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Supplemental Food Production With Plants: A Review of NASA Research

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Bioregenerative life-support systems for space have been investigated for 60 years, and plants and other photosynthetic organisms are central to this concept for their ability to produce food and O_2, remove CO_2, and help recycle wastewater. Many of the studies targeted larger scale systems that might be used for planetary surface missions, with estimates ranging from about 40 to 50 m^2 (or more) of crop growing area needed per person. But early space missions will not have these volumes available for crop growth. How can plants be used in the interim, where perhaps <5 m^2 of growing area might be available? One option is to grow plants as supplemental, fresh foods. This could improve the quality and diversity of the meals on the International Space Station or on the Lunar surface, and supply important nutrients to the astronauts for missions like Mars transit, and longer duration Martian surface missions. Although plant chambers for supplemental food production would be relatively small, they could provide the bioregenerative research community with platforms for testing different crops in a space environment and serve as a stepping stone to build larger bioregenerative systems for future missions. Here we review some of NASA's research and development (ground and spaceflight) targeting fresh food production systems for space. We encourage readers to also look into the extensive work by other space agencies and universities around the world on this same topic.

Keywords: crop, nutrient, salad, veggie, greenhouse, sustainable, ECLSS, controlled ecological life-support systems

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INTRODUCTION

Bioregenerative life support systems (BLSS) have been one of the most enduring life science research themes since the beginning of the space era in the 1950's (Myers, 1954). The use of photosynthetic organisms for food and oxygen production, along with CO_2 removal and water processing is central to this concept (Miller and Ward, 1966; Salisbury et al., 1997) and in 1962 discussions began on what crop plants to consider for space missions (Pilgrim and Johnson, 1962). But opportunities to test BLSS at a relevant scale in space have been limited due to volume and mass constraints of the spacecraft. Modest efforts at space crop production on board NASA's Space Shuttle, the Russian Mir station, and the International Space Station (ISS) have been underway since the 1990's, but most have been short duration studies and all have been limited due to volume, mass, and power constraints. To date, life-support systems for spacecraft and space stations have been based on physico-chemical (PC) principles, some of them regenerative, others relying on resupply (Shaw et al., 2020). For example, urine from the crew on the ISS is currently processed through a vapor compression distillation system and purified to recover potable water (Carter et al., 2018). Here we review only plant related testing in space for food production and eventual BLSS applications.

Food Production in Bioregenerative Life Support Systems

To supply food on space missions, the only option to date has been stowage and resupply of packaged, stabilized foods (Perchonok et al., 2012). Currently, the ISS receives several resupply missions of food each year, but this approach will be more costly as mission durations and distances increase (Perchonok et al., 2012). About 40–50 m^2 of crops grown under high light intensities would be needed to produce enough dietary calories for one human, and when coupled with insects to degrade inedible biomass and provide supplemental protein, the area could be reduced to 35–40 m^2 per person (Salisbury et al., 1997; Wheeler et al., 2008; Fu et al., 2016). Plantings of this size would also supply all the O_2 production and CO_2 removal for one human. However, these BLSS studies have all been ground-based, and opportunities to test and implement them in space have been limited. A logical approach might be to sequentially develop smaller BLSS capabilities on space missions where PC life-support systems are already in place; then as durations and distances increase, expand BLSS components where applicable (Gitelson et al., 1995; Wheeler, 2002; Morrow et al., 2004). While earlier approaches focused on larger scale food production for more full life-support (carbohydrate, fat, protein), micronutrients were not given as high a priority (e.g., Mitchell et al., 1996; Salsibury and Clark, 1996). But supplying even smaller amounts of fresh produce could supplement micronutrients such as vitamins C and B1, which may degrade in the packaged diet, provide dietary anti-oxidants, and improve the overall acceptability of meals for the crew (Cooper et al., 2017). Extensive work has been done by other space agencies and universities around the world to address these same issues (Wheeler, 2017). For example, the 1970's Oasis tests on the Russian Salyut Space Station were the first attempts at a human-monitored plant BLSS research in space (Porterfield et al., 2003). Here we review some NASA sponsored ground-based and space research with plants that could be used as supplemental fresh foods on early missions.

