AGU ADVANCING EARTH AND SPACE SCIENCES

Water Resources Research

REVIEW ARTICLE

10.1029/2025WR041273

Sustainable Water Systems in Space: A Review of Current Technologies and Future Prospects

David Bamidele Olawade[1,2,3], **James O. Ijiwade**[4], **and Ojima Zechariah Wada**[5,6]

[1]Department of Allied and Public Health, School of Health, Sport and Bioscience, University of East London, London, UK, [2]Department of Research and Innovation, Medway NHS Foundation Trust, Gillingham, UK, [3]Department of Business, Management and Health, York St John University, London, UK, [4]Department of Chemistry, Faculty of Science, University of Ibadan, Ibadan, Nigeria, [5]College of Science and Engineering, Division of Sustainable Development, Hamad Bin Khalifa University, Qatar Foundation, Education City, Doha, Qatar, [6]Global Eco-Oasis Sustainable Initiative, Ibadan, Nigeria

Key Points:

- The current state and future prospects of water management technologies for long-term human space missions are reviewed
- Technologies including water recycling systems, in situ resource utilization, and bioregenerative life support systems, were explored
- The potential applications of nanotechnology and AI-driven autonomous systems were also reviewed

Correspondence to:

O. Z. Wada,
ojimawada14@gmail.com

Citation:

Olawade, D. B., Ijiwade, J. O., & Wada, O. Z. (2026). Sustainable water systems in space: A review of current technologies and future prospects. *Water Resources Research*, *62*, e2025WR041273. https://doi.org/10.1029/2025WR041273

Received 6 JUN 2025
Accepted 18 NOV 2025

Author Contributions:

Conceptualization: David Bamidele Olawade, Ojima Zechariah Wada
Data curation: David Bamidele Olawade, James O. Ijiwade
Formal analysis: David Bamidele Olawade
Investigation: David Bamidele Olawade, James O. Ijiwade
Methodology: David Bamidele Olawade, James O. Ijiwade
Project administration: David Bamidele Olawade, Ojima Zechariah Wada
Visualization: James O. Ijiwade
Writing – original draft: David Bamidele Olawade, James O. Ijiwade
Writing – review & editing: David Bamidele Olawade, Ojima Zechariah Wada

Abstract Sustainable water management is a critical challenge in space exploration, where the limited availability of resources requires innovative approaches to ensure astronauts' survival on long-duration missions. This narrative review explores the key technologies and methods involved in water recycling, in situ resource utilization (ISRU), and bioregenerative life support systems (BLSS) essential for supporting human life in space. The Environmental Control and Life Support System (ECLSS) aboard the International Space Station has demonstrated significant progress in recycling water from urine, sweat, and humidity, achieving up to 93% recovery. However, challenges remain in reducing energy consumption, improving system durability, and ensuring water quality. ISRU technologies, particularly those aimed at extracting water ice from lunar and Martian environments, offer promising solutions for future missions, but they must overcome scalability and logistical hurdles. This review also highlights the potential of nanotechnology and AI-driven autonomous systems in enhancing water purification and management. Nanomaterials like graphene oxide membranes could revolutionize filtration efficiency, while AI could optimize real-time water quality monitoring and recycling processes. As space agencies push toward establishing colonies on the Moon and Mars, the development of sustainable, closed-loop water systems will be pivotal to the success of these missions. Continued research and innovation are essential to ensuring water resources are efficiently managed for long-term human presence in space.

1. Introduction

Water is a critical resource for sustaining life, both on Earth and in the context of long-term space exploration. Beyond hydration and hygiene, water is essential for oxygen generation, food production, and other life-supporting processes necessary for human survival. As space agencies set their sights on colonizing celestial bodies like the Moon and Mars, managing water resources becomes paramount. The logistical challenges of transporting water from Earth are considerable, with estimates suggesting that sending just one kg of water to low Earth orbit (LEO) can cost tens of thousands of dollars, and costs increase exponentially for more distant missions (CSIS Aerospace Security Project, 2022; Ma et al., 2024). For instance, transporting cargo to Mars can cost up to $50,000 per kilogram, and rockets' limited payload capacity further restricts the cargo that can be carried on each mission (Puumala et al., 2023). As a result, developing sustainable water management systems is critical to ensuring the success of extended space missions and future off-Earth colonies.

The environments of the Moon and Mars present significant challenges for water management due to extreme conditions, low gravity, and the lack of readily accessible liquid water (Puumala et al., 2023). For instance, the Moon experiences extreme temperature fluctuations, with temperatures reaching 127°C (260°F) during full sun and temperatures plummeting to −173°C (−280°F) during darkness. At the same time, the gravity is just one-sixth that of Earth (NASA, 2024b). Similarly, surface temperatures on Mars go as low as −153°C (−225°F) and as high as 20°C (70°F) with an average of −63°C and gravity around 60% lower than the Earth (NASA, 2024a). Despite these harsh conditions, the discovery of water ice in the regolith of both celestial bodies offers a potential water source for future missions (Pickett et al., 2020). However, one of the challenges in utilizing these local water sources is the uncertainty surrounding the quality of subsurface water, which may contain high levels of perchlorates, toxic salts and metals, or harmful organic compounds (Puumala et al., 2023).

Therefore, advanced extraction and purification systems will be necessary to make these water sources usable for human consumption and life support systems (Pickett et al., 2020; Puumala et al., 2023).

Space missions like those aboard the International Space Station (ISS) rely on closed-loop life support systems for water recycling. The ISS uses independent and simultaneous water treatment systems to recycle wastewater, including urine, condensate, and hygiene water (European Space Agency, 2019). However, these systems face several technical challenges. For example, the altered chemical composition of wastewater in space, particularly urine, with its higher calcium concentration, poses a risk of calcium carbonate deposits forming on surfaces, leading to corrosion (Ma et al., 2024). Additionally, current systems achieve about 90% water recovery from urine, highlighting the need for more efficient technologies to maximize water reuse (Ma et al., 2024). Therefore, future water management systems must address these challenges by improving water recovery rates, reducing energy demands, and utilizing in situ resources. In-situ resource utilization (ISRU), which involves harvesting water from extraterrestrial sources such as lunar or Martian ice, offers a promising solution to reduce reliance on Earth-bound resources (Michel et al., 2023; Starr & Muscatello, 2020). However, the extraction and purification of extraterrestrial water come with technical and logistical challenges, including the need for specialized equipment to access and process water reserves buried in regolith (Rapp & Inglezakis, 2024).

To address the significant energy demands of these extraction and purification processes, solar energy utilization in Sustainable Water Systems (SWS) can be realized by photovoltaic (PV) and photothermal conversion, each presenting distinct benefits for tackling water-related issues. Photovoltaic systems generate clean electricity for water pumping, desalination via reverse osmosis or electrodialysis, and powering sophisticated treatment methods such as photocatalysis and filtration, rendering them appropriate for decentralized applications in rural and off-grid areas (Ahmad & Schmid, 2002). Conversely, photothermal systems directly transform solar radiation into heat for applications including solar distillation, multi-effect desalination, membrane distillation, and water pasteurization, with innovative photothermal materials such as carbon-based absorbers and plasmonic nanostructures markedly enhancing evaporation efficiency. Hybrid PV-thermal solutions augment sustainability by concurrently producing electricity for pumping and operating treatment units, while providing thermal energy for desalination or disinfection, thereby enhancing total efficiency and resource usage (Ahmad & Schmid, 2002). These methodologies enhance the circular water-energy nexus, diminish reliance on fossil fuels, and conform to global sustainability objectives, while advancements in sustainable materials and decentralized designs guarantee accessibility, resilience, and minimized environmental impact. Recognizing the critical role of this water-energy nexus in enabling long-term habitation, this review evaluates these integrated technologies. Thus, this review aims to provide a comprehensive analysis of sustainable water management technologies for space exploration, focusing on current water recycling systems, advancements in filtration and purification, and the potential of ISRU for water extraction in off-Earth environments. As space missions extend in duration and distance, ensuring a reliable and sustainable water supply will be key to the success of human space exploration and the establishment of permanent habitats beyond Earth.

2. Water Recycling Technologies

In the context of space exploration, water recycling is essential because of the prohibitive costs associated with transporting water from Earth. With estimates suggesting that it costs thousands of dollars to send just one L of water into LEO (Colvin et al., 2020), the need for highly efficient water recovery systems becomes clear. As missions aim to extend the human presence beyond Earth to the Moon, Mars, and other celestial bodies, developing closed-loop systems that can recycle and purify water from waste is critical for sustainability. NASA's Environmental Control and Life Support System (ECLSS), used aboard the ISS, represents the forefront of water recycling technologies (Verbeelen et al., 2021). This system is designed to recover up to 93% of water from various waste streams, including urine, sweat, and atmospheric humidity, making it a vital technology for long-duration space missions (Maciolek & Best, 2019; Stromgren et al., 2022).

2.1. ECLSS Overview

The ECLSS is a sophisticated life support system designed to ensure the continuous availability of clean, potable water aboard the ISS (K. Yang et al., 2021). It integrates several sub-systems to recycle water and maintain a safe living environment for astronauts. Two key components of the ECLSS are the Oxygen Generation Assembly (OGA) and the Water Recovery System (WRS), which allow humans to live safely in space (Lee et al., 2021).

These systems play critical roles in waste and water management and oxygen production. The WRS recycles water from various sources, including urine, sweat, and cabin humidity (Zea et al., 2020). The WRS processes wastewater using a multi-step approach, beginning with filtration through multi-filtration beds and ion-exchange systems. These components remove organic contaminants, particulates, and unwanted ions from the wastewater. Catalytic oxidation is then employed to neutralize trace contaminants, ensuring the recycled water meets the stringent safety standards required for human consumption. This system, which enables water recovery, dramatically reduces the need for new water supplies from Earth, making it a key component of long-duration missions (Stromgren et al., 2022).

In addition to water recycling, the OGA uses water to generate oxygen for astronauts. The OGA relies on electrolysis, which splits water molecules into hydrogen and oxygen (Takada et al., 2019). Oxygen is then delivered to the cabin atmosphere for crew consumption, while hydrogen is vented into space or repurposed for other chemical processes. For example, the hydrogenation of carbon dioxide using ruthenium nanoparticles in ionic liquid media achieves a 69% methane yield, a potential fuel source for future missions (Melo et al., 2016). Although the OGA ensures a stable oxygen supply, the energy required to sustain these processes remains challenging, prompting ongoing research into more energy-efficient methods. Furthermore, research by Narita et al. (2015) shows that the photochemical mechanism by titanium (IV) oxide (titania) is capable of producing abiotic oxygen from liquid water under near ultraviolet (NUV) lights on the surface of exoplanets.

Despite the successes of the ECLSS, its systems are still energy-intensive, with an energy demand of around 9.6 kW, with the OGA consuming approximately 3.2 kW (33%; Akay et al., 2022) and facing technical challenges (K. Yang et al., 2021). Filters used in water recovery systems, for example, can become clogged over time due to the accumulation of waste particles. Additionally, the life spans of filtration membranes are limited, requiring regular maintenance and replacement, an impractical scenario for long-duration missions where resupply is infrequent. As a result, advancements in filtration technologies, such as developing durable, self-cleaning membranes, are critical areas of ongoing research. Improving energy efficiency across all subsystems is also a priority to ensure sustainable water recovery without overburdening the limited power resources available during space missions.

