# A Look at the Near Future: Industry 5.0 Boosts the Potential of Sustainable Space Agriculture

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***Abstract*—Colonization of man surpasses the tropospheric atmosphere of Earth and is targeting to create new generation of people in space, particularly Mars, in the future. This relies on the metabolic needs which include oxygen for breathing, and water and food for astronaut diet. The key aspect to achieve this goal is to employ sustainable agriculture even inside a spacecraft as it requires additional food supply when transporting more people from Earth to Mars in this case, given longer travel time is expected. Terrestrial-based agricultural technologies that are currently being utilized are brought by Industrial Revolutions (IR) 4.0 and 5.0. However, the knowledge on the interventions of IR 5.0 technologies is still fractional in relation to its potential for space farming. This study discusses the comparative differences of IR 4.0 and 5.0 in relation to its impacts to farm labor, cultivation and post-harvest system, green products and services, and agricultural supply chain; a systematic analysis of space farms on spacecraft and planetary surfaces as the exact future of farming; the dissection of foreseeable challenges and the roles of government, private industries and academic and research institutions for interleaving IR 5.0 and space agriculture; and the future directives concerning IR 5.0 technologies as tools for bioregenerative life support system and circular manufacturing. Here, the context of sustainable space agriculture is limited only to the adaptable technologies. Hence, this study established a framework that IR 5.0 can boost sustainable space farming in terms of adaptive cropping system, robot-based operations, and carbon neutrality.**

***Keywords—agriculture, astrobotany, future farming, Industrial Revolution 5.0, sustainable space farming***

## I. INTRODUCTION

Industrial Revolution (IR) 4.0 is prevalent as modern cutting-edge technologies (CETs) are being utilized in majority of aspects of multifaceted production systems. CETs including Internet of Things (IoT), big data, cloud computing, AI, and blockchain brought system efficiency on a much higher scale of productivity. On the other hand, Industrial Revolution 5.0 aims to bring back human role in synergy with CET, in contrast with IR 4.0 where human workforce is lessened on repetitive tasks. In IR 5.0, higher human skill, intelligence, and creativity is needed for optimization of manufacturing performance and alignment to environment protection and sustainability [1]. To improve precision agriculture, Agriculture 4.0, smart farming with artificial intelligence IoT (AIIoT) and big data solves the tedious process of traditional data gathering in farms, especially with large land area. As a solution, Agriculture 5.0 is designed to increase workforce with optimized process using robotics and artificial intelligence [2].

To assist this emerging issue leading to lowering crop production, boosting space farming could be a way to provide additional food supply on Earth and not just on space [3]. Increasing space farms, whether in space vehicle or on planetary surface, which are under controlled environments and taking advantage of photosynthetic organisms will lead to optimized crop productivity and generation of food and oxygen in space territories with IR 5.0 [4]. Successes to overcome space exploration challenges are more evident as public and private space agencies collaborate and compete for acquiring knowledge and practices to make humans multiplanetary species, living in International Space Stations (ISS), Moon, and Mars. Space farming in ISS solves the problem of insufficient supply of packaged food and costly restocking transportation [5]. In such controlled environment, Veggie plant-growth system operates with light-emitting diodes, root mat reservoir for passive water diffusion, and controlled release of fertilizers [6]. Cultivars chosen for such implementation must be compact, with tolerance to osmotic pressure and high growth rate even with low light intensity [5]. Candidate cultivars, including rice, potato and strawberry for lunar farming were selected based on their nutrient content and Biomass production per day. These efforts are made to establish regenerative life support systems (LSS) in space explorations [7].

This provides substantial role to the following: (1) a comparative analysis of the comparative differences of Industrial Revolutions 4.0 and 5.0 in relation to its impacts to farm labor, cultivation and post-harvest system, green products and services, and agricultural supply chain; (2) a systematic analysis of space farms on spacecraft and planetary surfaces as the exact future of farming; (3) the dissection of foreseeable challenges and the roles of government, private industries and academic and research institutions for interleaving IR 5.0 and space agriculture; and (4) the future directives concerning IR 5.0 technologies as tools for bioregenerative life support system and circular manufacturing. Here, the context of sustainable space agriculture is limited only to the adaptable technologies of IR 4.0 and 5.0.

