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AI-Driven Waste Management in Innovating Space Exploration

David Bamidele Olawade [1,2,3,*], Ojima Zechariah Wada [4,5], Tunbosun Theophilus Popoola [6], Eghosasere Egbon [7], James O. Ijiwade [6] and B. I. Oladapo [8,9]

1 Department of Allied and Public Health, School of Health, Sport and Bioscience, University of East London, London E16 2RD, UK
2 Department of Research and Innovation, Medway NHS Foundation Trust, Gillingham ME7 5NY, UK
3 Department of Public Health, York St John University, London E14 2BA, UK
4 Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Education City, Doha 34110, Qatar; ojimawada14@gmail.com
5 Global Eco-Oasis Sustainable Initiative, Ibadan 220212, Nigeria
6 Department of Chemistry, Faculty of Science, University of Ibadan, Ibadan 200005, Nigeria; ijiwadejames@gmail.com (J.O.I.)
7 Department of Tissue Engineering and Regenerative Medicine, Faculty of Life Science Engineering, FH Technikum, 1200 Vienna, Austria; eghosaseregabriel@gmail.com
8 Sustainable Development, De Montfort University, Leicester LE1 9BH, UK
9 School of Science and Engineering, Afe Babalola University, Ado-Ekiti 360102, Nigeria
* Correspondence: olawadedavid@gmail.com or d.olawade@uel.ac.uk

Abstract: This research evaluates advanced waste management technologies suitable for long-duration space missions, particularly focusing on artificial intelligence (AI)-driven sorting systems, biotechnological bioreactors, and thermal processing methods, such as plasma gasification. It quantitatively assesses the waste generated per crew member. It analyses energy efficiency, integration capabilities with existing life-support systems, and practical implementation constraints based on experimental ground and ISS data. Challenges are addressed, including energy demands, microbial risks, and integration complexities. The research also discusses methodological approaches, explicitly outlining selection criteria and comparative frameworks used. Key findings indicate that plasma arc technologies significantly reduce waste volume, although high energy consumption remains challenging. Enhanced recycling efficiencies of water and oxygen are also discussed. Future research directions and actionable policy recommendations are outlined to foster sustainable and autonomous waste management solutions for space exploration.

Keywords: space waste management; sustainable technology; artificial intelligence; bioreactors; plasma gasification; resource recovery

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Academic Editor: Lucjan Setlak

Received: 10 March 2025
Revised: 21 April 2025
Accepted: 27 April 2025
Published: 1 May 2025

Citation: Olawade, D.B.; Wada, O.Z.; Popoola, T.T.; Egbon, E.; Ijiwade, J.O.; Oladapo, B.I. AI-Driven Waste Management in Innovating Space Exploration. *Sustainability* **2025**, *17*, 4088. https://doi.org/10.3390/su17094088

1. Introduction

Space exploration has undergone monumental advancements since the mid-20th century, marked by the pioneering launches of human-made objects into orbit [1–3]. Early missions, such as those under NASA's Apollo program and the initial space station endeavours, were characterised by their relatively short durations, modest crew sizes, and minimal waste generation [4,5]. During these formative years, waste management in the context of space exploration was considered a secondary concern [6,7]. Waste generated during missions could be stored temporarily for disposal upon return to Earth or jettisoned into space, where it would harmlessly disintegrate in the atmosphere [8–10].

The landscape of space exploration has evolved dramatically, with the ambition of space agencies and burgeoning private sector interests in long-duration missions [11,12].

For example, crewed expeditions to Mars or establishing lunar habitats have positioned waste management as a pivotal issue [13–15]. The stakes are higher, and the logistical complexities of managing waste in space have become more daunting. With the extension of mission durations and the expansion of crew sizes, the volume of waste generated in space environments has surged [16,17]. A typical contingent of four astronauts aboard the International Space Station (ISS) now produces upwards of 2500 kg of waste annually, encompassing a variety of refuse, including food packaging, human excrement, and spent equipment [18,19]. This waste must be meticulously managed to safeguard crew safety, mitigate contamination risks, and preserve critical resources such as air and water [20,21]. The urgency of developing effective waste management solutions is accentuated by the prospects of future missions targeting more remote destinations, such as Mars or the Moon, where resupply missions are less feasible, and the luxury of returning waste to Earth is absent [22–24].

In stark contrast to Earth, where natural processes facilitate the decomposition of organic waste, the space environment lacks gravity, atmospheric dynamics, and soil activity, which are integral to terrestrial waste management practices [25,26]. In the microgravity conditions of space, such as those aboard the ISS, specialised systems are imperative for safe and efficient waste handling [27,28]. Techniques must be adapted to accommodate the unique challenges of space; for example, human waste requires drying, compacting, and secure storage processes, while wastewater is subject to rigorous filtration and purification to produce potable water [29,30].

The consequences of inadequate waste management in space extend beyond the immediate confines of crew health and comfort, posing substantial logistical and safety challenges [31–33]. Unprocessed waste occupies precious space aboard spacecraft, and if improperly handled, biological waste becomes a potential breeding ground for pathogens [34,35]. Chemical wastes, unless effectively contained and neutralised, pose significant toxic risks [36]. Moreover, imprudent waste disposal contributes to the escalating problem of space debris—nonfunctional satellites and remnants from past missions that clutter Earth's orbit and pose collision risks to ongoing and future space endeavours [37–39].

Smart waste management solutions leveraging human-centric AI and advanced biotechnology are being explored to address these multifaceted challenges [40,41]. AI and robotics are employed for their potential to classify autonomously and sort waste, enhancing resource recovery efficiency and converting waste into valuable by-products [42,43]. Advances in biotechnology, mainly through microbial bioreactors, offer promising methods for the bioconversion of organic waste into reusable resources [44,45]. Additionally, high-temperature thermal processing technologies such as plasma gasification and innovative strategies like in situ resource utilisation (ISRU) combined with 3D printing present new avenues for reducing waste volume and repurposing materials within the closed-loop ecosystems envisioned for future space habitats [45,46].

Thus, as we propel further into the cosmos, integrating human AI-driven technologies and sustainable practices in waste management is critical to ensuring the viability and success of prolonged space missions [47,48]. These advancements promise to enhance the sustainability of space exploration and forge a path toward more autonomous and resilient space missions [48,49].

This research addresses the escalating challenges of waste management in space, particularly as human missions extend in duration and distance from Earth. As traditional waste disposal methods become impractical for long-duration explorations and habitation on celestial bodies such as the Moon and Mars, there is a pressing need for innovative waste management technologies that are sustainable and efficient. This study aims to explore and integrate advanced solutions involving human-centric artificial intelligence

(AI), biotechnology, and thermal processing techniques to enhance waste management systems. These technologies are expected to maximise resource recovery, minimise waste accumulation, and ensure the integration of waste management systems with existing life support systems to boost overall mission sustainability. By leveraging these sophisticated technologies, this research seeks to develop smart waste management solutions that can operate autonomously, reduce logistical burdens, and mitigate the environmental impacts of space missions, ultimately supporting the long-term viability and safety of human space exploration.

