Engineering Journal issn: 0125-8281

Review

A Review of Mechanical Element Design of Lunar Greenhouse for Long-term Space Mission

Wares Chancharoen[1,*], **Rattanawalee Tobsri**[1], **Salida Chuphong**[1], **Piyachit Yingkiatinon**[2], **Kulanis Jintavanich**[2], **Napaporn Chantawong**[2], **and Chanikarn Wacharasindhu**[2]

1 Laboratory of Artificial Intelligence and Innovation in Medicine (AIIM), Princess Srisavangavadhana Faculty of Medicine, Chulabhorn Royal Academy, 906 Kamphaeng Phet 6 Rd., Talat Bang Khen, Lak Si, Bangkok 10210, Thailand
2 Sirindhorn International Institute of Technology, Thammasat University, 99 Paholyothin Rd., Khlong Nung, Klong Lung, Pathum Thani 12120, Thailand
*E-mail: wares.cha@cra.ac.th (Corresponding author)

Abstract. Humans have been learning to survive in space with the aim of prolonging the periods of missions. To be able to stay longer, the resources for a living are important for the crews. However, the payloads brought into space should be restricted because of the mass and cost limitations, so it is not often possible to transport limited resources like water or food from Earth to the Moon. In recent years, there has been a concept of a Moon Village established for humans to be able to stay in space longer. Consequently, a greenhouse module was proposed to meet the needs and was designed with concepts of the Moon's environment and Environmental Control and Life Support Systems (ECLSS). This review paper includes brief details of the greenhouse module design and the two main subsystems of a lunar greenhouse: agricultural subsystems and environmental control subsystems in mechanical engineering aspects. In addition, comparisons of the advantages, disadvantages, and challenges of the three designs of lunar greenhouse modules are provided since each design had its own characteristics. Thus, the engineers should choose a proper design by considering the requirements and limitations regarding the mission. Also, this review paper can further expand knowledge of designing greenhouse modules on the lunar surface and improving the subsystems in the greenhouse module in the engineering field.

Keywords: Greenhouse, Moon village, agricultural subsystem, environment control subsystem, space exploration.

ENGINEERING JOURNAL Volume 29 Issue 2
Received 24 March 2024
Accepted 18 February 2025
Published 28 February 2025
Online at https://engj.org/
DOI:10.4186/ej.2025.29.2.59

1. Introduction

Humans have come a long way since the era of Space 1.0, which was considered the era of astronomy and astrology, followed by Space 2.0, the space race era that led to the Apollo Project. Now, the world is entering the era of Space 4.0 after fulfilling the International Space Station (ISS) concept, known as the Space 3.0 era. The European Space Agency (ESA) had a vision of Space 4.0 as the global interaction of politics and governments, the private sector, and societies, including academics and citizens. According to ESA, the Moon Village concept was introduced to answer the expectation of the Space 4.0 vision [1].

As the concept of Moon Village was stated by Johann-Dietrich Wörner, ESA director general, at the 2016 ESA press conference, "Moon Village is not a single project, nor is it a fixed plan with a defined timetable. It is a vision for an open architecture and an international community initiative". According to Wörner, the definition of a village is a community of groups that have the same interest joining forces and simply coming together with an intention to share interests and potential [2]. The Moon Village concept allows interested parties and nations with similar goals and interests to express innovative ideas. Accordingly, with consideration of human habitation on the Moon, life support systems are certainly in consideration. Environmental Control and Life Support Systems (ECLSS) can exist to support humans in this Moon Village concept [3]. As there are many life support systems for humans, one of them that allows humans to live without concern for food, O2, heat, or water is the advanced life support system known as MELiSSA, introduced by ESA [4].

The Micro-Ecological Life Support System Alternative, MELiSSA, focuses on producing food, water, and O2 from the mission organic waste such as urine and CO2 [4]. MELiSSA was adopted by a terrestrial aquatic ecosystem, consisting of five main sub-processes called compartments, ranging from the anoxygenic thermophilic to the photo-eutrophic for higher plants [4]. As a result, the greenhouse module was proposed as an ideal concept for MELiSSA.

A greenhouse is a closed and controlled environment used to grow plants in the proper conditions for a small ecosystem. Not only can it be constructed on Earth, but it can also be built into spacecraft [5], as well as plans to build it on Mars and the Moon in the future. Moreover, the greenhouse can produce crops as food, water, O2, and heat, all of which are essential for human survival.

Accordingly, space architecture is the topic to design and construct inhabited environments in space that concerns the safety and habitability of humans living and other creatures to survive in extreme environments [6]. Moreover, space architects of lunar-base habitats classified the construction into three classes [7] according to Smith (1993); Class I is defined as pre-integrated or pre-assembled, which is ready to be used with the minimum of construction. This class was said to be appropriate for a short exploration mission like the Apollo project, a 14-day base using a cylindrical lunar module. Figure 1 shows an example of Class I which is the mobile pressurized excursion module.

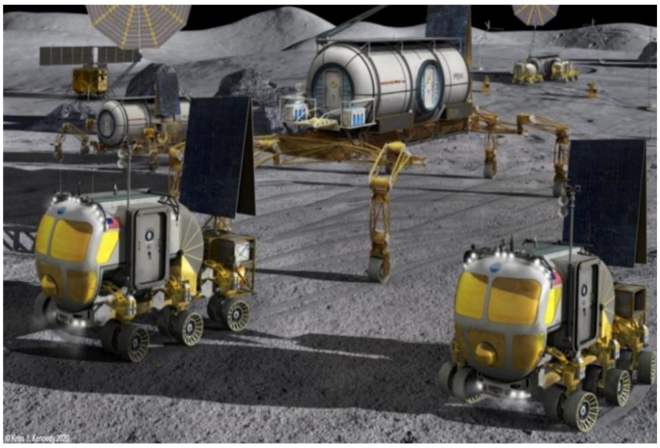


Fig. 1. Class I: Mobile Pressurized Excursion Module [8].

Class II habitat is called prefabricated, it can be defined as assembled, moved, adjusted, or expandable. The special requirement of this class was that the structures should be hybrid and expandable. Class II habitat aimed to settle or create accommodations [9]. An example of Class II is Fig. 2 which is the spherical inflatable habitat. Moreover, an example of a prefabricated space habitat was the lunar habitat presented by NASA in the late 1980s, an expandable sphere with 20 meters of diameter.

Fig. 2. Class II: Spherical Inflatable Habitat [10].

Abarbanel and Criswell modified the habitat to be rectangular in shape that had lunar regolith ballast on the top [9]. For Class III or in-situ derived and constructed, as shown in Fig. 3, it is the highest level of technology to construct a habitat on Lunar for a long duration. In this class, the habitat would be constructed in space and used for space resources, such as lunar concrete, lunar masonry, and caves [9]. Since Class III was said to be suitable for long-duration missions, the subsystems inside the habitat required to be considered like building a greenhouse on

Earth, it should also be tested before the launch and systematically well-constructed [9].

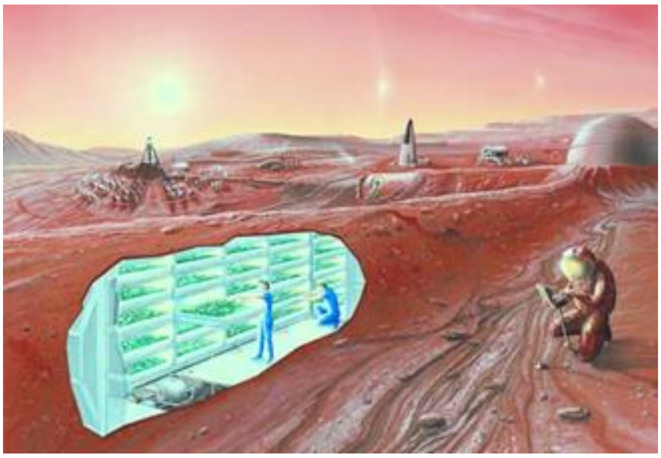


Fig. 3. Class III: concept of build-in construction on the surface [11].

The Greenhouse module (GHM) features three structural types including inflatable (Kevlar, Mylar), hybrid (inflatables with aluminum/titanium cores), and rigid (hexagonal aluminum/titanium) [12]. Lunar regolith serves as an external layer for radiation shielding, thermal insulation micrometeoroid protection and high-velocity dust ejected by surface activities such as landings and takeoffs [12], [13], with enhanced conductivity (0.012 to 1 W/m·K) for thermal storage [14]. Sulfur and MgO cement enhancing the strength 3D-printed structures. Concrete cubes made from regolith simulant demonstrate high compressive strength and resistance to hypervelocity impacts [13]. Inflatable domes reinforced with regolith fibers endure ±0.004 psid and 6 km/sec impacts, with automation enabling scalable, sustainable habitats [15]. The integration of contour crafting technology has further optimized 3D printing of lunar structures, allowing precise layering of sulfur-based regolith composites to improve durability and minimize material waste [13]. Additionally, advancements in automated construction using mobile emplacement systems have demonstrated the feasibility of assembling large-scale habitats with minimal human intervention, enhancing long-term sustainability for lunar missions [15]. However, the possibility of a human labor shortage could also be happened because of the limitations of the excessive cost, and the requirements of advanced technology when constructing by having robotics do the work for example [9].

At the present time, the habitat class that is the most suitable for building a lunar-base greenhouse is Class II, because this type of habitat required assembling the parts and materials from Earth to run the systems, being expandable, and being able to move around [7]. At present, greenhouse modules created in space and on the lunar surface still require humans to take control, look over the system, and keep developing most of the system and technology on Earth before shipping them to the Moon's surface [7]. In addition, if advanced technology were developed, the class III habitat greenhouse could be constructed by using lunar material on the Moon's surface for inhabitants.

However, there are numerous lunar greenhouse designs at the present time. Design modules for Moon habitats required consideration of two factors, the Moon environment such as Moon gravity which is about one-sixth of Earth's gravity and the living environment for humans which is covered in ECLSS [16]. The design of Zeidler et al. (2017) was created by having four inflatable petals and a rigid core in the middle, two pathways connected to the base structure Moon habitat, four deployable light concentrators to enable a hybrid natural and artificial illumination system (ILS), and emergency radiators. This design focused on the overall construction design, and important subsystems [17]. Furthermore, Boscheri et al. (2016) represented a distinctive design with similar subsystems, a brief explanation of the overall construction design, and detailed information on the greenhouse illumination system [18].

Additionally, according to Maiwald et al. (2021), the design was based on the existing EDEN International Space Station Mobile Test Facility (EDEN ISS MTF), which was designed in a cylindrical shape to preserve the original layout of the MTF design. The overall systems in the greenhouse layout of this design could be divided into two sections: a service section, which consists of the subsystems such as power distribution, air filtration, and the nutrient delivery system, and a deployable section, which had the planting area and all related equipment such as air ducts [19]. Nevertheless, in general, building a greenhouse on the Moon's surface requires considering the space law as well.

In addition to laws and protocols to ensure safety and prevent damage to life and the environment in space, there is no difference from Earth in having protocols and agreements for doing space missions. According to the International Space Law of the UN, the standards were divided into sections concerning lunar. Therefore, the Moon Agreements were used to relate to the lunar greenhouse module and be beneficial in the exploration and mission. The first significant article that applied to the greenhouse mission was the policy about limiting the activity to protect the Moon from exploring missions [20]. This policy was used to avoid harmful activities that could affect the ecological balance on the Moon. The second article concerned the state parties that could land space objects, spacecraft, and crews on their mission but should not disrupt another state party's mission on the Moon. The following article was to protect the life and health of the people working on the Moon. The state party should support safety with the objective of creating habitat, equipment, spacecraft, facilities, and all problems that occur during the missions [20]. The law stated that the parties should follow the agreement when doing or using all resources on the Moon properly [20]. To maintain the space law, the standards of the lunar-base greenhouse were established. However, human factors should also be assessed. For a living environment suitable for humans the following standards were required as the following Table 1. [21].

Table 1. Basic standard of environmental factors regarding the suitable living environment for humans [15], [21].