## II. COMPARATIVE DIFFERENCES OF INDUSTRIAL REVOLUTION 4.0 AND 5.0 IN AGRICULTURE

Advancement in farming and food systems can be exhibited in the digital transformation (DX) of the manufacturing set-up such as automated and networked farm, application of smart devices, and novel farm equipment. Thus, the technological projection and differences between Industry 4.0 and 5.0 in the field of agriculture in the context of farm

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labor, cultivation and post-harvest systems, green products and services, and agricultural supply chain is discussed here.

### A. *Farm Labor*

Farm labor in a traditional context, was incorporated to hard work and long hours [8]. This challenge led to the rise of smart farming where Industry 4.0 brought a new form of farming combining the basic farming practices and digital technology [9]. This set-up was incorporated nowadays to what is known as Agriculture 4.0 where agri-food systems became data-driven and automated [10]. Thus, from lengthy and dull tasks, smart farming basically helps the farm laborers to attain efficiency, increasing productivity and quality of food as well as environmental protection [10]. Contrary to the unsolicited theory of others that this concept will remove the farm laborers in the picture, this could complement their work, not replacing them. There are various accounts where agricultural development based on digital technologies was employed creating a more productive and connected agriculture industry [11-17]. Through robotics, big data, and artificial intelligence, farm equipment was improved and enhanced to accommodate the growing demands for agriculture as the human population increases rapidly [15]. Furthermore, Agriculture 4.0 complemented various technological concepts such as the integration of aquaponics and vertical farming and other configurations of food systems, and circular agriculture-primed bioeconomy. The main agenda of Industry 5.0 is to make manufacturing sustainable from an economic, ecological, and societal perspective establishing circular economy that focuses on human centric industry. This innovative technological, industrial and scientific revolution is expected to unveil the subsequent trend of interactive robots commonly known as cobots that have total awareness of human interaction [18]. It basically implies a strong co-working mechanism between human and computer through AI and robotics that can be used in space farming.

### B. *Cultivation and Post-harvest Systems*

Post-harvesting is the procedure of rapidly separating the plant from the soil. Adoption of the IoT for agricultural application has been the primary driver in increasing the number and quality of essential goods in the business by improving crop quality and crop yields. Indoor agriculture is now possible due to automated agriculture, which prevents land degradation while increasing production of sustainable food supply. Deep learning (DL) has begun as a method to discover for big data analysis, having multiple beneficial results in image processing, and object recognition. AI may also aid in reducing excessive food waste. Thus, it is one of the most significant scientific advances of the Industry 4.0 era, with potential to shift the food system from a unidirectional to a circular paradigm. Furthermore, vertical farming is growing rapidly. In accordance with NASA research, aeroponics could reduce water usage by 98%, nutrient injection by 60%, and pesticide application by10%, and it could induce plant yield up to 75% [19]. Advances in digital technology have brought radical improvements in agricultural industry by enabling intelligent monitoring and management systems and provision of real-time display numerous farm processes. IoT and AI have been used to develop adaptive fertigation systems, intelligent tractors and machineries, sensitive weed and insect control systems, closed-loop greenhouse cultivation, drones and robots for plant protection, storage chambers equipped with sensors, and crop health monitoring techniques [11-16]. In comparison to Industry 4.0, Industry 5.0 is viewed as the subsequent industrial evolution with the goal of utilizing the human specialists' ingenuity in association smart machines to in consideration of optimized resource utilization and consumer manufacturing solutions [20].