Preparing Crops for Space: The Concept of Crop Readiness Level

Space brings with it unique environmental constraints for crops. This inspired the concept of a Crop Readiness Level or CRL (Wheeler and Strayer, 1997), which is a maturation scale analogous to technology readiness levels (TRL) but for crops and BLSS. For example, short or dwarf growth, high harvest index, high yields, organoleptic acceptance, good nutrient content, and ability to control microbial contaminants are all desirable traits for the selection and maturation of CRL for space (Romeyn et al., 2019; Spencer et al., 2021). The current scale is focused on ISS and Mars transit needs, but surface settings with larger BLSS crop systems might consider different criteria or factors appropriate for those settings, such as higher macronutrient content, ability to grow in multispecies plantings, or radiation tolerance. Like applying TRL for aerospace hardware, a CRL approach provides a logical progression of testing for future space crops.

Historical Context of Preparing Crops for Spaceflight: Ground-Based Research

Decades of ground and flight research have gone into our current supplemental crop growth systems on the ISS. Around 1980, NASA started its Controlled Ecological Life-Support Systems (CELSS) program (MacElroy and Bredt, 1984). The CELSS Program focused largely on BLSS research for surface missions and agronomic crops that might be grown in large plantings (MacElroy et al., 1990; Wheeler, 2017), but CELSS also proposed a smaller "rack" sized plant system for growing supplemental food crops for near term and Mars transit missions. The term "salad machine" or "vegetable production unit" was used for this concept (Kliss and MacElroy, 1990).

Unlike the staple crops tested by NASA in the 1980's and 1990's (e.g., wheat, soybean, potato, peanut, sweet potato), leafy greens and small fruit crops (e.g., tomato and pepper) can be grown on the ISS and early missions to supplement the crew's diet. These supplemental food crops have a short shelf life but can have a high impact on the diet (Cooper et al., 2012). NASA ground testing included species such as spinach, lettuce, chard, green onion, leafy mustards such as pak choi, mizuna, and Chinese cabbage, radish, beet, dwarf tomato, dwarf pepper, strawberry, and dwarf plum trees (Knight and Mitchell, 1983; Gilrain et al., 1999; Subbarao et al., 1999; Goins and Yorio, 2000; Richards et al., 2004; Massa et al., 2006; Hummerick et al., 2010; Graham et al., 2015; Massa et al., 2016; Graham and Wheeler, 2016). To date, many of the leafy greens and "Red Robin" tomato have performed very well in these studies (Spencer et al., 2019; Spencer et al., 2020).

CROP PHYSIOLOGICAL CONCERNS

Impact of Atmospheric CO_2 Concentrations

Significant vegetable crop testing by NASA focused on the effects of CO_2 on crop growth and development (McKeehen et al., 1996; Spencer et al., 2019; Burgner et al., 2020). Elevating the CO_2 from ambient levels ~400 ppm to 1,000–2000 ppm increased growth and yield for most crops, as expected. But yields of some crops like radish and lettuce dropped at super-elevated CO_2 concentrations, e.g., 5,000 and 10,000 ppm, compared to 1,000 ppm (Mackowiak et al., 1994). Thus for typical CO_2 levels on the ISS (~3,000 ppm), most of these crops should grow well. But for Chinese cabbage, cv. Tokyo Bekana, the combination of moderately elevated CO_2 (900 ppm) and LED lighting decreased growth compared to lower CO_2 levels (Burgner et al., 2020). This response highlights the importance of conducting thorough ground testing prior to spaceflight (Romeyn et al., 2019).