Environmental Factors	Values	Units
Ambient temperature	18.2-26.7	Degree Celsius
Relative humidity	25-70	%
O_2 consumption	0.84	kg/person/day
Air pressure	99.9-102.7	kPa
Air pressure	0.52-1.11	kg/person/day
CO_2 production	0.726-1.226	kg/person/day
Metabolic load (Depend on activity, age, gender, and height)	2000-3700	kcal/person/day
Structural Resistance to Debris	3-4.5	km/sec

Furthermore, considering the human requirements, the environment of the lunar greenhouse should be following the standard of the prototype Bioregenerative Life Support Systems (BLSS) lunar greenhouse as shown in Table 2 [22].

Besides, when designing the greenhouse, other factors are also considered such as the number of crews, greenhouse areas, and type of plants to reach the requirement of greenhouse standard. In addition, the Moon's space protocol is used to prevent harmful activities in the lunar environment, limit the use of resources, and live safely just like being on Earth.

Therefore, this paper reviews subsystems of the lunar greenhouse design in mechanical elements with the objective of human living considerations. This is the novel review paper on the lunar greenhouse design of vital subsystems covered in mechanical engineering aspects.

The manuscript is structured as follows: in the second section, the framework of greenhouse subsystems is explained, followed by a detailed discussion, and then a conclusion.

Table 2. Standard of BLSS lunar greenhouse prototype regarding the suitable environment for growing plants in the greenhouse [22].

BLSS greenhouse prototype standard	Values	Units
Biomass production	1.6	kg/day
Electrical energy	136	kWh/day
Ambient temperature	21.1	Degree Celsius
Relative humidity	53.5	%
CO_2 consumption	1.006	g/kg
O_2 production	0.5	kg/day
Water condensate	10.5	kg/day

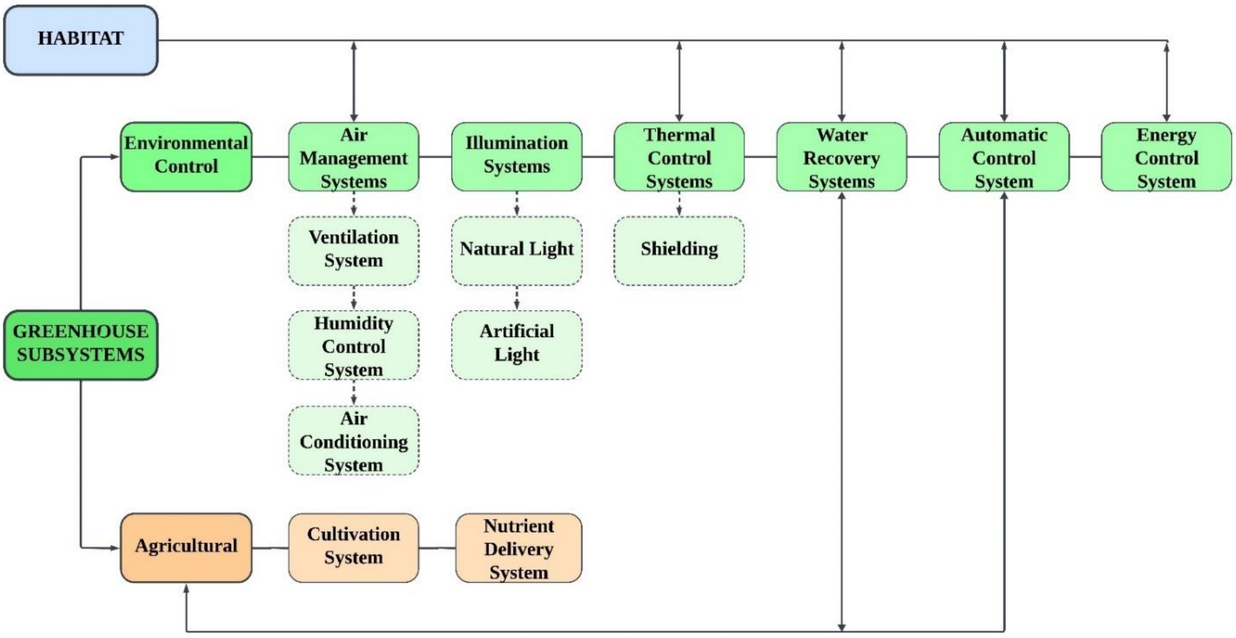


Fig. 4. Diagram of the subsystems framework for an ideal Lunar-base control subsystems.

2. Greenhouse Subsystems

The overview of the lunar greenhouse subsystems is shown in Fig. 4 according to the basic main systems of a greenhouse to maintain a suitable environment for growing plants consisting of temperature, relative humidity, water, fertilizers, CO_2 concentration, and lighting [23]. It can be divided into two main subsystems which are agricultural and environmental control subsystems. The agricultural system is about the cultivation system and the nutrient delivery system. Environmental control is about controlling surroundings conducive to the growth of plants which are considered in four main systems: air management, illumination, thermal control, and water recovery system [23]-[25].

2.1. Agricultural Subsystems

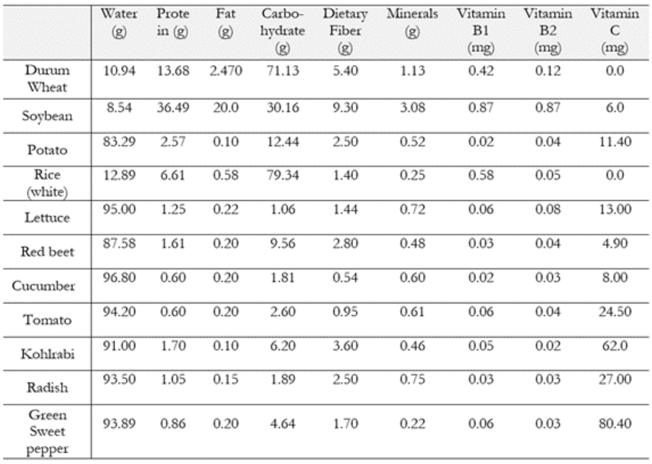
Agricultural Subsystems is the subsystem that is specifically related to plant growth consisting of a cultivation system (CS) and nutrient delivery system (NDS), greenhouse which divided into Agricultural and Environmental.

The CS was responsible for caring for the plant from seed to harvest. Since the plants have two components which are the root and shoot zone which grow completely differently. Therefore, the design considerations for the greenhouse module were planting area, nutrient composition, and environmental conditions. The other subsystem was NDS which responded to stores, mixed the nutrient, and delivered the mixture to the greenhouse module [26].

The target of this system was to provide food enough for the crews for the long-duration mission in space, which would include living on the lunar surface. The inputs of this system were air, CO_2, water, and nutrients from the life support system, and the outputs were crops, fresh water, and O_2. Examples of plants that were grown were tomatoes, cucumbers, and cabbage. According to the data from NASA on human requirements, astronauts require a specific number of calories per day depending on their weight and gender. Women need a smaller number of calories than men around 1,900 calories per day while men need 3,200 calories per day [27]. Following the Australia New Zealand Food Standards Code or FSC, there are eight main nutrients that the human body requires in one day; 50 g. of protein, 70 g. of fat, 24 g. of saturated fatty acids, 310 g. of carbohydrates, 90 g. of sugars, 2.3 g of sodium (salt), and 30 g. of dietary fiber which are considered for an adult that needs 8700 kJ or around 2,000 calories of energy per day. However, the information stated above was only the average standard. The energy required can be different in each person up to the activity that the person does each day [28]. Vitamins; A, B1, B2, B6, B12, and C, and minerals: calcium, iodine, and phosphorus were also recommended for the human body [29].

There are three prototypes of the greenhouse module that will be explained in this review paper. Each module grew some different crops: module design by Zeidler et al. (2017) grew wheat durum, soybean, potato, and rice (white) [17], while module design by Boscheri et al. (2016) grew wheat durum, soybean, and potato, lettuce, red beet, and white rice [18], and lastly, module design by Maiwald et al. (2021) grew lettuce, cucumber, tomato, kohlrabi, radish, and green sweet pepper [19]. The nutrient supply of each crop per 100 g. edible biomass as described in Table 3.

Table 3. Nutrients supply produced by each crop that suitable for a lunar-base greenhouse from the designs of Zeidler et al. (2017), Boscheri et al. (2016), and Maiwald et al. (2021) per 100 g. of edible biomass [21], [30].



	Water (g)	Protein (g)	Fat (g)	Carbo-hydrate (g)	Dietary Fiber (g)	Minerals (g)	Vitamin B1 (mg)	Vitamin B2 (mg)	Vitamin C (mg)
Durum Wheat	10.94	13.68	2.470	71.13	5.40	1.13	0.42	0.12	0.0
Soybean	8.54	36.49	20.0	30.16	9.30	3.08	0.87	0.87	6.0
Potato	83.29	2.57	0.10	12.44	2.50	0.52	0.02	0.04	11.40
Rice (white)	12.89	6.61	0.58	79.34	1.40	0.25	0.58	0.05	0.0
Lettuce	95.00	1.25	0.22	1.06	1.44	0.72	0.06	0.08	13.00
Red beet	87.58	1.61	0.20	9.56	2.80	0.48	0.03	0.04	4.90
Cucumber	96.80	0.60	0.20	1.81	0.54	0.60	0.02	0.03	8.00
Tomato	94.20	0.60	0.20	2.60	0.95	0.61	0.06	0.04	24.50
Kohlrabi	91.00	1.70	0.10	6.20	3.60	0.46	0.05	0.02	62.0
Radish	93.50	1.05	0.15	1.89	2.50	0.75	0.03	0.03	27.00
Green Sweet pepper	93.89	0.86	0.20	4.64	1.70	0.22	0.06	0.03	80.40

2.1.1. Concept of cultivation system

2.1.1.1. Types of containers

The first type called a V-shaped channel shown in Fig. 5 was a combination of the permanent and the disposable part. The V-shaped permanent part was considered as a growth channel which consisted of NDS inflow line, NDS outflow line, NDS pipes with misters, and a seed cultivation coil as a disposable part. The seed cultivation coil was made from plastic film and grow-fiber as the outer layer and the seed was put inside specifically for each plant. The advantage of this concept was the product line type that could be moved, and the channel was used for all plants [17].

The second type was called a tray system as shown in Fig. 6. This system was designed to operate in a room with a vertical layout consisting of plant trays, air ducts, nutrient solution lines, LED panels, and return lines. The cultivation of this system had a standard tray with a size of 0.4 x 0.6 m. which added the solution into it. The tray's design was handled using automatic processes. Each tray was used to grow only the same type of plants with the same stage of growth to minimize the used space. The tray lid was designed based on the morphological factors of each plant such as the largest plant diameter. For example, a 2-hole tray layout for tomatoes because it was a tall growing plant; and a 36-hole tray layout for small growing and space requirement plants, such as radish and green onion. The advantage of this concept was that the height of the grow-out position could be adjusted to vary from small growing plants to tall growing plants [26]. Plants absorb 1.266–1.741 kg/day of CO_2, from humans (778.7 g/day), and release 0.914–6 kg/day of O_2, sustaining the respiratory needs of six crew members. Humans consume 275.9 g/CM-day of water, while plants use 621.7 g/CM-day supported by a water recycling system for photosynthesis and biomass production [31].

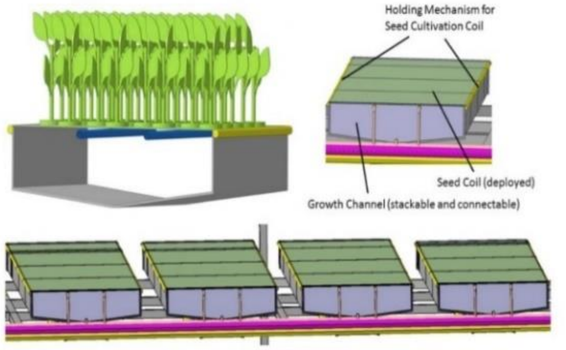


Fig. 5. V Shape Channels: a type of containers in concept of Cultivation System of Agricultural Subsystems of a Lunar-Base greenhouse [17].

