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Space Horticulture as a Green Shield: Life Force Foods and the Vedic Nexus for Deep-Space Astronaut Sustenance

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Abstract— *Sustaining human crews through multi-year interplanetary missions demands a food and life-support paradigm that extends far beyond calorie provisioning. This review synthesizes the emerging discipline of Space Horticulture — defined as the sovereign confluence of plant science, survival engineering, and human sustenance dedicated to nourishing, healing, and psychologically anchoring astronauts across long-duration deep-space journeys — and situates it within contemporary aerospace bioregenerative research, plant stress physiology, and ancient Vedic nutritional philosophy. Drawing on internationally established programmes, including the National Aeronautics and Space Administration (NASA) Veggie and Advanced Plant Habitat platforms, the NASA Deep Space Food Challenge, the European Space Agency (ESA) Micro-Ecological Life Support System Alternative (MELiSSA), and the Indian Space Research Organisation (ISRO) Compact Research Module for Orbital Plant Studies (CROPS), the paper traces the transition from mechanical life-support hardware toward closed-loop, bioregenerative ecosystems. It further reviews recent empirical evidence on plant physiological responses to microgravity, altered gravity, and ionising radiation; the emergence of duckweed (Wolffia spp.) as a rapid-cycle protein crop; comparative water-use efficiency of aeroponic and hydroponic cultivation; lunar and Martian regolith bio-conditioning strategies; the documented psychological benefits of crew horticultural activity; and the radioprotective role of dietary phytochemicals. The review then presents, in detail, the author's own three-dimensional (3D) printed nutrient-delivery research reported in the Dr. Jadala Shankaraswamy's book,* Space Horticulture *(Narendra Publishing House, 2026, ISBN 978-93-7763116-1) — believed to be the first global attempt at fabricating plant-based, fast-dissolving oral dispersible films (ODF) from shelf-stable powders of underutilised ethnic vegetables, namely Spine Gourd (Momordica dioica), Chekurmanis (Sauropus androgynus), and Alternanthera (Alternanthera sessilis), bound with Moringa gum and stimulated by Roselle (Hibiscus sabdariffa) calyx powder. The films demonstrated a saliva dissolution time of 115.55 ± 2.00 seconds, tensile strength of 1.394 ± 0.06 kg/mm², swelling index of 43.68 ± 2.55%, and were characterised by High-Resolution Liquid Chromatography-Mass Spectrometry (HR-LCMS) to contain 136 bioactive phytochemicals, Inductively Coupled Plasma Mass Spectrometry (ICP-MS) confirming 11 essential minerals, and Mass Spectrometry Quadrupole Time-of-Flight (MS-QTOF) profiling identifying 17 amino acids. These findings are interpreted as a mucosal, crumb-free nutrient delivery route uniquely suited to countering microgravity-induced gastrointestinal ('space-gut') malabsorption while simultaneously supplying radioprotective phytochemical load. The review concludes with a forward look toward lunar and Martian horticultural infrastructure including regolith bio-conditioning, aeroponic and hydroponic cultivation, robotic 3D-printed habitat construction, and India's Bharatiya Antariksha Station and Vision 2047 roadmap — arguing that the fusion of Vedic Prana-centred nutritional philosophy with cutting-edge additive food-manufacturing technology and validated plant-stress science constitutes a credible and culturally-rooted pathway toward Earth-independent, psychologically resilient deep-space food systems.*

Keywords— Space Horticulture; Bioregenerative Life Support System (BLSS); 3D-Printed Oral Dispersible Films; Life Force Foods (Prāṇa); MELiSSA; Deep Space Food Challenge; Lunar Regolith; Radioprotective Phytochemicals.

I. INTRODUCTION

As crewed exploration extends from low-Earth orbit toward the Moon and Mars, mission durations expand from months to years, rendering the pre-packaged, freeze-dried food paradigm of the twentieth century increasingly untenable [1], [2]. Stored space food undergoes progressive degradation of heat-sensitive vitamins, palatability, and psychological acceptability over multi-year transit, a limitation now widely recognised across the astronaut nutrition literature [1]–[3]. In response, space agencies have shifted strategic emphasis from carrying finite food inventories to cultivating living, self-renewing biological systems — a transition this review terms the movement from 'picnic basket' logistics to 'cosmic farming'.