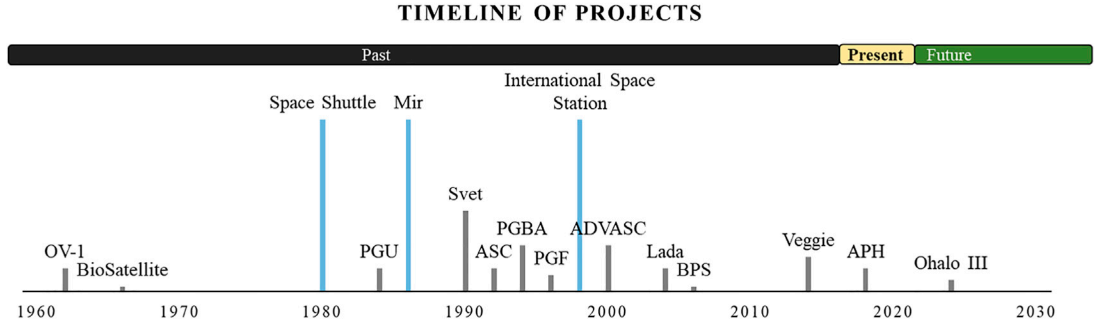

FIGURE 1 | Timeline of projects. Spaceflight hardware for bioregenerative crop production from 1960–2030. Past (black), present (yellow), and future (green) are indicated above the timeline. Platforms are indicated with a blue line while plant-specific hardware is indicated by a gray line. Length of the gray line represents the relative length of time that the hardware was/has been in operation. Orbital Vehicle 1 (OV-1; US Air Force), BioSatellite I and II (NASA), Plant Growth Unit (PGU; NASA), Svet (Roscosmos), Astroculture (ASC; Univ. Wisconsin/NASA), Plant Generic Bioprocessing Apparatus (PGBA; BioServe/NASA), Plant Growth Facility (PGF; NASA), Advanced Astroculture (ADVASC; Univ. Wisconsin/NASA), Lada (Roscosmos), Biomass Production System (BPS; NASA), Veggie (NASA), Advanced Plant Habitat (APH; NASA). Veggie and APH are currently in use on the International Space Station.

Plant Lighting

Using light emitting diodes (LEDs) to grow plants was proposed and patented through a NASA Commercialization Center at the University of Wisconsin (Barta et al., 1992). LEDs were first used in the Astroculture (ASC) plant chamber aboard the Space Shuttle (Morrow et al., 1995) then the Advanced Astroculture Chamber (ADVASC) (Link et al., 2003), and later the Veggie and Advanced Plant Habitat for the ISS, both of which are currently flying aboard the ISS (Massa et al., 2016; Morrow et al., 2016). To support the development of LED lighting for space, NASA sponsored ground testing from the early 1990's through the mid 2000's with leafy greens and other crops (Goins et al., 1997; Kim et al., 2004; Massa et al., 2008). These studies showed that both red and blue light improved plant photosynthesis and growth (Bula et al., 1991; Dougher and Bugbee, 2001; Yorio et al., 2001; Douglas et al., 2016). Subsequent LED studies revealed important roles for green and far-red light as well (Spencer et al., 2020). Recent NASA research showed that supplementing with far-red LEDs can act like adding more photosynthetically active radiation--PAR (400–700 nm) (Zhen and Bugbee, 2020), and that LEDs can achieve remarkable efficiencies (>3 μmol/J), which could greatly reduce electrical power needs for BLSS (Kusuma et al., 2020). This has far-reaching implications for future missions. In addition to electric lighting systems, solar lighting techniques that use concentrators and fiber optics were also explored for growing crops (Cuello et al., 2000; Nakamura et al., 2009).

Regardless of the lighting approach, nearly all these studies showed greater yields in response to increased PAR (Knight and Mitchell, 1983; Knight and Mitchell, 1988; Richards et al., 2004). Although some leafy greens are prone to physiological disorders like leaf tip burn at higher PAR (Barta and Tibbitts, 1991; Frantz et al., 2004), this key relationship between PAR and yield becomes a driving factor for planning crop systems for space. For NASA's Veggie plant chamber on the ISS, the PAR is adjustable up to ~450 μmol m^{-2} s^{-1} depending on distance between the plants and lights, but has typically been operated between 200 and 300 μmol m^{-2} s^{-1} (Massa et al., 2016).

NASA'S PAST, PRESENT, AND PLANNED PLANT CHAMBERS FOR SPACE

The first attempt to test BLSS concepts in space was with the Orbital Vehicle (OV-1) satellite mission in 1966, where NASA and the US Air Force monitored photosynthetic and respiratory gas exchange between duckweed (*Spirodella*) and *Chlorella* aglae (Ward et al., 1970). The subsequent BioSatellite 2 experiments tested wheat seedlings and pepper plants in microgravity (Conrad, 1968; Johnson and Tibbitts, 1968), but these were short flights with limited data recovery. NASA funded investigators F.B. Salisbury and G.E. Bingham also collaborated with Russian colleagues for a series of tests in the Svet plant chamber on Mir space station through much of the 1990's with research focusing on wheat production (Bingham et al., 1996, 2000). With the Shuttle program came more frequent trips to space and more chamber options for plant growth, such as the Plant Growth Unit (PGU) and subsequent Plant Growth Facility (PGF) (Halstead and Dutcher, 1987; Paul et al., 2001). These chambers were primarily for space and gravitational research. In comparison, the Astroculture (ASC) and Plant Generic Bioprocessing Apparatus (PGBA) were also used on the Shuttle but more focused on BLSS concepts (Bula et al., 1991; Morrow et al., 1995; Hoehn et al., 1997; Porterfield et al., 2003; Zabel et al., 2016) (**Figure 1**).