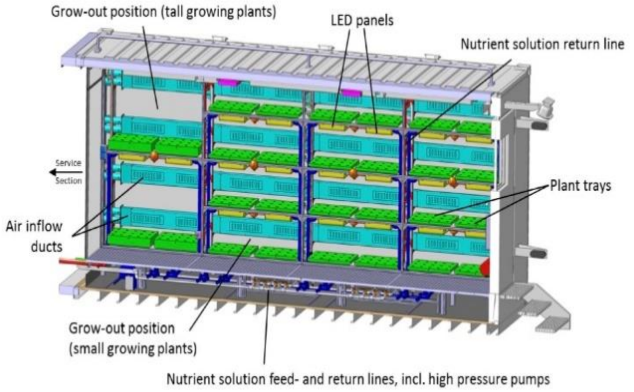


Fig. 6. Tray System: a type of containers in concept of Cultivation System of Agricultural Subsystems of a Lunar-Base greenhouse [26].

2.1.1.2. Types of configurations

Two types of configurations included mono crops and multiple crops, according to the study of the Greenhouse Module for Space System (Green MOSS) preliminary design [19]. Firstly, the mono crop configuration was used for growing the same plant in the module. The layout for hardware, positioning of the tools, and the path for piping of this system were different in each module [18]. Also, the amount of supply such as air, water, and nutrients, was more complex because each module had different types of crops, and each crop had different requirements. However, the light was easier to set up and adjust considering the same need for the crop. On the other hand, the multi crop configuration was used when the same module grows different types of crops, but all modules were the same so that it was convenient for managing the space more efficiently [18]. The layouts, tools, and path for piping were the same for each module. Therefore, it was easier to design and control.

2.1.2. Nutrient delivery system (NDS)

The selected technique for NDS was called the hybrid aeroponic-NFT or nutrient film technique. It consisted of aeroponic tubing and misters, a main reservoir, and four high-pressure pumps in order to deliver nutrient solutions to the plant. For this method, the roots were hung in the air and absorbed nutrients by fogging fluid. The following steps described how the NDS worked: the nutrient-rich water was stored in the MELiSSA input storage reservoir, next step was to adjust the composition and analyzed the pH, EC, ion-selective, and dissolved O2. At this step, the solution was ready to be used. Four high-pressure pumps were activated and sprayed the solution mist into the plant channels. Some unabsorbed solutions would flow down into the channel and would be picked up by the plant later, some would drain back into the reservoir [17]. Piping and drainage were redesigned to reduce microbial growth and simplify the FEG subfloor system [32]. High-pressure pumps deliver pH- and EC-adjusted nutrients, using 1,163 kWh/month (2% total energy) [33]. The C.R.O.P.® Biofilter converts urine into nitrate-rich fertilizer [32]. Nitrogen fixation produces 25.1 g/day of N_2 as NH_3 (19.1 g/day) and HNO_3 (42.4 g/day) [31]. Nutrient solutions (pH 5.5 ± 0.5, EC 1.9 ± 0.05 dS/m, O_2 80–100%) optimize uptake [12].

2.2. Environmental Control Subsystems

2.2.1. Air management system (AMS)

The air management system in the greenhouse is one of the significant systems that requires to be controlled since it can directly affect the growth rate of the plants. It is extremely important v the level of gases that plants release after breathing and the photosynthesis process. Moreover, the air management system of the lunar greenhouse had an advantage in recycling CO2 gas that the crews created by connecting the airflow inside the habitat with the greenhouse module as a cycle. The O2 produced by the plants passes through a filtering process before entering the habitat. AMS was related to the ECLSS term because this kind of management developed the way of living in space maintaining sustainable air management for breathing which was used in the limited space inside the habitat [17]. In the EDEN Next Gen module controls temperature (22°C/18°C), humidity (70% ±5%), airflow (8,116-8,281 m^3/h), gas composition (O_2: 24%, CO_2: 650 ppm), and air quality using HEPA, VOC filters, and UV-C to support plant growth in space [34]. Humans emit 778.7 g/day of CO_2, transferred to the greenhouse via ventilation [31]. Plants absorb 1.266

kg/day of CO_2, produce 0.914 kg/day of O_2, and regulate atmospheric levels [34]. The MELiSSA loop integrates the greenhouse, with LSS as backup for CO_2, O_2, and water exchange [12].

2.2.2. Ventilation system

In the greenhouse module, the ventilation system is also significant for air circulation and replenishing CO2. The less quality of air circulation decreases plant activity such as CO2 consumption rate and O2 production rate through photosynthesis and can also be the cause of disease [35].

Mechanical ventilation required inlet openings, exhaust fans, and electricity. This type of ventilation could be run under several weather conditions [36]. The greenhouse normally used two fans or more to design the ventilation system unless the greenhouse space was restricted because the installation cost could be expensive to be installed in limited space. The fan system was recommended to be designed by considering the ventilation rate and the area inside the greenhouse [37]. Because of the complex installation, the cost of the design of the fans and the system installation inside the greenhouse were expensive. Moreover, increasing the ventilation rate for mechanical ventilation also increased the cost of the systems, equipment, and operating cost [38]. Components include pre-filters, HEPA filters, VOC filters, dehumidifiers, heaters, and gas exchange modules. Fans operate at 3,000 Pa static pressure with 8,300 m^3/h airflow [34].

2.2.3. Humidity control system

In the greenhouse module, relative humidity in the air is one of the factors affecting the plants' growth rate. High humidity, higher than 85%, could increase the incidence of disease and decrease plant transpiration. Therefore, the greenhouse's humidity should be controlled and maintained at a level that does not affect the plants [36]. The normal condition of humidity for a greenhouse gas was around 50 - 85% [18]. The ideal humidity level was 80% at 27°C [39]. Moreover, the best ways of reducing and stabilizing the humidity level in the greenhouse were circulating the air inside the greenhouse and regular ventilation [40].

Furthermore, circulating the air by using an electric fan inside the greenhouse could be separated into three types: oscillating fans, hanging ceiling fans, and regular fans. The different types of fans created several air movements inside the greenhouse module; the first type of fan or oscillating fan was mainly used to ensure that all plants could be exposed to the air. Hanging ceiling fans were used for circulating warm air at the top of the dome. The last type of fan that was commonly used for circulating air was like the regular electric fan. This type of fan performed best when installed perpendicular to the intake fans for creating circular air movement inside the dome [40]. However, in dry conditions, it was recommended to use a misting system or wet pads to increase the water vapor in the air [41]. The misting system was the system that uses cooling vapor spraying inside the greenhouse for creating an ideal environment for growing the crops [42]. The EDEN ISS Antarctic Greenhouse humidity system condensed water vapor from plants for recycling, improving efficiency. From February to November 2018, it consumed 23,040 kWh, 33% of total energy use [33].

2.2.4. Air conditioning system

2.2.4.1. Air handling unit (air handler)

Air handling units or air handlers are machines used for circulating cold air inside the greenhouse as shown in Fig. 7. Moreover, it was used for maintaining optimum temperature and controlling the humidity of the air-handling product. Air handlers included a louver, a fan used for air circulation, a reheat coil as a heating element, and a cooling coil as a cooling element. This type of machine could be installed individually in the greenhouse. Moreover, a reheat coil and cooling coil could be used to exchange the heat with the air inside the greenhouse. The fans were used to circulate the air through the coil and send it outside through the dome.

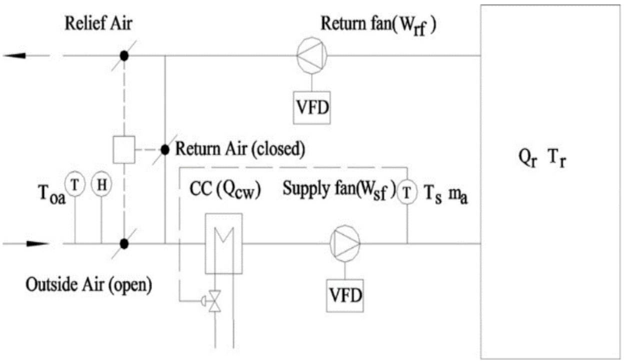


Fig. 7. Air Handling Units diagram used in Air Conditioning System of Environmental Control Subsystems of a Lunar-Base greenhouse [45].

Moreover, the louvers could be used to filter the air by removing unwanted elements inside the greenhouse such as water, dirt, and debris field [43]. On the other hand, the air handling unit also caused vibration, so it could make a loud noise [44]. Therefore, it was not suitable to install near the habitat. The sound of an air handling unit could affect the human living environment on the lunar surface. Safety features include HEPA filters (99.97% particle removal), UV-C sterilization, and CO_2 scrubbers. Computational Fluid Dynamic (CFD) simulations showed airflow of 8,116 m^3/h (warm) and 8,281 m^3/h (cold) with uniform tray distribution and duct velocity of ~3 m/s. Total pressure loss calculated via Eq. (1) was 5,673 Pa, including pre-filters (130 Pa), HEPA filters (1,300 Pa), and VOC filters (440 Pa) [34].

$$\Delta p = \zeta \cdot \frac{\rho \cdot v^2}{2} \qquad (1)$$

2.2.4.2. *Condenser*

A condenser is a device used to extract heat from the greenhouse air by different methods depending on its type. There were mainly four types of condensers: tubular condenser, air-cooled condenser, plate-type condenser, and direct-contact condenser [46]. The air inside the greenhouse was the heated air carrying a heat load consisting of water vapor, O2, CO2, CH4, etc., considered to be the main greenhouse gasses [47]. Since the Moon's gravity is one-sixth lower than Earth's, the air circulation inside this greenhouse module required forced circulation, like using fans for example. The four factors used to determine the utility of a condenser in a greenhouse were the used coolant, cost, fouling, and availability of non-condensable gasses. These factors concluded that air-cooled condensers were less expensive compared to other types and available for non-condensable gasses [46]– [49]. Furthermore, air-cooled condenser types did not require liquid coolant and could produce condensate water after cooling the air that could be used later, however, there is a high chance for fouling in this type of condenser [46]–[49]. The Condensing Heat Exchanger (CHX) removes up to 134 kg/day of water vapor at 288.6 K, providing 25.2 kW cooling capacity for high transpiration rates [34]. The Greenhouse Module (GHM) manages 29 kW of LED heat (462 kWh/day), with hybrid lighting reducing cooling demand to 47 kWh/day [12]. CFD adjustments, including upstream HEPA filters and inline baffles, improved condenser airflow. Latent heat removal, calculated via Eq. (3), is 3,506 W for 134 kg/day at 2,260 kJ/kg [34].

$$Q_{\text{latent}} = \Delta H_{\text{water}} \cdot \dot{m}_{\text{condensation}} \qquad (3)$$

2.2.5. Illumination system (ILS)

Light is an important factor in the greenhouse system since plants require light to initiate the plant's photosynthesis process. Certainly, the source of light comes from the Sun, thus the location of the greenhouse also affects the efficiency of the greenhouse and requires to be considered. The GHM illumination system provides 250–600 μmol/m²/s by day and 0–10 μmol/m²/s at night. LEDs consume 353 kW and 5,650 kWh/day (810 m² panels), while the hybrid option uses 573 kWh/day (330 m² panels, 300 m² collectors, 33% PAR) [12]. Efficient LEDs optimize photosynthesis, enabling plants to absorb 1,741.2 g/CM-day of CO_2 and release 1,364.2 g/CM-day of O_2 [31]. EDEN LUNA MTF (2022) uses 42 LEDs, consuming 19,033 kWh/month (28% total energy), with 11.23 kW (~898.4 W/m²) during a 17-hour photoperiod and 8.21 kW (~656.8 W/m²) in a 7-hour on dark period [33]. Batteries store 7,334 kWh (20% margin) for dark days, supported by solar cells producing 129 kWh/day with 30 m² panels, while 80 consecutive charging days can store 10,320 kWh, with 7,224 kWh usable at 70% battery efficiency, sufficient to power white LEDs and their cooling system for one dark day [12].