Space Horticulture, as proposed and defined in the Dr. Jadala Shankaraswamy's book *Space Horticulture: A Future Green Shield with Life Force Foods* (Narendra Publishing House, 2026, ISBN 978-93-7763116-1), is "the emerging, sovereign, and irreplaceable discipline at the confluence of plant science, survival engineering, and human sustenance ... with the singular and non-negotiable purpose of sustaining, nourishing, healing, and psychologically anchoring the human crew across the entirety of long-duration interplanetary missions" [4]. This definition deliberately positions horticulture not as a supplementary comfort but as a life-critical subsystem furnishing oxygen regeneration, water purification, medicinal compounds, and — through the Vedic lens explored later in this review — a tether of psychological and spiritual continuity with Earth [4].

This review has three integrated objectives. First, it consolidates the current state of bioregenerative life-support and space-crop cultivation research, spanning NASA's Veggie and Advanced Plant Habitat (APH) systems, the NASA Deep Space Food Challenge, ESA's MELiSSA closed-loop ecosystem, and ISRO's CROPS experiments [5]–[11]. Second, it expands the evidentiary base by reviewing recent peer-reviewed findings on plant physiological responses to microgravity and radiation [12]–[15], candidate rapid-cycle protein crops such as duckweed [20]–[22], comparative soilless cultivation efficiency [32], [33], lunar/Martian regolith bio-conditioning [29]–[31], the documented psychological benefits of crew horticultural engagement [23]–[25], and the radioprotective function of dietary phytochemicals [26]–[28]. Third, and centrally, it extracts and critically discusses the author's original three-dimensional (3D) food-printing research on plant-based oral dispersible nutrient films, together with the accompanying Vedic 'Life Force Foods' framework, projecting both toward future lunar and Martian applications in line with India's Vision 2047 space exploration roadmap [4].

While the integration of Vedic philosophy with space horticulture is a distinctive cultural contribution, it should be noted that this framework is presented as a conceptual and philosophical scaffold requiring empirical validation. The review distinguishes between the established peer-reviewed literature (Sections 3-5) and the author's original research (Section 6), which is currently documented in the author's monograph and presented here as a proof-of-concept requiring independent validation.

II. REVIEW METHODOLOGY

This is a narrative-integrative review. Primary source material was drawn from the author's book *Space Horticulture: A Future Green Shield with Life Force Foods — A Narrative Vedic Nexus to Sustain Astronauts on Deep Space Journeys* (Narendra Publishing House, New Delhi, India, 2026, ISBN 978-93-7763116-1) [4], which compiles the author's original 3D-printed nutrient film research alongside a synthesis of international bioregenerative life-support literature and Vedic physiological philosophy. The book was subjected to editorial review by the publisher but has not yet been independently peer-reviewed in a scientific journal.

This material was cross-verified and substantially extended through a supplementary literature search of peer-reviewed journals (2020–2026) and institutional space-agency sources covering: (i) NASA plant-growth hardware and challenge programmes [5]–[7]; (ii) ESA's MELiSSA programme [8], [9]; (iii) ISRO's CROPS module [10], [11]; (iv) plant physiological and molecular responses to microgravity, altered gravity, and ionising radiation [12]–[15]; (v) the 3D/4D oral-film drug and nutrient delivery literature [16]–[19]; (vi) duckweed (*Wolffia* spp.) as an emerging space protein crop [20]–[22]; (vii) empirical studies of astronaut psychological response to horticultural activity [23]–[25]; (viii) the radioprotective role of dietary phytochemicals and antioxidants [26]–[28]; and (ix) lunar/Martian regolith bio-conditioning and comparative soilless cultivation efficiency [29]–[33].

Literature Search Strategy: The supplementary literature search was conducted using Web of Science, Scopus, and Google Scholar with search terms including "space horticulture," "bioregenerative life support," "MELiSSA," "Veggie," "Advanced Plant Habitat," "microgravity plant physiology," "duckweed space protein," "regolith bio-conditioning," and "space nutrition." The search was restricted to peer-reviewed English-language publications from 2020 to 2026. Grey literature and conference abstracts were included only if they had been subsequently published as peer-reviewed articles.

Inclusion and Exclusion Criteria: Studies were included if they: (1) addressed plant growth, life support, or nutrition in spaceflight or space-analogue contexts; (2) presented original empirical data, systematic reviews, or validated models; (3) were published in peer-reviewed journals or official space agency technical reports. Studies were excluded if they addressed terrestrial agriculture without spaceflight relevance or were not available in English.

Numerical and analytical results reported for the author's ODF research (dissolution kinetics, tensile strength, swelling index, HR-LCMS, ICP-MS, and MS-QTOF profiling) are reproduced as documented in the author's book [4] and presented here as preliminary findings requiring independent validation.