2.2. Urine Recycling Technologies

Among the various waste streams in space, urine recycling is one of the most important for recovering water (Maciolek & Best, 2019). Since urine accounts for a significant portion of the water astronauts lose daily, effectively recycling this resource is crucial. On the ISS, urine is processed through the WRS, but future missions, especially those that extend beyond Earth orbit, require more advanced urine recovery systems. The Universal Waste Management System (UWMS) is a next-generation technology being developed for use aboard NASA's upcoming lunar Gateway and potentially for future Mars missions (Crusan et al., 2019). It incorporates improved urine-processing techniques designed to enhance recovery rates and reduce energy consumption compared to current systems (Maciolek & Best, 2019). Two promising technologies integrated into the UWMS include forward osmosis and vacuum distillation, which have demonstrated superior efficiency in water extraction. Forward osmosis is a low-energy process that leverages the natural diffusion of water across a semi-permeable membrane (Jain & Garg, 2021; Wang & Liu, 2021). Urine passes through this membrane, leaving behind contaminants, while the water is drawn into a solution that can later be purified. This method is more energy-efficient than traditional filtration systems, making it ideal for use in space with limited energy resources.

Another promising approach is vacuum distillation, which involves boiling urine at reduced pressure to separate water vapor from contaminants (Zhao et al., 2013). Since boiling points are lower in a vacuum, this process consumes less energy than standard distillation methods. For instance, the vacuum membrane distillation bioreactor VMDBR requires only 14 MJ/kg of energy for bioethanol production, which is less than standard distillation methods (J. Li et al., 2018). The collected water vapor is condensed and purified, offering a reliable source of clean water for astronauts. By incorporating these advanced technologies, future space missions can achieve greater water recovery rates while minimizing energy use, a critical factor for long-term sustainability in space. Figure 1 highlights every stage of a closed-loop urine recycling procedure for space missions, from collection to trash disposal. To prevent odour and microbiological growth, urine is first collected in specialized systems and then pre-treated. Technologies for filtration and separation eliminate solid contaminants, and then distillation or electrochemical processes purify the water and concentrate waste. Essential ingredients for

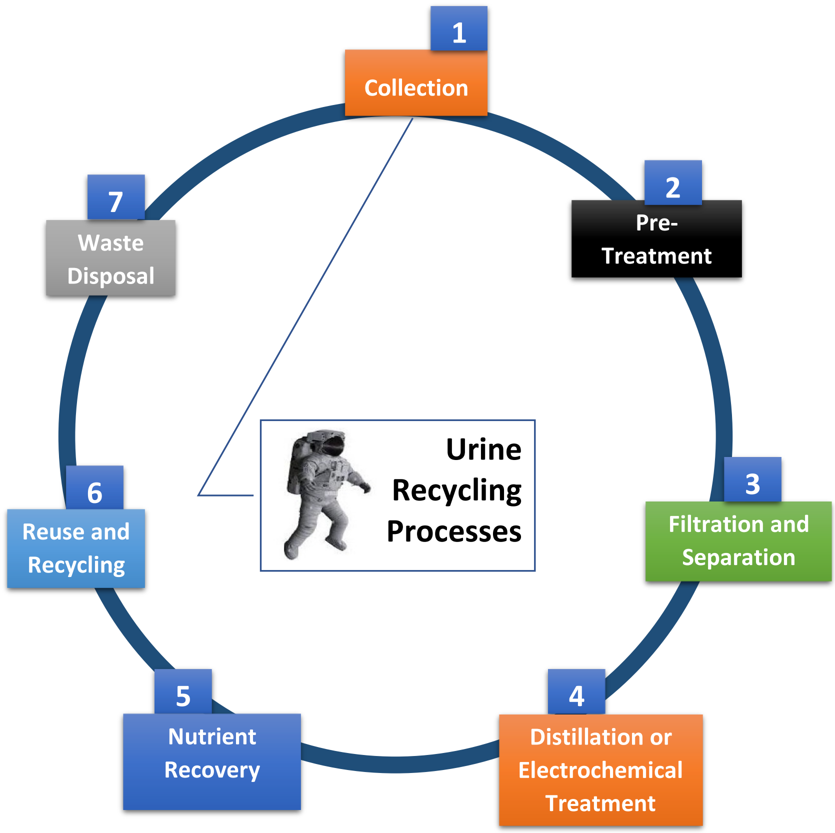

Figure 1. Closed-Loop Urine Recycling Process for Sustainable Space Missions ii.

hydroponic plant growth, such as nitrogen and phosphorus, are extracted by nutrient recovery systems, and the purified water is then stored for further use in drinking, hygiene, and plant systems. Finally, any remaining waste is compacted and stored, completing a cycle that conserves water, supplies nutrients, and minimizes waste for sustainable space exploration.

2.3. Greywater and Blackwater Management

Beyond urine, greywater (wastewater from hygiene activities like handwashing and cleaning) and blackwater (human waste) also need to be managed and recycled for space missions (Jurga et al., 2019). These waste streams present additional challenges due to biological contaminants, including harmful bacteria, viruses, and other pathogens. Ensuring the safe and efficient treatment of greywater and blackwater is essential for maintaining crew health and maximizing water recovery. Researchers are exploring microbial fuel cells (MFCs) as a potential solution to these challenges (Araneda et al., 2018). MFCs utilize microorganisms to break down organic waste, simultaneously treating wastewater and generating electricity. In this system, bacteria feed on organic matter, producing electrons as a by-product, which can then be harnessed to generate power (Obileke et al., 2021). The treated water is subsequently purified and recycled for reuse. This dual-purpose technology could offer significant advantages in future space missions, providing sustainable waste treatment and a supplemental energy source. Moreover, MFCs have the potential to be scaled for various mission scenarios, from small spacecraft to large planetary habitats (Flimban et al., 2019). Current research is focused on improving the efficiency of these systems, ensuring that they can handle the waste loads generated by larger crews and extended missions. For instance, modification of electrodes with nanomaterials and pretreatment techniques like sonication and autoclave disinfection show promising results in improving MFC execution for power generation and wastewater treatment (Sivasankar et al., 2019). Developing these technologies could revolutionize water recycling in space by addressing waste management and energy needs in a single integrated system.

3. In Situ Resource Utilization (ISRU)

ISRU refers to the process of harvesting and using local resources from celestial bodies to support human activities in space (Olthoff & Reiss, 2019). By utilizing materials such as water ice found on the Moon or Mars, ISRU enables missions to become more self-sufficient, reducing the need for costly and logistically complex resupply missions from Earth (Kleinhenz & Paz, 2020). Water, in particular, is a crucial resource that can be extracted from lunar regolith, Martian soil, and other extraterrestrial environments (He et al., 2021). These resources are typically found in the form of ice (Schlüter & Cowley, 2020), and once harvested, can be processed to meet the water needs for drinking, food production, oxygen generation, and other life-sustaining functions in space. ISRU technologies, therefore, play a vital role in advancing human exploration of the Moon, Mars, and beyond, making long-term habitation more feasible by minimizing reliance on Earth-based supplies (Bennett et al., 2020).

3.1. Water on the Moon

The discovery of water on the Moon has revolutionized the potential for establishing sustainable human habitats on its surface. For instance, this discovery has prompted interest in designing and automating smart habitats using microcontrollers and AI on LabVIEW (Meduri et al., 2021). Contrary to earlier beliefs that the Moon was completely dry, missions such as NASA's Lunar Prospector and the Lunar Reconnaissance Orbiter have confirmed the presence of water ice in permanently shadowed craters near the lunar poles (Qiao et al., 2019; Rubanenko et al., 2019). These craters in regions that never receive sunlight serve as cold traps where water molecules have accumulated over billions of years, likely from comet impacts or solar wind interactions. Harvesting this lunar water is essential for enabling long-term human presence on the Moon (Rastinasab et al., 2021; Song et al., 2021). One method under consideration involves heating the lunar regolith to release water vapor (Brisset et al., 2020; He et al., 2021). Lunar regolith containing small amounts of water ice can be heated using solar concentrators or electric heaters. The optimal mining temperature for water ice recovery is −53.15°C (−63.67°F). Modeling by Song et al. (2021) showed that the energy efficiency of thermal water ice extraction improves when seven or nine heating elements are used, compared to only five, because the additional heaters allow more uniform heating of the regolith and greater recovery of ice. As the ice sublimates and turns directly from solid to gas due to the lack of atmosphere, the water vapor is captured and condensed into liquid water. This water can then be processed and stored for future use. Heating regolith is a relatively straightforward approach, but the amount of water obtained from this method is often small and requires significant energy input (Brisset et al., 2020).

Another method being explored for lunar water extraction involves drilling and excavating deeper ice deposits (Joshi et al., 2019). These deposits, found beneath the surface of the Moon's polar craters, offer a more concentrated water source. Using robotic drills or human-operated systems, the ice can be excavated and brought to the surface, where it is melted and purified. NASA's Volatiles Investigating Polar Exploration Rover, whose operation ended in July 2024, is an example of a mission designed to assess the distribution and accessibility of water ice on the Moon, mapping potential sites for future extraction efforts. These ISRU technologies will be critical for the success of lunar bases, drastically reducing the need to transport large quantities of water from Earth. By utilizing the Moon's natural resources, lunar habitats could become more self-sufficient, ensuring a sustainable supply of water for astronauts to drink, produce oxygen, grow food, and conduct scientific research. For instance, the Chang'E-5 (Chinese lunar exploration mission and part of China's Chang'e program) lunar soil sample has been shown to possess photocatalytic properties that could enable artificial “extraterrestrial photosynthesis” (Y. Yao et al., 2022; Zhong et al., 2023). In this process, minerals in the regolith can use solar energy to drive reactions such as water splitting, releasing oxygen and producing useful byproducts. Such catalytic activity suggests a pathway toward a low-energy life support system on the Moon. Moreover, water extracted from the Moon could be used for fuel production, through electrolysis to separate hydrogen and oxygen, two key components for rocket propellant.

3.2. Water on Mars

While Mars presents a more challenging environment for water extraction compared to the Moon, it remains a promising destination for human exploration due to the significant evidence of water in various forms. Radar data from Mars Express show a 20-km-wide lake of liquid water underneath the solid ice of Mars' southern ice cap (Orosei et al., 2018). Although liquid water is not stable on the Martian surface due to its thin atmosphere and low temperatures (Rivera-Valentín et al., 2020), numerous missions, including NASA's Mars Odyssey and the Phoenix lander, have confirmed the existence of substantial water ice deposits below the surface, especially at higher latitudes. Additionally, Martian soil contains hydrated minerals such as clays and sulfates that trap water molecules within their structure, offering another potential water source for future missions (Jamanca-Lino & Guevara, 2023).

