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Assessment of the physical and psychological aspects of the current life support system on the International Space Station for sustainable space exploration

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Life support systems in space have been developed to recover a certain amount of oxygen and water. However, we still rely on resupplies for gas tanks, water bags, and food. To achieve sustainable human space exploration, we must also consider the astronauts' wellbeing. This research analyzes and assesses the status of essential life support elements, which are air, water, and food, as well as wellbeing elements, including clothing, hygiene, and healthcare, on the International Space Station. The types and quantities of resupplies for each element were estimated by synthesizing data from multiple sources and compared against baseline values established by the National Aeronautics and Space Administration (NASA) for one crew member per day. To evaluate the qualitative and psychological dimensions of dependence on resupply missions, astronaut feedback and comments documented in reports and articles from space agencies were also analyzed as important references. The results show that resupplies involve not only gas tanks and water bags but also a significant number of spare items to maintain recovery systems. Food completely relies on resupplies, and regarding wellbeing elements, although the mass supplied from Earth seems to meet the space agency's requirements, astronauts feel uncomfortable wearing the same clothes and using the same towels for days, especially exercise clothes, which can develop odors. It was also discovered that each resupply mission is inefficient as resupplies account for only 0.21% of the total launch mass. Relying on resupply missions has been associated with negative effects on both physical and psychological aspects, such as anxiety about the risk of running out of life support consumables, issues with stowage and odors caused by waste, and stress due to complicated cargo unloading and loading transfer operations. As humans explore the Moon and beyond, frequent resupplies will become impractical due to higher launch costs and longer delivery times, and suggestions for developing technologies to realize a sustainable human presence in space are being proposed.

KEYWORDS

life support system, wellbeing, space exploration, resupplies, sustainability

1 Introduction

The International Space Station (ISS) has been continuously occupied by astronauts since 2000. To maintain human presence in space, elements such as air, water, and food need to be either supplied from Earth or recycled on the International Space Station. The amounts of these elements required for one crew member per day are outlined in the National Aeronautics and Space Administration's (NASA's) Life Support Baseline Values and Assumptions Document (BVAD), which identifies specific physical quantities that define life support systems for human space programs from an analysis and modeling perspective. For instance, the mass of water required for one crew member per day is 4.350 kg (Anderson et al., 2018).

Technologies to recover air and water on the International Space Station have been developed, and it is said that approximately 51% of oxygen is recovered from carbon dioxide, and more than 90% of water is recycled. Studies are underway to increase these recovery rates to 75% for oxygen and 98% for water (Schneider and Shull, 2017). To achieve lower weight, power consumption, and volume, as well as better reliability and maintainability, new technologies are being considered. A liquid sorbent-based system, evaluated as an alternative, is proposed to consume 65% less power, weight, and volume than the solid-based CO_2 scrubbers currently used on the International Space Station (Rogers et al., 2017). A new Environmental Control and Life Support System (ECLSS) design has been developed to avoid known issues including dust generation that causes plugging for solid adsorbents, oxidative ammonia generation that leads to failures in vulnerable components, and pump failures associated with the oxygen generation assembly (Henson et al., 2021). The maintenance history of the ISS Water Recovery and Oxygen Generation Systems has been surveyed to understand hardware operating lifetimes and the crew-time required for maintenance tasks (Bagdigian et al., 2015).

Food is basically supplied from Earth, and technological gaps have been identified for long-duration missions to maintain balance between the use of resources, such as power, mass, and crew time, and the safety, nutrition, and acceptability of the food system (Cooper et al., 2011). NASA has led research projects to grow plants, targeting the development of fresh food production systems for future missions (Johnson et al., 2021). Clothes and towels are also supplied from Earth and discarded after use as there is no laundry system on the International Space Station. A new liquid laundry detergent formulation is currently under development (Ewert et al., 2022), along with concepts to sanitize clothes without using water (Ewert and Jeng, 2015).

Although increasing the recovery rate is important, we still heavily rely on resupply missions to deliver items such as gas tanks, water bags, and spare items to maintain these recovery systems. This paper analyzes and assesses the current effort status of air and water recovery systems by investigating and clarifying the types and masses of consumables and spare items supplied from Earth. It also analyzes and assesses the status of food resupplies and other elements, not only from a quantitative point of view but also from a qualitative perspective. Although the mass of food and clothes supplied from Earth seems to meet the space agency's requirements, the mass and variety of these elements might not be sufficient from a psychological standpoint. For instance, astronauts could grow tired of the food if the variety is insufficient, and it would be stressful if they would need to wear the same clothes and towels for days, which could develop odors. The negative psychological effects of relying on resupply missions and potential solutions to these issues will also be explored.

In this study, elements to maintain life in space correspond to categories such as air, water, and food. Wellbeing elements that affect an astronaut's physical and mental health correspond to categories such as clothing, hygiene consumables, and healthcare supplies. Although wellbeing may vary depending on each crew member's preferences, the elements mentioned above are selected as they are considered important for everyone. Clothing is an important element as it protects crew members from injury and helps them adjust to the environment inside the spacecraft. Hygiene items are necessary to keep one clean, including towels, wipes, dental floss, and toothbrushes. Healthcare consumables contain items used to maintain health, such as components for exercise equipment, and items to treat or diagnose crew members, such as medical kits. These elements are also described in NASA's BVAD, with each element corresponding to sections such as the Air Subsystem, Water Subsystem, Waste Subsystem, Environmental Monitoring, Food Interface, Clothing Systems, Crew Hygiene Systems, and Crew Healthcare (Anderson et al., 2018).

2 Materials and methods

To assess and discuss how life and wellbeing are maintained on the ISS, the types and mass of elements required and supplied from Earth were analyzed (Section 2.1). The percentage of these resupply items within the total launch mass was also calculated to provide a broader understanding of the inefficiency of the current approach, which relies on resupplies (Section 2.2).

In addition, to assess the situation from a qualitative point of view, comments and feedback from astronauts mentioned in studies by NASA (Whitmire et al., 2010; Baggerman et al., 2004a), Japan Aerospace Exploration Agency (JAXA), and articles interviewing astronauts (Stockton, 2017) were also gathered. The author's experience, having been engaged in the International Space Station Program for more than a decade, was also used to analyze facts and assess the negative effects of relying on resupply missions.

2.1 Types and mass of life support system and wellbeing elements

Details of each element supplied to the ISS can be obtained from NASA's Mission Integration Database Application System (MIDAS) portal. However, since the portal can only be accessed by employees engaged in the International Space Station Program and since the goal of this study is not to create a precise list of those elements but to analyze what is required to maintain the current recycling system and identify improvements needed in the future, a study conducted by NASA regarding the historical logistical mass delivered to the International Space Station (Leach and Ewert, 2021) was used.

NASA's study (Leach and Ewert, 2021) does not indicate the mass of each element and only mentions its percentage within the total mass of delivery items. It also includes information that the rate of food usage from October 2017 through February 2020 was 2.77 kg/crew member per day, and the food mass was 21% of the overall delivery mass. In this study, to estimate the mass of each item that has been supplied, the number of days during the period was counted, and the average number of crew members who stayed on the ISS from October 2017 through February 2020 was calculated. The number of astronauts who lived on the ISS was calculated using the information on each long-duration mission with its ISS arrival and ISS departure date (NASA, 2024). By combining these data, the author estimated the total delivery mass and the mass of each item.