III. FROM MECHANICAL LIFE SUPPORT TO BIOREGENERATIVE ECOSYSTEMS

3.1 NASA Veggie and the Advanced Plant Habitat (APH)

NASA's Vegetable Production System ('Veggie') is a compact, low-resource space garden employing clay-based 'plant pillows' pre-loaded with slow-release fertiliser to manage root-zone water and nutrient delivery under microgravity [5], [6]. Veggie has demonstrated successful on-orbit cultivation of 'Outredgeous' red romaine lettuce, 'Tokyo Bekana' Chinese cabbage, Mizuna mustard, and Red Russian kale aboard the International Space Station (ISS) [4], [6]. The Advanced Plant Habitat represents a substantially more automated successor: an enclosed, environmentally-controlled chamber instrumented with over 180 sensors and cameras and illuminated by tunable LED arrays (red 660 nm, blue 450 nm, far-red 730 nm, and infrared wavelengths) to optimise photosynthetic efficiency and enable detailed study of plant gene expression under spaceflight stress [4], [5]. Collectively, these platforms mark NASA's incremental transition from demonstrating that plant growth is possible in orbit to engineering production-scale, crew-interactive space gardens [4].

3.2 The NASA Deep Space Food Challenge

The NASA Deep Space Food Challenge, conducted in partnership with the Canadian Space Agency, is an international, multi-phase competition inviting innovators to design, build, and demonstrate food production technologies that are minimally resource-intensive yet maximally safe, nutritious, and palatable for missions of up to five years' duration, including transit to Mars [7]. The Challenge's 'Mars to Table' extension broadens participation to chefs and culinary innovators tasked with designing complete, Earth-independent food systems for the lunar and Martian surface [7]. This review situates the author's ODF research as directly responsive to the Challenge's core mandate: shelf-stable, nutrient-dense, minimal-waste food technology suited to multi-year autonomy [4].

3.3 ESA's MELiSSA Programme

The European Space Agency's Micro-Ecological Life Support System Alternative (MELiSSA), initiated in 1989, is architected as a closed-loop, bio-industrial ecosystem that mimics terrestrial biospheric function through five interconnected compartments comprising microbial bioreactors, wet-oxidation units, filtration stages, and higher-plant chambers [8], [9]. The system is designed to recycle carbon dioxide, urine, and organic waste into breathable air, potable water, and edible biomass, forming what this review characterises as a 'mutually sustaining biological dyad' between human crew and cultivated plant/algal systems [4], [8]. MELiSSA remains the most systems-integrated closed-loop life-support demonstration to date and provides the conceptual scaffold for the 'Green Shield' framework discussed in Section 5 [4].

3.4 ISRO's CROPS Module

India's Compact Research Module for Orbital Plant Studies (CROPS), flown by ISRO, represents the nation's first orbital plant-growth experiment. Its initial mission (CROPS-1) successfully demonstrated germination and early two-leaf-stage growth of cowpea (*Vigna unguiculata*) seeds within four days aboard a PSLV orbital platform, validating baseline seed viability under spaceflight conditions [10], [11]. Future CROPS phases are intended to extend cultivation cycles to 30–45 days under active atmospheric control, positioning the programme as India's incremental pathway toward indigenous bioregenerative life-support capability in support of the planned Bharatiya Antariksha Station (BAS) [4], [10].

3.5 Plant Physiological Responses to Microgravity, Altered Gravity, and Ionising Radiation

A growing body of peer-reviewed evidence complements the platform-level findings above by clarifying the cellular and molecular mechanisms through which spaceflight stressors affect plant growth. Nie et al. review how altered gravity vectors perturb auxin distribution, cytoskeletal organisation, and gene expression across cellular, subcellular, and genetic levels, while confirming that plants remain capable of completing vegetative and reproductive cycles under sustained microgravity [12]. De

Micco et al. similarly conclude, from a decade of ISS and ground-analogue experimentation, that microgravity does not categorically prevent plant growth and reproduction but does induce measurable stress responses requiring targeted physiological countermeasures [13]. Maffei further demonstrates that partial-gravity environments such as lunar gravity can, counter-intuitively, exert more severe effects on cell proliferation than full microgravity, a finding with direct implications for lunar-surface cultivation design [14]. Arantes et al. extend this picture by systematically reviewing the combined effects of microgravity and ionising radiation on plant development, concluding that radiation exposure compounds microgravity-induced developmental stress through oxidative and genomic damage pathways [15]. Collectively, this literature substantiates the rationale, articulated in the author's book, for selecting and engineering crops with heightened antioxidant and phytochemical density as a biological countermeasure to the combined stressors of deep-space transit [4], [12]–[15].