### C. *Green Products and Services*

While smart factories enhanced production, the IR 4.0 also had drawbacks such as the necessity for data sharing and communication standards that will bridge all areas of agriculture exploitation, and the farmers' capacity to invest and improve their farming process [21]. IR 5.0 aims to achieve sustainability in an era of fast climate change and rising demand for energy and resources focused on sustainable consumption and production [21]. Some of the method enhancements in esteems chain alteration and company models predicated on knowledge analysis, interchange, and collecting big data [22]. Thus, farmers may reap the benefits of real-time monitoring even in geographically challenged fields such as rural farms. As it shifts from mass customization to personalization, consumers can benefit from individualized products that may be of biofuel, biogas to green by-products like processed greens. Consumers could express their preferences throughout the design process, and the production line would modify accordingly at no added cost.

### D. *Agricultural Supply Chain*

Agri-food supply chain basically has five phases such as food production, industrial processing, distribution, marketing, and consumption. In the application of information technology at the present time, internet was utilized to enable the consumers to enter the system chain and remain linked. Through the integration of internet and agriculture, other new food supply models were employed such as online-to-offline, social commerce, and customer-to-customer [23]. Furthermore, IoT and big data plays a significant role in every phase of agri-food supply chain management as it provide smart recommendations to farmers toward precision farming and accurate risk assessment [24]. Through Industry 4.0, it links the consumer order networks, supply chains and even robots and smart devices on the automotive production level [17] while Industry 5.0 can help the customers to express more themselves on the products and services they want through the robust collaboration of human and computer [18]. Additionally, Industry 5.0 key concept of mass customization can be integrated to supply chain management through the disruptive technologies such as digital twins (DT), cobots, 5G, and beyond [1,2,18,20]. DT which supports the whole life cycle of the SCM can be incorporated to creation of digital replica for warehouses, inventories, and logistics. Interestingly, there is an account of a DT based approach that was utilized in the refrigerated transport of mango fruit [25].

Based on the differences and advantages of the two industrial revolutions (Fig. 1), this will prepare the agriculture sector to more advanced methods in the future and will foster space farming. This scenario will be ideal especially in space where specific environmental constraints reduce our ability to achieve the metabolic needs of astronauts. Indeed, the challenges of space farming imposed by altered gravity, movement of heat and water vapor, high and low extremes ambient temperatures, and atmospheric high volatile organic carbon contents and $CO_2$ concentrations, will be potentially overcome through different technological developments being implemented by IR 5.0 [3,4,26].

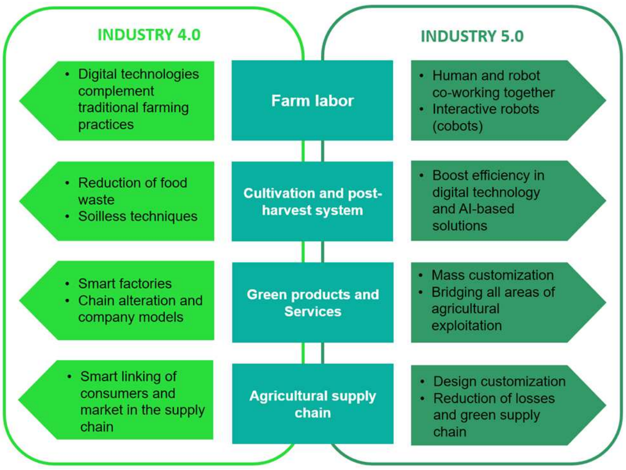


Fig. 1. Differences of IR 4.0 and IR 5.0 in the context of farm labor, cultivation and post-harvest system, green products and services, and agricultural supply chain.

## III. Space Agriculture is Future Farming

Colonizing the space above the human terrestrial territory relies on the technologies developed by engineers and scientists. Despite that Earth-based agricultural technologies have been existing for so long now, important questions still concern their applicability to space farming in microgravity spacecraft and partially studied planetary surfaces. Presented in Fig. 2 are the Industrial Revolution 5.0 interventions for three levels of sustainable space farming which sums up the advancements in space farms on space vehicle systems and planetary surfaces.