2. Methodology

A structured research approach was employed. Databases including Scopus, Web of Science, IEEE Xplore, NASA Technical Reports, and ESA publications were searched using keywords such as “space waste management”, “AI waste sorting”, “bioreactors in space”, and “plasma gasification”. Inclusion criteria encompassed peer-reviewed articles, conference papers, and technical reports published between 2018 and 2024, relevant to waste management technologies for space applications. The literature was selected based on technological relevance, practical implementation evidence, and integration capabilities with life support systems. A comparative thematic analysis focused on energy efficiency, implementation practicality, and sustainability impacts. Figure 1 was explicitly designed to support comparative analysis and clarity of technological implications.

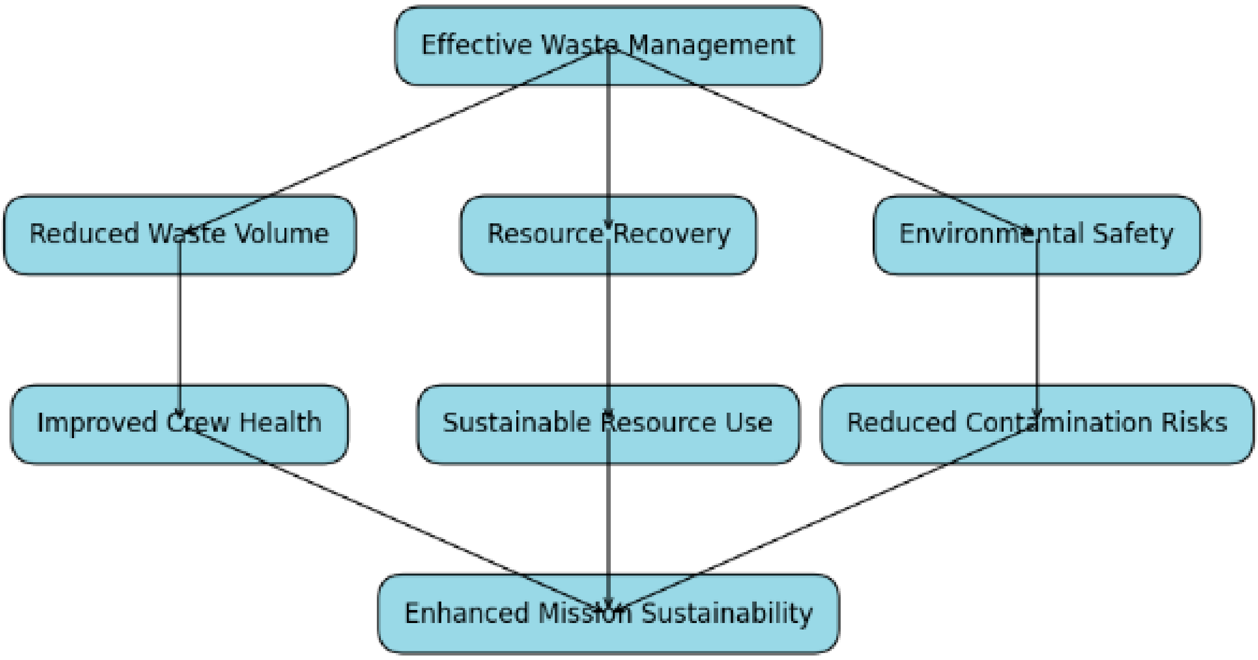

Figure 1. Impact of waste management on crew health and mission sustainability.

Space missions produce various types of waste—solid, liquid, and gas—that increase in volume with longer missions, larger crews, and more activities. Human waste, including urine and faeces, poses a significant challenge. At the International Space Station (ISS), urine is recycled into drinking water, while faecal matter is compacted and disposed of during reentry into Earth’s atmosphere. Although effective for short missions, these methods are insufficient for long-term exploration, such as potential Mars missions or lunar habitats requiring advanced biological waste processing. Solid waste includes used packaging, food scraps, and broken equipment, and the limited space in spacecraft complicates waste storage, necessitating compacting methods. As missions extend, efficient recycling systems become vital to lessen reliance on resupply from Earth. Chemical waste from experiments and operations, including hazardous materials, presents another challenge. It is stored until it can be safely managed on Earth, but this approach is impractical for deep-space missions [50–52]. Advanced neutralisation and recycling systems are essential to manage these wastes in space, converting toxins into valuable resources like fuel or oxygen, thus supporting sustainable long-term missions. Overall, waste management in space is complex and demands innovative solutions and technologies to ensure the safety and efficiency of future long-duration missions (Table 1).

Table 1. Energy requirements for waste processing systems.

Waste Processing Technology	Energy Requirements (kWh per ton)
Plasma Arc	500–1000
Pyrolysis	200–500
Bioreactors	50–150
Mechanical Compaction	10–50
Incineration	300–600
Waste Type and Corresponding Management Techniques	
Waste Type	Management Techniques
Organic Waste	Bioreactors, Composting
Inorganic Waste	Mechanical Compaction, Pyrolysis
Packaging Waste	Mechanical Compaction, Plasma Arc
Human Waste	Bioreactors, Advanced Filtration Systems
Chemical Waste	Incineration, Chemical Neutralization
Electronic Waste	Recycling, Plasma Arc

Complete Sterilisation of Biological Waste Measures

Advanced microbial bioreactors using genetically engineered microorganisms are vital for efficiently breaking down organic waste in space missions. These systems incorporate sterilisation methods, including high temperatures and chemical agents, to eliminate pathogens from by-products like methane and water. Incineration and pyrolysis effectively sterilise biological waste, ensuring safety. UV-C light sterilises air and surfaces, preventing pathogen replication. Waste processing units are isolated to mitigate contamination risks and are equipped with safety measures like double-sealed containers and automated sensors. Continuous health monitoring and air ventilation systems with HEPA filters ensure crew safety. Gaseous waste from life support and propulsion systems poses additional challenges, necessitating efficient air purification technologies. Current systems, like the ISS's Carbon Dioxide Removal Assembly, filter and recycle air, while water electrolysis generates oxygen. Future missions will require advanced systems to manage increased waste and support extended operations.

3. Traditional Waste Management Practices in Space

Traditional waste management in space missions, particularly on the ISS, adapts Earth-based techniques for microgravity. Waste is collected, compacted, and stored, with future missions considering jettisoning logistics modules or gasification. In situ resource utilisation (ISRU) aims to use local materials, exemplified by NASA's Mars 2020 Perseverance rover producing oxygen from Martian CO_2. RASSOR, a robotic miner, extracts resources from lunar and Martian regolith (NASA Kennedy Space Center, Merritt Island, FL, USA). Proposed missions target water ice extraction from lunar craters for life support. Experiments like EPICS enhance water conversion to oxygen and hydrogen, which is crucial for long-term habitation. The Archinaut project explores on-orbit manufacturing using materials from celestial bodies, showcasing 3D printing potential in space [52–54].