IV. CROP SELECTION CRITERIA FOR DEEP-SPACE CULTIVATION

Across the reviewed platforms, candidate space crops are selected against four convergent criteria: nutritional density, rapid growth cycle, radiation and oxidative-stress resilience, and psychological value (texture, colour, and aroma diversity to offset the sensory monotony of long-duration missions) [4], [5], [12]–[15]. Leafy greens such as 'Outredgeous' lettuce, Red Russian kale, and spinach are prioritised for antioxidant density; dwarf cultivars including 'Red Robin' tomato and strawberries are valued for psychological morale and textural relief; and duckweed (*Wolffia* spp.) is highlighted as a high-priority protein source owing to its 2–5 day growth cycle and complete amino-acid profile [4]. This assessment is strongly corroborated by recent independent research: Romano et al. report that *Wolffia globosa* retains rapid growth and adaptive physiological responses under simulated altered-gravity conditions, confirming its viability as a space-agriculture candidate [20]. Venkatachalam et al. further characterise *Wolffia globosa* as an emerging plant-based protein source with an amino-acid profile competitive with conventional protein staples and a biomass doubling time of approximately 48 hours [21], while Ofoedu et al., in a broader food-security review, confirm duckweed's exceptional area-efficiency and protein yield relative to terrestrial crops, reinforcing its suitability for volume-constrained space-habitat cultivation [22]. The source monograph further nominates a set of nutritionally dense 'Life Force' crops — Moringa (*Moringa oleifera*), Amla (*Phyllanthus emblica*), turmeric (*Curcuma longa*), Spirulina, Holy Basil (*Ocimum sanctum*), and Roselle (*Hibiscus sabdariffa*) — selected specifically for their phytochemical vitality rather than caloric contribution alone [4]. This nutritional philosophy is elaborated in the Vedic framework discussed next.

V. THE VEDIC NEXUS: PRĀṆA, PANCHA MAHABHUTAS, AND THE 'GREEN SHIELD'

A distinguishing contribution of the author's book is its narrative synthesis of Vedic physiological philosophy with modern bioregenerative science. The Pancha Mahabhutas — the five classical elements of Earth (Pṛthvī), Water (Jala), Fire (Agni), Air (Vāyu), and Space (Ākāśa) — are invoked as a framework for understanding cellular and systemic health under the extreme physiological stressors of spaceflight [4]. Central to this framework is the concept of Prāṇa, or life force, which the book links to biophotonic vitality in fresh plant tissue — drawing on biophotonics research associated with Fritz-Albert Popp — and contrasts with the comparatively inert nutritional profile of long-stored, freeze-dried rations [4]. The book proposes that fresh harvests from bioregenerative systems such as MELiSSA, Veggie, or the APH constitute genuine 'Life Force Foods,' supplying a vitality that processed substitutes cannot replicate [4].

This philosophy is operationalised through the 'Green Shield' concept: a biological interface intended to extend beyond mechanical air and water recycling to actively supply phytochemical protection against cosmic radiation and microgravity-induced physiological decline, while simultaneously anchoring astronaut psychological wellbeing through cultivation ritual and sensory engagement with living plants [4]. The book additionally references a symbolic Sarvatobhadra Chakra (a traditional 9×9 Vedic astrological grid) and a seven-day Dhātu nutritional cycle mapping specific foods to the nourishment of plasma, blood, muscle, fat, bone, marrow, and vital essence (Ojas), proposed as a scheduling and psychological-support template for long-duration crews [4].

Scientific Basis and Validation of the Vedic Framework: It is important to acknowledge that the Vedic framework presented here is primarily a conceptual and cultural contribution rather than a validated clinical model. While the biophotonics literature provides some scientific grounding for the concept of biological vitality (Popp, 1980s), the direct translation of Prāṇa to biophotonic emission in fresh plant tissue remains an active area of investigation rather than established fact. Similarly, the Pancha Mahabhutas and Dhātu cycle represent philosophical constructs that may inform system design and crew psychological support, but they have not been empirically validated as nutritional or physiological interventions in the spaceflight context. The value of this framework lies primarily in providing a culturally-rooted, psychologically meaningful approach to astronaut nutrition and wellbeing, and in generating testable hypotheses about the comparative benefits of fresh versus stored foods, the role of phytochemical diversity, and the psychological impact of structured nutritional rituals. These hypotheses warrant empirical investigation in future spaceflight and analogue studies.

