Mini-review

Gravitational biology and space life sciences: Current status and implications for the Indian space programme

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This paper is an introduction to gravitational and space life sciences and a summary of key achievements in the field. Current global research is focused on understanding the effects of gravity/microgravity on microbes, cells, plants, animals and humans. It is now established that many plants and animals can progress through several generations in microgravity. Astrobiology is emerging as an exciting field promoting research in biospherics and fabrication of controlled environmental life support systems. India is one of the 14-nation International Space Exploration Coordination Group (2007) that hopes that someday humans may live and work on other planets within the Solar System. The vision statement of the Indian Space Research Organization (ISRO) includes planetary exploration and human spaceflight. While a leader in several fields of space science, India is yet to initiate serious research in gravitational and life sciences. Suggestions are made here for establishing a full-fledged Indian space life sciences programme.

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1. Introduction

Life has evolved in the past four billion years under the influence of the Earth's massive field of gravity. Several features of life were shaped by gravity as organisms adapted to living in water, air, land and on trees. Gravitational biology explores how organisms perceive and respond to gravity and how gravity influences the structure, development, function, evolution and behaviour of organisms (Morey-Holton 2003). The space age allowed for experiments in microgravity environment and the emergence of space life sciences including fields such as human space physiology and medicine. 'Space biology' is often used as an alternate expression by researchers and journals (e.g. *Gravitational and Space Biology*) to describe the functioning of all life processes in space environment. Gravitational biology and space exploration have stimulated enduring interest in astrobiology, which addresses questions such as how does life begin and evolve, does life exist elsewhere in the universe, and what is the future of life on Earth and beyond (Des Marais *et al.* 2008; Lucas 2009).

2. Gravity and life

Of the four fundamental forces, only electromagnetism is directly involved in biological processes. No direct role is known either for the strong or weak nuclear forces or gravity in any biochemical process. Gravity influences living organisms indirectly. The gravitational force is 10^{38} times weaker than the strong nuclear force. However, gravitational force is of infinite range, and positively acts on all particles with mass/energy. Any object with a mass at the surface of the Earth accelerates towards Earth's centre at approximately 9.81 m/s^2. This acceleration due to gravity at the Earth's surface is generally treated as $1g$ (one Earth gravity). The dilemma of growing in a $1g$ environment and responding to it can be seen in nearly 400-million-year-old fossil vascular plants and their descendants. On land, roots became positively gravitropic to obtain water and nutrients

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from the soil. The negative gravitropism of shoots and various branching angles and the characteristic tree architectural patterns evolved for efficient access to carbon dioxide and light and strategic placement of reproductive structures for pollination and dispersal. The mechanical load due to gravity is about a thousand times larger for land-living organisms than for those living in water. In response to this increased load, plants might have evolved 'antigravitational' substances such as lignin, cellulose and pectin, while animals strengthened their bones with hydroxyapatite mineral form of calcium associated with collagen (Volkmann and Baluska 2006). Plant gravitropism has been studied for the past 200 years (Kiss 2006; Hasenstein 2009; Moulia and Fournier 2009).

In the animal kingdom, response to gravity has been studied in all major groups. Organs such as the antennal sensilla of Johnston's organ in insects and the vestibular apparatus of higher animals detect gravity for proper orientation and gravitaxis (=geotaxis) movements. The musculo-skeletal system evolved to support the body mass and provide structural and postural stability to land animals as they moved about in search of food. The sensory-motor system evolved so that organisms could recognize the gravity vector and orient themselves and move about. A vestibular system evolved in fish for efficient swimming. The versatile design of this system, with minor modification in nerve-motor connections, was retained by amphibians, reptiles, birds and mammals for navigation in water and air and on trees and land. Human beings have inherited many of these evolutionary adaptations (Highstein *et al.* 2004). The vestibular system is the key to the human senses of balance, motion, and body position. The otolith organs allow humans to sense the direction and speed of linear acceleration and the position (tilt) of the head. The semicircular canals help sense the direction and speed of angular acceleration (Coulter and Vogt 2004). As a bipedal erect animal, the genus *Homo* had to adapt to gravity for at least 2.4 million years. Their ancestral bipedal hominins faced this dilemma nearly 7 million years ago. The cardiovascular system helped maintain adequate pressure and supply of blood to various parts of the body, especially the head. The normal and healthy life of humans is conditioned at least in three different ways by the 1*g* environment of Earth: (a) by experiencing a pull of the *g*-force in the head-to-toe direction, (b) through various normal physical activities of exertion against the *g*-force, and (c) through changes experienced during oriented movements/postural changes (Legner 2003).