3.1. Ground-Based Simulations and Testing

Before deploying a waste management system in space, it undergoes rigorous ground testing to simulate microgravity using parabolic flights, drop towers, or neutral buoyancy labs. These tests ensure that the system operates effectively without Earth's gravity and identify necessary modifications. Prototypes are then evaluated aboard the International Space Station (ISS) to assess their performance in a microgravity environment. They involve real-time testing and iteration to integrate with existing life support systems and evaluate operational efficacy over time. Advanced computer simulations also play a vital role in predicting system functions under various space conditions, helping to identify potential failures early in development. This approach saves time and resources by refining designs before physical deployment. Once operational, sensors and monitoring devices collect data on energy consumption, waste processing efficiency, and containment integrity, providing essential evidence for ongoing optimisation [55,56]. Feedback from all testing phases drives continuous improvements, enhancing reliability, efficiency, and safety. The development process engages a diverse community of researchers and engineers to incorporate the latest scientific and technological advances. Extended mission simulations on Earth, in habitats mimicking space station conditions, test the systems' durability for deep-space missions and future lunar or Martian bases. This comprehensive validation ensures that waste management systems are theoretically sound and practically viable in harsh space conditions, contributing to mission sustainability and crew safety [57–59]. Figure 2 illustrates the daily waste by each astronaut, highlighting the cumulative impact over time.

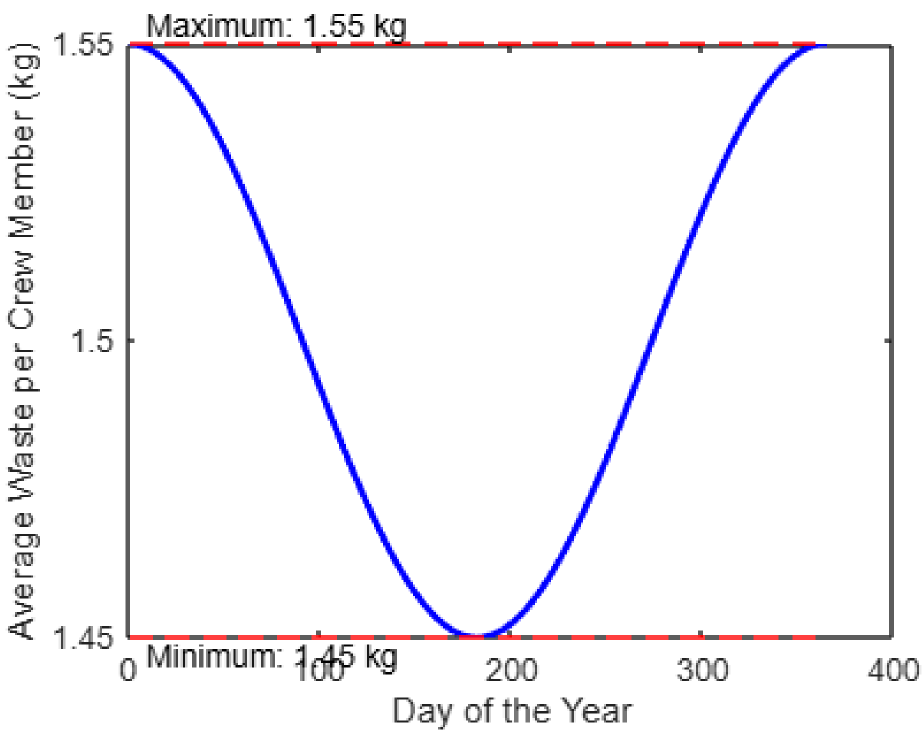

Figure 2. Average daily waste generation per crew member on the ISS.

3.2. Limited Storage Hampers Resource Recovery

Conventional waste management techniques in space missions are limited by the finite storage capacity of spacecraft, affecting the choice of recyclable materials and the effectiveness of space trash systems. Space is scarce on missions, and spacecraft or space stations cannot store waste for long periods [60–62]. On the ISS, waste accumulates for months and relies on periodic resupply missions for removal, highlighting inefficiencies in current water recovery systems. This traditional approach works for low Earth orbit (LEO) missions, where waste can be returned to Earth regularly. However, innovative waste management solutions are essential for more extended missions to the Moon, Mars, or beyond, where resupply is less feasible [63–65]. These solutions must reduce or repurpose waste to minimise storage needs, especially as mission durations increase. Innovations like closed bio-regenerative life support systems, microbial bioreactors, and in situ resource utilisation are vital for extending mission capabilities by efficiently repurposing a wider range of waste materials.

Traditional waste management in space also poses environmental risks, particularly with space debris. Discarding waste in space threatens satellite networks and the International Space Station, whether it burns up in Earth's atmosphere or remains in orbit. Uncontrolled disposal increases the risk of space debris, which can collide with operational satellites and spacecraft at high velocities. Over 23,000 pieces of debris larger than 10 cm are tracked in Earth's orbit, along with millions of smaller, untracked fragments that pose significant risks [66,67].

As space agencies and private companies pursue deeper missions to the Moon, Mars, and beyond, the inadequacies of traditional waste management methods become more evident. Limited storage, poor resource recovery, and environmental hazards associated with waste disposal highlight the need for innovative solutions to ensure the sustainability of long-duration and deep-space missions [68,69]. By leveraging advanced technologies, space missions can minimise their environmental impact and enhance waste management capabilities in exploration.

4. Smart Waste Management Technologies for Space

The challenges of space waste management have driven the development of advanced technologies to enhance sustainability in missions beyond low-Earth orbit. Innovative systems utilising AI, robotics, and biotechnology are being created to maximise resource recovery, minimise waste volume, and optimise efficiency in the isolated environments of space missions. These systems strive to establish sustainable, closed-loop processes that significantly lessen reliance on Earth-based resources. Key innovations include AI-driven sorting and recycling mechanisms that improve waste processing efficiency and biotechnological reactors that convert organic waste into biogas and other valuable products. In situ resource utilisation (ISRU) employs local materials, such as lunar or Martian soil, for construction, reducing the need for Earth resupply missions [70,71]. Advanced water recycling and CO_2 reduction systems, like the Sabatier process, are essential for regenerating vital resources. Technologies such as plasma arc pyrolysis are being explored to convert mixed waste into inert gases and energy. Automating waste handling and enhancing efficiency are crucial for enabling long-duration space missions and paving the way for self-sustaining waste management systems in future space exploration (Table 2).

Table 2. Overview of waste generation rates by mission type in a cost–benefit analysis.