2.1.1 Mass requirement and historical data for air elements

Air, especially oxygen, is partially recycled on the ISS. To evaluate whether the mass of oxygen tanks re-supplied from Earth is sufficient or not, the balance between the mass required for one crew member per day and the mass that was consumed, recovered, and re-supplied was simplified and described as shown in Equation 1.

$$M_{O2} = (M_{CO2} \times RR_{CO2\,to\,O2}) - (LR_{air} \times PPO2) + \left(M_{O2\,GenSys} + RM_{O2\,Tank}\right). \quad (1)$$

Here, M_{O2} is the mass of oxygen required for one crew member per day (kg/crew member per day) [kg/CM-d], M_{CO2} is the mass of carbon dioxide produced by one crew member per day [kg/CM-d], and both masses can be found in NASA's Life Support Baseline Values and Assumptions Document (Anderson et al., 2018). $RR_{CO2\ to\ O2}$ is the recovery rate by the recovery system, which is approximately 51% (Schneider and Shull, 2017). LR_{air} is the leak rate of the air for one crew member per day [kg/CM-d]. The International Space Station cannot maintain the air, and a small amount of it leaks into space. This amount is approximately 0.6 pounds or 0.272 kg of air (NASA, 2021). $PPO2$ is the partial pressure of the oxygen, which is 21%. $M_{O2\ Gen\ Sys}$ is the mass supplied by the ISS oxygen-generating system known as the oxygen generation assembly (OGA) for one crew member per day kg/CM-d, which has a range from 0.491 to 1.964 kg/CM-d (Bagdigian and Cloud, 2005). It is thought that the OGA has produced a total of 11,903 kg of oxygen for over 15 years since it was installed and activated in 2007 (Takada et al., 2023). $RM_{O2\ Tank}$ is the reserved mass supplied by the oxygen tank for one crew member per day [kg/CM-d] and is estimated using historical data (Leach and Ewert, 2021). To assess the entire air recovery system, the mass of spare items to maintain the recovery system was also estimated using the historical data (Leach and Ewert, 2021).

2.1.2 Mass requirement and historical data for water elements

Water is also partially recovered on the ISS, and its mass balance can be described as shown in Equation 2.

$$M_{H2O} = (M_{Out} + M_{Urine} \times RR_{Urine}) - (M_{O2\,Gen}) + (M_{H2O\ Sab} + RM_{H2O\ Tank}). \quad (2)$$

Here, M_{H2O} is the mass of water required for one crew member per day [kg/CM-d], which consists of drinking water, food rehydration water, medical water, personal hygiene, urinal flush, water contained in food, and metabolic water. M_{Out} is the mass of water used by one crew member per day [kg/CM-d], which contains crew latent humidity condensate, medical water, and personal hygiene. M_{Out} will be collected by the water recovery system, and all of it will be completely recycled. M_{Urine} is the mass of water in the crew's urine and the amount of urinal flush per day and per crew [kg/CM-d]. M_{H2O}, M_{Out}, and M_{Urine} could be obtained from NASA's Life Support Baseline Values and Assumptions Document (Anderson et al., 2018). RR_{Urine} is the recycling rate of urine obtained using ISS's Urine Processor, which is said to be 85% (Schneider and Shull, 2017). M_{O2Gen} is the mass of water used by the ISS OGA per day and per crew [kg/CM-d]. The OGA is designed to generate oxygen at a rate between 2.3 and 9.2 kg/day (Bagdigian and Cloud, 2005). As the OGA produced 11,903 kg of oxygen for over 15 years since it was installed and activated in 2007 (Takada et al., 2023) and since the mass ratio of oxygen to water is 8:9, water used to generate oxygen would be approximately 13,390.875 kg within 15 years. $M_{H2O\ Sab}$ is the mass of water supplied by the system, which uses the Sabatier reaction on the ISS per day and crew [kg/CM-d]. The Sabatier system is designed to produce 2,000 pounds or 907.184 kg per year based on a size of seven crew members (Smith et al., 2004). $RM_{H2O\ Tank}$ is the mass of water bag supplied from Earth per day and per crew [kg/CM-d], which will be estimated using historical data (Leach and Ewert, 2021). The mass of spare items to maintain the water recovery system was also estimated using historical data (Leach and Ewert, 2021).

2.1.3 Mass requirement and historical data for food elements

Food mass required for one crew member per day, food package waste, and waste food adhered to packaging can be found in NASA's Life Support Baseline Values and Assumptions Document (Anderson et al., 2018). The actual mass of each element delivered to the ISS between October 2017 and February 2020 is estimated using the ISS historical data (Leach and Ewert, 2021).

2.1.4 Mass requirement and historical data for clothing elements

The clothing mass required for one crew member per day can be found in NASA's Life Support Baseline Values and Assumptions Document (Anderson et al., 2018). Types of clothing are shirts, socks, undergarments, etc., and the mass delivered to the ISS between October 2017 and February 2020 is estimated using the ISS historical data (Leach and Ewert, 2021).

2.1.5 Mass requirement and historical data for hygiene elements

The mass of hygiene elements required for one crew member per day can be found in NASA's Life Support Baseline Values and Assumptions Document (Anderson et al., 2018). The detailed subcategories of hygiene elements and their mass delivered to the ISS between October 2017 and February 2020 are estimated using the ISS historical data (Leach and Ewert, 2021).

2.1.6 Mass requirement and historical data for healthcare elements

The mass required for healthcare elements, such as spare parts for exercise equipment and medical kit consumables, is not

TABLE 1 Mass of oxygen required for crew, recycled from carbon dioxide, leaking out of the space station, and supplied by the oxygen generation assembly, and from earth.

Term	Value	Unit	Source
Oxygen required for a crew member			
Mass of required oxygen for a crew member	0.818	kg/CM-d	Anderson et al. (2018)
Oxygen recycled from carbon dioxide			
Mass of recycled oxygen	0.529	kg/CM-d	1.040 [kg/CM-d] x 51 [%]
Carbon dioxide produced by crew	1.040	kg/CM-d	Anderson et al. (2018)
Recycling rate from carbon dioxide to oxygen	51	%	Schneider and Shull (2017)
Oxygen leaking out of the space station			
Mass of air leakage	0.011	kg/CM-d	0.272 [kg/day] x 21 [%]/5.269 [crew members]
Mass of air leakage rate	0.272	kg/day	NASA (2021)
PPO2 (oxygen partial pressure)	21	%	Anderson et al. (2018)
Oxygen supplied by the oxygen generation assembly			
Mass of oxygen supplied by the oxygen generation assembly	0.413	kg/CM-d	11,903 [kg/15 years]/(15 [years] x 365 [days] x 5.269 [crew members])
Oxygen supplied by the oxygen generation assembly [kg/15 years]	11,903	kg/15 years	Takada et al. (2023)
Oxygen resupplied from Earth			
Mass of resupplied oxygen [kg/CM-d]	0.057	kg/CM-d	0.269 [kg/CM-d] x 21 [%]
Mass of gas recharge [kg/CM-d]	0.269	kg/CM-d	61,296.14 [kg] x 2.04 [%]/(882 [days] x 5.269 [crew members])

Note. CM-d, crew member per day.

indicated in NASA's Life Support Baseline Values and Assumptions Document (Anderson et al., 2018). The NASA Crew Health Care System (CHeCS) Hardware Catalog, which consists of Countermeasures System (CMS), Environmental Health System (EHS), and Health Maintenance System (HMS), provides resupply schedule information (NASA, 2011). However, some items are replaced on an "as needed" basis, and some are replaced every 5–10 years, which means that there are no firm requirements that could be used to assess whether the items supplied between October 2017 and February 2020 were sufficient or not. However, the mass of each healthcare item supplied to the ISS was estimated using the ISS historical data (Leach and Ewert, 2021).