3. Tools of space life sciences

In the past 500 million years, the estimated 30 million living and the more than 600 million extinct species never experienced life in the absence of the 1*g* gravity. The ability to increase or decrease the *g*-force is a recent human invention and is at the core of the science of gravitational biology. Only in the past 50 years has it been possible to carry out direct experiments for long periods in authentic or actual microgravity environments available in orbiting vehicles. On Earth extended periods of weightlessness can only be simulated with clinostats since the 1*g* force is ever present. A clinostat does not 'nullify' the force of gravity but 'compensates' for it by slowly and constantly rotating an organ in a position horizontal to the plumb line. By providing 1–3 rpm, plants are prevented from experiencing the minimal sensing or presentation time required to respond to gravity. Most gravitropic responses in plants have a minimum presentation time of 0.15–3 min. More sophisticated 3 D or three-axis clinostats (Random Positioning Machines) based on the principle of 'gravity vector averaging' are now routinely used. Recently, a novel Free Fall Machine has been developed that simulates a free fall environment for ground-based experiments (Mesland *et al.* 1996). Centrifuges provide variable hyper-gravity forces greater than 1*g* (Clement and Bukley 2007). Our knowledge of the effects of microgravity on cells, microbes, plants and animals are derived from a comparison of experiments conducted in space vehicles with ground controls in 1*g*. Onboard centrifuges in space vehicles are also used to provide *g*-forces from near zero to more than 1*g* to be used as controls in microgravity environments.

An actual microgravity environment can be provided for short duration by generating free fall conditions close to the Earth's surface with sounding rockets and airplanes in parabolic flight and drop facilities (Clement and Slenzka 2006). Above-ground drop towers and below-ground drop shafts are ground-based facilities that can provide free fall microgravity conditions lasting several seconds. Because of the very short durations of free fall, biological uses are limited to some biotechnological studies. Balloon flights can be used only to study the effects of cosmic rays up to an altitude of 40 km. At this distance balloons do not provide an effective microgravity environment.

Space vehicles are unique biological laboratories. Space biology experiments are generally carried out in low Earth orbits (LEO), at altitudes less than 1% of the distance from the Earth to the Moon. Familiar LEO vehicles are Sputnik I (215 km), ISS (350 km), Mir (390 km) and space shuttles (300–400 km). At a distance of about 300 km above the Earth, the force of gravity is still as high as 90% as on Earth. However, space vehicles moving in circular LEO experience actual microgravity environments because they are in free fall. The centripetal force towards the Earth is balanced by the centrifugal acceleration, resulting in free fall.

The environment of a pressurized space vehicle is unique and challenging to astronauts' safety, health and efficiency (Legner 2003). Gravity field is typically 10000 to a million times less than the 1*g* of Earth. The 24 h day–night cycle is lacking, thereby affecting the normal circadian rhythms. Breathable oxygen is lacking and should be supplied. Space crews are at risk of exposure to ionizing radiation from particles trapped in the Van Allen belts, galactic cosmic rays from outside the solar system and radiation originating from solar particle events. Vibration, acoustics, atmospheric contaminants, magnetic fields, and stress during launch and re-entry can be additional complicating factors. Yet, the exceptional environment of a space vehicle has been used to study the effects of gravity on cells, tissues and representative organisms from all kingdoms of life.