Mission Type	Average Waste/Day (kg)	Total Waste per Mission (kg)	Mission Duration (Days)
International Space Station (ISS)	1.5 per crew member	Variable (based on crew size and duration)	Variable
Lunar Missions	2.0 per crew member	Calculated based on mission duration and crew size	10–30
Mars Missions	1.8 per crew member	Calculated based on mission duration and crew size	180–500
Waste Management System	Initial Setup Cost	Operating Cost/Year	Savings from Reduced Resupply (USD/year)
Plasma Arc	USD 500,000	USD 50,000	USD 200,000
Pyrolysis	USD 300,000	USD 40,000	USD 150,000
Bioreactors	USD 250,000	USD 30,000	USD 180,000
Mechanical Compaction	USD 100,000	USD 10,000	USD 50,000
Incineration	USD 400,000	USD 45,000	USD 120,000

4.1. Strategies for Waste Management

Integrating waste management with life support systems in spacecraft is essential for enhancing efficiency, minimising resource usage, and ensuring crew safety. Systems need to be designed that complement life support cycles, recycling waste by-products like water and carbon dioxide. Purified water from waste can be used for drinking, while carbon dioxide can be converted back into oxygen. Scalable modular units should be utilized to adapt to mission needs and crew size, allowing flexibility and easier upgrades without overhauling the entire system [72,73]. This modularity supports the incorporation of new technologies and simplifies maintenance. Energy management should be integrated to boost overall efficiency, using syngas from pyrolysis as an energy source for heating and lighting. Automated systems need to be implemented to monitor operations, maintaining optimal conditions by dynamically adjusting variables like temperature and gas levels. Systems need to be developed to convert waste into reusable resources, such as compost from organic waste or drinkable water from urine. Robust safety measures must be ensured to prevent contamination and foster collaboration among engineers, biologists, and chemists to create comprehensive solutions for sustaining human life in space (Table 3).

Table 3. Comparative analysis of terrestrial with space waste management systems.

Feature	Terrestrial Systems	Space Systems
Gravity Dependence	High	Negligible (Microgravity)
Microbial Risks	Naturally manageable	High, requires sterilisation
Resource Recycling	Variable, optional	Essential
Storage and Logistics	Extensive space available	Highly limited storage space
System Integration	Separate systems acceptable	Fully integrated with life-support

4.2. Waste Conversion

During extended missions to the Moon or Mars, AI-driven robotic systems could autonomously sort and classify astronaut waste, facilitating recycling and reducing storage needs. In lunar habitats, these systems could continuously process waste, recycling materials like plastics and metals for 3D printing, minimising reliance on Earth resources.

Bioreactors using microorganisms could convert organic waste into valuable by-products such as water, oxygen, and biogas, essential for long-duration missions where resupply is impractical [73,74]. For Mars bases, bioreactors could transform human waste and food scraps into methane for energy and water for reuse, supporting a closed ecological system. In situ resource utilisation (ISRU) could turn mission-generated waste and local regolith into building materials, enabling habitat construction or repairs on-site. High-temperature waste treatment methods like plasma arc and pyrolysis would efficiently reduce waste mass and volume, converting it into simpler compounds or inert gases. These modular systems would operate autonomously, ensuring sustainable water supply and enhancing crew health and habitat stability during deep-space missions [75,76] (Figure 3).

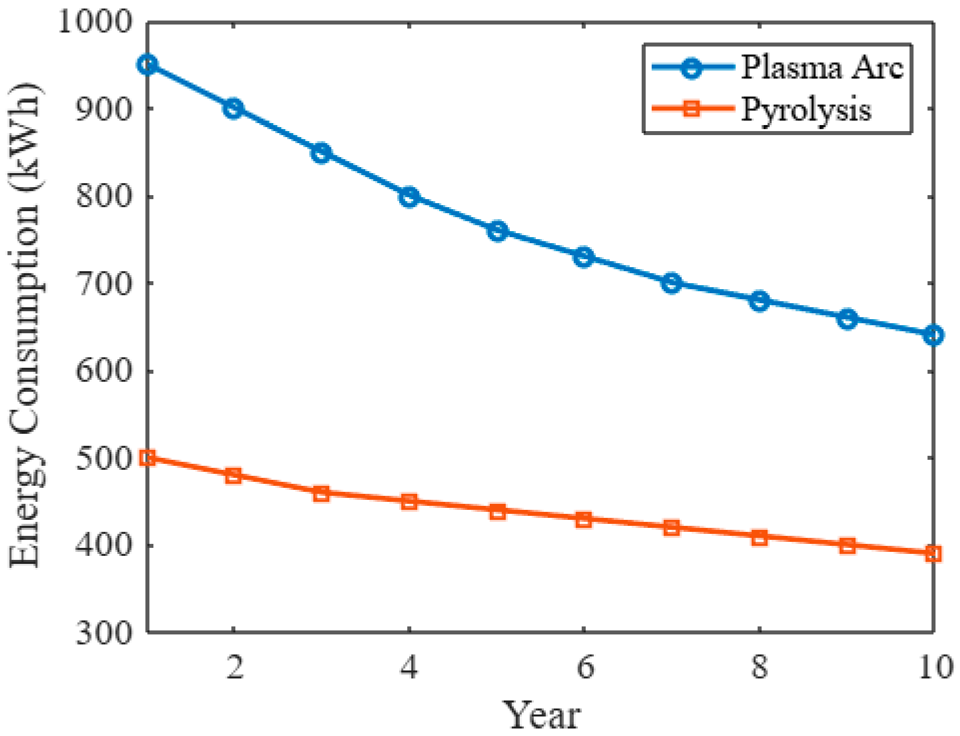

Figure 3. Energy consumption of plasma arc and pyrolysis technologies.

4.3. Smart Waste Management and Enhances Mission Sustainability

Plasma arc and pyrolysis are promising advanced waste management technologies for space missions, significantly reducing waste volume and converting it into valuable by-products. Plasma arc technology uses electrically generated plasma at temperatures up to 5000 °C, decomposing organic waste into hydrogen and carbon monoxide gases and inorganic material into stable slag. While highly effective in sterilisation and waste reduction, plasma arcs' substantial energy requirements pose challenges in energy-constrained space environments, potentially necessitating larger solar arrays or nuclear power systems, thus increasing mission costs and complexity.

Pyrolysis, operating at lower temperatures (400 °C to 700 °C) without oxygen, decomposes organic waste into bio-oil and syngas, products valuable for soil enrichment, refinement, and power generation. Although less energy-intensive than plasma arc, pyrolysis still demands consistent heating and additional processing systems, complicating its deployment in spacecraft. To mitigate energy constraints, integrating renewable energy sources or efficient nuclear systems, capturing waste heat for reuse, enhancing unit insulation, and designing modular systems can optimise overall energy efficiency.

