buoyancy-driven flows, rates of sedimentation and hydrostatic pressure. This determines a strong increase of surface tension that becomes predominant.

The reduced diffusion of waste products and CO₂ away from the cell caused by the absence of convection, may be also responsible for deleterious changes in pH with serious effects on cell metabolism [93]. Moreover, under microgravity, the lack of natural convection determines thicker boundary layers around plants leaves that reduce water vapor transpiration, as well as gas exchanges and heat transfer, further decreasing root water and nutrients uptake [34,94,95].

Thus, an irrigation and nutrient delivery system (NDS) effective in microgravity must be able to supply water, nutrients and air to roots in adequate quantities, as well as to act as a support for the various stages of plant growth, within the operational and safety constraints of a spacecraft [94,96]. For this aim, different rooting material and soils or hydroponic systems alternative to traditional ones have been considered in several experiments.

Considering the need of well-aerated and watered root zones to allow root respiration and the need to minimize moderately the solution volume to avoid the increase of the solution temperature, Monje et al. [33] proposed to use instead of aeroponic or hydroponic systems a substrate-based NDS system constituted by a 1–2 mm arcillite/Osmocote mix. Osmocote fertilizer, manufactured by Scotts company, is constituted by round resin-coated pellets containing encapsulated nutrients, which are released gradually during plant watering, avoiding the problem of astronauts to check the effective mixing of fresh nutrient or the recirculation of the nutrient solution. The choice of using 1–2 mm grain sizes derived from the consideration that a small-grained soil (0.5 mm) enabled good water distribution in the root zone, but prevented air to flow, while a grain soil larger than 2 mm (2–5 mm) enabled proper aeration, but may cause water to scatter or air to fill empty spaces between grains causing a reduced root hydration [97].

The basic system for the use of arcillite was first developed in the Astroculture series of tests for the Space Shuttle and the MiR Svet chamber by Morrow et al. [98]. Arcillite with a diameter of 1.5–3 mm was used as an inorganic rooting matrix for embedding porous stainless-steel tubes [98]. The experiments demonstrated that the water transfer rate mainly depended on the tubes pore size, the negative pressure degree on the nutrient solution and on the pressure differential between supply and recovery system and microgravity [99]. However, Superdwarf wheat plants growth during the 1996–1997 experiments in the growth chamber Svet on the Space Station Mir was performed using a natural zeolite clinoptilolite loaded with mineral salts, called Balkanine, developed in Bulgaria [100]. The moisture in the Balkanine and the movement of O_2 in wet substrates seemed likely to be the most critical parameter to control, which probably caused waterlogging and anoxia, and together with ethylene, present in the cabin air, caused flowering abortion thus affecting plants seed yield [79,100,101]. Certainly, the physics and geometrics of porous media particles are crucial design characteristics that influence root water, nutrient and gas exchange, thus affecting root growth and plant vigor [102]. However, under microgravity, changes in buoyancy, dominance of capillary forces, particle rearrangement, vehicle vibration, as well as a different water retention hysteresis of media particles determine changes in fluid distribution of water and air that affect the efficient delivery of water to the roots [102,103].

Recently, as reported by Massa and coworkers [104] in ISS experiments on leafy greens, arcillite was used for growing plants from seeds in plant pillows. These latter are small expandable bags containing two different sized arcillite substrates (0.6 mm at 100% or mixed 0.6 to 1–2 mm at 1:1 ratio) (Turface Proleague, Profile Products, LLC, Buffalo Grove, IL, USA) mixed with a polymer-coated controlled release fertilizer (Nutricote 18–6–8, type 180, Florikan, Sarasota, FL, USA) at rates of 7.5 g/1000 cm³ dry substrate [49,96]. Plant pillows containing surface sterilized seeds, are packed for flights under sterile air, ready to be housed within the Veggie baseplate that contains a root mat water reservoir [104]. This system shows good seed germination and substrate containment; however, the mat reservoir does not always provide the amount of water that growing crops need, requiring to be supplemented with a crew time-consuming manual watering [104]. In addition, given the fluid behavior in microgravity, astronauts can have problems to properly water the crops; therefore, different strategies must be considered in order to avoid over- or under-watering of plants [12,104].

Porous tubes in a bed of arcillite and slow-release fertilizer have been also used as growing substrate in the science carrier (SC), a tray-like component, of the 0.2 m² NASA Advanced Plant Habitat (APH) [95,101]. It is a quad-locker designed to interface with a standard EXPRESS Rack on the ISS developed in cooperation with ORBITEC [3,101,105]. The root zone is separated from the shoot zone by a thin layer of foam that contains the media, which supports the plants and reduces the evaporation of water within the media; above this layer there is a polycarbonate cover that holds the foam in place, providing structural integrity to the top of the assembly. The cover includes slots for growing plants and smaller holes to allow aeration of the root zone [101]. The SC, pre-planted with immobilized seeds, is transferred dry to the APH facility on ISS, and the plant growth experiments initiate when the SC module is installed in the APH growth chamber and primed, fully wetted by flooding the root zone for starting seed germination and removing air from the porous tubing and rooting media [105].