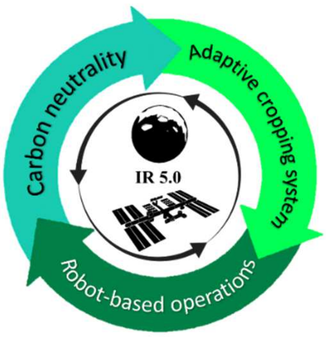


Fig. 2. Industrial Revolution 5.0 interventions for three levels of sustainable space farming: adaptive cropping system, robot-based operations, and carbon neutrality.

### A. Space Farms onboard Space Vehicle Systems

Design considerations of space vehicle systems with functional farms involve a set of spacecraft-specific environmental factors which is complicated as it includes intelligent controls of atmospheric carbon dioxide and ethylene, exhaust and ventilation for suitable heating and cooling, fertigation system for growth-induced cultivation, and space radiations [27,28] at the least to promote crop growth to ensure crew nutritional security and strict dietary concerns. The typical diet of astronauts onboard spacecraft consists of vacuum-preserved foods for at least six months of travel from the Earth surface. However, the next target of space agencies worldwide is to reach Mars which requires much longer duration of travel. Salad machine is the applied concept for developing a controlled environment, particularly adjusting light intensity and photoperiod [29]. Fresh foods that have been mostly cultivated and harvested are cabbage, carrots, lettuce, onions, radish, tomato [29]. Hence, it is noticeable that a typical disadvantage of in-space vehicle systems for farming is the limited volume available for plant growth. On Earth, a microgravity cultivation chamber has been developed to mimic the condition in the International Space Station [29]. This is called Vitacycle and involves a spinning cylinder with attached containers where plant seeds can be sown. In a more technical perspective, this is based on the principle of a clinostat which rotates to constantly change the direction of gravity vector perceived by plants. Recent advancement in technological devices for biological studies in altered gravity conditions resulted in the development of a novel device with built-in LED lighting system able to adjust photon flux density and light quality, where seeds are germinated and grown in petri dishes [30]. The main purpose of this device is to elucidate the interaction of light and gravity in root growth responses [31]. To advance this technology, automated injection of nutrients could be integrated, and this was initiated by the EU Horizon 2020 TIME SCALE project [32]. Instead of soil-based or gel-based cultivation, 3.5 L and 0.6 L of water as grow substrate have been employed resulting in longer root growth of green leafy vegetables when lesser water volume protocol was used [32].

### B. Space Farms on Planetary Surfaces

Plants in space must cope with the direct effect of space factors including microgravity and radiations. It has been demonstrated that these elements have a significant impact on the structural, chemical, morphological-structural, and physiological aspects of the growth of plants [30,32]. The interaction with numerous sources of variability, such as the biological source employed, the physiological stages of plants, the interplay between components, and the equipment used during the testing, may alter the responses of crops in space [30]. Indeed, astrobotany demands the state-of-the-art IR 5.0 technology. IR 5.0-centered space farm technologies can help scientists manage how vigorous a crop will evolve in space and the Earth's surface [3]. The Prototype Lunar Greenhouse (LGH) was designed by the University of Arizona to reuse wastewater and nutrients in orbit, supply food for astronauts, and air purification [3,4]. In this system, because the walls are translucent, the plants may get enough sunlight and radiation from the sun. This system is deployed autonomously—that is, by computers rather than human astronauts. With LGH, people on lengthy space voyages will always have access to wholesome, fresh food. In relation to bioregenerative life support system (BLSS), plants utilize $CO_2$ released by astronauts to grow and produce food while also producing oxygen through photosynthesis [33]. This concept of circularity makes use of output or by-product of other processes as input for other organisms. Because of the rarified atmosphere of the lunar environment, there is a very little impact on the electrical environment close to the moon's surface. Hence, the flow of photons and ions out from the solar wind, cosmic radiation, and galactic cosmic radiation, govern this environment [34]. On the light side, plasma electrons predominate, leaving the surface negatively loaded to a negative end on the order of the temperature, which is roughly -50 to -100 V [34]. A layer of sand that has partially flattened by dust and sandstorms covers the surface of Mars. These measurements yield a value for particle diameter of $1.5 \pm 0.2$ µm [34]. On Mars' surface, it has been recorded 95.5% $CO_2$, 2.7% N, 1.6% Ar, 0.13 % $O_2$, and 0.07% CO at a temperature of 0.9 kPa [34]. With different dust shields and 0.5 mm trace spacing, tests were conducted here on Earth laboratories to develop strategies aimed at promoting plant growth. To achieve a comparatively high level of dryness in the JSC Mars-1 simulant, it was maintained in a vacuum oven for several days at temperatures above 120°C and atmospheric pressures of roughly 1 kPa [34]. A Martian-friendly ecology will be operationalized with the help of controlled environmental conditions, ensuring healthy plant growth. It will be necessary to create an artificial ecosystem that is as comparable as possible to planet Earth [30]. These artificial Earth should incorporate a large portion of developing technologies like machine learning [35], intelligent systems [36], and robots [14] to enable system management.