2.2.5.1. *General information about lunar surface*

The lunar surface is divided into the near side and far side. The differences between those two sides are that the near side has a lot of lowlands represented by dark spots which are called maria. On the other hand, almost all of the far side surface is the highland which contains many craters [50]. The collision of the meteorites created the lunar regolith which covered the lunar surface [51]. It is a fine gray dust that contains breccia and pieces of the surrounding bedrock [52]. The area that had attracted scientists' interest was the south pole because of the possibility of the appearance of water ice in permanently shadowed areas. Lunar water ice in shadowed polar regions contains 5.6 ± 2.9 wt% water, totaling 2.9×10^{12} kg within the top ~0.1–0.3 meters. Extraction methods like thermal mining and MISWE drills require energy-efficient solutions to address low gravity challenges [14]. The lunar south pole features craters that are special because sunlight could not approach their interior. In comparison, the area around the lunar north pole has much fewer similarly sheltered craters [53], [54].

2.2.5.2. *Ideal location of lunar greenhouse*

The ideal location for building both human habitat and the greenhouse on the lunar surface is at the lunar south pole where scientists believed that the water ice might exist. Ice can be considered a resource to serve long-period missions [55]. The location of the lunar south pole is at 80°S to 90°S or in the center of the Antarctic polar circle [56]. Furthermore, the lunar south pole can provide the most daylight so that it can generate energy for human living by using solar power such as illumination systems [57]. One day on the Moon is equal to thirty days on Earth because it takes two weeks for each day and night [58]. During the sunlight period, the temperature starts at 54°C and increases during the day. On the other hand, it can decrease up to -203°C in the shadowed regions which leads to the possibility of ice and minerals [59]. Thus, the lunar south pole seems suitable for building the greenhouse. Furthermore, there is the area called Permanent Shadowed Regions (PSRs) near the lunar poles, about 10 kilometers in diameter, where sunlight cannot reach [60]. According to the Lunar Exploration Neutron Detector (LEND) data, scientists believe that water ice might exist because PSRs have an extremely cold environment [61]. When this hypothesis is confirmed, it will increase the chances of establishing a lunar habitat in the future since water is a limited resource that requires refilling.

From the lunar-base greenhouse design, each crop required a different amount and spectrum wavelength of light [17]. There were two hybrid light collection systems: natural and artificial light [18]. Natural light typically comes from sunlight and can be transmitted through fiber optics. The collectors had installed a dichroic reflector placed at the back of a light source; the dichroic reflector could only reflect visible light. The heat could be dissipated through the fixture's ends, decreasing the thermal load by eliminating the infrared light. Artificial light is visible light generated by artificial light sources such as torches, candles, lamps, etc. and normally consists of some infrared (IR) and ultraviolet (UV) radiation [62]. These two systems were working together and supported each other but could not be replaced [18]. There are advantages and disadvantages of these two systems provided in Table 4.

Table 4. Advantages and disadvantages of each natural light and artificial light used in the greenhouse on the Moon's surface [18].

System		Advantages	Disadvantages
Natural light	Solar collectors with fiber optics	○ Provide the necessary light level on a lunar day at any lunar location. ○ Provide micro-meteoroid & orbital debris (MMOD) and radiation prevention	○ Have low efficiency of light
	Light tubes	○ Have medium-light efficiency. ○ Provide MMOD and radiation prevention	○ Achieve an extremely small light level
Artificial light	Light emitting diodes (LEDs)	○ Have strong power and efficiency. ○ Have high photosynthetically active radiation (PAR) efficiency ○ Achieve a small distance from the plants. ○ Lifetime ⩾25,000 hrs.	○ Have excessive cost
	Metal halide lamps (MH lamp)	○ Have output nearly to the natural sunlight. ○ Leave a suitable amount of heat	○ Can be dangerous since it contains mercury. ○ Have low mass and power efficiency. ○ Can be hard to replace

2.2.6. Thermal control system (TCS)

The thermal control system (TCS) is particularly important to ensure the safety of the crews who live in space. There are many thermal systems that are used to create a suitable environment in the spacecraft, shielding is one of the most important ones. Space radiation consists of galactic cosmic rays which directly affect organisms because of the high-energy photons and weighty ions. The radiation level on the Moon's surface is much higher than the Earth's [63], [64]. The researchers had a hypothesis that the exposure to radiation in space could stimulate genome oxidation, and a rise in the telomerase enzyme activity that had protected the telomeric DNA of plants [65]. Moreover, the materials used for shielding could be divided into three types. The EDEN LUNA MTF (2024) uses coolant loops and plate heat exchangers for heat dissipation [32]. Antarctic winters (-43.5 °C) lower cooling demand, with monthly energy use at 7,551 kWh (11% total) [33]. CFD simulations optimized heat flow, with 9,856 W (day) and 5,154 W (night). The CHX condenses 134 kg/day of water vapor at 288.6 K, matching transpiration rates [34].

$$Q = \dot{m} \cdot c_p \cdot \Delta T \tag{4}$$

CFD analysis confirmed airflow of 8,116 m^3/h (warm) and 8,281 m^3/h (cold) with total pressure losses of 5,673 Pa, ensuring efficient cooling [34]. Thermal management is supported by the habitat system, with a thermal interface and an emergency heat exchanger for extreme loads [12].

2.2.6.1. *Quality shielding protective materials*

Quality shielding protective material was a basic method used to reduce and protect the radiation effect for the crew in space when working inside the greenhouse module or in the habitat. In this type of method, more thickness of the material was related to the high efficiency in radiation protection for humans [66]. To create a good shield, the conditions that should be considered are the quality of absorbing the radiation of the material. The material used for creating shields for protection against radiation in space was Polyethylene. Polyethylene is a material that has high hydrogen atoms. The high values of hydrogen atoms illustrate the high ability to absorb radiation [67]. Lunar regolith (>0.3 m) provides radiation protection and thermal stability, while Multilayer Insulation (MLI) achieves a heat flux of 7.13 W/m^2 in warm conditions [34].

2.2.6.2. *Electrostatic protection materials*

The spacecraft's surface can experience charging and discharging impacts during its orbital activity. For that purpose, the spacecraft's surface substance should be anti-static. A conductive translucent sheet of indium tin oxide (ITO) was coated on the exterior of the mirror reflection thermal control coating and added conductive components to the thermal control coatings. The ITO/PI/Al was one of the antistatic coating types in which the aluminium film (Al) was plated on the back side of polyimide film (PI), and the ITO was coated on the outside to diminish the charge and discharge impact of the area. Another type was to coat the ITO film on the perfluoro ethylene propylene film (F46). In addition, the silver-plated conductive F46 is lightweight, has excellent stability, can be turned into a wide-area product, and is simple to install [66]. Electrostatic protection materials shield electromagnetic radiation, with Electromagnetic Interference Shielding Efficiency (EMSE) calculated as Eq. (5).

$$SE = 10\log\left|\frac{P_1}{P_2}\right| = 20\log\left|\frac{E_1}{E_2}\right| \ (decibels, dB) \tag{5}$$

Metalized fabrics achieve SE up to 100 dB, conductive polymers like polypyrrole reach 36 dB, and nonwoven textiles provide up to 37 dB, offering lightweight, flexible shielding [68].

2.2.6.3. 2.2.6.3 Anti-radiation functional materials

Anti-radiation functional materials were used for specific requirements, such as light transmission properties for making windows on spacecraft. An example of material used is the combination of quartz which has good radiation resistance but is very brittle, and K9 glass which is very strong but not good in radiation resistance. Therefore, windows on the spacecraft used quartz and K9 as a supporter in the inner layer due to their strength and good radiation resistance. Additionally, adding $Bi2O3$, BaO, and PbO which are heavy metal oxides with high atomic numbers into the material can also improve the quality of anti-radiation material [66].

Besides, the outstanding characteristics of shielding are simple, lightweight, and can be adapted to a product that has a wide area. The anti-radiation functional materials are widely used for windows in spacecraft that have light transmission properties. Obviously, the different materials have different characteristics, and selecting the types of materials depends on the usage.

According to the lunar-base greenhouse design, heat also accumulated inside the LED panels when providing a light source in the greenhouse. Water was used to reduce the heat from LED panels since LEDs could be operated more efficiently at lower temperatures [69]. Therefore, this type of LED panel that dissipated heat through water was called a water-cooled LED. In each panel, there was a tube with water flowing through it, which cold went through the inlet and exchanged the heat then came out as warm water at the outlet [69]. The liquid-to-liquid heat exchanger design was based on the demanding crop production plan since each crop had distinct photosynthetically active radiation (PAR). For example, wheat framing had the maximum amount of heat that the water-cooling system should dissipate for the durum wheat petal was 89.8 kW, with a 10% margin, so this quantity of heat was transferred from water to the cooling liquid via the liquid-to-liquid heat exchangers [17].

Regolith effectively shields cosmic and solar radiation, offering durable, in-situ materials for cost-efficient [13]. A 0.5-inch sulfur/JSC-1 regolith block with 20% silica filler resisted a 1-mm aluminum sphere at 6 km/s, demonstrating durability, while regolith blocks effectively shield gamma and neutron radiation, proving suitable for extraterrestrial protection [15].

2.2.7. Water recovery system

A water recovery system was the method used to create more useful water that could be run inside the system. In the greenhouse module on the Moon, a water recovery system was used for extending and supporting the long-duration mission. There were ways of producing and recycling waste to create more water including the Sabatier system and hydrogen fuel cell, urine recovery process, JEM water recovery system, and Aqua membrane. Water recovery efficiency recycles 275.9 g/CM-day of wastewater from humans for irrigation and drinking [31].

2.2.7.1. Sabatier system and hydrogen fuel cells

The Sabatier system was a chemical method that used an electrolysis process to produce water. This method used the concept of an oxygen generation system to separate CO2 and H2 to produce additional water [70].

2.2.7.2. Urine recovery process

To recover water from humidity, technologies such as sorption/catalytic purification, salt saturation, preservation, and pasteurization of purified water had been used [71]. For urine recovery, urine was stabilized with a combination of H3PO4 and Cr6+ and held in a tank to restrain microbiological development and chemical stability. Then, urine would be distilled and routed through the water processor assembly (WPA) unit for additional purification before being utilized for drink And oxygen production [72].

2.2.7.3. JEM water recovery system (JWRS)

This system was invented for recycling urine water gotten from crews and then generating it into drinking water by the purification method. The experiment was interested in the liquid phase shown in the microgravity environment [73]. The JWRS was working due to three major treatment processes which were ion exchange, electrolysis, and electrodialysis. Magnesium and calcium were removed in the first stage to prevent clogging. The electrolysis process ran with high temperature and pressure to completely decompose the organic matter. Lastly, in the electrodialysis stage, ions that stayed in liquid were eliminated in this last stage to produce qualified water [73].

2.2.7.4. Aqua membrane

The method proposed one of the solutions of the aquaporin inside membrane (AIM) testing in space. According to Heider and Pesquet (2022) of the Thomas Pesquet Proxima mission [74], this approach could be used as a replacement for multi-filtration beds, considered as upload mass, for water recovery. Using the AIM as a filter consumed zero energy, which was considered a high-efficiency method to recycle wastewater since the Aquaporins are water channel proteins with high permeability and solute rejection. It was conducted in a microgravity environment, which consisted of syringes, plastic storage bags, plastic tubing, tubing clamps, stopcocks, plastic strips, parafilm, and the AIM module. The test could be divided into two setups: a pressure-driven setup and an osmotic-driven setup. A pressure-driven setup was used to treat ISS wastewater to test total organic carbon rejection in a microgravity environment, while an osmotic-driven setup was used to calculate the osmotic flux rate across the membrane. Furthermore, the samples were collected and sent back to Earth for analysis [74].