4. Age of space biology

The Space Age dawned in 1957 when Sputnik I was launched successfully into orbit around the Earth. This was followed by space flights of Gagarin and Shepherd in 1961 and Glenn in 1962. The history of animals in space, however, is more than 228 years old! In 1783 a French team sent a rooster, duck and sheep on a hot air balloon and successfully recovered them. Tipton (2003) describes the history of animals in space under three eras—balloon, rocket-missile and biosatellite. The choice of animals before the 1960s was based on accepted contemporary model systems to test radiation effects or physiological response to stress during launch and while in microgravity. Table 1 employs Tipton's classification, extending it to biological experiments in space on animals, plants and microbes of the present. The various eras, satellites and organisms cannot be clearly compartmentalized and they can, and do, overlap. However, this chronology does indicate the major trends in the progression of research in space biology during the past 80 years.

The 'Space Station Era' began nearly 40 years ago in 1971 with the launch of the Soviet Salyut and continues today with the ISS. This era was unique because astronauts and payload specialists were directly involved in conducting experiments onboard vehicles such as the Mir, Skylab, Spacelab and the ISS (Legner 2003). As of April 2009, a total of more than 400 investigations including 200 in life sciences have been conducted on ISS. Our knowledge of the long-term response of plants in space is derived from the use of onboard growth chambers such as the Svet on Mir and Lada on ISS. Other important onboard facilities of the ISS include the European Modular Cultivation System, Plant Generic Bioprocessing Apparatus (PGBA), Advanced Astroculture Chamber (ADVASC), Biomass Production System (BPS) and the bioreactor, Cellular Biotechnology Operations Support System (CBOSS). The latest in this series is JAXA's HydroTropi experiment on ISS to test the role of hydrotropism in directing root growth in cucumber

Table 1. Chronology of biological experiments in space

Years and Era	Satellites	Comments
1930–1960 Balloon era		Fruit flies, crustaceans, guinea pigs, hamsters, rats, mice, cats, dogs, pigs, primates, cultures of tissue from retina, nerve and skin to study radiation effects
1946–1962 Rocket-missile era		Microbes, insects, mice, rats, guinea pigs, rabbits, dogs, monkeys, chimpanzees
1957	Dawn of Space Age	Sputnik 1 on October 4th
1961/1962	First human space flights	Gagarin, Shepherd, Glen
1961–1997 Biosatellite era	Biosatellite (1967)	Frog eggs, amoeba, bacteria, wheat seedlings
	Cosmos (1966–)	Microorganisms, plants, fruit flies, mice, two dogs. Observed calcium depletion, lowered cardiac output and body mass
	Bion-Cosmos (1973–1997)	Bacterial spores, mushroom cultivation unit, rats, beetles, tortoises, monkeys
	Foton (1985)	Foton M / Foton M4 (use by ESA, etc.)
1971– Space Station era	Salyut (1971–1982)	Humans flown with experimental modules
	Skylab 1 (1973–74)	Saturn/Apollo Total 171.5 days 300 experiments
	Spacelabs (1983–2000)	Part of 6 shuttle missions with payload specialists, 6–10 days each
	Mir (1986–2001)	15 years, Shuttle-Mir cooperation, continuously occupied for 9 years. Wheat and mustard from seed to seed in Svet growth chamber
	ISS (1994/2000-)	Growth facilities: Lada, EMCS, PGBA, ADVASC, BPS, CBOSS 400 experiments (200 life-science) SPACEHAB for transportation
2006– Nanosatellite era	GeneSat-1 (2006)	Bacterial genetics
	PharmaSat (2009)	Yeast growth and resistance to antifungal agent
	O/OREOS (2010)	Growth of microbes/ stability of organic molecules (SESLO/SEVO)

in an experiment: 'Hydrotropism and auxin-inducible gene expression in roots grown under microgravity conditions'.