## IV. Interleaving of Industrial Revolution 5.0 and Space Agriculture

### A. Forseeable Challenges

Plants features on Earth are the result of a protracted evolutionary process in which organisms adapted to certain environmental conditions such as water, temperature, light, air, and nutrition availability. The various combinations of these characteristics have uttered the success of plants in various geographical places and Earth biomes. Thus, the ability of plants to survive and reproduce in extraterrestrial environments is influenced by the same factors that act on earth at different levels, as well as additional factors unique to space, such as ionizing radiation and altered gravity [35]. Radiation-induced damage in plants generally rises with increasing dosages [3,4,26,37]. Animals and plants exposed to high levels of radiation have been proven to have a greater incidence of anomalies such as pheno-deviants and degrees of fluctuating asymmetry [3,4,36]. Another distinct spatial aspect is the altered gravity. Throughout the lengthy evolutionary processes, plants have used gravity as the most stable and reliable signal for their growth. As a result, weightlessness affects plant biological processes at various phases of their seed-to-seed cycle [3,4,30]. Many plant tests have been conducted under stimulated or real microgravity, or partial gravity conditions including Moon gravity (0.17 $g$), and Mars gravity (0.38 $g$) to study how plants perceive gravity and respond under gravitational stress. As a result, the descent velocity of amyloplasts decreased under 0.3 $g$ gravity, affecting the development of the plant root system and, subsequently, the overall plant growth [28-34]. Translocating terrestrial technologies, most especially hardware, is seen as a problem for space infrastructure.

### B. Role of Government

The government, like any other industry, plays a critical role in space farming research and development, and in any other space activities. The United States is a leader in the peaceful, responsible, and long-term exploration and usage of outer space. US has established a space priorities framework, which prioritizes space sustainability and planetary preservation [38]. Similarly, Russia has a decree that provides legislative framework for space operations and encourages the use of space research and industrial potential to addressing socioeconomic, scientific, technological, and defense tasks of the Russian Federation [38]. These imply that government should harness the utilization of space to address the most pressing domestic and international concerns, while also leading the international community in protecting the advantages of space for present and future generations [38].

### C. Role of Private Industries

Farmers, food producers, and agricultural officials who seek to increase productivity and profitability can benefit from space-based technology. Since the outset, only public sectors have had access to space, but private space services are now a reality due to the support that the idea of private companies managing launch vehicles and space infrastructure received over the past ten years as demonstrated in Fig. 3. Private companies such as Elon Musk's SpaceX and Orbital Science Corp. received Commercial Orbital Transportation Services (COTS) contracts from National Aeronautics and Space Administration (NASA) to demonstrate cargo delivery to the International Space Station (ISS) [27]. As a result of increased commercial activity and improved private model efficiency in managing space access, it is now believed that these corporations, including Jeff Bezos' Blue Origin, have driven launch prices to all-time lows, making it cheaper and simpler to launch thousands of satellites for a variety of commercial purposes such as for crop management and existence of space farms for sustainable earth environment [27,39]. Furthermore, The Indian Department of Space (DOS) has been a forerunner in space technology adoption due to ongoing expenditures in the creation of domestic space infrastructure, launch systems, and ground systems and they provide the private sectors with satellite imagery and specialized services needed for the use of space technology for natural resource management [40]. However, the major challenge is the fact that due to the service-oriented relationship of private industries with the national space agency and the ecosystem's non-turnkey solution environment, the private sector's participation throughout the value chain is limited [39]. But with the future of space farming 5.0, NASA emphasizes that the private sector should be given more power and be supported to boost space services, setting the direction of change in balancing human and machine technology [38,39].