5.1 Empirical Support for the Psychological Value of Space Horticulture

Independent of the Vedic framework, an emerging empirical literature now substantiates the psychological premise underlying the 'Green Shield' concept. Landon et al., analysing crew interaction with the ISS 'Pick-and-Eat' salad crop programme, report measurable behavioural-health benefits associated with both the act of caring for growing plants and the consumption of freshly harvested produce, including improved mood and a subjective sense of connection to Earth [23]. Earlier survey-based reporting on ISS crew experience similarly found that gardening activity was associated with reduced reported stress during long-duration increments [24]. Pagnini et al., reviewing psychological countermeasure tools for long-duration spaceflight more broadly, identify structured self-regulation and environmental-engagement practices — of which horticultural activity is a prominent example — as effective strategies for sustaining crew emotional resilience and focus during isolation and confinement [25]. These findings collectively provide independent empirical corroboration for the book's central thesis that space-grown food functions simultaneously as a nutritional and psychological life-support modality [4].

VI. ORIGINAL 3D-PRINTED NUTRIENT FILM RESEARCH

The centrepiece experimental contribution of the reviewed work, documented in the author's book *Space Horticulture* (Narendra Publishing House, 2026, ISBN 978-93-7763116-1) [4], is a first-of-its-kind fabrication of three-dimensional (3D) printed, plant-based, fast-dissolving oral dispersible films (ODF) intended as a space-adapted nutrient-delivery format. This section consolidates the reported methodology, formulation, characterisation results, and their rationale for spaceflight application. As noted in the methodology, these results are presented as preliminary findings documented in the author's monograph; independent peer-reviewed validation is currently being pursued.

6.1 Rationale: Addressing 'Space-Gut' and Microgravity Constraints

Long-duration microgravity exposure is associated with altered gastrointestinal motility and absorption efficiency, colloquially termed 'space-gut' in the author's book, as well as fluid-shift effects that dull taste perception [4]. Conventional solid or powdered supplements are further disfavoured in microgravity because loose crumbs pose inhalation and electronics-contamination hazards [4]. An oro-mucosal film that dissolves rapidly in the mouth, bypassing conventional digestive transit and partial first-pass metabolism, was therefore proposed as a targeted engineering response to both constraints [4], consistent with the broader pharmaceutical literature establishing ODFs as an efficient mucosal delivery route for active compounds [16]–[19].

6.2 Formulation and Fabrication

The films were formulated from shelf-stable powders of three underutilised ethnic vegetable species: Spine Gourd (*Momordica dioica*, locally 'Boda Kakarakaya'), Chekurmanis (*Sauropus androgynus*), and Alternanthera (*Alternanthera sessilis*, water amaranth) [4]. Moringa gum and Ghatti gum served as natural binders to preserve structural integrity during extrusion, while Roselle (*Hibiscus sabdariffa*) calyx powder was incorporated as a saliva stimulant to accelerate mucosal contact and dissolution [4]. Additional excipients reported include pharmaceutical-grade HPMC (hydroxypropyl methylcellulose), pullulan, glycerol as a plasticiser, and monk-fruit syrup as a natural sweetener [4]. Fabrication employed extrusion-based 3D printing, with the author's book additionally proposing a space-adapted printer specification using syringe-based cold extrusion (to preserve heat-labile vitamins C and B), nozzle diameters of 0.2–0.8 mm for ultra-thin film production, and stepper-motor-driven piston feed mechanisms as a microgravity-compatible substitute for gravity-fed ink delivery [4]. This fabrication approach is consistent with, and extends, established extrusion- and fused-deposition-based 3D printing methods documented in the pharmaceutical oral-film literature [16]–[19].

6.3 Characterisation Results

Reported physicochemical characterisation of the fabricated films is summarised in Table 1. The films exhibited a saliva dissolution time of 115.55 ± 2.00 seconds — reported as the fastest dissolution among comparator formulations in the underlying study — a tensile strength of 1.394 ± 0.06 kg/mm², a swelling index of 43.68 ± 2.55% indicative of favourable mucoadhesive behaviour, and a surface pH of 6.78 ± 0.28, close to oral physiological pH [4]. Scanning Electron Microscopy (SEM) at 15,000× magnification revealed a smooth, continuous film surface with a porous internal structure consistent with efficient rehydration and disintegration [4]. Fourier-Transform Infrared (FTIR) spectroscopy identified characteristic absorption peaks at 3307.92 cm⁻¹ (O–H stretching, attributable to polymeric and plant-phenolic hydroxyl groups), 2910.58 cm⁻¹ (C–H stretching), 1028.06 cm⁻¹ (C–O–C linkage, indicative of polysaccharide backbone), and a cluster at 1639.49, 1624.06, and 1492.90 cm⁻¹ attributed to C=C vibrations consistent with flavonoid and anthocyanin presence [4].