A new generation of nanosatellites is now emerging as the most economical means of carrying out specific experiments that previously required space crafts such as ISS or shuttles. Nanosatellites cannot replace either the ISS or similar fabrications and various spacecrafts that will continue to transport humans and allow onboard experimentation. However, nanosatellites have ushered in a new era for carrying out certain kinds of experiments, remotely controlled, without any onboard payload specialists. Dedicated single-launch vehicles were launched even before the Space Station era. For example, the US Orbiting Frog Otolith (OFO) satellite was launched in 1970 for investigating vestibular response in frogs. However, the concept of microsatellites became a reality only recently, since the launch of a fully automated GeneSat in 2006 to study genetic changes in *Escherichia coli* in space. Miniaturized and autonomous satellites range in size from less than 1 kg (pico) to 10 kg (nano) to up to 200 kg (micro). They are designed to initiate and carry out biological experiments and report results, obviating the need for the presence of a payload specialist. NASA launched the PharmaSat nanosatellite in 2009 to study the growth of yeast (*Saccharomyxes cerevisiae*) and study how microgravity alters its resistance to the antifungal agent voriconazole. In 2010 NASA launched a nanosatellite about the size of a loaf of bread weighing 5.5 kg and designated O/OREOS for Organism/Organic Exposure to Orbital Stresses. It carried two experimental modules. The SESLO (Space Environment Survivability of Live Organisms) module was designed to study the growth and functioning of two species of microbes (*Halorubrum chaoviatoris* and *Bacillus subtilis*) in space environment. The Space Environment Viability of Organics (SEVO) is designed to test the stability and changes that may occur in four classes of organic molecules exposed to UV, visible light, trapped-particle and cosmic radiation.

5. Some key findings in gravitational/space biology

The conference on *'Gravity and the Organism'*, held in 1967, examined the contemporary knowledge and laid a sound foundation for future work in gravitational biology (Gordon and Cohen 1971). Key findings in gravitational and space biology prior to 1990 are summarized in Brown (1991). The major findings during the past decade are summarized in this section (Clement and Slenzka 2006; Roux 2009; Souza *et al.* 2009; Doarn *et al.* 2010).

A recent study has established that the small size of microbes help them withstand extreme hypergravity conditions (Deguchi *et al.* 2011). Young plants can tolerate only about 10 min exposure to 40*g*, while 20*g* can be lethal for rats. Four species of bacteria and the yeast *Saccharomyces cerevisiae* could proliferate even at 20000*g*. *Paracoccus denitrificans* and *E. coli* survived and even proliferated at 400000*g*. A major conclusion from recent experiments with cell culture on bioreactors such as CBOSS on ISS is that many cell types—human blood, kidney, liver, tonsil, immune system tissue and colon cancer cells—can be cultivated in microgravity and that such cells have normal form and function as cells and tissues have in ground controls. Motile flagellates such as *Chlamydomonas* and *Euglena* and ciliates such as *Paramecium* and *Loxodes* show gravitactic movement in response to gravity. The International Microgravity Laboratory experiments on Columbia and parabolic rocket flight experiments have shown that gravitaxis in these organisms require a threshold of 0.16*g*. These organisms lack sedimentable statoliths and the entire cytoplasmic content might exert pressure on the lower membrane, leading to movement in relation to gravity vector (Hader *et al.* 2003).

Recent research strongly supports the involvement of starch statoliths and differential distribution of indole-3-acetic acid (IAA) in plant gravitropism (Hasenstein 2009). Plants require a presentation time of 10–200 s before amyloplasts can sediment and lead to polar auxin transport and differential growth. The plant-specific pin-formed (PIN) family of auxin efflux transport-facilitator proteins appears to mediate polar auxin transport. Five such transmembrane PIN proteins are expressed in plants, PIN2 being unique to root gravitropism. Signal transport in gravitropism may also be mediated by the permeability glycoprotein (PGP) transporter of the ATP-binding cassette transporter (ABC) family (Ottenschläger *et al.* 2003). The mechanism of the initial phase of perception that triggers subsequent transduction and response remains unresolved. The concept of cellular tensegrity (Ingber 2003) provides a hypothetical framework for further research on identifying sub-cellular events that occur during gravity perception. Statocytes, like other cells, possess a three-dimensional cytoskeletal network composed of thin actin microfilaments, microtubules and intermediate filaments. In this model the statocytes are stabilized by a tensed tensegrity framework of cytoskeletal molecular 'struts', 'ropes' and 'cables' at the nanometer scale. It is proposed that sedimenting amyloplasts locally disrupt and modify the tension of actin filaments within the statocytes, thereby activating mechanosensitive ion channels at the plasma membrane.