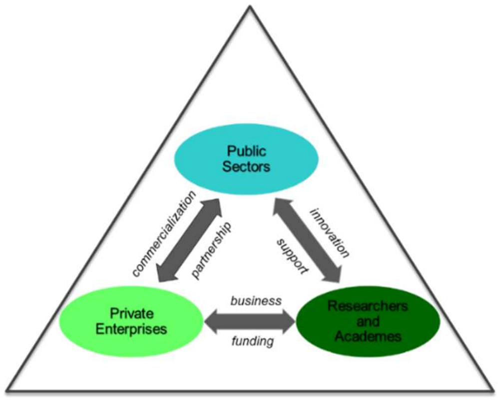


Fig. 3. Interrelated roles of public sectors, private industries, and research institutions on space agriculture 5.0.

### D. Role of Academe and Research Institutions

Constant industrial revolution has made it possible that satellite crop monitoring systems and remote sensing technologies for space farming have been progressively being explored by the academe and research organizations. With observations from space satellites, combined with high-end computer modeling, plant space research such as future study on plant selection, cultivation, and production based on environmental factors connected to space are considered [41]. Various research team has developed satellite-based global agricultural monitoring systems such as in China which is the CropWatch wherein its research team is a component of the

Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences [19,22]. The CropWatch offer evaluations of crop yield at various spatial scales that are based on a combination of cutting-edge techniques, ground-based indicators, and space remote sensing technologies [19,22]. Moreover, the Joint Research Centre (JRC) of the European Commission developed the Anomaly Hot-spots of Agricultural Production (ASAP) which is a web-based decision support system for the early warning of hotspots of agricultural production anomalies for the anticipation and prevention of food security crises through weather satellite and Earth Observation data analysis [19,22]. In the academe in United States, the Office of Biological and Physical Research, NASA, and the Agriculture in the Classroom (AITC) program of the Cooperative State Research Extension and Education Service (CSREES), United States Department of Agriculture (USDA), jointly developed the Space Agriculture in the Classroom (SAITC) program to boost middle school students' knowledge of and interest in agricultural and space sciences as well as their comprehension of agricultural activities both on Earth and in space [19,22]. The space agriculture curriculum's material covered current NASA research in the field and made connections between it and advantages for regional and global agriculture production as well as adjacent fields like food safety and nutrition [19,22]. Hence, the regular dissemination of yield estimations and crop monitoring by researchers that are spatially consistent and accurate will continuously enhance service delivery and strengthen policymakers' ability to make decisions [19,22].

## V. Potential of Sustainable Space Agriculture Using Terrestrial Technologies

Bioregenerative life support system (BLSS) and circular manufacturing are trends wherein products and goods are used repeatedly through suitable and proper management like reusing, remanufacturing, or recycling, thus creating extended and multiple product lifecycle (Fig. 4). In relation to space farming, Fig. 4 supports the carbon neutrality depicted in Fig. 2 which is of importance for farming in space vehicles and planetary surface to help preserve its natural environment.