2.2.8. Automatic control system

The EVE Robotic Payload automates plant cultivation using a TINA-based robotic arm with seven joints on a 5-meter rail, performing tasks like planting, monitoring, and harvesting in shared-autonomy mode. It includes multi-spectral cameras for health assessment, software-restricted operations, an emergency stop, and a modular design. EVE achieved a harvesting efficiency of 11.58 min/day/m^2, comparable to human systems like EDEN ISS (11.5 min/day/m^2) and superior to HI-SEAS II (31.2 min/day/m^2) [32], [75]. The EDEN ISS MTF (2018) Control Subsystem consumes 4,268 kWh/month (6% of total energy) [33]. The ACS in EDEN Next Gen greenhouse regulates airflow (8,116–8,281 m^3/h, 3,000 Pa), temperature (17,000 W heaters), humidity, CO_2 (350–5,000 ppm ±50 ppm), and O_2 (21–24% ±1%) using a 0.767 m^2 duct network, with manual redundancy for reliability [34].

2.2.9. Energy control system

The lunar greenhouse operates during extended day-night cycles (~708.75 Earth hours) using solar power, energy storage, and efficient subsystems. Key energy demands include illumination (4,618 W), fans (4,109 W), and thermal and humidity control (25198 kW peak) [34]. During the 14-day daytime, LED lighting uses 5650 kWh/day, requiring 462 kW/day cooling, while hybrid lighting reduces consumption to 573 kWh/day with 47 kWh/day cooling via 300 m^2 of solar collectors [12]. GaAs-based photovoltaic (PV) cells, with up to 30% efficiency, are the primary energy source for lunar applications, but require energy storage due to lunar nights. Li-ion batteries (150 Wh/kg) are commonly used, while hydrogen fuel cells offer long-term storage despite efficiency losses. Regenerative fuel cells and flywheels provide alternatives for surplus energy storage. Hybrid energy management combining PV, electrochemical, and thermal storage is essential for sustainable lunar greenhouse operations. Lunar polar regions, with up to 80% sunlight year-round, are ideal for solar panel installations, with outputs up to ~4,500 MWh/year using tracking arrays. Efficiency varies with temperature, as described by Eq. (6) [14].

$$\eta_{PV} = \eta_{ref} \cdot [1 - \gamma_{ref}(T_{cell} - T_{ref})] \tag{6}$$

where η_{ref} is 30.7%, γ_{ref} is 0.1791%/K, and T_{ref} is 28 °C. Equatorial systems require large storage for 14-day nights, while polar systems need less due to prolonged sunlight. [76]. The Table 5 provides a comparison in energy consumption, yield efficiency, or resource utilization rates under Lunar conditions.

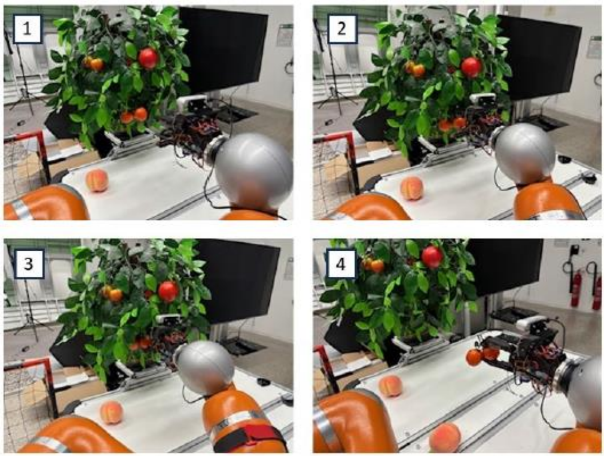


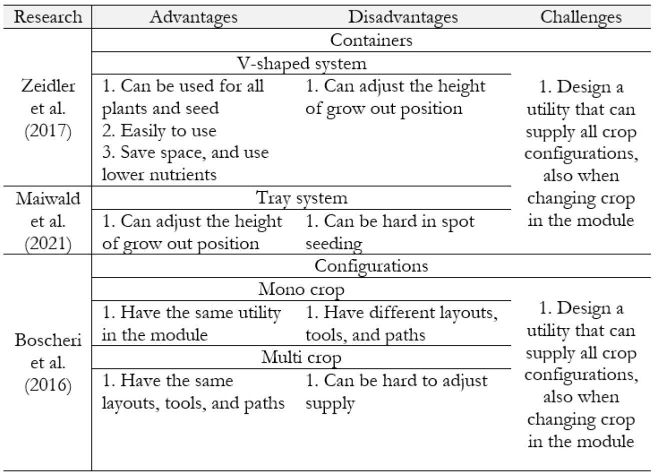
Fig. 8. Sequence of grasping tomato. (1) Target tomato identification. (2) Approaching target tomato. (3) grasping tomato and detaching it. (4) Transporting grasped tomato to basket [75].

Table 5. compares energy consumption, yield efficiency, and resource utilization for Zeidler et al, EDEN ISS and MELiSSA [12], [14], [17]-[19], [32]-[34].

Researches	Energy Consumption	Yield Efficiency	Resource Utilization	Air Management	Thermal Control	Humidity Control	Illumination System	Water Recovery
Zeidler et al. (2017)	26 kW (Ventilation)	1.04 kg/crew/day (Food)	80–90% (Water recovery)	CO_2: 1.266 kg/day	29 kW (LED heat)	80% at 27°C	5,650 kWh/day (Artificial light)	134 kg/day
Boscheri et al. (2016)	-	-	-	-	-	RH 50–85%	Hybrid (Fiber optics + LED)	-
Maiwald et al. (2021)	-	-	80–90% water recovery	8,116–8,281 m^3/h airflow	462 kWh/day (Water-cooled LED system)	RH 50–85%	573 kWh/day (hybrid)	134 kg/day recovery

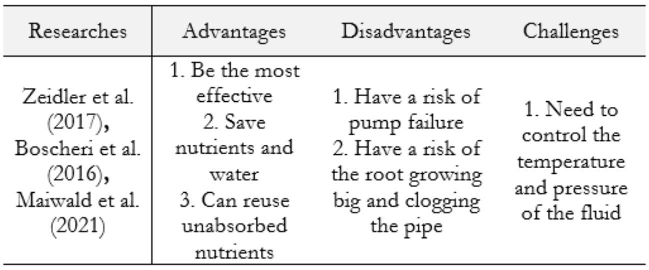
Researches	Energy Consumption	Yield Efficiency	Resource Utilization	Air Management	Thermal Control	Humidity Control	Illumination System	Water Recovery
EDEN ISS	4,618 W (lighting)	1.2–1.6 kg/day (Food)	80–90% (Water recovery)	CO_2: 1.2–1.741 kg/day	462 kWh/day (cooling)	50–85%	573 kWh/day (Hybrid lighting)	134 kg/day
MELiSSA	275.9 g/day (Water)	1.6 kg/day (Biomass)	136 kWh/day (Energy)	O_2: 0.5 kg/day	10.5 kg/day	-	-	10.5 kg/day

Table 6. Comparison of advantages, disadvantages, and challenges between three lunar greenhouse modules of cultivation system of an ideal lunar-base greenhouse subsystems from the designs of Zeidler et al. (2017) [17], Boscheri et al. (2016) [18], and Maiwald et al. (2021) [19].



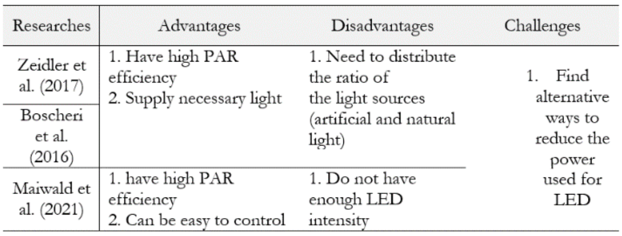
Research	Advantages	Disadvantages	Challenges
	Containers		
	V-shaped system		
Zeidler et al. (2017)	1. Can be used for all plants and seed 2. Easily to use 3. Save space, and use lower nutrients	1. Can adjust the height of grow out position	1. Design a utility that can supply all crop configurations, also when changing crop in the module
Maiwald et al. (2021)	Tray system		
	1. Can adjust the height of grow out position	1. Can be hard in spot seeding	
	Configurations		
Boscheri et al. (2016)	Mono crop		1. Design a utility that can supply all crop configurations, also when changing crop in the module
	1. Have the same utility in the module	1. Have different layouts, tools, and paths	
	Multi crop		
	1. Have the same layouts, tools, and paths	1. Can be hard to adjust supply	

Table 7. Comparison of advantages, disadvantages, and challenges between three lunar greenhouse modules of nutrient delivery system of an ideal lunar-base greenhouse subsystems from the designs of Zeidler et al. (2017) [17], Boscheri et al. (2016) [18], and Maiwald et al. (2021) [19].



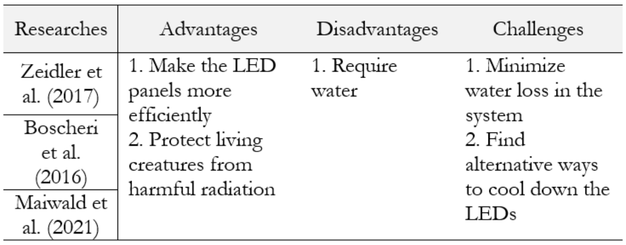
Researches	Advantages	Disadvantages	Challenges
Zeidler et al. (2017), Boscheri et al. (2016), Maiwald et al. (2021)	1. Be the most effective 2. Save nutrients and water 3. Can reuse unabsorbed nutrients	1. Have a risk of pump failure 2. Have a risk of the root growing big and clogging the pipe	1. Need to control the temperature and pressure of the fluid

Table 8. Comparison of advantages, disadvantages, and challenges between three lunar greenhouse modules of illumination system of an ideal lunar-base greenhouse subsystems from the designs of Zeidler et al. (2017) [17], Boscheri et al. (2016) [18], and Maiwald et al. (2021) [19].



Researches	Advantages	Disadvantages	Challenges
Zeidler et al. (2017)	1. Have high PAR efficiency 2. Supply necessary light	1. Need to distribute the ratio of the light sources (artificial and natural light)	1. Find alternative ways to reduce the power used for LED
Boscheri et al. (2016)			
Maiwald et al. (2021)	1. have high PAR efficiency 2. Can be easy to control	1. Do not have enough LED intensity	

Table 9. Comparison of advantages, disadvantages, and challenges between three lunar greenhouse modules of thermal control system of an ideal lunar-base greenhouse subsystems from the designs of Zeidler et al. (2017) [17], Boscheri et al. (2016) [18], and Maiwald et al. (2021) [19].



Researches	Advantages	Disadvantages	Challenges
Zeidler et al. (2017)	1. Make the LED panels more efficiently 2. Protect living creatures from harmful radiation	1. Require water	1. Minimize water loss in the system 2. Find alternative ways to cool down the LEDs
Boscheri et al. (2016)			
Maiwald et al. (2021)			

Table 10. Comparison of advantages, disadvantages, and challenges between three lunar greenhouse modules of air management system of an ideal lunar-base greenhouse subsystems from the designs of Zeidler et al. (2017) [17], Boscheri et al. (2016) [18], and Maiwald et al. (2021) [19].

Researches	Advantages	Disadvantages	Challenges
Zeidler et al. (2017)	Ventilation system (Mechanical)		
	1. Manage air circulation 2. Increase plant activity. 3. Produce O_2 by photosynthesis 4. Decrease problems in humidity and disease of plants 5. Can be used in different kinds of weather	1. Have a complex installation 2. Can be expensive for the cost of the fan design	1. Increase in ventilation rate to control climate 2. Reduce the cost 3. Simplify the complexity of the system
	Humidity control system		
	1. Decrease the incidence of disease. 2. Increase plant transpiration	-	1. Have an ideal humidity level for the greenhouse of 80% at 27°C 2. Reduce high humidity level by using fans. 3. Add more water vapor to the air by using the misting system
	Air conditioning system (Air handling units)		
	1. Circulate cold air. 2. Maintain temperature and humidity	1. Have high vibration. 2. Have loud noise	1. Should be installed far from the habitat
Boscheri et al. (2016)	Humidity control system		
	1. Decrease incidence of disease 2. Increase plant transpiration	-	1. Have normal relative humidity of greenhouse gas environment: 50-85%
Maiwald et al. (2021)	Ventilation system (Mechanical)		
	1. Manage air circulation. 2. Increase plant activity. 3. Produce O_2 by photosynthesis. 4. Decrease problems in humidity and disease of plants. 5. Can be used in different weathers	1. Have a complex installation. 2. Can be expensive for the cost of the fan design	1. Have enough air flow rate and area affected by the fan system design
	Air conditioning system (Air handling units)		
	1. Circulate cold air. 2. Maintain temperature and humidity	1. Have high vibration. 2. Have loud noise	1. Should be installed far from the habitat

Table 11. Comparison of advantages, disadvantages, and challenges between three lunar greenhouse modules of water recovery system of an ideal lunar-base greenhouse subsystems from the designs of Zeidler et al. (2017) [17], Boscheri et al. (2016) [18], and Maiwald et al. (2021) [19].