One key approach for extracting water on Mars involves targeting subsurface ice (Wasilewski, 2018). This ice, found in polar and mid-latitude regions, can be accessed through drilling (Wasilewski, 2018). Advanced drilling systems, designed to reach and melt the subsurface ice, could extract the water needed to support human missions. Once the ice is melted, the water can be purified and stored for use in life support systems. The challenge with this approach lies in developing drilling technologies that can withstand the harsh Martian conditions while efficiently extracting large volumes of water. Robotic missions, such as NASA's upcoming ExoMars mission, are expected to play a crucial role in locating and assessing the viability of these ice deposits for human use (De Sanctis et al., 2022).

In addition to subsurface ice, Mars offers another potential water source in the form of hydrated minerals (Jamanca-Lino & Guevara, 2023). These minerals in Martian soil contain chemically bound water that can be released through heating. Water vapor is released by mining these minerals and applying heat, which can then be captured, condensed, and purified. Although water yield from this process is lower than from subsurface ice, it provides an alternative water source in regions where ice deposits are scarce. This method requires significant energy input, but ongoing research aims to optimize the process for space missions.

Mars also has a trace amount of water vapor in its atmosphere (Fedorova et al., 2020), typically ranging from ∼10 to 50 parts per million per volume (ppmv; Belyaev et al., 2021) depending on season and location. While this corresponds to very low partial pressures, zeolite-based desiccants and related sorbents have been proposed to scavenge this moisture. Laboratory studies suggest that such materials can adsorb small but measurable quantities of water under Martian-like pressures and relative humidities, on the order of milligrams of water per gram of sorbent per day. For instance, a research by (Jänchen et al., 2007) shows that Zeolites and smectites on the Martian surface can adsorb about 2.5–25 wt% of water at low temperatures and a very low partial pressure of 0.001 mbar. The total yield, however, would be limited, and large masses of sorbent would be required to generate mission-relevant volumes of water, raising concerns about payload feasibility. Consequently, desiccant-based harvesting would likely function only as a supplementary system to subsurface ice extraction or perchlorate reduction. Nonetheless, including it as part of an integrated ISRU strategy highlights the importance of employing diverse methods to ensure redundancy and resilience in water supply for a Mars mission. The ability to extract water from Mars is crucial for enabling long-term human presence. Not only is water necessary for sustaining life, but it can also be used to produce oxygen and fuel for return missions. By relying on local water resources, future Mars missions can significantly reduce their dependence on Earth, making exploration and potential colonization more feasible. As ISRU technologies advance, the prospect of establishing sustainable human habitats on Mars becomes increasingly realistic.

4. Potential Technologies for In Situ Water Treatment in Space (Mars and Moon)

As human exploration extends beyond Earth, reliable in situ water treatment becomes critical for sustaining long-duration missions on Mars (Orosei et al., 2018) and the Moon (Qiao et al., 2019). Both environments offer potential water sources, such as ice in lunar craters and subsurface ice on Mars. Still, these must be treated to meet safety standards for human consumption, agriculture, and other life-support needs. Given the limited resources and harsh space conditions, water treatment technologies for these missions must be energy-efficient, durable, and capable of functioning autonomously over long periods (Pickett et al., 2020). Recent advancements in filtration systems, disinfection methods, and autonomous technologies offer promising solutions for in situ water treatment on other celestial bodies. For example, sand-substrate biofilters can replace chemical water purification in manned spaceflights, reducing costs and energy inputs (Thornhill & Kumar, 2018). Figure 2 shows six in situ water treatment technologies crucial for recycling water during space missions. Electrochemical treatment employs electric currents to break down impurities, and photocatalytic purification uses light-activated catalysts to clean without using chemicals. Bioreactors use microorganisms to break down organic pollutants, ion-exchange systems replace dangerous ions with safe ones, UV and ozone disinfection sterilize water, and membrane filtration (e.g., reverse osmosis) eliminates contaminants at a molecular level. When combined, these techniques provide a dependable, multi-phase strategy for preserving water quality in space.

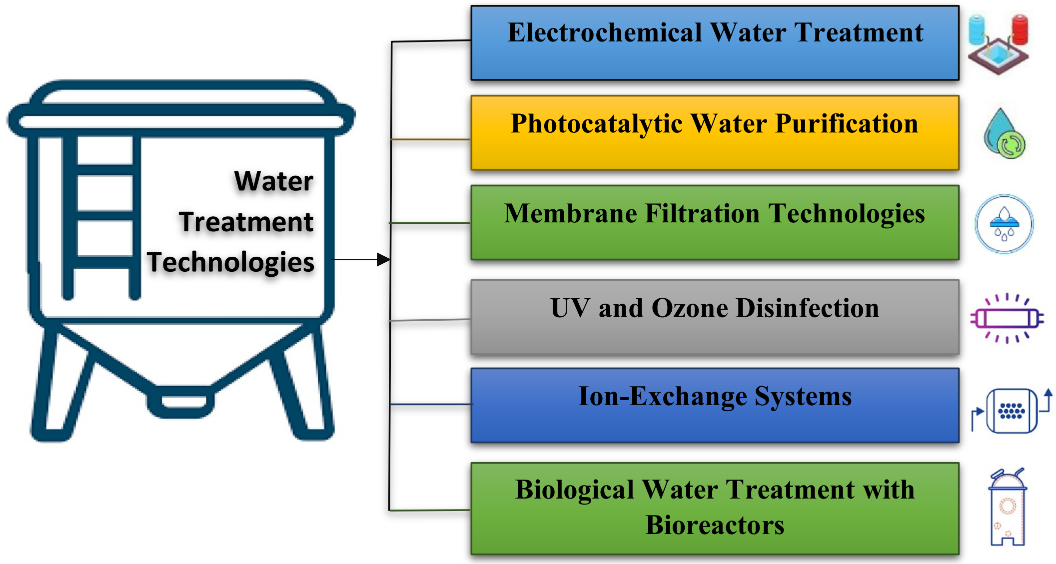

Figure 2. In-Situ Water Treatment Technologies in Space iii.

4.1. Electrochemical Water Treatment

Electrochemical water treatment technologies, including electrocoagulation and electrodialysis, present effective solutions for in situ water treatment in space (Chaplin, 2019). Current research shows that electrocoagulation can remove heavy metals, suspended solids, and organic compounds (Moradi et al., 2021) from water using an electrical current to induce coagulation and precipitation. Studies have demonstrated the effectiveness of these systems in treating contaminated water on Earth (Srimuk et al., 2020), with the potential for adaptation in space applications due to their low chemical input requirements and compact design (Vishnu et al., 2020). Similarly, electrodialysis has been tested for its ability to desalinate water by using electric fields to separate dissolved salts from water (T. H. Chen et al., 2021). Recent advances have improved the energy efficiency of electrodialysis, making it a more viable option for space missions where energy resources are limited (Simões et al., 2020). These systems are particularly useful for treating briny water extracted from Martian ice deposits or lunar regolith, where dissolved salts are common (Severin & Hayes, 2019).

4.2. Photocatalytic Water Purification

Photocatalytic water purification is another promising technology for treating water in space (Long et al., 2020). This process uses photocatalysts like titanium dioxide (TiO_2) to harness light, preferably solar or UV, to generate reactive oxygen species that break down organic pollutants and kill pathogens. Research conducted by the ESA has shown that photocatalytic systems are effective at treating wastewater on Earth, and similar approaches could be applied to treat water extracted from lunar or Martian environments (Ren et al., 2021; Rueda-Marquez et al., 2020). The benefit of photocatalysis is its low energy requirement (Bellotti et al., 2023), especially when solar energy can be used as the light source. However, adapting these systems for space missions requires optimization for microgravity conditions, as the behavior of fluids and catalysts may differ outside of Earth's gravitational field.

4.3. Membrane Filtration Technologies

Membrane-based filtration is fundamental to water treatment systems because it effectively eliminates dissolved salts, bacteria, and organic pollutants. Methods like nanofiltration (NF) and reverse osmosis (RO) have been extensively utilized in terrestrial and extraterrestrial applications due to their capacity to deliver dependable and high-quality water (Jamil et al., 2018). These technologies are frequently hindered by fouling, elevated energy requirements, and the necessity for regular membrane replacement, which can be especially problematic during extended missions (Buelke et al., 2018).

Research has increasingly concentrated on sophisticated membrane designs that enhance permeability, diminish fouling, and prolong operating longevity to address these issues. Promising advancements include the incorporation of nanoparticles, facilitating membranes with improved selectivity and diminished energy demands. Section 6.1 comprehensively examines nanotechnology-enabled membranes, including graphene oxide (T. Chen et al., 2021; M. Yao et al., 2020; Ye et al., 2021). One of the most promising nanomaterials for space water filtration is graphene oxide. Graphene oxide membranes are incredibly thin yet strong and possess unique properties that make them ideal for water purification. Some of their properties include high surface area, mechanical durability, atomic thickness, nanosized pores, and reactivity toward water pollutants, providing excellent water purification efficiency for water desalination (Homaeigohar & Elbahri, 2017). They can be engineered with specific pore sizes to filter out contaminants, including salts, heavy metals, and organic molecules. These membranes allow water molecules to pass through while blocking larger particles, resulting in a more efficient filtration process than conventional materials. Additionally, graphene oxide membranes are less prone to fouling, a common issue with traditional filtration systems that leads to reduced performance over time (Karkooti et al., 2020).

4.4. UV and Ozone Disinfection

Ultraviolet (UV; X. Li et al., 2019) and ozone (Epelle et al., 2022) disinfection methods are commonly used for sterilizing water and are being explored for space applications. UV disinfection uses high-energy UV-C light to destroy the DNA of bacteria, viruses, and other pathogens, preventing them from replicating (Narita et al., 2020). NASA has successfully used UV light to disinfect drinking water aboard the ISS, and similar systems are being developed for future lunar and Martian habitats. Ozone disinfection, another method under investigation, involves the generation of ozone gas (O_3), which acts as a powerful oxidizing agent to neutralize pathogens and break down organic pollutants (Gorito et al., 2021). Ozone systems are compact and effective, making them suitable for the confined environments of space habitats. Both UV and ozone treatments can serve as the final stage of water treatment, ensuring that any microbial contaminants that survive earlier filtration processes are eliminated (Shi et al., 2021).

However, these active disinfection systems require a consistent power supply, which can be scarce in deep space. To address this, solar-powered water treatment (SWT) technology offers a dual solution: providing renewable electricity to power UV and ozone generations via photovoltaics, and offering direct photothermal purification. According to Ge, Feng, et al. (2025), Ge, Guo, et al. (2025), SWT is compatible with SWS and enhances their effectiveness by enabling autonomous and energy-efficient water recycling in resource-limited environments. Through photothermal and photovoltaic mechanisms, SWT systems can purify wastewater, extract water from extraterrestrial ice, and generate hydrogen and oxygen, all supporting astronaut survival, clean energy production, and space industry development. Recent progress in this area focuses on overcoming key operational hurdles like salt deposition and energy efficiency. For example, novel photothermal systems using a thermal gradient fabric evaporator (Ge, Feng, et al., 2025; Ge, Guo, et al., 2025) or a weaved cylinder evaporator (Zhang, Wang, et al., 2025; Zhang, Zhang, et al., 2025) have demonstrated superior salt rejection capabilities and high evaporation rates, making them durable candidates for high-salinity desalination in sustained operations. Although challenges such as microgravity, radiation, and variable solar flux remain, ongoing innovations in materials, treatment methods, and intelligent controls make SWT a key enabler for sustainable energy-intensive processes like disinfection, reinforcing the operational goals of SWS in both extraterrestrial and terrestrial contexts.