### A. *Technology as Tool for Bioregenerative Life Support System*

Bioregenerative Life Support System (BLSS) technologies is a necessary tool in providing life support in space including plants, decreasing in situ reliance on earthly supplies providing the whole space agriculture system with air, water, and nourishment they need while preventing extraterrestrial bodies from being contaminated by recycling waste [33]. BLSS technologies have been used for space exploration [33]. Space farming is considered as an initial prerequisite for long term life support as it provides basic sustenance like water and food with suitable nutritional value [2,4,26,33]. Advanced technologies fostered various BLSS experimental systems in agriculture with terrestrial simulations [42-43]. All the system's technologies and models ensure the capability of recycling wastes and crop's primary needs through interconnected compartments, including the photosynthetic food production, atmospheric regeneration compartment, waste decomposition compartment, and the photosynthetic heterotrophic food production compartment [2,4,33]. These compartments act as the fundamental support in the whole ecological system, interact with the environment and control support system [42,43]. The most advanced BLSSs refer to the MELiSSA (Micro-Ecological Life Support System Alternative) project [32], and Lunar Place 1 Space 180 [44]. MELiSSA is a circular life support system aiming to the highest degree of autonomy and to produce food, water, and oxygen from wastes [45]. Lunar Place 1 results in 100% of $H_2O$ and $O_2$ regeneration including the purification from sanitary wastewater like urine and solid waste, 92% crop regeneration, but runs with 83% food regeneration and 98% material regeneration [43]. To achieve sustainable agriculture in space, assessment scheme is needed that will serve as a strategic research path for development. As the primary necessity for space farming, the technological advancement of agricultural systems is necessary [33]. Development in the process of utilizing in-situ resources, like substrate soil to prepare earth-like substrates is also needed [45,46]. The chemical and physical regenerative approach for biological redundancy, treating waste using regeneration technology and air regulation control, should also be aimed at developing [33,47]. One last factor is to establish sustainable regeneration rate of water, oxygen, and microorganisms closer to 100%.

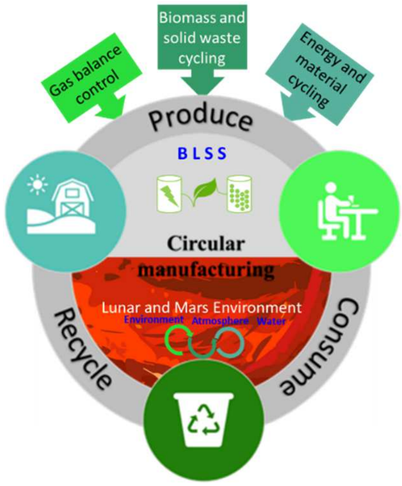


Fig. 4. A framework showing the existing terrestial technologies, factors to be considered for extraterrestrial deployment, and assesment scheme for sustainable space agriculure feasibility

### B. *Technology as Tool of Circular Manufacturing*

Circular economy and sustainability are no longer new biosecurity and bio-conservation paradigms [48]. A comprehensive framework in terms of economic benefits, environmental impact, and resource scarcity, and a strategical approach for implementation of circular manufacturing have also been developed for terrestrial farming [48]. A framework for bioenergy plant options by the transformation or reuse of agricultural waste as another example of circular economy applications [49]. Circular approaches in small-scale food production systems including agroforestry, aquaculture, integrated agriculture-aquaculture, vertical farming, hydroponics, aquaponics, aeroponics, and permaculture for sustainable use of water, nutrients, and energy resources were identified in a recent study [50]. It was also established that sustainable circular food systems using the socio-technical transition theory and the associated challenges and solutions for production, consumption, and food waste management could help carbon neutrality here on Earth and expectedly in space [51]. Space farming provides useful insights towards sustainable farming. A comprehensive sustainable food chain model showed how biomass in bioreactor-based farming can be used for fertilizer and energy production, and mushroom cultivation [51]. Another study also suggests research on sustainable food culture, edible insects, and algae-based food to solve food security problems in space [52]. These terrestrial technologies of circular manufacturing can be applied as well for sustainable space agricultural systems.

## VI. CONCLUSION

Based on the critical systematic analysis done in this study, it was found that Industrial Revolution 5.0 exhibits potential terrestrial technologies that could boost space farming and solve its impeding issues mainly in bioregenerative life support system and the core aspects of circular economy in space. Collective efforts of government, private, and research institutions should take place to achieve a virtuous closed cycle in plant-based BLSSs. Sustainable space farming is not a mere concept anymore as numerous studies have been performed in space and space-like laboratories on Earth. It is recommended to integrate more IR 5.0 technologies that could enhance farming automations in space.

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