2.2 Mass required to deliver resupply items to the ISS

The objectives of this section are to understand the amount of mass required to deliver supply items from Earth to the ISS and analyze the efficiency of the current resupply system. There were 10 long-term space station missions, from Expedition 53 through 62, between October 2017 and February 2020, and 22 unmanned missions were launched to carry supply items to the ISS (NASA, 2024).

For each unmanned or cargo supply mission, data regarding the rocket's and spacecraft's dry mass (mass without propellant), propellant mass, and the mass breakdown of the payloads, including elements to maintain life and wellbeing on board ISS, were gathered from each mission's fact sheets such as "Northrop Grumman CRS-11 Mission Overview" (NASA, 2015), as well as rocket's user manual such as "Soyuz User's Manual" (Arianespace, 2012). Spacecraft carry various types of payload items, and for NASA's mission, these are categorized as "crew supplies," "science investigations," "spacewalk equipment," "vehicle hardware," "computer resource," "unpressurized payloads," and "Russian hardware." In this study, "crew supplies" are regarded as the elements that support life and wellbeing on the ISS. For Russian missions, supply items are categorized as dry cargo, air/oxygen, water, and fuel. In this study, "dry cargo," which consists of food, medical supplies, hygiene items, "air/oxygen," and "water" is regarded as life support and wellbeing elements.

Although launch vehicles, spacecraft, and payloads are discarded after use, we have taken into consideration that the first stage of the Falcon 9 rocket's engines is reused, and approximately 90% of water is recycled on the ISS.

3 Results and discussions

3.1 Mass breakdown of supply items

By combining data that show the rate of food usage from October 2017 to February 2020 was 2.77 kg/CM-d (Leach and Ewert, 2021), the food mass was 21% of the overall launch mass (Leach and Ewert, 2021), the number of days during the period was 882 days, the average number of crew members during the period was approximately 5.269 persons (derived from each crew members' ISS arrival and departure date) (NASA, 2024), and the total mass delivered to the ISS during the period was estimated to be approximately 61,296.14 kg.

As the percentage of each subcategory within the total mass can be found in NASA's study (Leach and Ewert, 2021), the mass breakdown of the supplied items was calculated and is listed in the Supplementary Material.

3.1.1 Analysis and assessment of the air supply and recovery systems

As shown in Equation 1 and Table 1, M_{O2}, the mass of oxygen required for one crew member per day, is 0.818 kg/CM-d (Anderson et al., 2018).

M_{CO2}, the mass of carbon dioxide produced by one crew member per day, is 1.04 kg/CM-d (Anderson et al., 2018). $RR_{CO2\ to\ O2}$, the recovery rate by the recovery system, is approximately 51% (Schneider and Shull, 2017). By multiplying these numbers, approximately 0.529 kg/CM-d of oxygen is recycled from carbon dioxide. LR_{air}, the leak rate of the air for one crew member per day, is approximately 0.6 pounds or 0.272 kg (NASA, 2021). *PPO2*, the partial pressure of the oxygen, is 21% (Anderson et al., 2018). By multiplying these two numbers and dividing by the average number of persons staying on the ISS, which is 5.269 persons, the mass of oxygen leaking outside is estimated to be approximately 0.011 kg/CM-d. $M_{O2\ Gen\ Sys}$, the mass supplied by the ISS OGA, is approximately 0.413 kg/CM-d, which could be calculated using the data that the OGA has produced 11,903 kg of oxygen for over 15 years (Takada et al., 2023), and this is dividing by 15 years, 365 days, and 5.269 persons. $RM_{O2\ Tank}$, the reserved mass supplied by the gas tank for one crew member per day [kg/CM-d], was estimated as 0.269 kg/CM-d; this was based on the fact that the percentage of "Gas Recharge" was 2.04% of the total mass delivered from Earth between October 2017 and February 2020 (Leach and Ewert, 2021). The total mass was estimated to be approximately 61,296.14 kg, the number of days during the period was 882 days, and the average number of crew members during the period was approximately 5.269 persons, as detailed in Section 3.1. As the PPO2 (oxygen partial pressure) is 21%, the oxygen supplied by the gas recharge system is estimated to be 0.057 kg/CM-d.

In summary, although only 51% of oxygen is recovered from carbon dioxide and the fact that air has been leaking out from the space station, generating oxygen using the OGA and recharging gas from Earth seems to be sufficient to meet the required mass of 0.818 kg/CM-d.

However, risks such as losing functionality to recover oxygen from carbon dioxide or producing oxygen from water by the OGA exist, and an increase in the air leak rate could also happen anytime. For instance, as mentioned above, the average air leak rate is approximately 0.272 kg/day, and by applying the air density of 0.0807 pounds/ft^3 or 1.293 kg/m^3 (Williams, 1949), the air leakage rate is approximately 0.211 m^3/day. Since the pressurized section of the ISS has a capacity of approximately 32,333 ft^3 or 915.569 m^3 (NASA, 2018), this means that approximately 8.4% of the total pressurized volume leaks out every year and needs to be re-supplied from Earth or generated from other resources, such as water. In August 2020, there was an air leakage that was assumed to be caused by a crack in a module/facility on the Russian side, and the air leakage temporarily increased to approximately five times the normal level (NASA, 2021). An unexpected air leak and an unknown leak source could be a threat and stress factor for astronauts. To increase the recovery rate from carbon dioxide to oxygen, NASA is working on the technology development under the Space Technology Mission Directorate (STMD)-sponsored Spacecraft Oxygen Recovery (SCOR) project (Schneider and Shull, 2017).

One interesting result was found by analyzing the historical data of the supply items. Figure 1 shows the pie chart of the relative mass of the supply items related to the air recovery system. Although it was found that the gas resupply system from Earth provides enough oxygen for the astronauts, it accounted for only 20.7% of the total mass of the air system. The other 79.3% of the mass were spare items to maintain the air recovery system. For instance, "filters" refer to air filters used to maintain air quality, while "monitoring and control" contains items used to maintain a steady ISS environment, such as air revitalization, atmospheric monitoring, and the thermal control system. "Kits" are cleanliness supplies and nitrous/oxygen recharge system (NORS) maintenance kits. This means that even if we were to increase the oxygen recovery rate from carbon dioxide and generate more oxygen using the OGA and were able to stop supplying the gas recharge system, we would still need to resupply spare items to maintain the OGA. From these facts, it would be necessary to design and develop systems that not only focus on increasing the oxygen recovery rates but also minimize the amount of spare items or manufacture those items by utilizing 3-D printing or additive manufacturing technologies on board the space station. As the majority of spare parts identified as candidates for on-demand manufacturing on ISS are metals, additive manufacturing processes for metals in space are being studied (Prater et al., 2021).

3.1.2 Analysis and assessment of the water supply and recovery system

As described in Equation 2 and Table 2, M_{H2O}, the mass of water required for one crew member per day, is 4.350 kg/CM-d (Anderson et al., 2018).