4.5. Ion-Exchange Systems

Ion-exchange technology is another potential solution for in situ water treatment on the Moon and Mars, particularly for removing dissolved salts and heavy metals from extracted water (Malik et al., 2019). Ion-exchange resins work by exchanging undesirable ions in the water, such as calcium or magnesium, with safer ions such as K^+, Mg^{2+}, and Ca^{2+}, with removal efficiencies of 56.0%, 93.5%, and 85.4%, respectively (Mudau et al., 2022). Recent studies have highlighted the effectiveness of ion-exchange systems in softening water and removing toxic elements like lead and arsenic (A. S. C. Chen, Wang, et al., 2020), which may be present in Martian or lunar water sources. One of the advantages of ion-exchange systems is their ability to be regenerated, allowing them to be used repeatedly without the need for frequent resupply of materials. This makes them particularly useful for long-term missions where resupply from Earth is limited.

4.6. Biological Water Treatment With Bioreactors

Biological water treatment using microbial bioreactors represents a cutting-edge approach to water recycling in space. For instance, the membrane-aerated biofilm reactor can achieve up to 96% total organic carbon removal efficiency and up to 82% denitrification efficiency for treating urine and hygiene wastewater for space applications (Zhan et al., 2022). These systems leverage microbial communities to break down organic contaminants and recycle nutrients for use in space agriculture. NASA's research on bioregenerative life support systems (BLSS) has demonstrated the potential of bioreactors to recycle water from human and plant waste, creating a closed-loop system that reduces the need for external water supplies. Microbial fuel cells (MFCs), which generate electricity as bacteria break down organic matter, offer a dual benefit by producing clean water and energy (Obileke et al., 2021). This technology could be integrated into future lunar or Martian habitats to treat wastewater, generate power, and recycle nutrients, supporting water management and agricultural needs. Studies have shown that MFCs are particularly efficient in low-energy environments, making them ideal for space applications.

5. Technological and Logistical Challenges

While significant strides have been made in water recycling technologies and ISRU, several critical challenges hinder the realization of fully sustainable water management systems for long-duration space missions. These challenges centre primarily on energy consumption, gravity, system durability, contamination risks, and scalability. Addressing these issues is vital for enabling the self-sufficiency of future space habitats on the Moon, Mars, and beyond, where resupply from Earth will not be feasible.

5.1. Drilling Challenges Beyond Mars

Off-Earth drilling faces challenges such as microgravity, vacuum conditions, temperature fluctuation, weight limitation, and lack of real-time drilling analysis and communication (Knez & Khalilidermani, 2021). While these constraints are particularly relevant for small-body or asteroid mining, they provide important context for developing robust drilling systems that could be adapted for Martian exploration.

5.2. Energy Requirements

The high energy demand is one of the most significant challenges in space-based water recycling and ISRU technologies (Q. Yang et al., 2024). Current water recycling systems, such as those aboard the ISS, are energy-intensive. Processes like urine distillation, water filtration, and oxygen generation through electrolysis consume considerable power, which is a limited resource during space missions. For example, NASA's Water Recovery System (WRS) on the ISS uses multifiltration and catalytic oxidation (Volpin et al., 2020), requiring continuous power input to function effectively. As missions extend beyond LEO to the Moon or Mars, where solar energy may not always be available or reliable, the issue of energy consumption becomes even more critical.

In remote environments such as the lunar poles or deep space, where access to solar power is restricted due to long periods of darkness, alternative energy sources must be developed to sustain water recovery systems. For example, a lunar-based solar thermal power system can provide the desired energy for equipment development (Lu et al., 2019). Nuclear-powered systems, such as small modular reactors, are being considered for future lunar and Martian bases, but their deployment comes with technical and safety challenges. Reducing the energy requirements of water recycling technologies remains an essential goal for researchers. The proposed Automatic Contingency Management system can optimally alleviate faults in the Water Recycling System (WRS) regarding energy consumption and the effects of the fault (Tang et al., 2018). Advances in low-energy filtration membranes, more efficient electrolysis systems, and energy recovery techniques are critical areas of ongoing development to make space water management systems more sustainable.

5.3. Maintenance and Durability

The harsh environment of space poses another challenge for water recycling systems, particularly regarding the durability and maintenance of these systems. Components such as filtration membranes, pumps, and catalytic reactors are subject to wear and tear over time. On long-duration missions, the ability to perform regular maintenance or replace faulty parts is limited, making system reliability a top priority. A robust fault management system, functionally redundant systems, and a resilient architecture are essential for assessing reliability concerns on long-duration space missions (Edwards et al., 2021). Current systems on the ISS require regular maintenance to replace filters, repair mechanical parts, and ensure continued functionality. In the context of a mission to Mars, where the round-trip time for communication alone can be up to 40 min and resupply missions would be rare, frequent maintenance and repairs would be impractical.

A significant focus of research is improving the longevity of critical components and developing self-monitoring systems that can detect issues before they become critical. Filtration membranes, for example, can degrade over time due to clogging or irreversible fouling by organic and inorganic materials. Research suggests that physically irreversible fouling is the dominant form of membrane fouling in anaerobic membrane bioreactors, accounting for a significant percentage of total fouling (Hafuka et al., 2019). Efforts are being made to develop more durable, self-cleaning membranes that can operate efficiently for longer periods without requiring replacement. For instance, the hierarchical structured nanofibrous membrane developed in this study by Cao et al. (2022) has antifouling and visible-light-induced self-cleaning performance, making it a good candidate for treating complex oily wastewater. Similarly, developing more robust pumps, valves, and other mechanical components is essential to minimize maintenance requirements.

5.4. Contamination

Water contamination is a major concern in closed-loop systems, where water is constantly recycled and reused. The buildup of biofilms, microbial growth, and chemical contaminants can compromise water quality and pose serious health risks to astronauts. Spacecraft water monitoring systems need technological advances to identify and counteract waterborne microbial contamination, posing health risks to astronauts with lowered immune responsiveness (Amalfitano et al., 2020). On the ISS, advanced filtration systems are used to remove organic and inorganic contaminants from recycled water but ensuring that these systems maintain water quality over time is a constant challenge. Biofilms, which are thin layers of microorganisms that adhere to surfaces, can develop inside pipes, filtration systems, and storage tanks, leading to blockages, reduced system efficiency, biofouling, corrosion, loss of function, and potentially harmful microbial contamination (Mettler et al., 2022; Zea et al., 2020). Space environments exacerbate this issue because microgravity can alter the behavior of fluids, making it easier for microorganisms to thrive in these systems (Gesztesi et al., 2023). Researchers are working on antimicrobial coatings and advanced water monitoring technologies to detect contamination early and prevent biofilm formation. Implementing automated disinfection protocols using UV light or chemical treatments could also help mitigate the risk of contamination. Moreover, microbial contamination is not the only concern. Trace chemical contaminants from spacecraft materials, such as volatile organic compounds, can accumulate in recycled water, necessitating additional purification steps to ensure water safety. Continuous water quality monitoring systems that can detect even low levels of contaminants in real-time are critical for maintaining safe water supplies in space. Molecularly imprinted polymer sensors and microwave spectroscopy are promising real-time water quality monitoring technologies, with characteristics like sensing range and detection limit verified outside laboratory conditions (Yaroshenko et al., 2020). Additionally, the submersible sensor probe combines UV/Vis and fluorescence spectroscopy for in situ water quality monitoring, providing real-time results for quick response to changes in water quality (Goblirsch et al., 2023). Furthermore, ensuring the long-term durability of these sensors in extreme environments is paramount; innovations in materials, such as the development of heat-resistant core-sheath yarn sensors for high-temperature applications, demonstrate a pathway toward creating robust and reliable monitoring components suitable for space missions (Xu et al., 2024).

5.5. Scalability

The systems currently deployed on the ISS are designed to support a small crew of around six astronauts (Yamaguchi et al., 2023). However, as space agencies and private enterprises plan for larger-scale missions, such as a colony on Mars or a lunar base, scaling these systems to support larger populations presents significant engineering and logistical challenges. For example, the demands of a colony of 100 people would far exceed the current capacities of water recycling systems in place on the ISS. Scaling up water recycling systems involves increasing their throughput and ensuring that they remain efficient, durable, and easy to maintain. Larger systems must also handle a more diverse waste stream and contaminants, as larger populations generate more waste. The increased demand for water in a larger habitat would also mean that storage and distribution systems must be expanded, requiring careful planning to ensure that water is available where and when needed. Furthermore, the infrastructure required to support large-scale ISRU operations, such as extracting water from Martian ice or lunar regolith, will need to be significantly more advanced than current prototype systems. This involves designing systems that can continuously extract, purify, and store large quantities of water while operating autonomously for extended periods. The logistics of transporting and assembling such systems on the Moon or Mars and ensuring their long-term operation in harsh environments present additional challenges that engineers must address. Emerging technologies are beginning to address this challenge, such as the development of meter-scale, three-dimensional photothermal textiles that decouple ion and thermal diffusion, offering a pathway for scalable, high-flux, and long-term solar desalination (Zhang, Wang, et al., 2025; Zhang, Zhang, et al., 2025).

Overall, electrochemical and membrane-based systems show a wide range of energy costs, with some advanced configurations (e.g., bioelectrochemical, electrically enhanced MBRs) offering improved efficiency and lower costs (Table 1). Photocatalytic systems, especially those using solar energy, have the potential for low operational energy and simultaneous energy production, but cost data are still emerging. UV, ozone, and ion-exchange systems are effective but were not directly quantified in the available research. Integration and hybridization of these technologies are key trends for improving energy efficiency and cost-effectiveness in water treatment.

6. Future Prospects and Innovations

As humanity sets its sights on long-term exploration and colonization of celestial bodies such as the Moon and Mars, the future of water management in space becomes a pivotal concern. The ability to autonomously manage, recycle, and procure water in hostile environments far from Earth is essential for the survival and well-being of astronauts. Future space colonies must have closed-loop systems for water purification, recycling organic wastes, and minimizing consumable inputs to maximize recovery for astronaut survival (Pickett et al., 2020). Efficient water management systems must balance energy efficiency, reliability, and scalability while reducing the need for human intervention (Bernardo et al., 2021). Technological advances in water recycling, ISRU, and bio-regenerative systems promise sustainable solutions for space habitats. For instance, bioregenerative life support systems (BLSSs) like MELiSSA aim to recover nutrients from waste streams and produce fresh food, oxygen, and water for long-term space exploration missions (Verbeelen et al., 2021). Key areas of innovation include nanotechnology for advanced filtration, autonomous systems for real-time water quality management, and artificial intelligence (AI) to enhance these systems' overall efficiency and reliability.