Automated waste management systems leveraging AI and robotics significantly enhance efficiency in microgravity by reducing manual handling. Automation minimises human intervention, allowing crew members to focus on critical mission tasks, which is crucial for distant missions with limited resupply options. These systems convert organic waste into vital resources such as water and oxygen, reducing storage needs and resupply frequency. AI-driven classification and sorting utilise convolutional neural networks (CNNS) for visual identification and support vector machines (SVMS) with sensors for accurate sorting. Deep reinforcement learning (DRL) further optimises robotic handling strategies. Integrating these advanced technologies into waste management significantly reduces logistical costs and enhances mission sustainability and success (Figure 4) (Table 4).

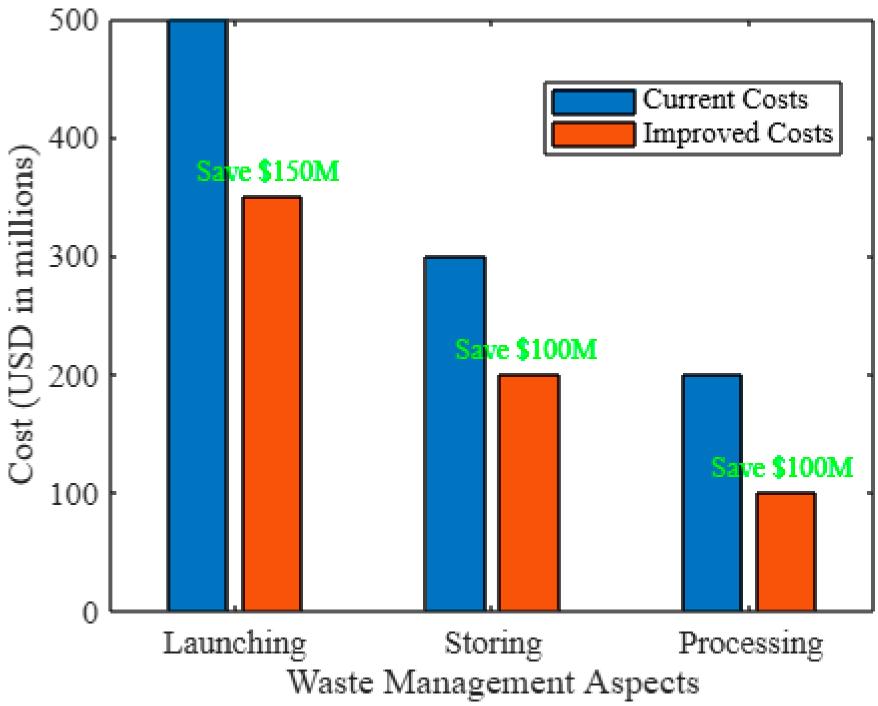

Figure 4. Cost analysis of waste management in space.

Table 4. Efficiency metrics of current enhanced recycling systems.

Efficiency Metrics of Current vs. Enhanced Recycling Systems		
System	**Current Recycling Efficiency (%)**	**Enhanced Recycling Efficiency (%)**
Water Recycling	90	98
Air Recycling	75	85
Solid Waste Recycling	30	50
International Standards for Space Waste Management		
Standard/Organisation	Key Guidelines	Focus Area
Space Systems—Debris Mitigation	Limit debris released during normal operations	Debris Management
COSPAR Planetary Protection Policy	Avoid biological contamination of celestial bodies	Environmental Protection
NASA Procedural Requirements 8715.6B	Waste disposal for spacecraft and associated hardware	Waste Disposal and Processing

Table 4. *Cont.*

Efficiency Metrics of Current vs. Enhanced Recycling Systems		
System	**Current Recycling Efficiency (%)**	**Enhanced Recycling Efficiency (%)**
UN Office for Outer Space Affairs	Long-term sustainability of outer space activities	Sustainable Space Exploration
Inventory of Waste Management Equipment on the ISS		
Equipment	Manufacturer	Capacity
Closed-Loop System	Boeing (Washington, DC, USA)	Processes 6 kg/day
O_2 Generation System	Airbus (Blagnac, France)	2 kg O_2/day
Urine Processor Assembly	Lockheed Martin (Bethesda, MD, USA)	1.5 L/day
Solid Waste Compactor	Thales Alenia Space (Cannes, France)	50 kg of waste
Water Recovery System	Hamilton Sundstrand (Windsor Locks, CT, USA)	6 L/day

5. Challenges and Considerations

5.1. Practical Constraints and Implementation Realities

Practical limitations identified from ground-based and ISS experimental data include significant energy requirements for plasma arc gasification, necessitating enhanced solar arrays or nuclear energy, the latter carrying inherent safety risks demanding rigorous containment measures. AI-driven waste sorting, while promising, faces computational limitations in space environments due to restricted onboard computational resources, as evidenced by ISS-based testing and ground simulations. Although highly efficient in laboratory conditions, bioreactor systems encountered microbial containment challenges and fluctuating processing efficiencies under microgravity conditions aboard the ISS, highlighting the need for optimised sterilisation and containment solutions [77,78]. Future technological designs must address these operational limitations through modular and energy-efficient designs to ensure practical implementation in deep-space missions. (Table 5) (Figure 5).

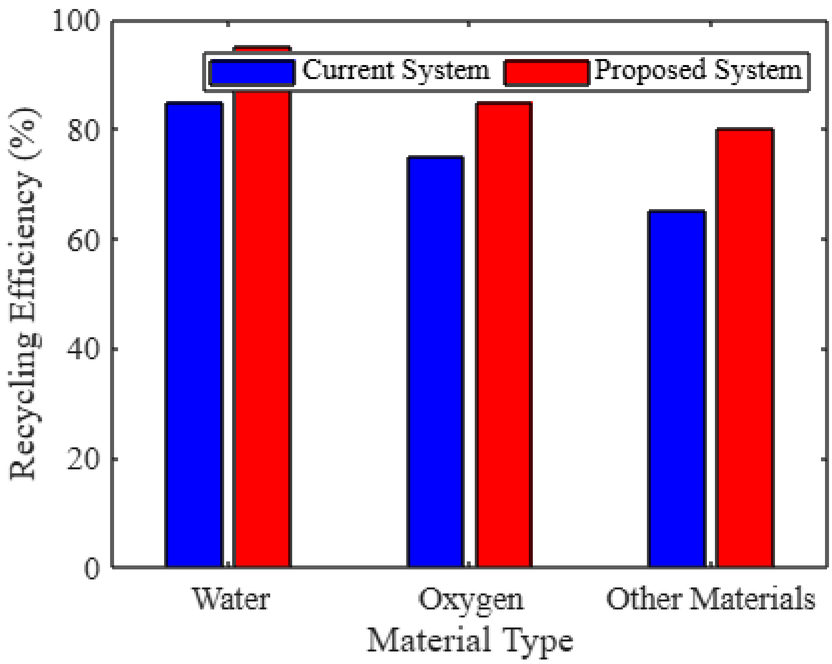

Figure 5. The recycling efficiency of the current system is in line with the proposed systems.