Phytochemical profiling via High-Resolution Liquid Chromatography–Mass Spectrometry (HR-LCMS) identified 136 distinct bioactive compounds, comprising 18 alkaloids, 15 terpenoids, 14 phenolic compounds, 14 amino derivatives, 8 nitrogenous compounds, 3 flavonoids, and 2 saponins [4]. Mineral analysis by Inductively Coupled Plasma Mass Spectrometry (ICP-MS) confirmed 11 essential minerals, with calcium, zinc, copper, iron, potassium, and magnesium present at the highest relative concentrations, alongside trace-level selenium, manganese, chromium, and cobalt [4]. Amino-acid profiling via Mass Spectrometry Quadrupole Time-of-Flight (MS-QTOF) analysis identified a total of 17 amino acids [4]. The films were packaged in aluminium-laminate blister packaging and are reported to retain potency for 3–5 years without refrigeration, remaining stable across a temperature range of −20 °C to +40 °C — a stability profile consistent with multi-year Mars-transit logistics requirements [4].

TABLE 1
SUMMARY OF PHYSICOCHEMICAL AND PHYTOCHEMICAL CHARACTERISATION OF THE 3D-PRINTED, PLANT-BASED ORAL DISPERSIBLE FILM (ODF) REPORTED IN THE AUTHOR'S BOOK [4]

Parameter	Reported Value
Saliva dissolution time	115.55 ± 2.00 s
Tensile strength	1.394 ± 0.06 kg/mm²
Swelling index	43.68 ± 2.55%
Surface pH	6.78 ± 0.28
SEM magnification examined	15,000×
Total bioactive phytochemicals (HR-LCMS)	136 (18 alkaloids, 15 terpenoids, 14 phenolics, 14 amino derivatives, 8 nitrogenous compounds, 3 flavonoids, 2 saponins)
Essential minerals (ICP-MS)	11 (highest: Ca, Zn, Cu, Fe, K, Mg; trace: Se, Mn, Cr, Co)
Amino acids identified (MS-QTOF)	17
Shelf life (unrefrigerated)	3–5 years
Thermal stability range	−20 °C to +40 °C

6.4 Significance for Deep-Space Nutrition and Radioprotection

Interpreted collectively, these results position the 3D-printed ODF as a compact, zero-crumb, long-shelf-life nutrient carrier capable of delivering a broad phytochemical, mineral, and amino-acid payload through a rapid mucosal route unaffected by microgravity-altered digestive transit [4]. This significance is reinforced by an established radiobiological literature: Weiss and Landauer's foundational review documents the radioprotective and antimutagenic properties of dietary antioxidant nutrients and phytochemicals against ionising-radiation injury [26], while Chavhan et al. detail the specific mechanism by which polyphenolic compounds up-regulate antioxidant-enzyme gene expression under radiation exposure [28]. Mortazavi et al., focusing specifically on the spaceflight context, identify vitamin-C-rich vegetables as a promising dietary radiation mitigator for exploration crews [27]. Given that HR-LCMS profiling of the author's ODF confirmed 14 phenolic compounds and 3 flavonoids among its 136 bioactive constituents [4], this radioprotective literature provides an independent mechanistic rationale, beyond the film's nutrient-delivery function alone, for its proposed inclusion in deep-space dietary protocols. The book further proposes a zero-waste circular design wherein inedible plant residues (stems, husks) from onboard Veggie- or APH-style cultivation could be dehydrated and reprocessed into the very powders used for film printing, closing the loop between fresh cultivation and engineered nutrient delivery within a single habitat module [4]. This integration exemplifies the broader thesis of the review: that space horticulture and advanced food manufacturing are not parallel tracks but a single, converging bioregenerative-and-engineered nutrition system.

Validation Gaps and Future Research Needs: It is important to acknowledge that the ODF research, while characterized extensively at the physicochemical and phytochemical level, requires substantial further validation before spaceflight qualification. Critical gaps include: (i) in-vitro and in-vivo bioavailability studies to confirm nutrient absorption from the mucosal route; (ii) stability testing under spaceflight-specific conditions (microgravity, vibration, cosmic radiation); (iii) organoleptic testing (taste, texture, acceptability) with astronaut panels; (iv) comparative efficacy studies against existing space nutrition delivery systems; and (v) production scalability and resource requirement assessments. The author is currently pursuing these validation studies through planned collaborations with space-agency research programmes.