Researches	Advantages	Disadvantages	Challenges
Zeidler et al. (2017), Boscheri et al. (2016), Maiwald et al. (2021)	Sabatier system and hydrogen fuel cells		
	1. Can produce the freshwater	1. Keep the wastewater remain 2. Cannot be good for long missions	1. Should develop new methods for long missions sustainably
	Urine recovery process		
	1. Can recycle the wastewater and urine	1. Need chemical substances 2. Require more complexity for higher purification	1. Should develop new methods for long missions sustainably
	JEM water recovery system		
	1. Can recycle urine 2. Can be easy and most preferable	-	1. Should develop new methods for long missions sustainably
	Aqua membrane		
	1. Can recycle the wastewater and urine 2. Have high efficiency	1. Can be tested only on space 2. Have a complicated method	1. Should develop new methods for long missions sustainably

3. Discussion

In the agricultural part, there are many planting methods such as using soil, soil-like, and soilless such as hydroponic [77]. However, those methods carry more weight, for example, the hydroponic method requires a large amount of water [78]. It can also affect the increase of humidity because water always evaporates when a certain temperature and pressure are reached. Thus, this method is preferable to use on Earth. Since the transportation of the water required a massive amount of energy and cost [79], the agricultural method in the lunar greenhouse used the aeroponic method which did not involve soil and spraying water with nutrients direct to the plant root that was hanging in the air [17]. The concept of a cultivation system was considered between a tray system and a V-shape channel as discussed in Table 6. The tray system could grow a variety of crops and replace the withered seed by changing the tray lid as needed while the V-shape channel was vice versa [17], [26]. In greenhouse modules, also shown in Table 6, mono crops and multi crops could be both selected for growing plants in space. In addition, the nutrient delivery system is the system that controls the condition of the storage area for the delivery of plants from Earth to space. Since transporting plants in space needs more consideration than transporting plants on Earth, there are also some environmental states that need to be maintained inside the storage area as discussed in Table 7 [70]. Plants absorb 1.266–1.741 kg/day of CO_2 and release 0.914–6 kg/day of O_2, supporting a six-member crew [34]. Water recycling sustains plant growth, but CO_2-O_2 balance optimization remains a challenge [12] [31].

In the air management system, there are three main systems that were used inside the greenhouse module (GHM) included: the ventilation system, humidity control system, and air condition system. As shown in Table 8, mechanical ventilation is recommended to be used in GHM in space because it can operate in specific conditions controlled by installing specific devices [37], [38]. Humidity control devices are mostly used to create air movement inside the GHM. Electric fans are used because they can maintain the most suitable surroundings for plants. This method can help to stabilize the humidity in a certain range in an uncontrollable environment [40]. If the air were too dry, the misting system would be applied to increase the humidity by spraying water vapor into the atmosphere. The topic of air condition systems illustrates two types of machines: air handling units and condensers. The air handling unit is the device that used only heating and cooling elements mainly operated by electricity, to control the temperature inside the GHM. However, it is limited for installation far from the habitat because of loud noise produced by vibration [44]. The condenser is one of the air conditioning devices to extract heat from the GHM. The several types of condensers illustrate the difference in function. When focusing on the cost factor, the air-cooled condenser is a less expensive type of condenser that can run the system in space [49]. The AMS efficiently transfers CO_2 from the crew to the greenhouse, integrating with the MELiSSA loop for atmospheric stability [12]. Further optimization is needed to regulate fluctuating atmospheric conditions [34].

For the illumination system, there are two types of light technologies that work together to initiate the photosynthesis process for the crops as discussed in Table 9. First, natural light is considered between light tubes and solar collectors with fiber optics. The solar collectors with fiber optics are better than the light tubes since the solar collectors with fiber optics can provide the necessary level of light on a lunar day at any position, but the light tube's performance can achieve an extremely small light level [18]. Next, artificial light is considered between LEDs and MH lamps. LEDs have higher power and efficiency of mass [18]. Moreover, when the wavelength is determined, the LEDs had more PAR efficiency than MH lamps. Although the MH lamp's output is almost similar to natural sunlight, it is unsafe since it consists of mercury banned in space [18]. Therefore, the illumination system of this GHM is selected to use solar collectors with fiber optics and LEDs. The location for installing GHM on the Moon is an additional factor involved in the light system because the south pole of the Moon is the best area for receiving sunlight [53], [54]. GHM lighting consumes 5,650 kWh/day, but hybrid solar-LED systems reduce this to 573 kWh/day [12]. Energy storage solutions remain a key challenge for prolonged lunar nights [76].

For the thermal control system in Table 10, there is the water-cooling system used to reduce the heat from LED panels in order to make LED more efficient and send the heat out of the GHM into the residence [17], and the radiation shielding used to protect the living creature from space harmful radiation by using three main materials: quality shielding protective, electrostatic protection, and anti-radiation functional [66], [67]. Quality shielding protective material is common to use. The electrostatic protection material is outstanding since it is simple, lightweight, and can be used with a wide area [66]. The anti-radiation functional material is usually used for windows that have light transmission properties [66]. However, the selection of each material requires to be considered for its application. The EDEN LUNA MTF cooling system uses 7,551 kWh/month, while water recovery recycles 275.9 g/CM-day of wastewater [31], [32]. Passive thermal management needs further improvement [34].

Since water is difficult to transport in space, the water recovery system is significant to be used in the greenhouse to support the longer mission [78]. There are many ways to produce or recycle water as discussed in Table 11. The first method is to produce the water by chemical method, the electrolysis process is to remove the CO2 and H2 to create water [70]. Other methods are recycling wastewater such as urine. In the urine recovery process, the water can be recovered from the humidity by the technologies; the urine can be stabilized with a combination of chemical substances in a tank and can use the water processor assembly for more purification. Another technique is the JEM water recovery system, which is the method consisting of three treatment processes; ion exchange, electrolysis, and electrodialysis to create drinkable water [73]. The last method is the Aqua membrane used to replace the multi-filtration beds using an AIM to filter the water which consumed zero energy and was the high-efficiency method [74]. Of all the methods above the JEM water recovery system is the easiest method and can provide purification to water, so this method is the most preferable method to recycle the water. Moreover, the greenhouse will not be very cold when installing the radiator since the heat can still enter the greenhouse through the wall and ceiling to ensure that heat is suitable for the crops. The system efficiently recycles 275.9 g/CM-day of wastewater, with the CHX removing 134 kg/day of water vapor for reuse [31], [34]. While filtration ensures purity, further research is needed to optimize microbial control and assess long-term sustainability under lunar conditions [12], [33].

In Automatic Control System, The EVE Robotic Payload enhances greenhouse efficiency by automating tasks such as planting, monitoring, and harvesting. With a TINA-based robotic arm, it achieves a harvesting efficiency of 11.58 min/day/m², comparable to the EDEN ISS system and significantly better than manual alternatives [32], [75]. The Automatic Control System (ACS) regulates key environmental parameters, including airflow (8,116–8,281 m³/h), temperature, humidity, CO_2 (350–5,000 ppm), and O_2 levels (21–24%), ensuring stable conditions for plant growth [34]. Despite these advancements, long-term reliability of automation systems in lunar conditions remains uncertain, with challenges such as dust contamination, mechanical wear, and extreme temperatures posing risks to performance [12], [31]. Additionally, the integration of automation with greenhouse subsystems optimizes nutrient delivery, water recycling, and energy management, but further research is needed to ensure adaptability to lunar environmental shifts and extended darkness [33].

For Energy Control System, The Energy Control System is critical for maintaining the greenhouse's operations during lunar day-night cycles (~708.75 Earth hours). During the 14-day daytime, solar power provides energy to support high-demand systems, such as LED lighting (5,650 kWh/day) and cooling (462 kWh/day). The introduction of hybrid lighting systems reduces overall energy consumption to 573 kWh/day, significantly improving efficiency [12]. Battery storage plays a vital role in supporting operations during the 14-day lunar night. Current systems can store up to 7,334 kWh, with 70% efficiency, ensuring energy availability for essential functions like lighting, cooling, and air management during prolonged darkness. However, the extended duration of lunar nights poses challenges, requiring improved energy storage and management systems to enhance reliability [76]. Solar power, especially in polar regions with 80% sunlight year-round, offers a sustainable solution, but efficiency drops under extreme temperature variations, as described by Eq. (6) [14].

Developing a sustainable greenhouse on the Moon is essential for long-term human habitation. Figure 9 presents six key factors for designing an optimal greenhouse module, addressing air regulation, radiation shielding, and resource management. Figure 10 highlights four major challenges, including resource limitations, low gravity, spatial constraints, and shielding requirements. These considerations are crucial for ensuring the feasibility of lunar agriculture and sustaining human presence.

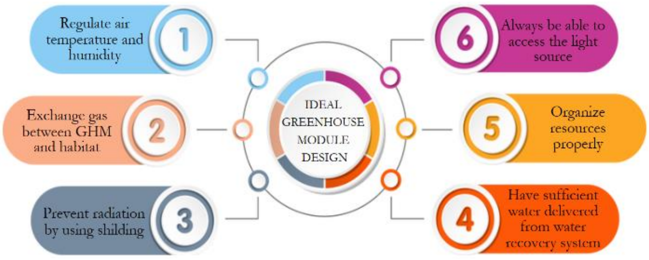


Fig. 9. Six Important Factors considering permanent habitant on the Moon's surface of building and designing the main subsystem for an ideal greenhouse module on the Moon's surface.

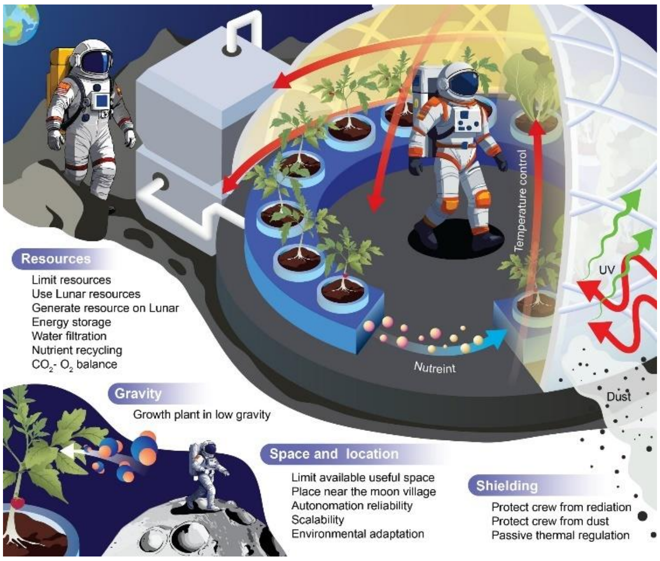


Fig. 10. Four Main Challenges considering permanent habitant on the Moon's surface of designing an ideal Lunar-Base greenhouse module.