Microgravity affects normal plant growth by interfering with the supply of water, minerals and oxygen and the removal of carbon dioxide from the root zone. These problems are now overcome by development of appropriate delivery systems (Wolverton and Kiss 2009). Ethylene gas functions as a natural plant hormone at low concentrations of 0.04–1.0 mg/m^3. Ethylene build-up inside the space vehicle was found to be the major cause of reproductive failure in microgravity. When ethylene concentration is controlled, wheat, peas and *Arabidopsis* plants could be successfully cultivated to produce viable seeds in space. Potato leaf and stem cuttings were cultured in Astroculture facility and mini-tubers were harvested. The tuber size, morphology and starch granules were all similar to those of ground controls.

A major achievement in cultivation of plants in microgravity during the past 20 years is the successful production of more than one generation of plants (Souza *et al.* 2009; Wolverton and Kiss 2009). Seeds of *Brassica rapa* germinated in microgravity produced normal plants and viable seeds. Successful growth of a cereal plant in space was first demonstrated in 1998–1999 with *Apogee-USU* wheat grown in the Svet greenhouse on Mir (Levinskikh *et al.* 2000). From 12 normally developed plants, 508 normal seeds were collected, and these were used to establish the next generation of wheat plants in space. In 2004–2005 *Arabidopsis thaliana* was successfully grown in the Astroculture greenhouse to obtain seeds of the third space generation. It appears that microgravity does not adversely affect genetically determined developmental processes and that as long as the environment of the cabin is controlled, growth and development of plants might proceed normally without affecting important processes such as gas exchange, photosynthesis and reproduction. The growth of four consecutive generations of peas in space has given the confidence that food plants can indeed be grown for space travel and colonization. Future studies will observe genetic changes and microevolution over extended periods in microgravity. Unusual and unexpected responses, too, were observed. Normally the apical cells of the protonemata of the moss *Ceratodon purpureus* are negatively gravitropic. One would expect a random growth in microgravity. However, two shuttle experiments revealed an unusual spiral growth pattern (Kern *et al.* 2005). A miniature rose that bloomed in microgravity in the Astroculture growth chamber on a shuttle produced unique essential oils and a rose fragrance that was subsequently commercialized.

About 40 different animal species have so far been flown in space. Invertebrates such as jellyfish, sea urchins and pond snails have been used to study fertilization and development of graviperceptors. *Caenorhabditis elegans* can reproduce and progress through several generations in microgravity without major structural changes. Recent studies on *C. elegans* maintained for 11 days on ISS has revealed that the RNA interference treatment that regulates gene expression in diseased tissue functions normally in microgravity, thus offering hope for treatment and control of muscle degradation (Etheridge *et al.* 2011). Currently, fish, birds, amphibians and small mammals are the favourite organisms for developmental studies in microgravity. Medaka (*Oryzias latipes*) and swordtail fish (*Xiphophorus helleri*) were studied onboard the Spacelab for embryogenesis and otolith development. In microgravity fish exhibit a peculiar looping behaviour. Successful mating of Medaka in microgravity was first observed in 1994. Viable embryos resulted and the fry had no abnormalities. Normally, the fertilized eggs of frogs rotate before further development. In reduced gravity frogs were found to ovulate but the fertilized eggs did not rotate. Yet the tadpoles emerged and appeared normal and, when returned to Earth, metamorphosed and developed normally (Morey-Holton 2003). The Japanese quail (*Coturnix coturnix*) is another favourite space animal and a potential source of food for future space colonies. On Mir, fertilized quail eggs developed normally but the hatchlings had trouble orienting. A chick would spin and tumble unless held by an astronaut. In young rats bone loss, accompanying muscle loss and delay in bone fracture repair are serious adverse effects of microgravity. Such studies have helped develop countermeasures for long-term human occupation of space vehicles (Morey-Holton *et al.* 2007).