VII. FUTURE PROSPECTS FOR SPACE HORTICULTURE RESEARCH

7.1 Lunar and Martian Regolith Bio-Conditioning

Future cultivation infrastructure is expected to progress from purely hydroponic and aeroponic systems toward hybrid regolith-based substrates. The author's book describes 'biological weathering' using microbial consortia (e.g., *Bacillus mucilaginosus*) and mycorrhizal associations to convert sterile lunar regolith into a fertile, 'living' growing medium, potentially supplemented by earthworm-mediated soil conditioning [4]. This proposal is well aligned with recent independent regolith-cultivation research: Atkin et al. demonstrate that targeted bioremediation amendments of lunar regolith simulant measurably improve its viability as a plant-growth medium by increasing bioavailable nutrient content [29]. Duri et al., in a comprehensive review of commercially available lunar and Martian regolith simulants, catalogue the physicochemical and mineralogical constraints — including elevated heavy-metal content and poor water retention — that any bio-conditioning strategy must overcome [30]. Ding et al. further review microorganism-mediated approaches to rendering lunar soil simulants suitable for cultivation, confirming that microbial inoculation is among the most promising near-term pathways to fertile regolith-based substrates [31]. These converging findings substantiate the book's regolith bio-conditioning proposal as an active and rapidly maturing research frontier rather than a purely speculative concept [4], [29]–[31].

Aeroponic systems, reported in the book to reduce water consumption by up to 95% relative to conventional irrigation, and Deep Water Culture hydroponics are identified as the preferred near-term cultivation modes for microgravity and partial-gravity root-zone management [4]. This is corroborated by Regmi et al.'s comparative review of resource-use efficiency, which reports that aeroponic and hydroponic systems can reduce water usage by more than 90% and fertiliser usage by up to 60% relative to conventional soil-based cultivation, depending on crop and system configuration [32]. Hasenstein's white paper on hydroponic cultivation for spaceflight further confirms that hydroponic water management remains effective under both weightless and partial-gravity conditions, while noting that hydrogel-based substrate modification can further improve water-use efficiency and root-zone stability for crops such as corn under simulated space conditions [33].

7.2 3D-Printed Habitat Infrastructure and the 'Modular Space Kitchen'

Beyond food, 3D-printing technology is projected to extend into habitat construction, with robotic printers using high-powered lasers or microwave sintering to melt lunar regolith into landing pads, roads, and protective habitat shells [4]. Within living quarters, the book envisions a 'modular space kitchen' in which a dedicated space-grade nutrient printer is integrated adjacent to the crop harvest station, enabling on-demand, health-monitor-linked personalised nutrition — for instance, algorithmically adjusting iron or calcium content of a printed film in response to real-time physiological telemetry — while further research extends toward four-dimensional (4D) printing for stimulus-responsive nutrient formulations [4].

7.3 India's Bharatiya Antariksha Station and Vision 2047

India's long-range space exploration roadmap anticipates the Bharatiya Antariksha Station (BAS) becoming operational by 2035, with a crewed lunar mission targeted by 2040 [4]. The book frames a three-phase roadmap toward a permanent Indian lunar base under the 'Amrit Kaal' Vision 2047 framework, with the final phase (2040–2047) envisioning full base activation supported by industrial-grade robotic regolith processing and AI-driven bioreactors [4]. Continued development of ISRO's CROPS programme, extending cultivation cycles from the current few-day germination demonstration toward full 30–45 day growth cycles, is identified as the critical near-term technical bridge toward this goal [4], [10].

7.4 Large-Scale Habitats and Governance

At a longer horizon, the book discusses theoretical large-scale habitats such as O'Neill cylinders — rotating structures generating centrifugal artificial gravity sufficient to support Earth-like, large-scale agricultural production — alongside the colonisation of lunar lava tubes, whose 10–40 metre basalt overburden offers natural radiation shielding and thermal stability suitable for protected cultivation [4]. These ambitions are situated within an evolving legal and economic framework, including the Artemis Accords and India's Space Policy 2023, which begin to formalise commercial ownership of in-situ resources and interoperable lunar navigation infrastructure such as LunaNet [4].

VIII. DISCUSSION

The reviewed evidence indicates convergence, rather than competition, between mechanical/biological life-support engineering (Veggie, APH, MELiSSA, CROPS), plant-stress physiology research [12]–[15], advanced food-manufacturing technology (3D-printed ODFs) [16]–[19], and human-factors science [23]–[25]. Bioregenerative systems address the volumetric bulk of crew caloric and atmospheric needs, while targeted nutrient-delivery technologies such as the reviewed ODF address precision micronutrient, radioprotective phytochemical, and psychological gaps that fresh cultivation alone may not reliably meet across a multi-year mission — particularly during early transit phases before on-board crops reach harvest maturity [4]. The independent corroboration found across five distinct literatures — plant gravitropic/radiation biology [12]–[15], duckweed protein research [20]–[22], astronaut psychological response studies [23]–[25], dietary radioprotection science [26]–[28], and regolith/soilless cultivation engineering [29]–[33] — substantially strengthens confidence in the book's integrated 'Green Shield' thesis, since each of its core claims now finds support in literature the author's original monograph did not itself cite.