M_{Out}, the mass of water, including crew latent humidity condensate, medical water, and personal hygiene water, is 2.720 kg/CM-d, and M_{Urine}, the mass of water from crew's urine and urinal flushes, is 1.500 kg/CM-d (Anderson et al., 2018). As RR_{Urine}, the recycling rate of the urine by the ISS's Urine Processor, is estimated to be 85% (Schneider and Shull, 2017), water recovered from urine would be 1.275 kg/CM-d. M_{O2Gen}, the mass of water used by the ISS OGA per day and per crew, can be estimated as approximately 0.464 kg/CM-d based on the calculation provided in Section 2.1.2. This calculation shows that water used to generate oxygen would be approximately 13,390.875 kg within 15 years, with an average crew size of 5.269 persons from October 2017 to February 2020. $M_{H2O\ Sab}$, the mass of water supplied by the Sabatier reaction on the ISS per day and crew, is estimated to be 0.352 kg/CM-d; this estimate is based on the Sabatier system's design to produce 2,000 pounds or 907.184 kg of water per year for a crew size of seven members (Smith et al., 2004), with an average crew size of 5.269 persons during the period from October 2017 to February 2020. $RM_{H2O\ Tank}$, the mass of water bag supplied from Earth, is estimated to be 1.121 kg/CM-d; this estimate is based on the fact that the percentage of "Water System" accounted for 8.50% of the total mass delivered from Earth between October 2017 and February 2020 (Leach and Ewert, 2021). The total mass was estimated to be

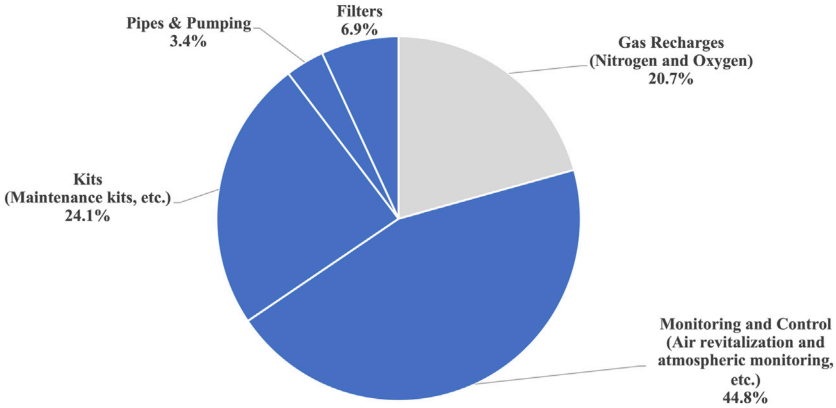

FIGURE 1
Mass breakdown of supplied items with regard to air recharge and recovery systems.

approximately 61,296.14 kg over a period of 882 days, with an average crew size of approximately 5.269 persons, as discussed in Section 3.1.

From the estimation mentioned above, although a certain amount of water is used by the OGA, enough water is recovered and supplied to meet the required mass of 4.350 kg/CM-d. There are also studies aimed at improving the total water recovery rate to up to 98% by recovering more than 90% of water from urine brine (Schneider and Shull, 2017).

Figure 2 shows the relative mass of the supply items related to the water recovery system. The "Water System" accounts for 75.8% of the total mass. It not only includes the water resources themselves, such as water containers and resupply water tanks, but also items used to operate and maintain the water recovery system, such as the water supply system, water sample collection packets, and other water-based consumables (Leach and Ewert, 2021). The remaining 24.2% consists of "toilet hardware" (12.1%), which includes toilet replacement hardware and urine receptacles, and "waste containments" (12.1%), which contains water waste bags and solid waste containers (Leach and Ewert, 2021). From these data, it can be concluded that more than 24.2% of the mass consists of consumables and spare items necessary for maintaining the water recovery and waste systems. Even if water could be recovered completely from urine and urinal flushes, we will still need to keep supplying these spare items to maintain the improved water recovery system. As highlighted in Section 3.1.1, although it is important to increase the recovery rate, it would also be beneficial to design a system that minimizes the need for spare items or manufacture these items utilizing 3-D printing or additive manufacturing technologies in space.

3.1.3 Analysis and assessment of the food elements

Table 3 shows the food mass required for one crew member per day and the estimated mass of each item delivered to the ISS between October 2017 and February 2020. The required food mass ranges from 1.830 to 2.390 kg/CM-d, depending on the study, with food mass excluding packaging estimated at 1.510 kg/CM-d (Anderson et al., 2018). The mass of "packaged food" and "food kits" delivered from Earth was estimated as 2.161 kg/CM-d and 0.055 kg/CM-d, respectively, as the percentage of "packaged food" was 16.38% and "food kits" was 0.42% of the total mass delivered from Earth between October 2017 and February 2020 (Leach and Ewert, 2021). The total mass during this period was estimated to be approximately 61,296.14 kg, with 882 days in the period and an average crew size of approximately 5.269 persons, as described in Section 3.1. "Packaged food" contains food bags, and "food kits" are nutritional supplement kits, small food kits, and chewing gum kits (Leach and Ewert, 2021). The mass of waste generated includes "food packaging waste," which is 0.260 kg/CM-d, and "waste food adhered to packaging," which is 0.100 kg/CM-d (Anderson et al., 2018).

Figure 3 shows the estimated ratio of supplied food to waste. In this study, we used the food mass without packaging, which is 1.51 kg/CM-d (Anderson et al., 2018), to estimate food supplied from Earth. Of this mass, approximately 80.7% is resupplied food, while 19.3% becomes waste. Currently, there is no food production or recycling system on board ISS, so all of the supplies related to food, which are the food itself, its package, and the food adhered to packaging, will be consumed or discarded. As a short-term goal, reducing the amount of the food package could lower the amount of total launch mass and the waste generated. In the mid-to-long term, implementing a food production system, especially one that uses the minimum amount of water, would help reduce the amount of launch mass. Food production by crop plants, chemical synthesis, and 3-D printing is not currently feasible but could be more practical in the future (Jones, 2018). As a goal, we should aim to develop a circulating system that could reuse food packages, recycle wasted food, and change human feces into fertilizers using decomposers.

As indicated above, we could say that enough food is currently supplied to the ISS. However, the human space program is not simple math, and to establish a sustainable human presence in space, we would also need to consider the astronaut's wellbeing. Although fresh fruits and vegetables are delivered to the ISS in some of the cargo supply missions and various research projects to grow plants in space exist (Johnson et al., 2021), astronauts rely on packaged foods. There are voices from the ISS crew members that they would prefer more food variety for long-duration missions, and they get tired of certain foods (Cooper et al., 2011). From a wellbeing point of view, it

TABLE 2 Mass of water required for crew, recycled by the water recovery system, used by the oxygen generation assembly, and supplied from Sabatier reaction and earth.

Term	Value	Unit	Source
Water required for a crew member			-
Total mass of water required for a crew member	4.350	kg/CM-d	Anderson et al. (2018)
Drinking water	2.000	kg/CM-d	
Food rehydration water	0.500	kg/CM-d	
Medical water	0.050	kg/CM-d	
Personal hygiene	0.400	kg/CM-d	
Urinal flush	0.300	kg/CM-d	
Water contained in food	0.700	kg/CM-d	
Metabolic water	0.400	kg/CM-d	
Water recycled (excludes urine and urinal flush)			
Mass of recycled water (excludes urine and urinal flush)	2.720	kg/CM-d	Anderson et al. (2018)
Crew latent humidity condensate	2.270	kg/CM-d	
Medical water	0.050	kg/CM-d	
Personal hygiene	0.400	kg/CM-d	
Water recycled from urine and urinal flush			
Mass of water recycled from urine and urinal flush	1.275	kg/CM-d	1.500 [kg/CM-d] x 85 [%]
Urine	1.200	kg/CM-d	Anderson et al. (2018)
Urinal flush	0.300	kg/CM-d	
Recycling rate of the urine processor	85	%	Schneider and Shull (2017)
Water used to generate oxygen			
Mass of water used by the oxygen generation assembly	0.464	kg/CM-d	11,903 [kg/15 years] x 9/8 [mass ratio of oxygen to water]/(15 [years] x 365 [days] x 5.269 [crew members])
Oxygen supplied by oxygen generation assembly	11,903	kg/15 years	Takada et al. (2023)
Water supplied by the Sabatier reaction			
Mass of water supplied by the Sabatier reaction	0.352	kg/CM-d	907.184 [kg/year and 7 persons]/(365 [days] x 7 [crew members])
Water supplied by the Sabatier system	907.184	kg/year and 7 crew members	Smith et al. (2004)
Water supplied from Earth			
Mass of the water system supplied from Earth	1.121	kg/CM-d	61,296.14 [kg] x 8.50 [%]/(882 [days] x 5.269 [crew members])

Note. CM-d, crew member per day.

would be very important to develop a food production system that provides fresh and a wide variety of food options.