Table 5. Comparative analysis of waste management technologies.

Technology	Processing	Energy (kWh/ton)	Suitability for Space Use	By-Product Utilization
Plasma Arc	High volume reduction	500–1000	High (requires significant power)	Syngas for energy
Pyrolysis	Moderate volume reduction produces biochar, oil, and syngas	200–500	Moderate (less energy than plasma but still significant)	Biochar for soil enhancement, syngas for energy
Bioreactors	Organic waste to biogas and compost	50–150	High (low energy, valuable by-products)	Compost for growing food, biogas for energy
Mechanical Compaction	Compacts solid waste to reduce volume	10–50	Very High (low energy, simple technology)	None (reduces storage space only)
Incineration	High volume reduction, sterilisation of waste	300–600	Moderate (efficient but requires energy for high heat)	Heat can be used for energy
Projected Waste Volumes for Future Deep-Space Missions				
Mission Type	days	Crew Size	Daily Waste/Crew	Total Waste
Mars	900	6	1.8 kg	9720 kg
Asteroid Mining	180	4	1.5 kg	1080 kg
Lunar Habitat	365	5	1.5 kg	2738 kg

5.2. Economic Implications and Environmental Impacts

Evaluating innovative waste management technologies in space indicates that long-term savings from resource recovery and reduced resupply needs can outweigh initial high investment costs. While these systems require substantial upfront investments in development, deployment, and crew training, their return on investment improves as they lessen dependency on Earth for resources, providing a break-even point for space agencies and private companies. International partnerships are vital for funding and advancing these technologies, with successful collaborations reducing individual cost burdens and enhancing capabilities. The commercial potential for private companies in the space sector is significant in space waste management and in developing spin-off technologies for Earth. Effective waste management contributes to environmental sustainability by minimising space debris and conserving raw materials. Technologies like plasma arc gasification support closed-loop systems for long-duration missions. Integrating waste management with existing life support systems, such as air filtration and water recovery, is crucial for crew health and mission success. Systems must efficiently recycle waste while ensuring safety and thoroughly sterilising biological waste to prevent contamination [78,79]. The Controlled Ecological Life Support System (CELSS) exemplifies this integration, regenerating essential life-support materials for crew sustainability (Figure 6).

5.3. Summarise the Challenge

Managing waste in space presents unique challenges, underscored by the significance that illustrates waste management's complexity for space missions. Each International Space Station (ISS) crew member generates about 1.5 kg of waste daily, leading to a total of 4.5 to 9 kg daily for crew sizes of 3 to 6, or 1642 to 3285 kg annually. High-energy waste treatment technologies, like plasma arc systems, face integration challenges due to limited power on spacecraft, consuming 500 to 1000 kilowatt-hours per ton processed. The cost of launching payloads into space is approximately USD 10,000 per pound, making waste reduction or reprocessing into functional materials crucial for potential savings of hundreds of thousands of dollars annually. Currently, the ISS recycles about 90% of water and 42% of oxygen from waste, with food packaging (20%), human metabolic waste (30%), and inedible food parts (25%) comprising the waste types. For a Mars mission with a six-person crew lasting several years, total waste could exceed 25,000 kg. Efficient waste management is vital for astronaut health, safety, and mission sustainability, necessitating innovative systems that minimise energy use and maximise recycling (Figure 7).

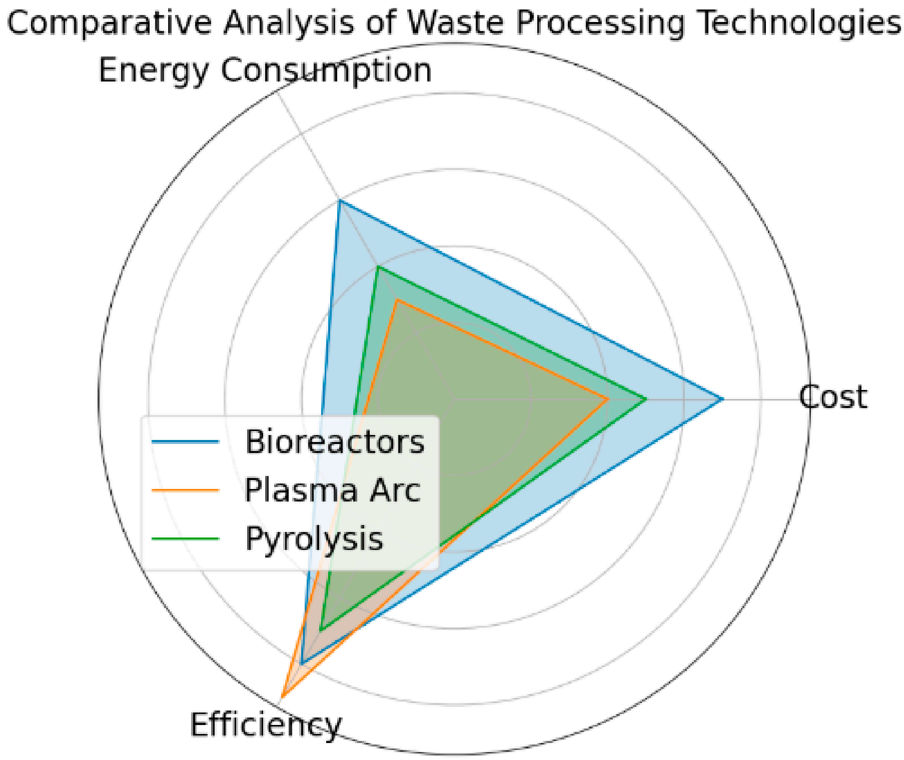

Figure 6. Comparative analysis of waste processing technologies.