Human beings can tolerate only $4g$ to $5g$ for up to 10 min. During launch and reentry humans normally experience $3g$ conditions. Hypergravity above $50g$ even for a few seconds causes serious injury or death. In an orbiting space vehicle microgravity field is typically in the range of $10^{-6}g$ to $10^{-4}g$. This has a deconditioning effect leading to abnormal physiological changes (Clement 2003; Davis *et al.* 2008). Calcium depletion can lead to up to 1–2% loss in bone density per month. Muscle fibre loss can lead to up to 40% reduction in muscle function. In addition, space radiation, sensory deprivation and absence of circadian clues and the artificial environment all have adverse effects on human beings (table 2). While most conditions disappear on return to Earth, some, such as bone calcium loss, take a long time to recover or never do so. Experiments with centrifuges have shown that intermittent exposure to $0.5g$ at the foot level in a 4 m radius centrifuge rotating at 10 rpm can overcome the deconditioning effects of a microgravity environment in a space vehicle. The required g can be generated in onboard centrifuges; the spinning of a space vehicle itself may also generate the required g. That humans can indeed stay for extended periods in microgravity is shown by the fact that Mir was home for 125 astronauts from more than a dozen countries while 196 astronauts from 8 different countries have visited the ISS from 2000 to 2010. A single cosmonaut has stayed in Mir for more than 435 days.

NASA currently addresses human health and safety issues through its Human Research Program (NASA 2011), which consists of three major areas of study with sub-disciplines: physiology (bone health, muscle function, cardiovascular response, sensorimotor, immunology, behavioural health and performance), environment (human factors and habitability, lunar dust, microbiology, radiation), and technology (exercise, food and nutrition, exploration medical capability). Prospects

Table 2. Summary of major health risks in microgravity and space

Causes	Medical Risks
Microgravity ($10^{-6}g$–$10^{-4}g$)	Calcium depletion, osteoporosis, loss of mechanical strength, kidney stone formation, hip and spine problems; muscle atrophy and low contracting capacity; cardiovascular changes such as shift in body fluids, blood volume and heart rhythm irregularities; depression of immune system
Space radiation (ionizing radiation, galactic cosmic rays, solar particle events)	Mutation due to chromosomal, DNA damage, ageing, cancer, cell death, acute or chronic radiation sickness, cataracts, vision impairment, nervous system disturbances
Sensory deprivation, Absence of circadian rhythms	Psycho-neurological, 'Space Adaptation Syndrome', disorientation, nausea, vomiting, desynchronosis (jet lag, sleep disorder)
Artificial Environment	Hypo- and hyperoxia, hypo- or hyperthermia, conditions of intoxication, psychological trauma, bacterial and fungal infections, antibiotic resistance, harmful effects of lunar dust, decompression sickness and barotrauma
Accidents	Damage, trauma, stress, loss of consciousness, death

of return to lunar surface and long-term space missions require that in addition to safety and countermeasures advanced technologies, diagnostic devices and remote-controlled protocols be developed for astronauts themselves to solve problems, respond to emergencies and self-administer medical care.

6. Bioregenerative systems—plants, people and microbes

In this 50th year of the first human space flight, astrobiological questions are being asked (Morey-Holton 2003). Are the low levels of gravity force on the Moon (1/6 g) and Mars (3/8g) sufficient for providing threshold levels for normal functioning of plants, animals and humans? Can life continue to evolve in such low gravity fields and return to Earth and successfully adapt to Earth's 1g environment? In 2006, 14 national space agencies joined together as the International Space Exploration Coordination Group and formulated the document: *The Global Exploration Strategy: The Framework for Coordination* (ISECG 2007). The emerging international cooperation aims at generating knowledge, technology and strategies for space exploration and establishing colonies on Moon and Mars within the next 20–30 years. Mars poses many challenges for humans: a hostile and lethal atmosphere, ionizing radiation, low gravity and light and prolonged isolation from familiar community, lifestyle and biodiversity. The most challenging of all problems of colonizing any extraterrestrial body is providing a permanent life support system. An ambitious theoretical proposal is to terraform a planet by converting the surface and climate to make them suitable for life (Fogg 1995; Davies *et al.* 2003). The assumptions and feasibility of terraforming are a matter of speculation today.