3.1.4 Analysis and assessment of the clothing elements

Table 4 shows the mass required for clothing and the estimated mass of each element delivered to the ISS. The clothing mass required for one crew member per day varies from 0.206 to 1.690 kg/CM-d, depending on the study (Anderson et al., 2018). The total mass of clothing items supplied from Earth was estimated to be 0.396 kg/CM-d; this estimation is based on the percentage of "Clothing," which accounted for 3.00% of the total mass delivered from Earth between October 2017 and February 2020 (Leach and Ewert, 2021). The total mass delivered during this period was approximately 61,296.14 kg, the number of days during the period was 882 days, and the average number of crew members was approximately 5.269 persons, as described in Section 3.1. If we just compare the number with the required mass, it could be concluded that a sufficient amount of clothing is supplied from Earth.

However, the reality behind these data is that astronauts wear the same clothes, including underwear, for days (or weeks, depending on the type). For instance, they wear shirts for 7 days, underwear for two to 3 days, and only get new exercise clothes every 5 days. Crew members spend their time exercising for 2.5 hours every day, and as they need to reuse it again, they hang up their

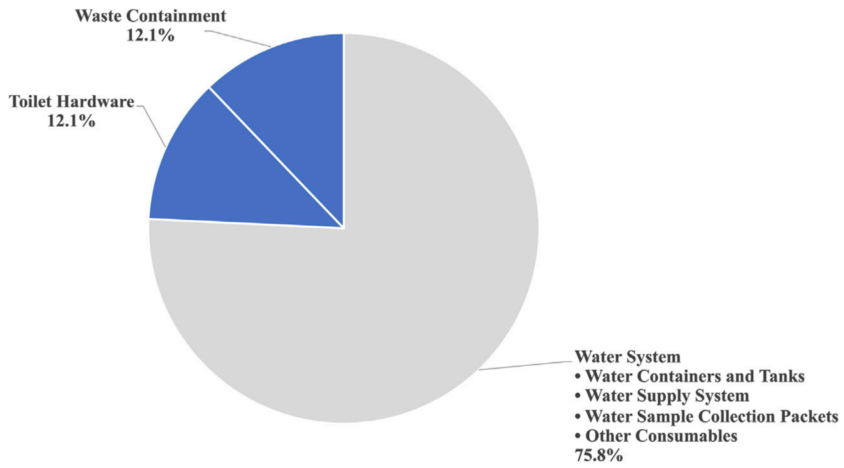

FIGURE 2
Mass breakdown of supplied items with regard to water recovery systems.

TABLE 3 Mass of food required for crew, supplied from Earth, and food-related waste.

Term	Value	Unit	Source
Food required for a crew member			
Mass of food as-shipped and packaged (study in 2002)	1.830	kg/CM-d	Anderson et al. (2018)
Mass of food as-Shipped and packaged (study in 2017)	2.390	kg/CM-d	
Mass of food consumed without packaging (study in 2014)	1.510	kg/CM-d	
Food supplied from Earth			
Mass of packaged food	2.161	kg/CM-d	61,296.14 [kg] x 16.38 [%]/(882 [days] x 5.269 [crew members])
Mass of food kits (kits includes nutritional supplement kits, small food kits, and chewing gum kits)	0.055	kg/CM-d	61,296.14 [kg] x 0.42 [%]/(882 [days] x 5.269 [crew members])
Waste			
Mass of food packaging waste	0.260	kg/CM-d	Anderson et al. (2018)
Mass of waste food adhered to packaging	0.100	kg/CM-d	

Note. CM-d, crew member per day.

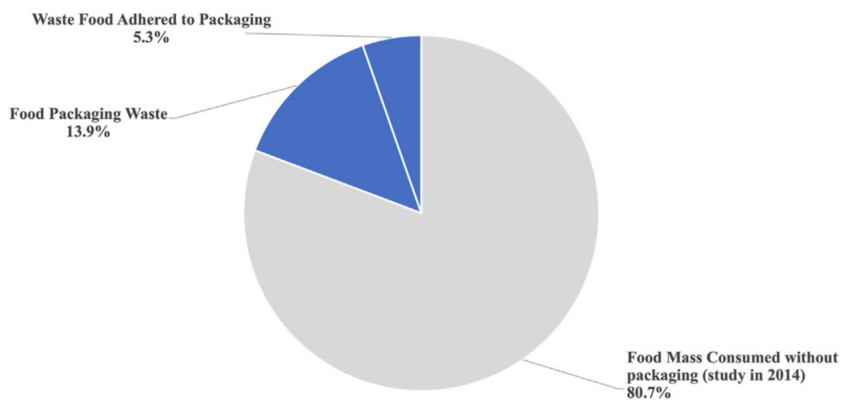

FIGURE 3
Mass breakdown of supplied food and waste.

TABLE 4 Mass of clothing required for crew and that supplied from Earth.

Term	Value	Unit	Source
Clothing required for a crew member			
Mass of clothing required for a crew member	0.206 to 1.690	kg/CM-d	Anderson et al. (2018)
Clothing supplied from Earth			
Total mass of clothing supplied from Earth	0.396	kg/CM-d	-
Shirts	0.119	kg/CM-d	61,296.14 [kg] x 0.90 [%]/(882 [days] x 5.269 [crew members])
Undergarments	0.067	kg/CM-d	61,296.14 [kg] x 0.51 [%]/(882 [days] x 5.269 [crew members])
Socks	0.032	kg/CM-d	61,296.14 [kg] x 0.24 [%]/(882 [days] x 5.269 [crew members])
Gloves	0.004	kg/CM-d	61,296.14 [kg] x 0.03 [%]/(882 [days] x 5.269 [crew members])
Footwear	0.016	kg/CM-d	61,296.14 [kg] x 0.12 [%]/(882 [days] x 5.269 [crew members])
Harness/tethers	0.020	kg/CM-d	61,296.14 [kg] x 0.15 [%]/(882 [days] x 5.269 [crew members])
Belts	0.004	kg/CM-d	61,296.14 [kg] x 0.03 [%]/(882 [days] x 5.269 [crew members])
Shorts	0.032	kg/CM-d	61,296.14 [kg] x 0.24 [%]/(882 [days] x 5.269 [crew members])
Pants	0.024	kg/CM-d	61,296.14 [kg] x 0.18 [%]/(882 [days] x 5.269 [crew members])
Generalized	0.020	kg/CM-d	61,296.14 [kg] x 0.15 [%]/(882 [days] x 5.269 [crew members])
Specialized/other	0.059	kg/CM-d	61,296.14 [kg] x 0.45 [%]/(882 [days] x 5.269 [crew members])

Note. CM-d, crew member per day.

TABLE 5 Mass of hygiene elements required for crew and that supplied from Earth.