Compared to standard gravity, watering systems for μ-gravity must deal with water containment, the lack of natural drainage and impaired aeration of the rootzones (Bingham et al., 2000; Steinberg et al., 2002; Jones et al., 2011). This began ground testing of porous membranes, tubes, or plates to contain the water and allow capillary movement to the roots (Wright et al., 1988; Dreschel and Sager 1989; Koontz et al., 1990), as well as flight testing of hybrid approaches that use porous tubes to sub-irrigate a solid rooting matrix (Morrow et al., 1992; Bula et al., 1991). ASC and PGBA also used porous thermo-electric plates to cool and dehumidify the air, while recycling the condensate back to the plants (Morrow et al., 1995; Hoehn et al., 1997; Conrad, 1968; Dreschel and Sager 1989;Johnson and Tibbitts, 1968; Khodadad et al., 2020; Koontz et al., 1990; Morrow et al., 1992; Schuerger et al., 2021; Stutte et al., 2005; Wright et al., 1998).

TABLE 1 | NASA crops grown in spaceflight in Veggie and APH.

Crop	Scientific Name	Experiments	Experiment Flight Grow Dates
Red Romaine Lettuce	*Lactuca sativa* cv. Outredgeous	VEG-01A VEG-01B VEG-03A VEG-03D VEG-03E VEG-03F VEG-03I VEG-03J	May 8, 2014–June 10, 2014 July 8, 2015–Aug. 10, 2015 Oct. 25, 2016–Dec. 28, 2016 Sept. 26, 2017–Nov. 23, 2017 Feb. 5, 2018–April 6, 2018 Feb. 9, 2018–April 9, 2018 Jan. 4, 2021–Feb. 2, 2021 Jan. 4, 2021–Feb. 2, 2021
Green Leaf Lettuce	*Lactuca sativa* cv. Waldmann's Green	VEG-03D VEG-03E VEG-03F	Sept. 26, 2017–Nov. 23, 2017 Feb. 5, 2018–April 6, 2018 Feb. 9, 2018–April 9, 2018
Dwarf Romaine	*Lactuca sativa* cv. Dragoon	VEG-03G VEG-03I	Oct. 25, 2018–Nov. 28, 2018 Jan. 4, 2021–Feb. 2, 2021
Zinnia	*Zinnia hybrida* cv. Profusion	VEG-01C	Nov. 16, 2015–Feb 14, 2016
Chinese Cabbage	*Brassica rapa* var. Chinensis cv. Tokyo Bekana	VEG-03B VEG-03C	Jan. 20, 2017–May 31, 2017 April 3, 2017–May 31, 2017
Mizuna Mustard	*Brassica rapa* var. japonica	VEG-03D VEG-03E VEG-04A VEG-04B	Sept. 26, 2017–Nov. 23, 2017 Feb. 5, 2018–April 6, 2018 June 4, 2019–July 9, 2019 Oct. 1, 2019–Nov. 28, 2019
Red Kale	*Brassica napus* cv. Red Russian Kale	VEG-03G VEG-03I	Oct. 25, 2018–Nov. 28, 2018 Jan. 4, 2021–Feb. 2, 2021
Wasabi Mustard	*Brassica juncea* cv. Wasabi	VEG-03H VEG-03I	March 9, 2019 - April 6, 2019 Jan. 4, 2021 - Feb. 2, 2021
Dwarf Pak Choi	*Brassica rapa* var. Chinensis cv. Extra Dwarf	VEG-03H VEG-03I VEG-03L	March 9, 2019–April 6, 2019 Jan. 4, 2021–Feb. 2, 2021 Feb. 8, 2021–Apr. 13, 2021
Amara Mustard/Ethiopian Kale	*Brassica carinata*	VEG-03K	Feb. 8, 2021–Apr. 13, 2021
Radish	*Raphanus sativus*	PH-02	Nov. 3, 2020–Nov. 30, 2020
Pepper	*Capsicum annuum* cv. Española Improved	PH-04	July 12, 2021

By 2000, plant growth systems were launched to the ISS. First was the ADVASC (Link et al., 2003) and then the Biomass Production System (BPS) (Stutte et al., 2005), both of which were double, mid-deck, locker-sized chambers. In 2014 the Veggie chamber was added to the ISS, with a second unit added in 2017. The Advanced Plant Habitat (APH), a quad, locker-sized chamber that provides a wide range of environmental control, was based on Astroculture principles (Zhou et al., 1998) and installed on the ISS in 2017 (Massa et al., 2016; Morrow et al., 2016). Unlike the ADVASC, BPS, and APH, Veggie was intended to be collapsible for stowage, open to the cabin atmosphere, and easily accessible for the crew, much like the Russian Svet and Lada systems (Bingham et al., 1996; 2000) To date, Veggie has been used more than any other chamber in space to study fresh food production for astronauts.