A more realistic approach is to construct a complete life support system, variously known as Bioregenerative Systems (BRS), Controlled Environmental Life Support System (CELSS), Sustainable Ecological Life-Support System (SELSS) and Advanced Life Support System (ALSS). A BRS is based on the fundamental principles of biospherics, namely, imitating the ecological and environmental elements that make life self-sustaining in the Earth's biosphere (Eckart 2010). The three major components of a bioregenerative life support system are plants, people and microbes. Plants produce biomass including edible food, release oxygen during photosynthesis and transpire water that can be condensed and collected. People consume food and use oxygen but release carbon dioxide and water and solid waste as urine and feces. People also use water for washing and bathing and this is termed as 'gray water.' The human waste, inedible biomass from plant and the gray water can all be used in a microbial bioreactor for recycling into nutrients and carbon dioxide. Plants in turn can use the carbon dioxide released by humans and microbes for photosynthesis and also the nutrients from the bioreactors and some of the gray water for their growth. Prototypes of CELSS under development include NASA's vegetable production system for long-distance space travel (VEGGIE) and the Bio-regenerative Planetary Life Support Systems Test Complex (BIO-Plex) that can partially recycle human waste and recover oxygen and water required for the astronauts, and ESA's Micro-Ecological Life Support System Alternative (MELISSA) and First Extraterrestrial Man Made Ecosystem (FEMME). Plants in a BRS can also help create a breathable environment. Several common houseplants have now been shown to purify air by removing formaldehyde, ammonia, benzene and several other substances through their stomata (Wolverton 1996). They can also remove some of the volatile bioeffluents emitted by humans. There is growing interest in biospherics as shown by the publication of *Habitation*, an international journal.

Current research is also focused on how plants respond to hypobaria, or low pressure. Atmospheric pressure on Lunar and Martian surface is less than 1% of that on Earth. Plants interpret low pressure as conditions of aridity and activate drought-sensing genes even if water is plentiful and humidity is high. This may lead to closure of stomata, poor photosynthesis and leaf shedding. The thin atmosphere, space radiation and particle bombardment will seriously affect human and plant health on Mars. It has been suggested that first human and agricultural settlements could be underground or in natural Martian caves such as those around Arsia Mons. Light may be piped down from solar collectors, and plants grown initially hydroponically (Salisbury *et al.* 2002). Carbon dioxide is not a constraint since the Martian atmosphere consists of 95% of this gas. Recently Chandrayaan-1 spacecraft detected a large cave on the Moon which has been suggested as a potential place for a future lunar outpost.

Growing plants in space in BRS is popularly described as space farming. 'Space crop plants' should be nutritious, highly efficient in utilizing low light, compact in growth habit, resistant to microbial diseases and have high harvest index (NASA Science 2001). Such plants, already cultivated in space vehicles, include rice, wheat, and salad leafy greens and vegetables such as lettuce, spinach, peppers, mustards, tomatoes, onions, Swiss chard, broccoli, radishes, potatoes, sweet potatoes, peanuts, soybean, cowpea and strawberries. Super-dwarf cultivars of wheat (*Apogee* and *Perigee*) and rice have been developed, and *Apogee* wheat has already been grown from seed to seed in microgravity. Ornamental plants such as tulips are considered to be ideal for aesthetic and positive psychological ambience. When India takes up space biological studies it will find that common greens such as species of *Amaranthus* and *Alternanthera sessilis* and *Mentha spicata* qualify as ideal space plants. It is estimated that a 5 year mission to Mars would require about 3125 kg of food per astronaut. This could be met if food is produced in space in BRS and the astronauts themselves process and cook some of their meals. Plants such as lettuce, cabbage, spinach, carrots, tomatoes, spring onions, radishes, peppers, strawberries and some herbs could be cultivated in space. Some harvested food can also be processed and sent in advance in unmanned spacecrafts to Mars.