Term	Value	Unit	Source
Hygiene elements required for a crew member			
Mass of hygiene elements Required for a crew member	0.781	kg/CM-d	Anderson et al. (2018)
Total mass of hygiene elements supplied from Earth			
Total mass of hygiene elements supplied from Earth	0.791	kg/CM-d	-
Towels/wipes	0.475	kg/CM-d	61,296.14 [kg] x 3.60 [%]/(882 [days] x 5.269 [crew members])
Solutions/creams	0.032	kg/CM-d	61,296.14 [kg] x 0.24 [%]/(882 [days] x 5.269 [crew members])
Deodorant	0.000	kg/CM-d	61,296.14 [kg] x 0.00 [%]/(882 [days] x 5.269 [crew members])
Dental	0.008	kg/CM-d	61,296.14 [kg] x 0.06 [%]/(882 [days] x 5.269 [crew members])
Shaving	0.000	kg/CM-d	61,296.14 [kg] x 0.00 [%]/(882 [days] x 5.269 [crew members])
Cargo	0.047	kg/CM-d	61,296.14 [kg] x 0.36 [%]/(882 [days] x 5.269 [crew members])
Other Items	0.230	kg/CM-d	61,296.14 [kg] x 1.74 [%]/(882 [days] x 5.269 [crew members])

Note. CM-d, crew member per day.

exercise clothes to dry them up (NASA, 2020). This could be very painful, and it also develops an odor, which bothers the astronauts on board ISS (Stockton, 2017).

Clothes are basically discarded after they are used, and developing a laundry system would significantly reduce the total mass supplied from Earth and could likely contribute to the crew's wellbeing. It would be a trade-off of its benefit, cost, and risk, and as discussed in Section 3.1.1 and Section 3.1.2, we would need to take spare parts and maintenance activities into account. Instead of using water, making the most of the space environment, such as ultraviolet rays and vacuum, might be an option.

3.1.5 Analysis and assessment of the hygiene elements

Table 5 indicates the mass requirement of the hygiene elements, which is 0.781 kg/CM-d (Anderson et al., 2018), as well as the mass of each hygiene item supplied to the ISS. Hygiene products include items like towels, wipes, dental floss, toothbrushes, toothpaste

TABLE 6 Mass of healthcare elements required for crew and that supplied from Earth.

Term	Value	Unit	Source
Healthcare elements required for a crew member			
Mass of healthcare elements required for a crew member	N/A	-	-
Healthcare elements supplied from Earth			
Total mass of healthcare elements supplied from Earth	0.132	kg/CM-d	-
Fitness	0.066	kg/CM-d	61,296.14 [kg] x 0.50 [%]/(882 [days] x 5.269 [crew members])
Medical kits	0.045	kg/CM-d	61,296.14 [kg] x 0.34 [%]/(882 [days] x 5.269 [crew members])
Small items	0.003	kg/CM-d	61,296.14 [kg] x 0.02 [%]/(882 [days] x 5.269 [crew members])
Exposure	0.004	kg/CM-d	61,296.14 [kg] x 0.03 [%]/(882 [days] x 5.269 [crew members])
Cardio	0.003	kg/CM-d	61,296.14 [kg] x 0.02 [%]/(882 [days] x 5.269 [crew members])
Monitoring	0.012	kg/CM-d	61,296.14 [kg] x 0.09 [%]/(882 [days] x 5.269 [crew members])

Note. CM-d, crew member per day.

containers, shaving cream, razors, mouthwash, shampoo, skin lotion, deodorant, sunblock, lip balm, and makeup. The mass of each hygiene item supplied from Earth was estimated to be 0.791 kg/CM-d as the percentage of "Hygiene" was 6.00% of the total mass delivered from Earth between October 2017 and February 2020 (Leach and Ewert, 2021); the total mass was estimated to be approximately 61,296.14 kg, the number of days during the period was 882 days, and the average number of crew members during the period was approximately 5.269 persons, as detailed in Section 3.1. As mentioned in the previous sections, if we only compare the number with the required mass, it could be concluded that a sufficient number of hygiene items is supplied from Earth.

One aspect that could be pointed out is that the mass of "Towels/Wipes" was 0.475 kg/CM-d, which accounts for 60% of the entire hygiene items. As we can easily imagine, "towels/wipes" are necessary to stay clean and refreshed, but the reality is that crew members only receive one towel every 5 days, and they need to reuse towels that were used to wipe their sweat after exercise and rinse off shampoo (NASA, 2020). This means if we could develop a laundry system or a recycling system to provide fresh towels and wipes, it could not only save the amount of supply and reduce waste but also could be a huge contribution to the crew's wellbeing.

3.1.6 Analysis and assessment of the healthcare elements

Table 6 shows the mass of each healthcare item supplied from Earth, which was estimated as 0.132 kg/CM-d as the percentage of "Health" was 1.00% of the total mass delivered from Earth between October 2017 and February 2020 (Leach and Ewert, 2021). The total mass was estimated to be approximately 61,296.14 kg, the number of days during the period was 882 days, and the average number of crew members during the period was approximately 5.269 persons, as described in Section 3.1. Healthcare elements contain items used to maintain health, treat, or diagnose crew members. For instance, "Fitness" items include parts for exercise equipment such as treadmills and cycle ergometers. There are also "Medical Kits," i.e., ISS Medical Accessory Kit. It also includes medical monitoring equipment, dosimeters, and harmful exposure protection equipment.

From the result, "Fitness" items that include spare parts of exercise equipment were approximately 50% of the total healthcare element mass. Harnesses and bungees for the treadmill and exercise ropes for the Advanced Resistive Exercise Device (ARED) are replaced approximately every 3 or 6 months (NASA, 2011), and if consumables or spare items could be designed for manufacturing and preparation on the ISS using technologies such as 3-D printing, it could potentially reduce the mass of supplies and waste. For instance, a belt pulley, which is one of ARED's components, has a mass of approximately 32.205 kg. The belt pulley consists of a pulley, a metal exercise rope, and a cable arm rope. Exercise ropes are replaced every 3 months, and cable arm ropes are replaced every 6 months (NASA, 2011). If we assume that the metal exercise rope's mass is 4 kg and fabricate the rope in space, we could reduce 16 kg of exercise rope mass every year.

3.1.7 Summary of the life support and wellbeing element assessment

Figure 4 shows the summary of Section 3.1.1 through Section 3.1.6. Regarding air and water, efforts have been made to improve the recovery rates, but the analysis in the previous sections shows that elements resupplied to the ISS are not limited to gas tanks and water bags; the current recovery system also requires a significant number of spare items to maintain the recovery rate. To realize a sustainable human presence in space or minimize resupplies from Earth, it would be necessary to design a system that reduces the need for spare items for maintenance or develop technologies, such as 3-D printing, to manufacture spare items in space. Food requires the largest amount of mass to be resupplied from Earth, and developing a food production system will improve the status and crew member's wellbeing. A waste recovery system that utilizes decomposers to change faces and food adhered to packages to fertilizers would also be needed.

For wellbeing elements, which are clothing, hygiene, and healthcare elements, although the mass supplied from Earth seems to meet their current requirement stated in NASA's Life Support Baseline Values and Assumptions Document (Anderson et al., 2018), the requirement itself might need to be reconsidered to achieve sustainable human space exploration as crew members are currently using the same clothes and towels for days, which is affecting their wellbeing.