Recent NASA Spaceflight Studies of Supplemental Food Production

To date, the series of 12 leafy green tests in NASA's Veggie chamber on the ISS included lettuce (several cultivars), mizuna, Chinese cabbage, wasabi mustard, red Russian kale, amara mustard, and pak choi (**Table 1**). The first studies used "Outredgeous" red romaine lettuce and an ornamental crop, "Profusion" zinnia (Massa et al., 2015). Tests with Chinese cabbage showed leaf chlorosis on some of the plants (Burgner et al., 2020). Analyses of nutrient content of red romaine lettuce grown in Veggie found no significant difference between the ground control and spaceflight treatment of each experiment. Some growth differences were found across the three studies, each conducted a year apart, and are attributed to different environmental conditions (Khodadad et al., 2020). The crop microbiome did vary, with a considerably more diverse microbial community found on space ground produce, especially the leaves. Lettuce growth improved with better approaches to watering by astronauts. Throughout most of the Veggie tests, water management has been challenging, with lettuce having insufficient water in some early tests, while zinnia plants had too much, primarily due to a ventilation system failure (Schuerger et al., 2021). The baseline Veggie watering system is a passive wicking design, where water from a reservoir wicks to plant pillows, which are filled with arcillite media and controlled-released fertilizer (Massa et al., 2017a; Massa et al., 2017b). The capillary watering approach has thus far been inconsistent due to materials and design issues. These issues have not been addressed to date so Veggie experiments have relied largely on direct manual watering. The watering system in APH consists of porous tubes surrounded by arcillite media (Morrow et al., 2016), and to date it has worked well. Recently the radish plants grown in APH were consumed by astronauts (John et al., 2021). A second crop, chile peppers (Spencer et al., 2019), began growing for the first time in APH in orbit on July 12, 2021 (**Table 1**).

Ohalo III

NASA's next step toward space crop production will be the Ohalo III chamber, targeted for the ISS as early as 2024. This rack-sized crop production system will be atmospherically closed to recycle transpired humidity and will contain various automation and sensing capabilities. Ohalo III is designed to be evolvable and expandable and will initially test different water delivery and volume optimization concepts for growing plants in microgravity. As a permanent addition to the ISS, Ohalo III should be able to investigate operational challenges associated with the sustained production of crops in space and will hopefully achieve the long desired "vegetable production unit" for a Mars transit mission (Kliss and MacElroy, 1990; Kliss et al., 2000).

DISCUSSION

NASA has sponsored extensive research on growing various species of leafy vegetables and small fruits in controlled environment chambers. This research revealed the importance of managing water and nutrient supplies to the plants, the effects of elevated and super-elevated CO_2 on plants, and the profound influence of light on crop growth and development. This in turn has driven the development and testing of LED lighting and other new technologies for space crop production. Other key gaps exist in our knowledge base, such as the effects of reduced gravity on the plants and their support systems, such as water delivery, and the effects of space radiation. Most of this testing occurred in "ground" settings, but small plant chambers have been built and tested in space. These chambers have become successively larger with better environmental control, but none have been used with the sole intent for providing fresh food for the astronauts. Exploratory tests with the Veggie plant chamber are beginning to do this, but a dedicated "vegetable production unit" with better environmental control is still needed.

Concluding Remarks

BLSS using plants to generate food and oxygen while recycling CO_2 and water will help achieve more autonomous living on other planets; however, developing a large BLSS on surface settings could be decades in the future, and this will be dictated in part by mission architectures of the various space agencies. Nonetheless, continued ground research on these systems is needed to understand their integration with other environmental control technologies, their sustainability, and their costs in terms of mass, power, volume, and crew time. Part of the evolution toward these BLSS systems will be testing smaller components or subsystems in space settings like the ISS and early surface missions. A logical stepping stone in this progression will be using smaller plant chambers to provide supplemental, fresh foods to augment stored foods. These fresh foods could reduce diet fatigue and provide key nutrients that degrade in the packaged food supplies. Understanding the operation, cost, and sustainability of these smaller food-crop production systems will provide critical information for evolving toward a larger BLSS of the future.

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