4. Conclusion

In conclusion, this paper of a review of the mechanical element design of a lunar greenhouse for long-term space missions focuses on the systems for producing food, water, and O2 which increase the opportunity for comfortable living during long missions on the Moon and for permanent inhabitants. To summarize, as shown in Fig. 4 the important subsystems that need to be considered when designing the greenhouse module on the lunar surface are agricultural subsystems and environmental control subsystems which are divided into air management systems, illumination systems, thermal control systems, and water recovery systems. This review paper categorized mainly three module designs and provides a comparison of the advantages, disadvantages, and challenges of each design. The decision to choose the proper design depends on the requirements. Finally, this paper concluded the important factors and challenges shown in Fig. 9 and Fig. 10 for building a greenhouse on the Moon's surface which are: the ambient temperature and relative humidity inside the greenhouse should be adjusted to provide the best condition for growing plants; the gasses produced from a greenhouse and the human habitat should be able to exchange between the two such as O2 and CO2; the greenhouse structure, mainly shielding, should be able to withstand the outside of the Moon environment like Moon dust and radiation in example; the greenhouse should have sufficient water supply which mainly came from the water recovery system from human habitat; the resources in the greenhouse should be organized properly to achieve the high efficiency when growing plants including nutrients and water; and the greenhouse should be able to receive the light source from the Sun as much as possible which lead the location of building the greenhouse since the light is the main factor of photosynthesis of the plants.

Besides, when the Moon Village concept becomes a reality, the knowledge of building a greenhouse surely would be a big step to achieve the dream of living on the Moon because a greenhouse is part of the ECLSS and can advance the space food industry. The concept of building a greenhouse could lead to building a living environment in the habitat on the Moon's surface just like being on Earth. However, as of now the idea of the designs are only in concept since it is yet to be built on the Moon's surface there are still unforeseen considerations to be discovered later. In this review paper, there are still limitations while researching the greenhouse designs since there are few designs and prototypes regarding the lunar-base design; therefore, this paper only focuses on important systems for the greenhouse in the mechanical engineering aspect. Nevertheless, this paper did not conclude the other topics such as the overall structure in space architecture aspect, suitable materials for construction, and the interaction point of design between the Moon habitat and the lunar-base greenhouse, etc., thus these topics could be further studied and researched later. The Greenhouse Module (GHM) uses diverse structures and lunar regolith for shielding and insulation. While systems for agriculture, air, water, and thermal control support plant and human life, challenges in energy efficiency, resource use, and automation reliability need further refinement for long-term lunar missions.

Acknowledgement

Author Contributions: Conceptualization, W.C., S.C., P.Y., K.J., N.C. and C.W.; Methodology, W.C., S.C., P.Y., K.J., N.C. and C.W.; Writing—original draft preparation, W.C., S.C., P.Y., K.J., N.C. and C.W.; Writing—review and editing, W.C., and R.T.; Supervision, W.C.; Project administration, W.C.; Funding acquisition, W.C.. All authors have read and agreed to the published version of the manuscript.

This research project is supported by Chulabhorn Royal Academy (Fundamental Fund by National Science Research and Innovation Fund (NSRF): fiscal year 2024) (FRB670024/0240 Project code 198471).

References

[1] Ministerial Council, "What is Space 4.0," *European Space Agency (ESA)*, 2016. [Online]. Available: https://www.esa.int/About_Us/Ministerial_Council_2016/What_is_space_4.0. [Accessed: Mar. 3, 2023].

[2] Ministerial Council, "Moon Village," *European Space Agency (ESA)*, 2016. [Online]. Available: https://www.esa.int/About_Us/Ministerial_Council_2016/Moon_Village. [Accessed: Mar. 6, 2023].

[3] G. Petrov, D. Inocente, M. Haney, N. Katz, C. Koop, A. Makaya, and J. Hoffman, "Moon Village reference masterplan and habitat design," in *Proceedings of the 49th International Conference on Environmental Systems*, July 2019.

[4] C. Lasseur, et al., “MELiSSA: The European project of closed life support system,” *Gravitational and Space Biology*, vol. 23, no. 2, 2010.

[5] R. Peldszus and H. Dalke, “Design for the psychological habitability of spacecraft on extended exploratory missions,” *Supplemental Material*, pp. 4173–417, 2009.

[6] I. L. Schlacht, “SPACE HABITABILITY: Integrating human factors into the design process to enhance habitability in long-duration missions,” in *Proceedings of the International Astronautical Congress*, 2012.

[7] A. Smith, “Mechanics of materials in lunar base design,” *The Journal of Applied Mechanics*, vol. 46, no. 6, pp. 268–271, 1993.

[8] T. R. Gill, “HDU pressurized excursion module (PEM) prototype systems integration,” *NASA Technical Reports*, 2011. [Online]. Available: https://ntrs.nasa.gov/api/citations/20110011015/downloads/20110011015.pdf. [Accessed: Mar. 6, 2023].

[9] H. Scott and S. Brent, *Out of This World: The New Field of Space Architecture Library of Flight*. 2009. [Online]. Available: https://arc.aiaa.org/doi/book/10.2514/4.479878. [Accessed: May 10, 2023].

[10] W. Belvin, J. Watson, and S. Singhal, “Structural concepts and materials for lunar exploration habitats,” in *Proceedings of the Space 2006 Conference*, vol. 3, 2006.

[11] T. Erin, “Building a space habitat in the classroom,” *Science in School*, 2011. [Online]. Available: https://www.scienceinschool.org/article/2011/habitat/. [Accessed: May 10, 2023].

[12] K. Eriksson, O. Doule, and L. Poulet, “Architectural concepts for lunar greenhouse within the MELiSSA framework,” in *Proceedings of the 65th International Astronautical Congress (IAC)*, Toronto, Canada, 2014.

[13] N. J. Werkheiser, M. R. Fiske, J. E. Edmunson, and B. Khoshnevis, “Development of additive construction technologies for application to development of lunar/Martian surface structures using in-situ materials,” in *Proceedings of the CAMX Conference*, Dallas, TX, 2015.

[14] W. Wu, J. Shen, H. Kong, et al., “Energy system and resource utilization in space: A state-of-the-art review,” *The Innovation Energy*, vol. 1, no. 2, p. 100029, 2024. doi: 10.59717/j.xinn-energy.2024.100029.

[15] R. Fiske, W. McGregor, R. Pope, et al., “Lunar in situ material-based surface structure technology development efforts at NASA/MSFC,” *NASA Technical Report*, NASA Marshall Space Flight Center, Huntsville, AL, USA, 2007.

[16] H. Benaroya, *Engineering Approaches to Lunar Settlements*, in *Building Habitats on the Moon*, 2018.

[17] C. Zeidler, V. Vrakking, M. Bamsey, L. Poulet, et al., “Greenhouse module for space system: A lunar greenhouse design,” *Open Agriculture*, vol. 2, no. 1, pp. 116–132, 2017.

[18] G. Boscheri, M. Lamantea, C. Lobascio, and C. Paille, “The MELiSSA GreenMOSS preliminary design study: A greenhouse module on the lunar surface,” in *Proceedings of the International Conference on Environmental Systems*, vol. 352, 2016.

[19] V. Maiwald, V. Vrakking, P. Zabel, D. Schubert, et al., “From ice to space: A greenhouse design for Moon or Mars based on a prototype deployed in Antarctica,” *CEAS Space Journal*, vol. 13, no. 1, pp. 17–37, 2021.

[20] W. Robert, “United Nations Office for Outer Space Affairs,” *United Nations Treaty Resources*, 2015. [Online]. Available: https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/moon-agreement. [Accessed: May 10, 2023].

[21] P. Zabel, “System analysis & evaluation of greenhouse modules within Moon/Mars habitats,” in *Proceedings of the 39th COSPAR Scientific Assembly*, Mysore, India, 2012.

[22] P. Sadler, G. Giacomelli, R. Furfaro, R. Patterson, and M. Kacira, “Prototype BLSS lunar greenhouse,” *SAE Technical Paper*, 2009.

[23] D. Kolokotsa, G. Saridakis, K. Dalamagkidis, S. Dolianitis, and I. Kaliakatsos, “Development of an intelligent indoor environment and energy management system for greenhouses,” *Energy Conversion and Management*, vol. 51, no. 1, pp. 155–168, 2010.

[24] P. Srivani, Y. C. Devi, and S. H. Manjula, “A controlled environment agriculture with hydroponics: Variants, parameters, methodologies, and challenges for smart farming,” in *Proceedings of the International Conference on Information Processing*, 2019, vol. 978.

[25] S. Zhang, Y. Guo, S. Li, et al., “Investigation on environment monitoring system for a combination of hydroponics and aquaculture in greenhouse,” *Information Processing in Agriculture*, vol. 9, no. 1, pp. 123–134, 2022.

[26] D. Schubert, “Greenhouse module for space system: A lunar greenhouse design,” *Open Agriculture*, vol. 2, no. 1, pp. 91–115, 2017.

[27] S. May, “Eating in space,” *NASA STEM on Station*, 2015. [Online]. Available: http://www.nasa.gov/audience/foreducators/stem-on-station/ditl_eating. [Accessed: May 10, 2023].

[28] R. Winger, “Australia New Zealand food standards code,” *Food Control*, vol. 6, no. 14, p. 355, 2003.

[29] *Harvard Health*, “Listing of vitamins,” 2009. [Online]. Available: https://www.health.harvard.edu/staying-healthy/listing_of_vitamins. [Accessed: May 10, 2023].

[30] J. B. Montville, J. K. Ahuja, C. L. Martin, et al., “USDA food and nutrient database for dietary studies (FNDDS),” *Procedia Food Science*, vol. 2, pp. 99–112, 2013.

[31] H. Miyajima, “Life support systems trade study for lunar habitation with greenhouse food production,”

in *Proceedings of the 48th International Conference on Environmental Systems (ICES)*, Albuquerque, NM, USA, 2018.

[32] V. Vrakking, C. Philpot, D. Schubert, et al., "System design of the EDEN LUNA greenhouse: Upgrading EDEN ISS for future Moon mission simulations," in *Proceedings of the 53rd International Conference on Environmental Systems (ICES)*, Louisville, KY, USA, 2024.

[33] P. Zabel, V. Vrakking, C. Zeidler, et al., "Energy and power demand of food production in space based on results of the EDEN ISS Antarctic greenhouse," in *Proceedings of the 51st International Conference on Environmental Systems (ICES)*, St. Paul, MN, USA, 2022.

[34] J. Schroth, "Development of the atmosphere management system of the EDEN Next Gen greenhouse module for long-term space missions," *Diplomarbeit*, Technische Universität Dresden, Faculty of Mechanical Science and Engineering, 2021.

[35] T. Kozai, C. Kubota, and B. R. Jeong, "Environmental control for the large-scale production of plants through in vitro techniques," *Plant Cell, Tissue and Organ Culture*, vol. 51, pp. 49–56, 1997.

[36] A. J. Both, "Cooling and ventilation," *Greenhouse Magazine*, 2011. [Online]. Available: https://www.greenhousemag.com/article/greenhouse-0611-cooling-ventilation/. [Accessed: May 10, 2023].

[37] W. Robert, "Ventilation and cooling of greenhouses," *Controlled Environment Agriculture Center (CEAC), University of Arizona*, 2003. [Online]. Available: https://ceac.arizona.edu/sites/default/files/ventilation_and_screening_of_ghs.pdf. [Accessed: May 10, 2023].

[38] J. A. Watson, C. Gómez, D. E. Buffington, et al., "Greenhouse ventilation," *Florida Online Journals*, 2019.

[39] R. R. Shamshiri, J. W. Jones, K. R. Thorp, et al., "Review of optimum temperature, humidity, and vapor pressure deficit for microclimate evaluation and control in greenhouse cultivation of tomato," *International Agrophysics*, vol. 32, no. 2, pp. 287–302, 2018.

[40] F. J. Baptista, B. J. Bailey, and J. F. Meneses, "Effect of nocturnal ventilation on the occurrence of *Botrytis cinerea* in Mediterranean unheated tomato greenhouses," *Crop Protection*, vol. 32, pp. 144–149, 2012.

[41] N. Katsoulas, A. Baille, and C. Kittas, "Effect of misting on transpiration and conductances of a greenhouse rose canopy," *Agricultural and Forest Meteorology*, vol. 106, no. 3, pp. 233–247, 2001.

[42] M. Romero-Gámez, A. Anton, T. Soriano, E. M. Suárez-Rey, and N. Castilla, "Environmental impact of green bean cultivation: Comparison of screen greenhouses vs. open field," *Journal of Food, Agriculture & Environment*, vol. 7, no. 3–4, pp. 132–138, 2017.