6.1. Nanotechnology and Advanced Filtration

Nanotechnology offers exciting prospects for advancing water purification and filtration systems, particularly in the energy-limited environments of space. Traditional water recycling systems, while effective, often face challenges such as high energy consumption, membrane fouling, and the limited lifespan of filtration components (Zhu & Jassby, 2019). By enabling the design of nanomaterials and nanostructured membranes with tailored surface properties and pore sizes, nanotechnology can enhance filtration efficiency, reduce fouling, and improve the durability of filtration systems (Barhate & Ramakrishna, 2007).

Furthermore, nanotechnology enables the development of multifunctional materials that filter water and actively break down contaminants through catalytic reactions. For instance, nanocomposite materials can be designed to degrade organic compounds and kill bacteria, reducing the risk of contamination in closed-loop water systems. For instance, nanocomposite hydrogels incorporating graphene oxide (GO) sheets and quaternary ammonium salt can exhibit antibacterial properties with bacterial-killing efficacy of approximately 90% towards *E. coli* and near-quantitative values (99.90%) when irradiated (Han et al., 2021). These advanced filtration technologies could significantly reduce the energy requirements of water recycling systems by streamlining the purification process and extending the lifespan of key components. As space missions become more ambitious, integrating nanomaterials like graphene oxide into water filtration systems will ensure reliable and efficient water management.

6.2. Autonomous Water Systems

The future of space exploration will likely rely heavily on autonomous systems capable of functioning with minimal human oversight. Water management systems that can autonomously monitor, adjust, and optimize water quality and recycling processes in real-time will be essential for maintaining long-term space habitats. These autonomous systems, driven by advances in artificial intelligence (AI) and machine learning, have the potential to revolutionize water management by predicting system failures, reducing energy consumption, and improving overall efficiency.

Table 1
Comparison of Key Technologies Considered for Water Treatment

Technology	Energy cost (kWh/m^3)	Efficiency/Notes	Cost (\$/m^3)	References
Electrochemical Membrane Technologies (EMTs)	0.01–5 (varies by process)	High removal efficiency for various contaminants; pilot-scale CNT membranes are notably efficient	0.25–1.20 (ED); <0.50 (wastewater)	Balogun et al. (2024), Alkhadra et al. (2022),
Photocatalytic Water Purification (PFCs, PMRs)	Not always specified; solar-driven, so low operational energy	Simultaneous pollutant removal and energy generation; efficiency depends on catalyst/materials	Cost analysis ongoing; PFCs promising for low-cost operation	Ni et al. (2023)
Membrane Filtration (UF, NF, RO)	Not specified here; generally, 0.2–2 (literature)	Effective for a wide range of pollutants; fouling and energy use are challenges	Varies; integration with electrochemical or bioelectrochemical systems can reduce costs	Balogun et al. (2024), Giwa et al. (2019), Urtiaga (2021)
UV and Ozone Disinfection	Not directly addressed	Highly effective for disinfection; energy and cost depend on scale and water quality	Not specified	
Ion-Exchange Systems	Not directly addressed	Effective for ion removal; energy and cost depend on regeneration method	Not specified	
Biological Water Treatment (Bioreactors, MBRs)	Not specified; eMBR integration reduces energy use	High effluent quality: membrane fouling and energy use are main challenges	Varies; eMBR and hybrid systems improve efficiency	Giwa et al. (2019)

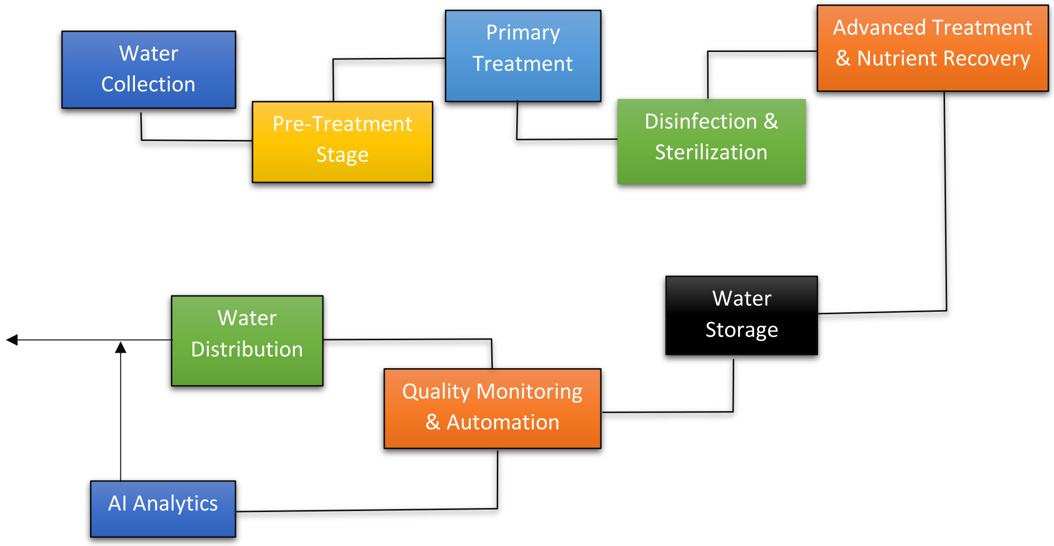

Figure 3. AI-Powered Autonomous Water Management System (AI Analytics involves algorithms that analyze data from the system to predict failures, optimize treatment efficiency, and ensure water quality standards are met automatically).

To achieve this level of autonomy, AI-powered systems must move beyond simple automation to intelligent, data-driven control. Instead of relying on pre-programmed schedules, these systems use real-time sensor data to understand and react to the state of the water and the hardware. Concrete applications of this principle are emerging in terrestrial water management and provide a blueprint for space systems. For instance, a critical function is ensuring microbiological safety. Deep convolutional neural networks can autonomously analyze microscopic images from water samples to detect and classify harmful pathogenic bacteria (such as E. coli) with over 99% accuracy, replacing time-consuming conventional protocols (Awwad et al., 2024; Frincu, 2025). Beyond pathogen detection, machine learning algorithms like Random Forest and Support Vector Machines can process data from spectroscopic sensors for real-time water classification as clean, contaminated, or disinfected, thereby verifying the efficacy of treatment processes (Durgun, 2024). Furthermore, AI can synthesize data from multiple sources, such as an integrated Internet of Things sensor network, to model comprehensive Water Quality Indexes and enable dynamic early warning systems (Sun et al., 2024; Yang et al., 2022; Zou et al., 2025).

This robust monitoring capability is the foundation for further autonomous functions. Training machine learning algorithms on large data sets from system operations makes it possible to predict when components are likely to fail, allowing for preventive maintenance before a critical issue arises (Naik et al., 2020). By identifying patterns in system behavior, these algorithms can also optimize water recycling processes, reducing the need for energy-intensive interventions and extending the life of key system components (H. Chen, Wang, et al., 2020; Icke et al., 2020). In the context of ISRU, AI systems could coordinate the extraction, purification, and distribution of water, ensuring that resources are used efficiently (L. Li et al., 2021). For example, AI could adjust the power consumption of water extraction systems based on real-time energy availability, making decisions that balance resource extraction with the broader needs of the habitat (Drogkoula et al., 2023). Such predictive control has been shown to reduce electrical energy consumption by up to 71% in complex terrestrial energy systems (Coccia et al., 2021).

Integrating AI into water management systems also offers the potential for greater resilience in the face of unforeseen challenges. By dynamically adjusting water usage and recycling rates, autonomous systems could adapt to changing conditions, such as a sudden increase in water demand due to unforeseen crew activities or a decrease in available energy. This level of adaptability is crucial for long-term missions, where resupply from Earth may not be possible for months or even years. By leveraging AI and machine learning, future water systems could become more self-sufficient, reducing the need for human intervention and freeing astronauts to focus on more mission-critical tasks.

Figure 3 illustrates a conceptual framework for an AI-Powered Autonomous Water Management System designed for remote environments like space missions. The process begins with water collection from condensed

10.1029/2025WR041273

moisture and wastewater, followed by pre-treatment, filtration, and pH correction. AI algorithms can optimize purification through membrane filtration and electrochemical techniques in the primary treatment phase. Subsequent disinfection using ozone and UV technologies eradicates pathogens. During advanced treatment and nutrient recovery, AI monitors systems like ion-exchange for salt removal and manages bioreactors that break down organic materials. The purified water is then stored for both potable and non-potable uses. A critical feedback loop is established through quality monitoring and automation, where sensors evaluate water quality, enabling the AI to make real-time adjustments and ensure efficient distribution based on specific needs.

7. Conclusion

Sustainable water management in space is one of the most critical challenges in enabling the long-term survival of human missions beyond Earth. It requires an integrated approach that combines advanced water recycling technologies, ISRU, and innovative life support systems. Each of these elements plays a vital role in addressing the unique demands of space exploration, where the finite nature of resources and the logistical difficulties of resupply from Earth necessitate efficient and closed-loop solutions. The progress in these areas, particularly in developing recycling technologies and ISRU, offers promising pathways for supporting future lunar and Martian habitats. However, significant technological, logistical, and energy-related challenges remain, and overcoming these obstacles will be essential for ensuring the sustainability of human life in space.

Water recycling technologies have advanced considerably, with systems like NASA's Environmental Control and Life Support System (ECLSS) aboard the ISS already demonstrating high recovery rates of up to 93%. These systems form the backbone of current life support operations but must be further refined to reduce energy consumption, improve durability, and mitigate contamination risks. In parallel, ISRU technologies are gaining traction to extract water from extraterrestrial environments such as the lunar regolith and Martian regolith. By utilizing locally available resources, ISRU reduces the dependency on Earth for water supplies, opening the door to more autonomous and self-sustaining missions. However, the scalability of these systems remains a challenge, particularly as space agencies look to support larger crews and establish permanent habitats.

Continued research and innovation are crucial for addressing the remaining hurdles in sustainable water management. Future developments in nanotechnology, advanced filtration systems, and autonomous water management could significantly enhance the efficiency and reliability of space water systems. Integrating artificial intelligence (AI) and machine learning into these systems can transform how water resources are managed, with real-time monitoring, predictive maintenance, and optimization of processes playing key roles in ensuring that astronauts have access to clean and safe water. As space agencies and private companies move forward with ambitious plans to establish human presence on Mars and other yet-to-be-possible habitable planets, the success of these missions will depend heavily on the development of reliable and sustainable water management technologies. Closed-loop systems capable of recycling and managing water for large populations will be critical in reducing reliance on Earth-based resupply missions. The successful implementation of these technologies will pave the way for the next era of human space exploration, where sustainable habitats can thrive in the most extreme and isolated environments.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

Data were not used, nor created for this research.

Acknowledgments
The authors acknowledge Qatar National Library (QNL) for providing open access funding.