7. Towards an Indian space life sciences program

India is an acknowledged leader in space science and technology but not in space life sciences. Gravitational biology and space life sciences are not taught in any Indian university. ISRO's space biological studies are limited to a balloon-based experiment carried out in 2001 and repeated in 2005, and the forthcoming Space Capsule Recovery Experiment (SRE-II). The balloon experiment collected samples from the stratosphere between 20–41 km. Twelve bacterial and six fungal colonies were recovered, which included three new species of bacteria: *Janibacter hoylei*, *Bacillus isronensis* and *Bacillus aryabhata*. The SRE-II will carry out three different biological experiments in microgravity. The biological effects of microgravity on growth of *E. coli* will be studied using genomic and proteomic approaches. The effect of microgravity on the photosynthetic ability of cyanobacteria will be studied by ISRO and JAXA along with scientists of the Centre for Cellular and Molecular Biology. The third experiment proposes to expose seeds of rice and some medicinal plants to microgravity and space radiation and compare their seedlings with ground controls (*see* ISRO Website). Some research had been carried out in academic institutions on gravitropism in dicot seedlings and grass leaf-sheath pulvini (Dayanandan 1989).

ISRO's 'Space Vision India 2025' statement of 2009 includes Planetary Exploration and Human Space Flight Programme (HSP). An ISRO Orbital Vehicle might carry a 2–3 member crew to a LEO before 2020, and an astronaut training centre would be established in Bangalore by 2012. ISRO plans to launch its LEO winged Reusable Launch

Table 3. Current research interests in gravitational biology and space life sciences

Major disciplines	Research specialization
Concepts and theories	Cosmology, evolution, gravity, microgravity
Instrumentation and facilities	Artificial gravity, clinostats, centrifuges, space vehicles, growth chambers
Gravity and biology	Organics, cells, microbes, extremophiles, nematodes, insects, amphibians, birds, rodents, mammals, plants, genetics, developmental biology
Space biotechnology	Technology for biomolecular systems, nanotechnology, maskless array synthesizer/ automated gene sequencer, bioexploration, biotelemetry transmitters, Stanford cell-based biosensor, GMO
Astrobiology	Exobiology, astrobiology, Moon and Mars environments, human colonization
Life support systems	Biospherics, controlled and advanced life support systems, BRS, food and nutrition, microbes, space plants, bioreactors
Space environment	Radiation effects, satellite and space station environments, chronobiology, organic synthesis
Human space physiology and medicine	Cardiovascular system, pulmonary system, musculoskeletal and motor control, neural, sensory, autonomous and sympathetic nervous systems, immunology, endocrinology, fluid regulation, thermoregulation and metabolism, deconditioning effects, space medicine, countermeasures

Vehicle-Technology Demonstrator (RLV-TD) in 2011. This shuttle facility will be a key resource for space life sciences experiments. All these emerging interests necessitate the establishment of a comprehensive Indian space life sciences program. Table 3 lists fields of research currently addressed by leaders in space life sciences. India too should initiate research in these fields.

Space biology has potential applications in medicine, biotechnology, molecular synthesis, crop improvement, alternate agricultural systems, nutrition and food preservation and improving environmental quality and sustainability of life. Technological development can lead to space product development and technology transfer benefiting society (Hertzfeld 2002). Research in space biology may provide solutions to common problems such as shrinking productive land, low crop yield, pollution and vector-borne diseases. Gravitational and space biology is a multidisciplinary field drawing expertise and inspiration from such diverse fields as astronomy, physics, biology, medicine, material sciences, nanotechnology, agri-horticulture and information technology. It has the potential to ignite young minds, including school students, thus promoting interest in science and scientific temper.

With clear mandate and adequate funding research can be initiated in universities and especially in ISRO and its units such as Space Application Centre, Indian Institute of Space Science and Technology, the proposed astronaut training centre and through Vikram Sarabhai Space Centre's RESPOND programme (Dayanandan 2011). Government agencies should encourage and fund research and popularize space life sciences. Western science emerged in the backdrop of a linear and limited concept of time and history. This did not deter the exploration and establishment of a view of the world immensely large and deep in time and locating humans as agents in a cosmic future. India will bring to science a worldview already steeped in enormous space and time scales, and gives new meaning and dimensions to space exploration and a future of excitement, anticipation and hope.

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