Recovery Rate and Mass of Resupply Items / **Suggestions to Minimize Resupplies**

	Recovery Rate	Resupplies: Resources [kg/CM-d]	Resupplies: Spare Items [kg/CM-d]	Remarks	Suggestions to Minimize Resupplies
Healthcare Elements	0%	0.132	N/A (No Recycling System)	• 50% of mass are spare items for exercise equipment	☐ Design Exercise System to minimize spare items or develop technologies such as 3D printing to manufacture spares in space
Hygiene Elements	0%	0.791	N/A (No Recycling System)	• 60% of mass are towels/wipes • Crew gets only one towel in five days	☐ Develop a Laundry System that; ✓ Requires minimum amount of water ✓ Utilizes Space environment (vacuum, etc.) ☐ Produce or Recycle clothes and towels using technologies such as 3D printing in space
Clothing	0%	0.396	N/A (No Recycling System)	• Crew wears same clothes for days and causes odor issue	
Food	0%	2.216	N/A (No Recycling System)	• Limited food variety →Crew gets tired of certain foods	☐ Develop a circular food production that; ✓ Requires minimum water ✓ Utilize decomposers to change waste to fertilizers
Water	93.0% →NASA is aiming 98%	1.121 (75.8%)	0.359 (24.2%)	• 24.2% of mass are spare items	☐ Design to minimize spare items or develop technologies such as 3D printing for spares
Air (Oxygen)	51.0% →NASA is aiming 75%	0.269 (20.7%)	1.031 (79.3%)	• 79.3% of mass are spare items	☐ Design to minimize spare items or develop technologies such as 3D printing for spares

FIGURE 4
Summary of assessing the life support and wellbeing elements.

Developing a laundry system that requires a minimum amount of water or manufacturing clothes and towels on board the ISS might be helpful. If we were to develop such a laundry system and reuse all clothes and towels for 1 year, we would be able to save approximately 760.990 kg of clothes (calculated using the mass of clothes supplied to the ISS, which is 0.396 kg/CM-d, the average number of crew members, which is 5.269 persons, and 365 days/year) and 913.187 kg of towels/wipes (based on the mass of towel/wipes supplied to the ISS, which is 0.475 kg/CM-d). If cargo transportation costs approximately $20,000 per kilogram (NASA, 2018), a total of $33.484 million in costs could be saved per year. It could also free up more cargo space, which could be used to deliver more science experiments. NASA and Procter & Gamble (P&G) have been studying the development of an environmentally friendly liquid laundry detergent formulation to deal with strict resource constraints in space (Ewert et al., 2022). However, there are challenges in reducing water usage and developing a method to recover water after use. Instead of using water, the feasibility of technologies that utilize the space environment, such as ultraviolet rays and vacuum, should also be considered. For instance, there are trade studies comparing different sanitation options, such as the use of ultraviolet lamps to generate ozone for eliminating microbes from clothing and vacuum chambers that sanitize by excavating air into the cabin and venting the last bit to space as most microbes cannot survive in vacuum (Ewert and Jeng, 2015).

3.2 Quantitative and qualitative assessment of the resupply system

Based on the approach detailed in Section 2.2, data regarding rockets and spacecraft's dry mass (mass without propellant), propellant mass, and the mass breakdown of the payloads, which includes elements used to support life and wellbeing on board the ISS, were gathered. Details for each cargo supply mission can be found in the Supplementary Material.

Figure 5 shows the waterfall chart of the mass used to deliver resupply items to the ISS, the mass recovered or recycled, and the mass of the waste. To deliver 21 tons of life support and wellbeing items, which account for only 0.21% of the total launch mass, 699 tons of rocket dry mass, 9,311 tons of propellant, and 103 tons of cargo spacecraft are needed. The sum of water mass recovered onboard the ISS and the first stage engine mass of Falcon 9's rocket is 114 tons, which accounts for only 1.13% of the total mass. The remaining mass, which is 10,019 tons, or 98.87% of the total mass, is discarded. This mass production, consumption, and disposal system is extremely inefficient, not eco-friendly, and not sustainable. There are several negative effects associated with relying on this resupply system.

First, there is a risk of running out of consumables such as gas tanks, water bags, and food packages. This could happen if launch vehicles or resupply cargo spacecraft fail to deliver these items to the ISS. For instance, in 2015, the Russian cargo resupply spacecraft "Progress M-27M," which was scheduled to be launched in April, lost control after the launch and failed to deliver the resupply items to the International Space Station. "Space X CRS-7," a mission scheduled in June right after "Progress M-27," also failed to resupply items due to a malfunction of the Falcon 9 rocket. As a result, Japan's "KOUNOTORI 5" mission, scheduled to be launched in August, received a request from NASA to carry approximately 200 kg of additional supplies, including equipment for a water recycling system. "KOUNOTORI 5" successfully delivered important items to the ISS, but this example indicates that anything could happen and the risk of a shortage in life support system consumables cannot be ignored.

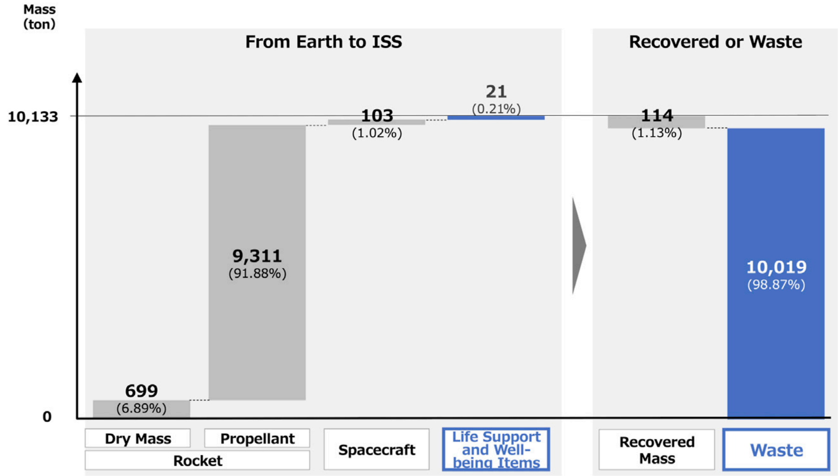

FIGURE 5
Mass launched from earth, recovered, and discarded.

Second, waste is a huge problem on the ISS. Except for air and water, food containers, experimental equipment, and other wastes are discarded after they have been used. There is no "garbage collection day" like on Earth, and waste can only be disposed of by placing it into a cargo supply spacecraft docked to the ISS and burning it up with the spacecraft after undocking and during its atmospheric re-entry. A "cargo resupply spacecraft" becomes a "garbage truck." On average, resupply missions are scheduled approximately 10 times per year, and while these spacecraft are not docked to the ISS, waste is temporarily stored on the ISS. Stowage management is critical on board the ISS and has been regarded as a major issue due to inadequate stowage volume and inadequate stowage tracking system/methodology (Baggerman et al., 2004a). In space, items can easily flow away due to the microgravity environment, and it is common for the crew members to spend their time just to find equipment or tools that will be used for scientific experiments. Temporary stowed waste occupies a certain amount of area in each module of the ISS, making stowage management much more difficult. Odor is also an issue due to the waste, and the crew has noted in the past that the smell from the waste management system and body waste have been an issue during food consumption as it will lead the crew members to lose appetite and reduce caloric intake (NASA, 2022).

The third downside of relying on the resupply system is that it requires complicated cargo transfer operations. As mentioned previously, stowage management is an issue on the ISS, and in addition to daily or routine logistics operations to consolidate and relocate items, crew members need to prepare for the cargo spacecraft's arrival, unpack resupply items from visiting logistics spacecraft, and pack temporarily stowed trash into a departing logistics spacecraft for disposal. The location of waste in the spacecraft for disposal is very important since the center of mass must be taken into account for attitude control of the deorbiting spacecraft. Ground control teams prepare dozens of pages of detailed lists of waste, which are used by the astronauts as a procedure. The same process also applies to resupply items delivered by cargo spacecraft, and crew members will be directed by the detailed procedure to stow each item in its designated location. This loading and unloading activity is a very complex and labor-intensive event, not only for crew members but also for the ground control team. If we could produce and manufacture consumables, spare items, and scientific equipment and reuse, repair, and recycle those items on the ISS, we would be able to reduce the burden on astronauts and ground control teams, allowing for more crew time to create additional value. This will also contribute to reducing the amount of packaging and cushioning materials to protect materials from launch vibrations, which could save more stowage space in the spacecraft and on board the space station.