References

Ahmad, G., & Schmid, J. (2002). Feasibility study of brackish water desalination in the Egyptian deserts and rural regions using PV systems. *Energy Conversion and Management*, *43*(18), 2641–2649. https://doi.org/10.1016/S0196-8904(01)00189-3

Akay, Ö., Bashkatov, A., Coy, E., Eckert, K., Einarsrud, K., Friedrich, A., et al. (2022). Electrolysis in reduced gravitational environments: Current research perspectives and future applications. *NPJ Microgravity*, *8*(1), 56. https://doi.org/10.1038/s41526-022-00239-y

Alkhadra, M., Su, X., Suss, M., Tian, H., Guyes, E., Shocron, A., et al. (2022). Electrochemical methods for water purification, ion separations, and energy conversion. *Chemical Reviews*, *122*(16), 13547–13635. https://doi.org/10.1021/acs.chemrev.1c00396

Amalfitano, S., Levantesi, C., Copetti, D., Stefani, F., Locantore, I., Guarnieri, V., et al. (2020). Water and microbial monitoring technologies towards the near future space exploration. *Water Research*, *177*, 115787. https://doi.org/10.1016/j.watres.2020.115787

Araneda, I., Tapia, N. F., Allende, K. L., & Vargas, I. T. (2018). Constructed wetland-microbial fuel cells for sustainable greywater treatment. *Water*, *10*(7), 940. https://doi.org/10.3390/w10070940

Awwad, A., Husseini, G. A., & Albasha, L. (2024). AI-Aided robotic wide-range water quality monitoring system. *Sustainability*, *16*(21), 9499. https://doi.org/10.3390/su16219499

Balogun, H., Ojelade, O., Kareem, A., Giwa, A., Amusa, H., Yusuf, A., et al. (2024). Cost and energy requirements of electrochemical membrane systems: A critical review and data analysis. *Journal of Environmental Chemical Engineering*, *12*(5), 113733. https://doi.org/10.1016/j.jece.2024.113733

Barhate, R. S., & Ramakrishna, S. (2007). Nanofibrous filtering media: Filtration problems and solutions from tiny materials. *Journal of Membrane Science*, *296*(1–2), 1–8. https://doi.org/10.1016/j.memsci.2007.03.038

Bellotti, P., Huang, H. M., Faber, T., & Glorius, F. (2023). Photocatalytic late-stage C-H functionalization. *Chemical Reviews*, *123*(8), 4237–4352. https://doi.org/10.1021/acs.chemrev.2c00478

Belyaev, D., Fedorova, A., Trokhimovskiy, A., Alday, J., Montmessin, F., Korablev, O., et al. (2021). Revealing a high water abundance in the upper mesosphere of Mars with ACS onboard TGO. *Geophysical Research Letters*, *48*(10), e2021GL093411. https://doi.org/10.1029/2021GL093411

Bennett, N. J., Ellender, D., & Dempster, A. G. (2020). Commercial viability of lunar in-situ resource utilization (ISRU). *Planetary and Space Science*, *182*, 104842. https://doi.org/10.1016/j.pss.2020.104842

Bernardo, P., Iulianelli, A., Macedonio, F., & Drioli, E. (2021). Membrane technologies for space engineering. *Journal of Membrane Science*, *626*, 119177. https://doi.org/10.1016/j.memsci.2021.119177

Brisset, J., Miletich, T., & Metzger, P. (2020). Thermal extraction of water ice from the lunar surface - A 3D numerical model. *Planetary and Space Science*, *193*, 105082. https://doi.org/10.1016/j.pss.2020.105082

Buelke, C., Alshami, A., Casler, J., Lewis, J., Al-Sayaghi, M., & Hickner, M. A. (2018). Graphene oxide membranes for enhancing water purification in terrestrial and space-born applications: State of the art. *Desalination*, *448*, 113–132. https://doi.org/10.1016/j.desal.2018.09.008

Cao, W., Ma, W., Lu, T., Jiang, Z., Xiong, R., & Huang, C. (2022). Multifunctional nanofibrous membranes with sunlight-driven self-cleaning performance for complex oily wastewater remediation. *Journal of Colloid and Interface Science*, *608*, 164–174. https://doi.org/10.1016/j.jcis.2021.09.194

Chaplin, B. P. (2019). The prospect of electrochemical technologies advancing worldwide water treatment. *Accounts of Chemical Research*, *52*(3), 596–604. https://doi.org/10.1021/acs.accounts.8b00611

Chen, A. S. C., Wang, L., Sorg, T. J., & Lytle, D. A. (2020). Removing arsenic and co-occurring contaminants from drinking water by full-scale ion exchange and point-of-use/point-of-entry reverse osmosis systems. *Water Research*, *172*, 115455. https://doi.org/10.1016/j.watres.2019.115455

Chen, H., Chen, A., Xu, L., Xie, H., Qiao, H., Lin, Q., & Cai, K. (2020). A deep learning CNN architecture applied in smart near-infrared analysis of water pollution for agricultural irrigation resources. *Agricultural Water Management*, *240*, 106303. https://doi.org/10.1016/j.agwat.2020.106303

Chen, T., Butt, F. S., Zhang, M., Wei, X., Lewis, A., Radacsi, N., et al. (2021). Ultra-permeable zeolitic imidazolate frameworks-intercalated graphene oxide membranes for unprecedented ultrafast molecular separation. *Chemical Engineering Journal*, *419*, 129507. https://doi.org/10.1016/j.cej.2021.129507

Chen, T. H., Chen, Y. A., Tsai, S. W., Wang, D. M., & Hou, C. H. (2021). Development of an integrated capacitive-electrodialysis process (CapED) for continuous, low-energy electrochemical deionization. *Separation and Purification Technology*, *274*, 119063. https://doi.org/10.1016/j.seppur.2021.119063

Coccia, G., Mugnini, A., Polonara, F., & Arteconi, A. (2021). Artificial-neural-network-based model predictive control to exploit energy flexibility in multi-energy systems comprising district cooling. *Energy*, *222*, 119958. https://doi.org/10.1016/j.energy.2021.119958

Colvin, T. J., Crane, K., & Lal, B. (2020). Assessing the economics of asteroid-derived water for propellant. *Acta Astronautica*, *176*, 298–305. https://doi.org/10.1016/j.actaastro.2020.05.029

Crusan, J., Bleacher, J., Caram, J., Craig, D., Goodliff, K., Herrmann, N., et al. (2019). NASA's gateway: An update on progress and plans for extending human presence to cislunar space. In *IEEE Aerospace Conference Proceedings*. https://doi.org/10.1109/AERO.2019.8741561

CSIS Aerospace Security Project. (2022). *Cost of space launches to low Earth orbit*. OurWorldinData. Retrieved from https://ourworldindata.org/grapher/cost-space-launches-low-earth-orbit

De Sanctis, M. C., Altieri, F., Ammannito, E., De Angelis, S., Ehlmann, B., Ferrari, M., et al. (2022). Exploring the shallow subsurface of Mars with the Ma_MISS spectrometer on the ExoMars Rover Rosalind Franklin. *Planetary Science Journal*, *3*(6), 142. https://doi.org/10.3847/PSJ/ac694f

Drogkoula, M., Kokkinos, K., & Samaras, N. (2023). A comprehensive survey of machine learning methodologies with emphasis in water resources management. *Applied Sciences*, *13*(22), 12147. https://doi.org/10.3390/app132212147

Durgun, Y. (2024). Real-time water quality monitoring using AI-enabled sensors: Detection of contaminants and UV disinfection analysis in smart urban water systems. *Journal of King Saud University Science*, *36*(9), 103409. https://doi.org/10.1016/j.jksus.2024.103409

Edwards, R., Smith, C. A., & Whitley, S. (2021). Reliability for a 50+ year mission - Interstellar probe. In *Proceedings - Annual reliability and maintainability symposium*. https://doi.org/10.1109/RAMS48097.2021.9605752

Epelle, E. I., Macfarlane, A., Cusack, M., Burns, A., Amaeze, N., Richardson, K., et al. (2022). Stabilisation of ozone in water for microbial disinfection. *Environments*, *9*(4), 45. https://doi.org/10.3390/environments9040045

European Space Agency. (2019). Water in space. *Science & Exploration*. Retrieved from https://www.esa.int/Science_Exploration/Human_and_Robotic_Exploration/International_Space_Station/Water_in_space

Fedorova, A. A., Montmessin, F., Korablev, O., Luginin, M., Trokhimovskiy, A., Belyaev, D. A., et al. (2020). Stormy water on Mars: The distribution and saturation of atmospheric water during the dusty season. *Science*, *367*(6475), 297–300. https://doi.org/10.1126/science.aay9522

Flimban, S. G. A., Ismail, I. M. I., Kim, T., & Oh, S. E. (2019). Overview of recent advancements in the microbial fuel cell from fundamentals to applications: Design, major elements, and scalability. *Energies*, *12*(17), 3390. https://doi.org/10.3390/en12173390

Frincu, R. M. (2025). Artificial intelligence in water quality monitoring: A review of water quality assessment applications. *Water Quality Research Journal*, *60*(1), 164–176. https://doi.org/10.2166/wqrj.2024.049

Ge, C., Feng, X., Xu, D., Liu, K., An, A. K., & Fang, J. (2025). Exploring solar-powered water treatment in outer space: Technologies, challenges, and opportunities for sustainable space habitats. *Space Habitation*, *1*(1), 100006. https://doi.org/10.1016/j.spaceh.2025.100006

Ge, C., Guo, S., Li, W., Zhang, X., Chen, B., Feng, X., et al. (2025). Active thermal field integration for marangoni-driven salt rejection and water collection. *Advanced Functional Materials*, 2421067. https://doi.org/10.1002/adfm.202421067

Gesztesi, J., Broddrick, J. T., Lannin, T., & Lee, J. A. (2023). The chemical neighborhood of cells in a diffusion-limited system. *Frontiers in Microbiology*, *14*, 1155726. https://doi.org/10.3389/fmicb.2023.1155726

Giwa, A., Dindi, A., & Kujawa, J. (2019). Membrane bioreactors and electrochemical processes for treatment of wastewaters containing heavy metal ions, organics, micropollutants and dyes: Recent developments. *Journal of Hazardous Materials*, *370*, 172–195. https://doi.org/10.1016/j.jhazmat.2018.06.025

Goblirsch, T., Mayer, T., Penzel, S., Rudolph, M., & Borsdorf, H. (2023). In situ water quality monitoring using an optical multiparameter sensor probe. *Sensors*, *23*(23), 9545. https://doi.org/10.3390/s23239545

Gorito, A. M., Pesqueira, J. F. J. R., Moreira, N. F. F., Ribeiro, A. R., Pereira, M. F. R., Nunes, O. C., et al. (2021). Ozone-based water treatment (O3, O3/UV, O3/H2O2) for removal of organic micropollutants, bacteria inactivation and regrowth prevention. *Journal of Environmental Chemical Engineering*, *9*(4), 105315. https://doi.org/10.1016/j.jece.2021.105315

Hafuka, A., Mashiko, R., Odashima, R., Yamamura, H., Satoh, H., & Watanabe, Y. (2019). Digestion performance and contributions of organic and inorganic fouling in an anaerobic membrane bioreactor treating waste activated sludge. *Bioresource Technology*, *272*, 63–69. https://doi.org/10.1016/j.biortech.2018.09.147

Han, J., Feng, Y., Liu, Z., Chen, Q., Shen, Y., Feng, F., et al. (2021). Degradable GO-Nanocomposite hydrogels with synergistic photothermal and antibacterial response. *Polymer*, *230*, 124018. https://doi.org/10.1016/j.polymer.2021.124018