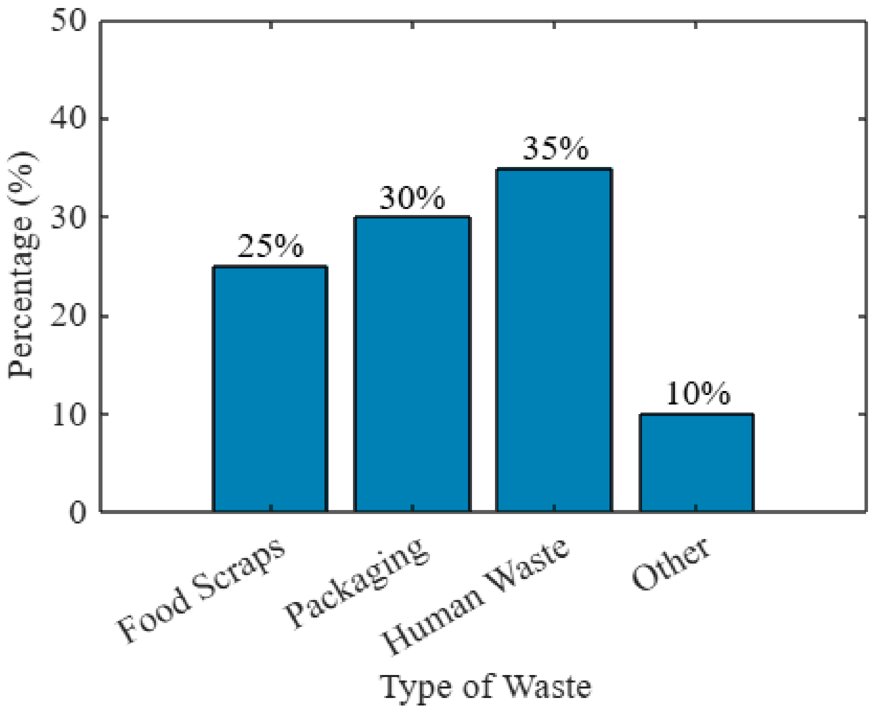

Figure 7. Breakdown of waste types generated on space missions.

6. International Collaboration and Policy

International collaboration involving multiple space agencies and private entities like NASA, ESA, Roscosmos, SpaceX, and Blue Origin is essential for advancing smart waste management in space. As space exploration becomes increasingly global, establishing standardised waste management protocols is vital. These collaborations create a practical framework under international environmental and space law, promoting long-term sustainability through the waste hierarchy concept. Such cooperative efforts are crucial for ensuring efficiency, safety, and sustainability in the international domain of space operations.

With the commercialisation of space exploration and the growing involvement of various countries and private entities, standardised waste management protocols are more important than ever. This standardisation ensures that government-led and privately operated missions adopt a unified waste handling, processing, and disposal approach. The lack of coordination poses significant risks, including the accumulation of space debris that threatens satellites, spacecraft, and human habitats [80,81]. Coordinated efforts are necessary to mitigate these risks and enhance the safety of space operations.

International standards emphasising waste treatment and resource recycling are pivotal for minimising the environmental impact of space activities. Agencies like NASA, ESA, and Roscosmos, with their experience in collaborative projects such as the International Space Station (ISS), play a key role in advancing waste management systems. These collaborations have led to developing technologies for air filtration, water recovery, and waste storage, which are crucial for long-duration missions like NASA's Artemis program and ESA's ExoMars mission.

Collaboration allows countries and organisations to share knowledge and technologies, leading to more efficient waste management systems [82,83]. By working together, space agencies can establish common standards for international missions, ensuring adherence to shared environmental and safety protocols. As missions extend to lunar bases or Mars colonies, regulations must evolve to manage waste and ecological impacts effectively, focusing on sustainability and integrating advanced waste processing technologies.

6.1. Actionable Stakeholder Roadmap

The Stakeholder Roadmap for Policy Implementation suggests the following: Years 1–2: Establish an international collaborative task force involving NASA, ESA, SpaceX, and Blue Origin to pilot advanced waste management technologies aboard the ISS, focusing on AI and bioreactor modules. Years 3–4: Evaluate performance outcomes, standardise technology practices, and begin integration plans for lunar and Mars missions, leveraging insights from ISS tests. Year 5 and Beyond: Formalise global standards through treaties mediated by the United Nations Office for Outer Space Affairs, ensuring widespread international compliance and cohesive policy adherence to sustainable waste management practices (Figure 8).

6.2. Private Companies, International Policy, and Global Cooperation Need

The increasing involvement of private companies like SpaceX and Blue Origin in space exploration introduces new dynamics and technological innovations. These companies are pioneering commercial space travel, offering fresh perspectives in operations management, including manufacturing, supply chain, and waste management. For instance, SpaceX's Starship is being developed for Mars missions and requires sophisticated waste management systems for long-duration space habitation. Figure 9 shows a line graph showing the cumulative waste generated over the expected duration of a Mars mission based on crew size and mission length.

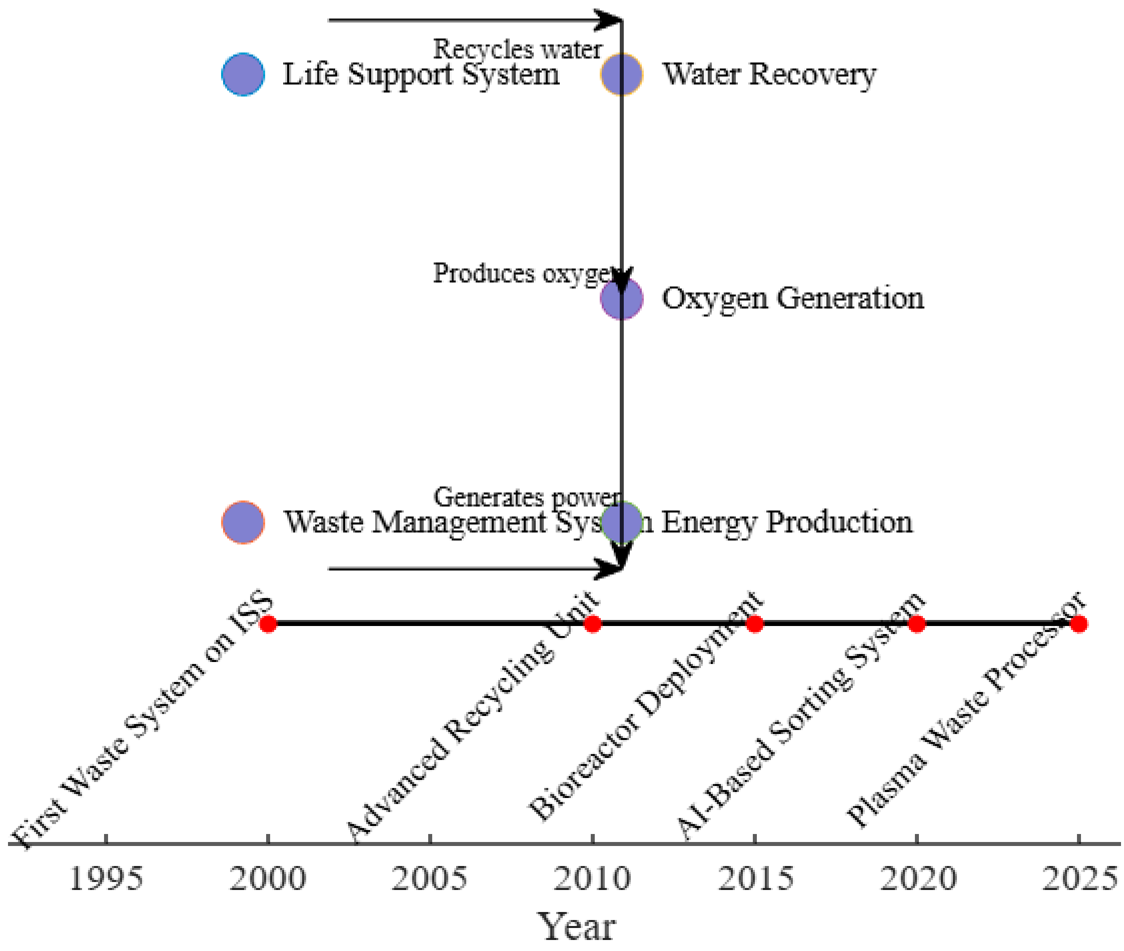

Figure 8. Integration and timeline of waste management systems with life support systems.