Finally, it is important to consider the negative effect on an astronaut's wellbeing or quality of life. As already discussed in Sections 3.1.3–3.1.5, astronauts prefer to have more food variety for long-duration missions, and they get tired of certain foods and feel uncomfortable wearing the same clothes and using the same towels for a couple of days, especially exercise clothes, which will develop odors. Astronauts will be able to survive or live with the situation as it is part of their job and as they understand that supplying items from Earth is not easy, but if we are exploring further in space or if more and more people travel to space as tourists, the current situation could be stressful and would not be acceptable.

Figure 6 summarizes the discussion mentioned above.

Regarding the wellbeing of human beings, in addition to improving the situation of food, clothes, and hygiene elements, we might also need to consider supplying natural capital such as soil, plants, and a way to generate airflow that simulates a breeze on Earth. Astronauts who stay on the ISS for several months have various ways to refresh themselves, such as exercising for approximately 2.5 hours a day, gazing at Earth, or talking with family and friends. In addition, crew members have mentioned that natural elements were very helpful in reducing stress, with comments such as "Before going to sleep I watered the pea and oat plants. This is a little space garden. When I smell it, it seems I can smell the Earth. I feel great." (Whitmire et al., 2010), and "Mostly

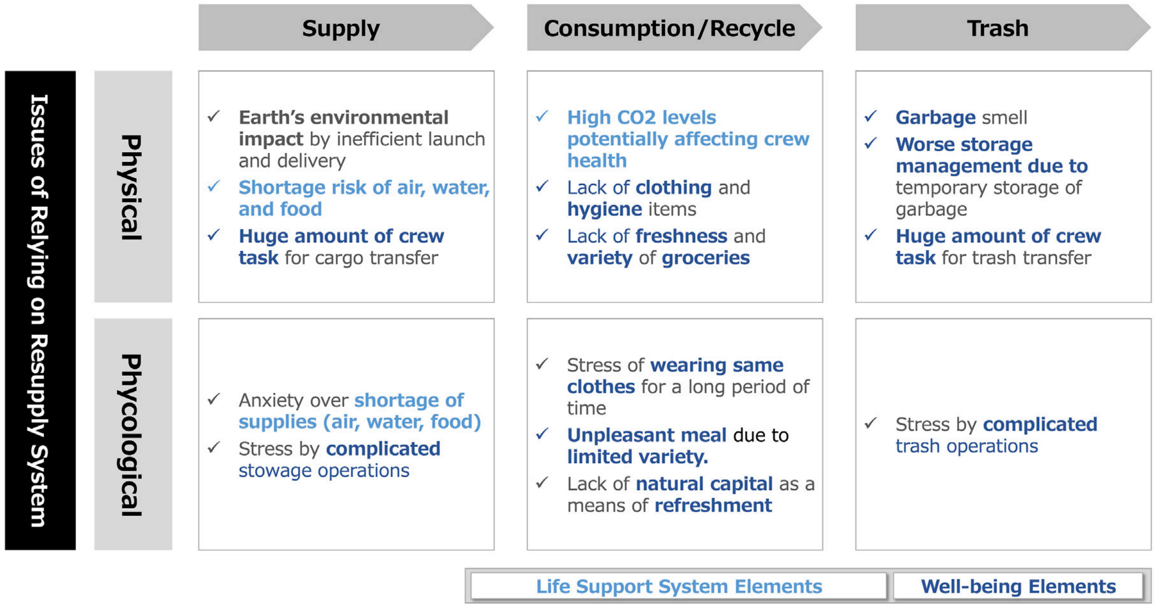

FIGURE 6
Issues of relying on the resupply system.

what you miss is people. Friends and family. And weather. Even just the wind, rain, sun, going outside" (Stockton, 2017). The JAXA has issued a "Space Life Story Book," which is a collection of voices of JAXA astronauts about their life in space. Some of the comments were like, "I was playing and listening to the recorded sound of rain and rivers flowing," "I missed the birds singing and the sound of water," "The plants (wheat) I was growing for experiments were very relaxing," and "After returning to Earth, I was moved by the wind, which was not constant in strength and direction, and the smell of plants and trees, which were pleasant. I was also impressed by the taste of food and water on Earth." (JAXA, 2020). The message derived from these comments is that the absence of nature could be a source of distress when living in space. It is almost impossible to simulate or imagine this artificial environment as long as we live on Earth. Even in megacities on Earth, if you take one step outside of buildings, it is filled with elements created by nature, such as wind, birdsong, and the smell of trees and flowers. Probably, people experienced a similar situation during the COVID-19 pandemic, when they opened their windows and were reminded of how fresh the air was. Currently, humans in space are unable to experience this, and finding a way to reproduce the environment on Earth could become a huge contribution to the mental health or wellbeing of the crew members.

4 Conclusion

The life support system and wellbeing elements on the International Space Station were assessed. It is expected that recovery rates will increase to 75% for oxygen and 98% for water. However, this study discovered that the current recovery system requires frequent resupply and a significant number of spare items. Resupply missions are scheduled approximately 10 times per year to deliver gas tanks and water bags, and 79.3% of the mass related to the air recovery system's resupply items were spare items, and more than 24.2% of the mass related to the water recovery system and the waste system's resupply items were consumables and spare items. Hopefully, the air and water recovery systems will be improved in the future with a system design that requires fewer spare items and crew time for maintenance. Even if spare parts are required, the important point in this study is to design spare parts that could be manufactured in the space station that uses technologies such as 3D printing so that it can minimize the number of resupply missions. There is no recycling system for food, clothes, towels, and such elements that affect crew members' wellbeing. Experiments such as growing vegetables, fruits, and crops on the space station are in progress, and hopefully, we will be able to develop a food production system based on these technologies. Given that all feces are discarded and 5.3% of the mass related to food resupply items consists of waste food adhered to food packaging, we might be able to utilize these as organic fertilizers using decomposers. If we were to develop a laundry system and reuse all of the clothes and towels for 1 year, we would be able to save approximately 760.990 kg of clothes and 913.187 kg of towels/wipes. In other words, $33.484 million in costs could be saved per year. It could also be a huge contribution to a crew member's wellbeing as it would help reduce the stress of using the same underwear and towels, as well as the odor from exercise clothes.

Current resupply missions can be described as a "linear economy," where most supplies are produced, consumed, and disposed of. We need to keep in mind that to supply elements to support the life of the crew members, it requires massive mass and energy to launch rockets and cargo spacecraft, and approximately 98.87% of the entire launch mass is wasted in order to deliver life support items, which accounts for only 0.21%. Resupply missions are not only inefficient but also have various negative effects on the crew from physical and psychological aspects. Current astronauts understand that they will have to deal with these aspects, but as humans explore the Moon and beyond, they cannot expect frequent resupplies. As a commercial space station is planned to be developed and more tourists are unlikely to withstand these situations, it will be required to develop a system that can reduce the amount of resupplies and ultimately recycle all life support and wellbeing elements in space. A standard or a guideline to evaluate the design of the recovery or recycling system that could minimize the total amount of consumables and spare items by producing these elements in space might be helpful. In addition, as the current recovery system cannot achieve a 100% recovery rate, a study on defining the minimum amount of types of natural capital that will support the current system will also be important for sustainable space exploration.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

SI: conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, software, validation, visualization, writing–original draft, and writing–review and editing. YY: conceptualization, funding acquisition, supervision, writing–original draft, and writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frspt.2024.1461389/full#supplementary-material

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