He, L., Wang, C., Zhang, G., Pang, Y., & Yao, W. (2021). A novel auger-based system for extraterrestrial in-situ water resource extraction. *Icarus*, *367*, 114552. https://doi.org/10.1016/j.icarus.2021.114552

Homaeigohar, S., & Elbahri, M. (2017). Graphene membranes for water desalination. *NPG Asia Materials*, *9*(8). e427. https://doi.org/10.1038/AM.2017.135

Icke, O., Van Es, D. M., De Koning, M. F., Wuister, J. J. G., Ng, J., Phua, K. M., et al. (2020). Performance improvement of wastewater treatment processes by application of machine learning. *Water Science and Technology*, *82*(12), 2671–2680. https://doi.org/10.2166/wst.2020.382

Jain, H., & Garg, M. C. (2021). Fabrication of polymeric nanocomposite forward osmosis membranes for water desalination—A review. *Environmental Technology & Innovation*, *23*, 101561. https://doi.org/10.1016/j.eti.2021.101561

Jamanca-Lino, G., & Guevara, C. G. (2023). Water production from hydrated sulfates on Mars. A geological and technical assessment. *International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management: SGEM*, *23*(6.1). https://doi.org/10.5593/sgem2023/6.1/s28.56

Jamil, S., Vigneswaran, S., & Jeong, S. (2018). Application of forward osmosis membrane in nanofiltration mode to treat reverse osmosis concentrate from wastewater reclamation plants. *Water Science and Technology*, *77*(8), 1990–1997. https://doi.org/10.2166/wst.2018.087

Jänchen, J., Möhlmann, D., & Stach, H. (2007). Water and carbon dioxide sorption properties of natural zeolites and clay minerals at Martian surface temperature and pressure conditions. *Studies in Surface Science and Catalysis*, *170*, 2116–2121. https://doi.org/10.1016/S0167-2991(07)81108-6

Joshi, D., Eustes, A., Rostami, J., Gottschalk, C., Dreyer, C., Liu, W., et al. (2019). How can drilling engineers help revolutionize space transport and colonize the solar system: Focusing on lunar water-ice. In *Proceedings - SPE annual technical conference and exhibition*. https://doi.org/10.2118/195803-ms

Jurga, A., Janiak, K., Ratkiewicz, K., & Podstawczyk, D. (2019). An overview of blackwater data collection from space life support systems and its comparison to a terrestrial wastewater dataset. *Journal of Environmental Management*, *241*, 198–210. https://doi.org/10.1016/j.jenvman.2019.03.135

Karkooti, A., Rastgar, M., Nazemifard, N., & Sadrzadeh, M. (2020). Graphene-based electro-conductive anti-fouling membranes for the treatment of oil sands produced water. *Science of the Total Environment*, *704*, 135365. https://doi.org/10.1016/j.scitotenv.2019.135365

Kleinhenz, J. E., & Paz, A. (2020). Case studies for lunar ISRU systems utilizing polar water. In *Accelerating space commerce, exploration, and new discovery conference, ASCEND 2020*. https://doi.org/10.2514/6.2020-4042

Knez, D., & Khalilidermani, M. (2021). A review of different aspects of off-earth drilling. *Energies*, *14*(21), 7351. https://doi.org/10.3390/en14217351

Lee, J., Kim, Y., & Lee, J. (2021). Development trends of life support system for the manned space exploration. *Journal of Space Technology and Applications*, *1*(1), 85–103. https://doi.org/10.52912/jsta.2021.1.1.85

Li, J., Zhou, W., Fan, S., Xiao, Z., Liu, Y., Liu, J., et al. (2018). Bioethanol production in vacuum membrane distillation bioreactor by permeate fractional condensation and mechanical vapor compression with polytetrafluoroethylene (PTFE) membrane. *Bioresource Technology*, *268*, 708–714. https://doi.org/10.1016/j.biortech.2018.08.055

Li, L., Rong, S., Wang, R., & Yu, S. (2021). Recent advances in artificial intelligence and machine learning for nonlinear relationship analysis and process control in drinking water treatment: A review. *Chemical Engineering Journal*, *405*, 126673. https://doi.org/10.1016/j.cej.2020.126673

Li, X., Cai, M., Wang, L., Niu, F., Yang, D., & Zhang, G. (2019). Evaluation survey of microbial disinfection methods in UV-LED water treatment systems. *Science of the Total Environment*, *659*, 1415–1427. https://doi.org/10.1016/j.scitotenv.2018.12.344

Long, Z., Li, Q., Wei, T., Zhang, G., & Ren, Z. (2020). Historical development and prospects of photocatalysts for pollutant removal in water. *Journal of Hazardous Materials*, *395*, 122599. https://doi.org/10.1016/j.jhazmat.2020.122599

Lu, X., Yao, W., Wang, C., & Ma, R. (2019). Exergy analysis of a lunar based solar thermal power system with finite-time thermodynamics. *Energy Procedia*, *158*, 792–796. https://doi.org/10.1016/j.egypro.2019.01.209

Ma, B., Bai, Y., Hu, C., Xie, B., Zhang, J., Ulbricht, M., & Zheng, L. (2024). Space aquatic chemistry: A roadmap for drinking water treatment in microgravity. *Environmental Science & Ecotechnology*, *19*, 100344. https://doi.org/10.1016/j.ese.2023.100344

Maciolek, K. A., & Best, S. L. (2019). How do astronauts urinate? The history of innovations enabling voiding in the void. *Urology*, *128*, 8–13. https://doi.org/10.1016/j.urology.2018.11.065

Malik, L. A., Bashir, A., Qureashi, A., & Pandith, A. H. (2019). Detection and removal of heavy metal ions: A review. *Environmental Chemistry Letters*, *17*(4), 1495–1521. https://doi.org/10.1007/s10311-019-00891-z

Meduri, S. P., Shekar, C. N. P. V. C., Meduri, A., & Diwan, N. (2021). Design and smart automation of lunar and Martian habitat using STM32H7 microcontroller and LabView. In *Proceedings of the 6th international conference on inventive computation technologies, ICICT 2021*. https://doi.org/10.1109/ICICT50816.2021.9358529

Melo, C. I., Szczepańska, A., Bogel-Łukasik, E., Nunes Da Ponte, M., & Branco, L. C. (2016). Hydrogenation of carbon dioxide to methane by ruthenium nanoparticles in ionic liquid. *ChemSusChem*, *9*(10), 1081–1084. https://doi.org/10.1002/cssc.201600203

Mettler, M. K., Parker, C. W., Venkateswaran, K., & Peyton, B. M. (2022). Antimicrobial coating efficacy for prevention of Pseudomonas aeruginosa biofilm growth on ISS water system materials. *Frontiers in Microbiology*, *13*, 874236. https://doi.org/10.3389/fmicb.2022.874236

Michel, B., Pierre, W. B., Véronique, D., Bernard, F., Manuel, G., & Linli, G. (2023). *Planetary exploration Horizon 2061*. Elsevier. https://doi.org/10.1016/C2020-0-01626-9

Moradi, M., Vasseghian, Y., Arabzade, H., & Mousavi Khaneghah, A. (2021). Various wastewaters treatment by sono-electrocoagulation process: A comprehensive review of operational parameters and future outlook. *Chemosphere*, *263*, 128314. https://doi.org/10.1016/j.chemosphere.2020.128314

Mudau, F., Motsa, M., Hassard, F., & de Kock, L. A. (2022). Resin-loaded heterogeneous polyether sulfone ion exchange membranes for saline groundwater treatment. *Membranes*, *12*(8), 736. https://doi.org/10.3390/membranes12080736

Naik, K., Holmgren, A., & Kenworthy, J. (2020). Using machine learning to automatically detect anomalous spacecraft behavior from telemetry data. *IEEE Aerospace Conference Proceedings*, 1–14. https://doi.org/10.1109/AERO47225.2020.9172726

Narita, K., Asano, K., Naito, K., Ohashi, H., Sasaki, M., Morimoto, Y., et al. (2020). 222-nm UVC inactivates a wide spectrum of microbial pathogens. *Journal of Hospital Infection*, *105*. https://doi.org/10.1016/j.jhin.2020.03.030

Narita, N., Enomoto, T., Masaoka, S., & Kusakabe, N. (2015). Titania may produce abiotic oxygen atmospheres on habitable exoplanets. *Scientific Reports*, *5*(1), 13977. https://doi.org/10.1038/srep13977

NASA. (2024a). Mars facts. *Mars*. Retrieved from https://science.nasa.gov/mars/facts/

NASA. (2024b). Moon facts. *The Moon*. Retrieved from https://science.nasa.gov/moon/facts/

Ni, J., Wen, Y., Pan, D., Bai, J., Zhou, B., Zhao, S., et al. (2023). Light-driven simultaneous water purification and green energy production by photocatalytic fuel cell: A comprehensive review on current status, challenges, and perspectives. *Chemical Engineering Journal*, *473*, 145162. https://doi.org/10.1016/j.cej.2023.145162

Obileke, K. C., Onyeaka, H., Meyer, E. L., & Nwokolo, N. (2021). Microbial fuel cells, a renewable energy technology for bio-electricity generation: A mini-review. *Electrochemistry Communications*, *125*, 107003. https://doi.org/10.1016/j.elecom.2021.107003

Olthoff, C., & Reiss, P. (2019). In-situ resource utilization - Technical aspects. In *Promoting productive cooperation between space lawyers and engineers*. https://doi.org/10.4018/978-1-5225-7256-5

Orosei, R., Lauro, S. E., Pettinelli, E., Cicchetti, A., Coradini, M., Cosciotti, B., et al. (2018). Radar evidence of subglacial liquid water on Mars. *Science*, *361*(6401), 490–493. https://doi.org/10.1126/science.aar7268

Pickett, M. T., Roberson, L. B., Calabria, J. L., Bullard, T. J., Turner, G., & Yeh, D. H. (2020). Regenerative water purification for space applications: Needs, challenges, and technologies towards "closing the loop". *Life Sciences and Space Research*, *24*, 64–82. https://doi.org/10.1016/j.lssr.2019.10.002

Puumala, M. M., Sivula, O., & Lehto, K. (2023). Moving to Mars: The feasibility and desirability of Mars settlements. *Space Policy*, *66*, 101590. https://doi.org/10.1016/j.spacepol.2023.101590

Qiao, L., Ling, Z., Head, J. W., Ivanov, M. A., & Liu, B. (2019). Analyses of lunar orbiter laser altimeter 1,064-nm Albedo in permanently shadowed regions of polar crater flat floors: Implications for surface water ice occurrence and future in situ exploration. *Earth and Space Science*, *6*(3), 467–488. https://doi.org/10.1029/2019EA000567

Rapp, D., & Inglezakis, V. J. (2024). Mars In Situ Resource Utilization (ISRU) with focus on atmospheric processing for near-term application—A historical review and appraisal. *Applied Sciences*, *14*(2), 653. https://doi.org/10.3390/app14020653

Rastinasab, V., Hu, W., & Tahmasebi, M. K. (2021). Water recognition on the moon by using thz heterodyne-spectrometer for identifying the appropriate locations to extract water for providing oxygen for breathing and fuel for spaceships' propulsion on the moon with cubesat. *Aerospace*, *8*(7), 186. https://doi.org/10.3390/aerospace8070186