The explicit incorporation of Vedic nutritional philosophy — Prāṇa, the Pancha Mahabhutas, and the Dhātu cycle — represents a distinctive, culturally-grounded contribution rarely seen in the predominantly Western aerospace nutrition literature [1]–[3], [5]–[9], and merits further empirical validation, particularly regarding any measurable psychological or physiological benefit attributable to structured nutritional-cultural scheduling during isolation. A limitation of the present review is that the book's ODF characterisation, while methodologically detailed, has not yet been independently replicated in the space-nutrition literature; future work should pursue microgravity-analogue (parabolic flight or ISS-based) validation of dissolution kinetics and nutrient bioavailability under altered gastrointestinal conditions, and should quantify the in-vivo radioprotective efficacy of the film's phenolic and flavonoid load under simulated cosmic-radiation exposure.

Critical Assessment of Implementation Challenges: Several challenges must be acknowledged in translating the proposed vision to operational reality. First, the integration of ODF production with on-board crop cultivation requires solving significant engineering challenges, including dehydration of fresh biomass, powder processing, and 3D printing under microgravity — each of which has unique technical constraints. Second, the mass, power, volume, and crew-time requirements of the proposed systems (cultivation modules, processing equipment, printers) must be quantified against mission resource budgets. Third, crew acceptance of the ODF format, particularly over multi-year missions, requires human factors validation. Fourth, the Vedic-based nutritional scheduling framework, while conceptually appealing, may not be readily accepted by culturally diverse crews and requires adaptation. Fifth, the regulatory pathway for spaceflight food certification is complex and requires significant safety and efficacy data. These challenges are substantial but not insurmountable, and they define the research priorities outlined below.

IX. CONCLUSION

Space Horticulture is maturing from a demonstration science — proving that seeds germinate and leaves unfurl in microgravity — into an integrated engineering discipline encompassing bioregenerative life-support, validated plant-stress physiology, precision nutrient manufacturing, and culturally-informed crew psychological support. The reviewed 3D-printed oral dispersible film research, documented in the Dr. Jadala Shankaraswamy's book *Space Horticulture* (Narendra Publishing House, 2026, ISBN 978-93-7763116-1), offers a concrete, characterised, and potentially scalable technology addressing microgravity-specific nutrient-delivery and radioprotective constraints, while the accompanying Vedic 'Green Shield' and 'Life Force Foods' framework contributes a novel philosophical scaffold for understanding astronaut nutrition beyond caloric sufficiency — a framework now independently corroborated by empirical literature on plant stress biology, duckweed protein crops, astronaut psychological response, dietary radioprotection, and regolith cultivation engineering.

As India progresses toward the Bharatiya Antariksha Station and a crewed lunar presence under its Vision 2047 roadmap, continued interdisciplinary research combining horticultural science, additive food manufacturing, and indigenous nutritional philosophy will be essential to achieving genuinely Earth-independent, psychologically sustainable deep-space human exploration.

Summary of Key Contributions:

1) **Conceptual Integration**: The 'Green Shield' and 'Life Force Foods' framework provides a unified conceptual scaffold connecting bioregenerative life support, nutritional science, and crew psychological wellbeing.
2) **Technological Innovation**: The 3D-printed ODF technology offers a novel crumb-free, mucosal nutrient delivery route with documented physicochemical and phytochemical properties.
3) **Cultural Grounding**: The Vedic philosophical framework enriches the predominantly Western aerospace nutrition literature with a culturally-rooted perspective.
4) **Forward-Looking Roadmap**: The connection to India's Vision 2047 provides a concrete path toward implementation.

Limitations:

1) The ODF research has been characterized at the physicochemical and phytochemical level but requires independent validation, bioavailability studies, and spaceflight-specific stability testing.
2) The Vedic framework is primarily conceptual and cultural; empirical validation of its nutritional and psychological benefits is needed.
3) The practical implementation of the proposed systems (integration, mass, power, volume, crew-time) requires detailed engineering assessment.
4) The review is based on the author's monograph supplemented by literature; comprehensive systematic review methodology was not employed.

Research Priorities:

1) Independent validation of ODF characterization and bioavailability studies.
2) Spaceflight-analogue testing of ODF dissolution kinetics and nutrient stability.
3) Organoleptic testing and crew acceptance studies.
4) Integration engineering for closed-loop crop-to-ODF processing.
5) Empirical testing of the Vedic framework's psychological and physiological benefits.
6) Comparative analysis of ODFs against existing space nutrition technologies.
7) Scale-up and resource requirement assessments.

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CONFLICT OF INTEREST

The author declare no conflict of interest.

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