[43] Y. S. Chen, S. S. Hsiau, H. Y. Lee, and Y. P. Chyou, "Filtration of dust particulates using a new filter system with louvers and sublouvers," *Fuel*, vol. 99, pp. 118–128, 2012.

[44] A. J. Campanella, "Vibration reduction in air handling systems," *The Journal of the Acoustical Society of America*, vol. 136, no. 4, p. 2207, 2014.

[45] G. Wang and L. Song, "Air handling unit supply air temperature optimal control during economizer cycles," *Energy and Buildings*, vol. 49, pp. 310–316, 2012.

[46] Y. H. Zurigat, "Greenhouse – state of the art review and performance evaluation of dehumidifier," Ph.D. dissertation, University of Jordan, Amman, Jordan, 2008.

[47] J. M. Duxbury, "The significance of agricultural sources of greenhouse gases," *Fertilizer Research*, vol. 38, no. 2, pp. 151–163, 1994.

[48] K. Phair, *Direct Steam Geothermal Energy Conversion Systems*. Elsevier, 2016.

[49] O. Sarfraz and C. Bach, "A literature review on heat exchanger air side fouling in heating," in *Proceedings of the International Refrigeration and Air Conditioning Conference at Purdue*, vol. 2234, pp. 1–9, 2016.

[50] F. Sohl and G. Schubert, "Interior structure, composition, and mineralogy of the terrestrial planets," in *Elsevier Reference Module in Earth Systems and Environmental Sciences*, vol. 10, 2015.

[51] T. S. Ross, *Encyclopedia of the Solar System*. Amsterdam, Boston: Academic Book Publishers, 2007.

[52] C. Meyer, "Lunar regolith," *NASA Lunar Petrographic Educational Thin Section Set*, pp. 46–48, 2003.

[53] H. Jeremy, "NASA takes aim at Moon with double sledgehammer," *Space.com*, 2008. [Online]. Available: https://www.space.com/5018-nasa-takes-aim-moon-double-sledgehammer.html. [Accessed: May 10, 2023].

[54] J. Lynn, "NASA - Lunar South Pole," *NASA*, 2010. [Online]. Available: https://www.nasa.gov/mission_pages/LRO/multimedia/lroimages/l20100927_southpole.html. [Accessed: May 10, 2023].

[55] D. Brian, "Lunar living: NASA's Artemis base camp concept – Artemis," *NASA Artemis Blog*, 2020. [Online]. Available: https://blogs.nasa.gov/artemis/2020/10/28/lunar-living-nasas-artemis-base-camp-concept/. [Accessed: May 10, 2023].

[56] W. Robert, "An astronaut gardener on the Moon - Summits of sunlight and vast lunar caves in low gravity," *Science 2.0*, 2016. [Online]. Available: https://www.science20.com/robert_inventor/an_astronaut_gardener_on_the_moon_summits_of_sunlight_and_vast_lunar_caves_in_low_gravity-180516. [Accessed: May 10, 2023].

[57] E. Jane, “Moon Village could allow people to ‘thrive over the long term’ in space,” *Dezeen*, 2021. [Online]. Available: https://www.dezeen.com/2021/07/07/moon-village-human-centric-inflatable-habitat-the-moon/. [Accessed: May 10, 2023].

[58] M. J. C. Linares, “The days of the Moon: Science, magic or poetry?,” *SEDERI: Yearbook of the Spanish and Portuguese Society for English Renaissance Studies*, 2000.

[59] E. Mahoney, “Moon’s south pole is full of mystery, science, intrigue,” *NASA*, 2022. [Online]. Available: http://www.nasa.gov/feature/moons-south-pole-is-full-of-mystery-science-intrigue. [Accessed: May 10, 2023].

[60] M. L. Litvak, I. G. Mitrofanov, A. B. Sanin, W. V. Boynton, G. Chin, J. B. Garvin, D. Golovin, L. G. Evans, K. Harshman, A. S. Kozyrev, and A. Malakhov, “LEND studies of diversity of PSRs on the Moon,” in *Proceedings of the Lunar and Planetary Science Conference*, vol. 1765, 2011.

[61] A. Sanin and I. Mitrofanov, “Searching for water ice permafrost: LEND results for about three years of observations,” in *Proceedings of the Annual Meeting of the Lunar Exploration Analysis Group*, vol. 3020, 2012.

[62] R. C. Romanhole, J. A. Ataide, P. Moriel, and P. G. Mazzola, “Update on ultraviolet A and B radiation generated by the sun and artificial lamps and their effects on skin,” *International Journal of Cosmetic Science*, vol. 37, no. 4, pp. 366–370, 2015.

[63] J. Perez, “Why space radiation matters,” *NASA*, 2017. [Online]. Available: http://www.nasa.gov/analogs/nsrl/why-space-radiation-matters. [Accessed: May 10, 2023].

[64] D. Mrigakshi, “How space radiation threatens lunar exploration,” *Smithsonian Magazine*, 2023. [Online]. Available: https://www.smithsonianmag.com/science-nature/how-space-radiation-threatens-lunar-exploration-180981415/. [Accessed: May 10, 2023].

[65] M. Berger, “Exploring the impact of space radiation on plants,” *Texas A&M University*, 2022. [Online]. Available: https://bcbp.tamu.edu/exploring-the-impact-of-space-radiation-on-plants/. [Accessed: May 10, 2023].

[66] Z. Shen, Y. Xia, Y. Liu, Y. Ding, and C. Zhao, “Protection of materials from space radiation environments on spacecraft,” *IOP Conference Series: Materials Science and Engineering*, vol. 585, no. 1, p. 012098, 2019.

[67] W. Jim, “NASA - Fire away, Sun and stars! Shields to protect future space crews,” *NASA*, 2007. [Online]. Available: https://www.nasa.gov/vision/space/travelinginspace/radiation_shielding.html. [Accessed: May 10, 2023].

[68] S. Maity, K. Singha, P. D. Bnath, and M. Singha, “Textiles in electromagnetic radiation protection,” *Journal of Safety Engineering*, vol. 2, no. 2, pp. 11–19, 2013. doi: 10.5923/j.safety.20130202.01.

[69] E. Nederhoff, “LEDs for greenhouse lighting,” *Practical Hydroponics & Greenhouses*, pp. 31–40, 2010.

[70] **[70]** G. Spazzafumo, “Cogeneration of power and substitute of natural gas using electrolytic hydrogen, biomass and high temperature fuel cells,” *International Journal of Hydrogen Energy*, vol. 43, no. 26, pp. 11811–11819, 2018.

[71] N. M. Samsonov, L. S. Bobe, V. M. Novikov, et al., “Systems for water reclamation from humidity condensate and urine for space station,” *JSTOR*, 1994. [Online]. Available: https://www.jstor.org/stable/44614974. [Accessed: May 12, 2023].

[72] F. Volpin, U. Badeti, C. Wang, J. Jiang, J. Vogel, S. Freguia, D. Fam, J. Cho, S. Phuntsho, and H. K. Shon, “Urine treatment on the International Space Station: Current practice and novel approaches,” *Membranes*, vol. 10, no. 11, pp. 116–132, 2020.

[73] *JEM Water Recovery System*, “Space Station Research Explorer on NASA.gov,” 2019. [Online]. Available: https://www.nasa.gov/mission_pages/station/research/experiments/explorer/Investigation.html#id=2049. [Accessed: May 10, 2023].

[74] H. Elizabeth and P. Thomas, “The Thomas Pesquet Proxima mission: An overview of accomplishments and science results,” in *Proceedings of the International Astronautical Congress*, 2022.

[75] A. F. Prince, W. Friedl, L. Klüpfel, et al., “Preliminary study on how an autonomous robotic system can impact the crew time during plant cultivation on the lunar surface,” in *Proceedings of the 75th International Astronautical Congress (IAC)*, Milan, Italy, 2024.

[76] J. Silva-Rodriguez and X. Li, “Solar power generation profile estimation for lunar surface solar PV systems,” *arXiv preprint*, arXiv:2402.14783, Feb. 2024. [Online]. Available: https://arxiv.org/abs/2402.14783.

[77] A. Fussy and J. Papenbrock, “An overview of soil and soilless cultivation techniques—chances, challenges, and the neglected question of sustainability,” *Plants*, vol. 11, no. 9, p. 1153, 2022.

[78] P. H. Gleick, “Water and energy,” *Annual Review of Energy and the Environment*, vol. 19, no. 1, pp. 267–299, 1994.

[79] I. Panet, J. Flury, R. Biancale, T. Gruber, J. Johannessen, M. R. van den Broeke, T. van Dam, P. Gegout, C. W. Hughes, G. Ramillien, and I. Sasgen, “Earth system mass transport mission (e.motion): A concept for future Earth gravity field measurements from space,” *Surveys in Geophysics*, vol. 34, pp. 141–163, 2013.

Wares Chancharoen was born on November 18th, 1989, in Bangkok province, Thailand. He received the B.S. degree in mechanical engineering from King Mongkut's University of Technology Thonburi, Thailand, in 2012 and the M.S. and Ph.D. degrees in information science at Nagoya University, Japan. He is currently the lecturer at Princess Srisavangavadhana College of Medicine, Chulabhorn Royal Academy, Thailand. His research interest includes the space medicine, space engineering, mechanical engineering, and medical device design. In 2018, he awarded the Emerging Space Leadership (ESL) from the International Astronautical Federation (IAF), France. In 2019, he got the recognition award from the Deep Space Food Challenge as the one of international team around the world from phase 1, which conducted by The National Aeronautics and Space Administration (NASA), the Canadian Space Agency (CSA) and the Methuselah foundation.

Rattanawalee Tobsri was born on April 24th, 2002, in Bangkok Province, Thailand. She received the B.S. degree in Electronic and Telecommunication Engineering from the Faculty of Technical Education at King Mongkut's University of Technology North Bangkok, Thailand, in 2024. She was an internship at Simes Engineering Company Limited, as a preventive maintenance. And internship at Royal Irrigation Department as a Telecommunication Division. After graduation, she worked as an assistant research engineer at Chulabhorn Royal Academy, Thailand.

Salida Chuphong was born on July 3rd, 1999, in Songkhla province, Thailand. She received a B.S. Degree in Mechanical Engineering field from Sirindhorn International Institute of Technology, Thammasat University, Thailand. She worked as an intern at I-Tail Corp. Ltd. as a piping engineer. After graduation, she worked as an asistant research engineer at Chulabhorn Royal Academy. Her research interests include fluid dynamic behavior, food printing technology, and 3D printing technology.

Piyachit Yingkiatinon was born on October 29th, 2000 in Bangkok province, Thailand. She received a B.S. Degree in Mechanical Engineering field from Sirindhorn International Institute of Technology, Thammasat University, Thailand. She was an internship in Engineering for a preventive maintenance unit Ajinomoto Ayutthaya company, Thailand. Since 2023, she is currently an Engineer at commercial vehicle company.

Kulanis Jintavanich was born on July 11th, 2001 in Bangkok province, Thailand. She received a B.S. Degree in Mechanical Engineering field from Sirindhorn International Institute of Technology, Thammasat University, Thailand. She is currently a research and development engineer in the automotive industry.

Napaporn Chantawong was born on September 28th, 2001 in Bangkok province, Thailand. She received her Bachelor of Engineering in field of Mechanical Engineering from Sirindhorn International Institute of Technology, Thammasat University, Thailand. She was an intern at B.Grimm BIP Power 1,2 Limited as an Efficiency Engineer during the internship program in 2022. She is currently working in oil and gas industry as an Mechanical Engineer.

Chanikarn Wacharasindhu was born on May 18th, 2001 in Bangkok province, Thailand. She received a B.S. Degree in Mechanical Engineering field from Sirindhorn International Institute of Technology, Thammasat University, Thailand. In 2022, she was an intern at EGCO Group in Efficiency sector. She is currently Mechanical Engineer working in EPC (Engineering Procurement Construction) Business.