Ren, G., Han, H., Wang, Y., Liu, S., Zhao, J., Meng, X., & Li, Z. (2021). Recent advances of photocatalytic application in water treatment: A review. *Nanomaterials*, *11*(7), 1804. https://doi.org/10.3390/nano11071804

Rivera-Valentín, E. G., Chevrier, V. F., Soto, A., & Martínez, G. (2020). Distribution and habitability of (meta)stable brines on present-day Mars. *Nature Astronomy*, *4*(8), 756–761. https://doi.org/10.1038/s41550-020-1080-9

Rubanenko, L., Venkatraman, J., & Paige, D. A. (2019). Thick ice deposits in shallow simple craters on the Moon and Mercury. *Nature Geoscience*, *12*(8), 597–601. https://doi.org/10.1038/s41561-019-0405-8

Rueda-Marquez, J. J., Levchuk, I., Fernández Ibañez, P., & Sillanpää, M. (2020). A critical review on application of photocatalysis for toxicity reduction of real wastewaters. *Journal of Cleaner Production*, *258*, 120694. https://doi.org/10.1016/j.jclepro.2020.120694

Schlüter, L., & Cowley, A. (2020). Review of techniques for In-Situ oxygen extraction on the moon. *Planetary and Space Science*, *181*, 104753. https://doi.org/10.1016/j.pss.2019.104753

Severin, B. F., & Hayes, T. D. (2019). Electrodialysis of concentrated brines: Effects of multivalent cations. *Separation and Purification Technology*, *218*, 227–241. https://doi.org/10.1016/j.seppur.2019.02.039

Shi, Q., Chen, Z., Liu, H., Lu, Y., Li, K., Shi, Y., et al. (2021). Efficient synergistic disinfection by ozone, ultraviolet irradiation and chlorine in secondary effluents. *Science of the Total Environment*, *758*, 143641. https://doi.org/10.1016/j.scitotenv.2020.143641

Simões, C., Pintossi, D., Saakes, M., Borneman, Z., Brilman, W., & Nijmeijer, K. (2020). Electrode segmentation in reverse electrodialysis: Improved power and energy efficiency. *Desalination*, *492*, 114604. https://doi.org/10.1016/j.desal.2020.114604

Sivasankar, P., Poongodi, S., Seedevi, P., Sivakumar, M., Murugan, T., & Loganathan, S. (2019). Bioremediation of wastewater through a quorum sensing triggered MFC: A sustainable measure for waste to energy concept. *Journal of Environmental Management*, *237*, 84–93. https://doi.org/10.1016/j.jenvman.2019.01.075

Song, H., Zhang, J., Ni, D., Sun, Y., Zheng, Y., Kou, J., et al. (2021). Investigation on in-situ water ice recovery considering energy efficiency at the lunar south pole. *Applied Energy*, *298*, 117136. https://doi.org/10.1016/j.apenergy.2021.117136

Srimuk, P., Su, X., Yoon, J., Aurbach, D., & Presser, V. (2020). Charge-transfer materials for electrochemical water desalination, ion separation and the recovery of elements. *Nature Reviews Materials*, *5*(7), 517–538. https://doi.org/10.1038/s41578-020-0193-1

Starr, S. O., & Muscatello, A. C. (2020). Mars in situ resource utilization: A review. *Planetary and Space Science*, *182*, 104824. https://doi.org/10.1016/j.pss.2019.104824

Stromgren, C., Burke, C., Cho, J., Cirillo, W., Owens, A., & Howard, D. (2022). Regenerative ECLSS and logistics analysis for sustained lunar surface missions. In *IEEE Aerospace Conference Proceedings* (pp. 1–10). https://doi.org/10.1109/AERO53065.2022.9843674

Sun, Y., Wang, D., Li, L., Ning, R., Yu, S., & Gao, N. (2024). Application of remote sensing technology in water quality monitoring: From traditional approaches to artificial intelligence. *Water Research*, *267*, 122546. https://doi.org/10.1016/j.watres.2024.122546

Takada, K., Velasquez, L. E., Van Keuren, S., Baker, P. S., & McDougle, S. H. (2019). Advanced oxygen generation assembly for exploration missions. In *49th international conference on environmental systems*.

Tang, S., Niu, G., Zhang, B., Thakker, A., Vivanco, S., Martin, R., & Moore, C. (2018). Automated contingency management for water recycling system. In *Proceedings of the annual conference of the prognostics and health management society*. PHM. https://doi.org/10.36001/phmconf.2018.v10i1.542

Thornhill, S. G., & Kumar, M. (2018). Biological filters and their use in potable water filtration systems in spaceflight conditions. *Life Sciences and Space Research*, *17*, 40–43. https://doi.org/10.1016/j.lssr.2018.03.003

Urtiaga, A. (2021). Electrochemical technologies combined with membrane filtration. *Current Opinion in Electrochemistry*, *27*, 100691. https://doi.org/10.1016/J.COELEC.2021.100691

Verbeelen, T., Leys, N., Ganigué, R., & Mastroleo, F. (2021). Development of nitrogen recycling strategies for bioregenerative life support systems in space. *Frontiers in Microbiology*, *12*, 700810. https://doi.org/10.3389/fmicb.2021.700810

Vishnu, N., Sharma, C. S., & Senthil Kumar, A. (2020). A low-cost and miniaturized electrochemical cell for low-sample analyses. *Microchemical Journal*, *159*, 105591. https://doi.org/10.1016/j.microc.2020.105591

Volpin, F., Badeti, U., Wang, C., Jiang, J., Vogel, J., Freguia, S., et al. (2020). Urine treatment on the international space station: Current practice and novel approaches. *Membranes*, *10*(11), 327. https://doi.org/10.3390/membranes10110327

Wang, J., & Liu, X. (2021). Forward osmosis technology for water treatment: Recent advances and future perspectives. *Journal of Cleaner Production*, *280*, 124354. https://doi.org/10.1016/j.jclepro.2020.124354

Wasilewski, T. G. (2018). Evaluation of drilling-based water extraction methods for Martian ISRU from mid-latitude ice resources. *Planetary and Space Science*, *158*, 16–24. https://doi.org/10.1016/j.pss.2018.05.012

Xu, D., Gao, C., Liu, Y., Ge, C., Wei, Y., Peng, Z., et al. (2024). Heat-resistant core-sheath yarn sensor with high durability and thermal adaptivity for fire rescue. *Device*, *2*(8), 100366. https://doi.org/10.1016/j.device.2024.100366

Yamaguchi, S. P., Itakura, R., & Inagaki, T. (2023). ISS/JEM crew-task analysis to support astronauts with intra-vehicular robotics. In *IEEE international workshop on robot and human communication, RO-MAN*. https://doi.org/10.1109/RO-MAN57019.2023.10309405

Yang, K., Yang, C., Yang, H., & Zhou, C. (2021). Complexity evaluation of an environmental control and life-support system based on directed and undirected structural entropy methods. *Entropy*, *23*(9), 1173. https://doi.org/10.3390/e23091173

Yang, L., Driscol, J., Sarigai, S., Wu, Q., Lippitt, C. D., & Morgan, M. (2022). Towards synoptic water monitoring systems: A review of AI methods for automating water body detection and water quality monitoring using remote sensing. *Sensors*, *22*(6), 2416. https://doi.org/10.3390/s22062416

Yang, Q., Dong, R., Zhu, R., Wang, X., & Yang, S. (2024). Electrochemical catalytic synthesis of CH3OH for In-situ resource utilization. *Chemical Engineering & Technology*, *47*(1), 88–97. https://doi.org/10.1002/ceat.202200458

Yao, M., Tijing, L. D., Naidu, G., Kim, S. H., Matsuyama, H., Fane, A. G., & Shon, H. K. (2020). A review of membrane wettability for the treatment of saline water deploying membrane distillation. *Desalination*, *479*, 114312. https://doi.org/10.1016/j.desal.2020.114312

Yao, Y., Wang, L., Zhu, X., Tu, W., Zhou, Y., Liu, R., et al. (2022). Extraterrestrial photosynthesis by Chang'E-5 lunar soil. *Joule*, *6*(5), 1008–1014. https://doi.org/10.1016/j.joule.2022.04.011

Yaroshenko, I., Kirsanov, D., Marjanovic, M., Lieberzeit, P. A., Korostynska, O., Mason, A., et al. (2020). Real-time water quality monitoring with chemical sensors. *Sensors*, *20*(12), 3432. https://doi.org/10.3390/s20123432

Ye, J., Wang, Y., Li, Z., Yang, D., Li, C., Yan, Y., & Dai, J. (2021). 2D confinement freestanding graphene oxide composite membranes with enriched oxygen vacancies for enhanced organic contaminants removal via peroxymonosulfate activation. *Journal of Hazardous Materials*, *417*, 126028. https://doi.org/10.1016/j.jhazmat.2021.126028

Zea, L., McLean, R. J. C., Rook, T. A., Angle, G., Carter, D. L., Delegard, A., et al. (2020). Potential biofilm control strategies for extended spaceflight missions. *Biofilms*, *2*, 100026. https://doi.org/10.1016/j.bioflm.2020.100026

Zhan, C., Zhang, L., Ai, W., & Dong, W. (2022). Green and sustainable treatment of urine wastewater with a membrane-aerated biofilm reactor for space applications. *Water*, *14*(22), 3704. https://doi.org/10.3390/w14223704

Zhang, Q., Wang, M., Yu, H., Xu, N., Xiao, X., Pan, L., et al. (2025). High-flux and anti-salt solar desalination via scalable photothermal textiles with vertically confined water layers. *Device*, *3*(6), 100709. https://doi.org/10.1016/j.device.2025.100709

Zhang, R., Zhang, W., Ren, H., Liu, K., Yang, S., Chen, B., et al. (2025). A current-adaptive evaporator with optimized energy utilization for self-cleaning high-salinity desalination. *Advanced Functional Materials*, *35*(5), 2414427. https://doi.org/10.1002/adfm.202414427

Zhao, Z. P., Xu, L., Shang, X., & Chen, K. (2013). Water regeneration from human urine by vacuum membrane distillation and analysis of membrane fouling characteristics. *Separation and Purification Technology*, *118*, 369–376. https://doi.org/10.1016/j.seppur.2013.07.021

Zhong, Y., Low, J., Zhu, Q., Jiang, Y., Yu, X., Wang, X., et al. (2023). In situ resource utilization of lunar soil for highly efficient extraterrestrial fuel and oxygen supply. *National Science Review*, *10*(2), nwac200. https://doi.org/10.1093/nsr/nwac200

Zhu, X., & Jassby, D. (2019). Electroactive membranes for water treatment: Enhanced treatment functionalities, energy considerations, and future challenges. *Accounts of Chemical Research*, *52*(5), 1177–1186. https://doi.org/10.1021/acs.accounts.8b00558

Zou, S., Ju, H., & Zhang, J. (2025). Water quality management in the age of AI: Applications, challenges, and prospects. *Water*, *17*(11), 1641. https://doi.org/10.3390/w17111641