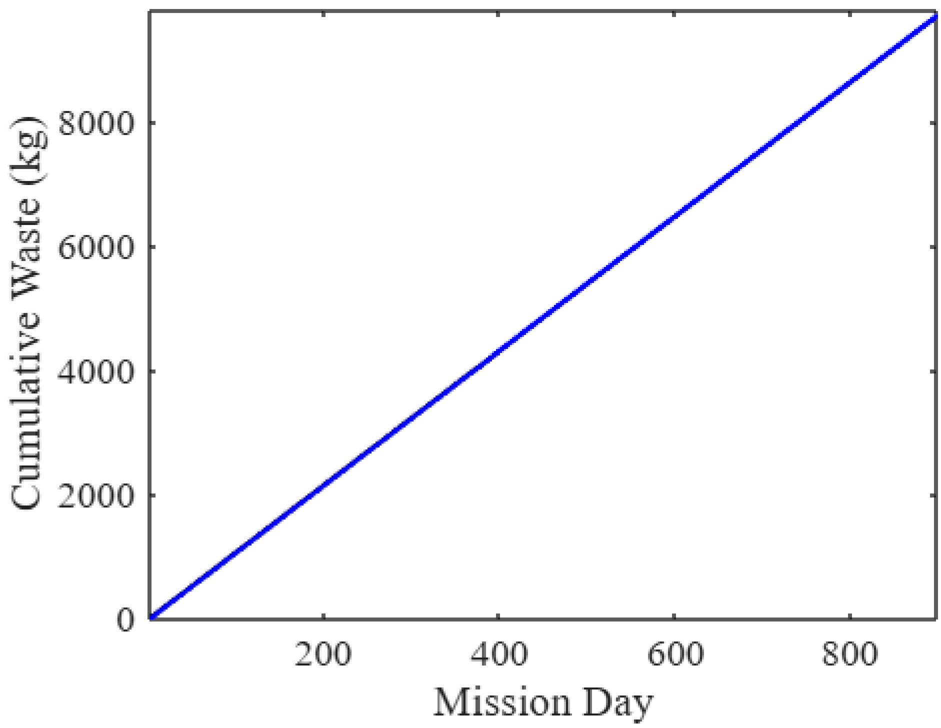

Figure 9. Projected waste accumulation during a Mars mission.

As space exploration expands to include more nations and commercial entities, the need for an international regulatory framework for waste management becomes increasingly urgent. Based on treaties like the Outer Space Treaty of 1967, current space law provides a basic structure but lacks detailed waste management and debris mitigation regulations. Efforts are underway to develop comprehensive guidelines, such as the United Nations Committee on the Peaceful Uses of Outer Space's Space Debris Mitigation Guidelines, which suggest the best practices to limit debris but do not address waste management beyond low-Earth orbit. Significant international collaboration is essential to create policies encompassing waste reduction, recycling, and handling hazardous materials. The space community can ensure sustainable waste management by enhancing cooperation among space agencies, private companies, and regulatory bodies. As the number of missions increases, the coordinated management of space resources is vital to minimise environmental impacts and establish a sustainable human presence in space for future generations.

6.3. Future Research and Recommendations

This document highlights critical areas for advancing smart waste management technologies in space exploration, particularly for long-duration missions to Mars and lunar bases. It emphasises the need for methods to process more materials with higher recovery rates. Research should prioritise converting waste into usable resources like water, oxygen, and building materials through advanced chemical and biological processes. Energy efficiency is vital, necessitating the exploration of low-energy processing technologies and energy recovery systems that transform waste into energy. Automating waste sorting and processing is essential to reduce human involvement, allowing crew members to focus on other critical tasks. Developing AI-driven robotics for autonomous waste identification, sorting, and processing is a priority. Given space and weight constraints in spacecraft, research into innovative materials and designs that minimise the size and weight of waste management systems without sacrificing efficiency is necessary. Enhancing the durability and reliability of these technologies is crucial for long-term operations in harsh space conditions. Integrating waste management into habitat design is also essential, ensuring that these systems work seamlessly with life support functions like food production and air purification. Establishing international standards for waste management in space is essential for global practice standardisation and technology sharing.

7. Conclusions

This research provides a novel, comprehensive evaluation of cutting-edge waste management technologies tailored explicitly for long-duration space missions. This study uniquely addresses the multifaceted challenges of sustainable waste management beyond low-Earth orbit by integrating artificial intelligence-driven sorting systems, microbial bioreactors, and thermal processing techniques. Among the key findings, plasma arc gasification demonstrates the highest waste volume reduction efficiency (up to 90%), but its high energy demand of 500–1000 kWh per ton poses significant operational constraints. Pyrolysis offers a balanced solution, reducing waste volume moderately at a lower energy range (200–500 kWh per ton), but it necessitates additional handling systems. Notably, efficient bioreactors consume the least energy (50–150 kWh per ton) and effectively convert organic waste into vital resources, such as oxygen and water, essential for prolonged missions. The analysis quantified current ISS recycling efficiencies, revealing a 90% water recycling rate with potential improvements of up to 98% using advanced methods. However, implementation faces challenges like microbial containment under microgravity conditions, computational limitations for onboard AI systems, and significant initial investment costs. This study underscores the critical balance between energy consumption, recycling efficiency, and operational practicality, proposing clear directions for developing sustainable, integrated solutions essential for future space exploration.

Author Contributions: Conceptualization, D.B.O. and B.I.O.; Methodology, O.Z.W., T.T.P., E.E., J.O.I. and B.I.O.; Software, D.B.O., O.Z.W. and J.O.I.; Validation, O.Z.W., E.E. and J.O.I.; Formal analysis, D.B.O., O.Z.W. and E.E.; Investigation, O.Z.W.; Resources, T.T.P. and J.O.I.; Data curation, D.B.O., J.O.I. and B.I.O.; Writing—original draft, D.B.O.; Writing—review & editing, T.T.P., E.E. and B.I.O.; Visualization, E.E.; Supervision, T.T.P. and E.E.; Project administration, J.O.I. and B.I.O.; Funding acquisition, T.T.P. and B.I.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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