The speed of dry media watering can adversely affect the overall moisture distribution within the root module in microgravity [101]. The validation experiments of the APH done on ISS between October 2017 and March 2018 were successfully carried out, ending with the harvest after 30 days of growth of WT Arabidopsis and Apogee semi-dwarf wheat plants [105].

Sierra Nevada Corporation (SNC) is proposing to test on ISS a new aeroponic/hydroponic plant growth system, called Astro GardenTM, with the aim to create a larger food production installation for long lasting space missions in cis-lunar environment and lunar surface [106]. The current system design includes eight modules, one nursery and one water processing module (WPM). The nursery has the same structure of the modules, but it is conceived for a higher planting density. Modules and nursery have a growing area of 0.0928 m^2 , for a 0.835 m^2 of total growing area fitting in a pallet envelope of ~ 63.5 cm $\times 61$ cm $\times 188$ cm [107,108]. The main aims of the new hardware are to further develop microgravity tolerant hydroponics, aeroponic or modified thin-film systems, investigate spray droplet capture and water/nutrient solution recycling and test different salad crop candidates for use in space [107]. Three series of ground-based experiments have been already done in the Phase 1 Astro Garden, Phase 2 Astro Garden and the parabolic flight test campaigns. In the aeroponic spray trial, it was found that the spray velocity dominates the gravitational force exerted on the fluid mass, therefore aeroponics is a viable nutrient delivery mechanism in microgravity. Moreover, forced air was found a practicable method for removing free droplets from airstream without damaging root structure, but ineffective in removing the nutrient solution that creates a film on the surface of the root structure hindering further uptake of nutrients and oxygen. Design modifications would be necessary to solve this problem and only the technology demonstration on ISS may provide the validation of the media less nutrient delivery and recovery systems [106].

A real-time ion-specific sensor may be useful to continually check the level of individual ions in the nutrient solution [106]. However, a technological solution able to monitor and control on-orbit water quality has not yet been tested in Space and is not feasible in a system like VEGGIE [84,104]. Indeed, recent advances in remote sensing techniques allow monitoring plants' responses to environmental changes before visual symptoms occur on ISS. In particular the interior root-zone growth area of the APH, which is separated into four independently controlled quadrants, have temperature, moisture and oxygen levels sensors that allow to monitor the effects of microgravity on plant physiology, even on larger plants, comparing them with ground studies during the entire life cycle of plants in real time [53,101,105]. In addition, the comparison between plants grown in VEGGIE plant pillow system with those grown on Earth with other growth systems, even if under simulated microgravity, is not possible because plant pillows constrain the growth of plants [109,110]. However, it can be very useful to study on ISS issues related to plant-microbial ecology, plant nutrients and human nutrition and behavioral health [53].

The PTPNDS hydroponic porous approach), was initially proposed by Dreschel and Sager [108], improved in the subsequent years [111] and used in several experiments for space agriculture with [84,85,112] or without [67] simulated microgravity. The system has been used for its tubular shape and the ability to retain water (avoid any free water leakage) and transfer the water to the roots or in the substrate by capillary forces and avoid problems related to a lack of oxygen in the rhizosphere, which are essential features for the application of clinorotation simulating microgravity [113]. The porous tube was initially built as a hydrophilic porous polyethylene tube with a pore diameter of 20 µm and 0.3 cm wall thickness included in a 2.5 cm solid polyvinyl chloride (PVC) pipe. In this system, the plant root zone grew directly on the surface of the nutrient-supplying inner porous tube and was surrounded by the air space of the outer PVC external shell [108]. The implementation of the system was done by developing hydraulic pressure control systems for laboratory scale crop tests, studying its effects on pore size and root zone volume, developing physical and mathematical models to describe it and utilizing the system to grow crop plants in simulated and real microgravity, like that of the Russian Svet hardware [111,113].

In the PTPNDS used by Rivera et al. [84] and Colla et al. [85], the empty space for root zone was completely filled with perlite (\emptyset 1–2 mm), and the nutrient solution flowed through the microporous tubes under slight negative pressure (–0.6 kPa) thanks to a siphon as previously described by Dreschel and Sager [108] and Tibbits et al. [114]. The siphon had as unique problem of creating air bubbles that may break the water flow through capillary by surface tension. Rivera et al. [84] fixed this problem by connecting the porous tubes in series, to expulse any air bubble entering the system through the tubes, collecting them in the corners of a manifold and generating a positive pressure inside the system to eliminate air bubbles.

6. Conclusions

In the near future, space exploration will increase, and the cultivation of plants may be necessary and advantageous to supplement the dietary needs and sustain the wellbeing of the crew members in flights and orbital platforms. Experiments on board of ISS are still necessary to reconcile technical problems with productivity and qualitative aspects. The main constraints on ISS are the attempts to optimize the water and nutrient delivery systems in microgravity, to satisfy the needs of cultivated species. Cultivar selection plays a crucial role in completing the components choice for the adequate farming system to maximize this latter efficiency. Further experimentation must be done on LEDs to maximize plant growth and quality at a light intensity maintained maximum around 300–400 μ mol m⁻² s⁻¹. On the other hand, energy demand, at the moment, is not a problem of main concern on ISS, even if the actual setting of ISS has no free space for storing a larger plant growth hardware. Nonetheless, numerical simulations should be carried out to consider the energy demand, time evolution and battery capacities to obtain robust results for design applications.

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