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Review

Toward net-zero in space exploration: A review of technological and policy pathways for sustainable space activities

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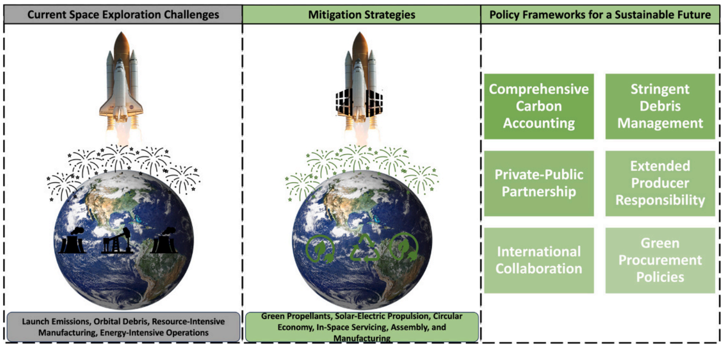
HIGHLIGHTS

- Rocket launches produce CO2, black carbon, and water vapor in the atmosphere.
- Space debris threatens future missions, requiring better debris management.
- Green propulsion, like electric systems, reduces emissions in space missions.
- Reusable rockets cut manufacturing needs, reducing overall environmental costs.
- Solar power drives sustainability, powering satellites and spacecraft efficiently.

GRAPHICAL ABSTRACT



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ABSTRACT

Space exploration's environmental impact presents a critical challenge to global net-zero objectives, particularly through launch emissions, orbital debris accumulation, and energy-intensive manufacturing processes. This narrative review examines technological and policy pathways toward sustainable space activities, analyzing emerging green propulsion systems, renewable energy integration, and circular economy applications in spacecraft design. The review evaluates the efficacy of current sustainability initiatives, including hydroxyl-free hydrazine propulsion, solar-electric systems, and advanced satellite technologies for environmental monitoring. Critical assessment of regulatory frameworks reveals gaps in international governance, highlighting the need for standardized carbon accounting and emissions trading schemes in space operations. The analysis extends to public-private research and development partnerships (PPRDPs), examining their role in accelerating sustainable innovation through information spillover effects and agglomeration externalities. While technological advancements demonstrate promise, particularly in reusable launch systems and space-based solar power (SBSP), significant challenges persist in deep-space mission sustainability, regulatory enforcement, and cost barriers to green technology adoption. This review synthesizes current progress and limitations in sustainable space

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exploration, providing insights for policymakers, industry stakeholders, and researchers working toward net-zero space operations. The findings emphasize the necessity of harmonizing space exploration objectives with environmental preservation through integrated technological innovation and international cooperation frameworks.

1. Introduction

The global push for sustainability has permeated all sectors, including space exploration (Iliopoulos and Esteban, 2020; Nahtigal, 2022). In recent years, the commitment to achieving net-zero carbon emissions has become a priority for governments, corporations, and individuals alike. Space exploration, once viewed solely as a symbol of human advancement and technological prowess, is now increasingly scrutinized for its environmental impact. While it holds significant potential to contribute solutions to Earth's sustainability issues—such as through satellite-based environmental monitoring, space-based solar power, and even asteroid mining for rare resources—it paradoxically poses threats to the very planet it seeks to protect. It presents environmental hazards, which include space debris, light pollution, and stratospheric ozone depletion resulting from rocket emissions and reentry particles (Miraux, 2022). Similarly, human space travel exerts a significant environmental impact, with an hourly emission of over 1500 kg CO_2-equivalent, which is 2000 times more than the average individual's emission rate (Dallas et al., 2021). It is important to note that the proliferation of anthropogenic garbage in Low Earth Orbit (LEO) constitutes a substantial challenge to space sustainability, endangering both present and prospective space endeavours (Newman and Williamson, 2018). Rocket launches are one of the most visible contributors to space exploration's environmental impact. The immense energy required to propel spacecraft into orbit generates significant emissions. The major reaction control system engines of the Space Shuttle generate visible plume spectra, which exhibit various emissions, including molecular and atomic species, along with notable discrepancies in the spatial distribution of emitting species (Hester et al., 2009). The fuel used in rocket launches—whether it be liquid oxygen, kerosene, or solid rocket fuel—releases a mix of carbon dioxide (Kokkinakis and Drikakis, 2022), black carbon (Maloney et al., 2022), and other pollutants into the atmosphere. Unlike emissions from other industries, these pollutants are discharged directly into the upper layers of the atmosphere, where their effects can be more concentrated and prolonged. Black carbon, in particular, has a notable warming effect when it remains in the stratosphere, as it absorbs heat and exacerbates the greenhouse effect (Shrestha et al., 2010; Maloney et al., 2022). Thus, despite its comparatively smaller scale than terrestrial industries, space exploration's carbon footprint per launch can have outsized consequences for global climate change.

Efforts to address these challenges and move toward a net-zero future in space exploration are multifaceted. One of the most promising areas of development is in green propulsion technologies. Unlike traditional chemical rockets, which rely on the combustion of fuels that emit large quantities of greenhouse gases, electric propulsion systems offer a cleaner alternative. For instance, Green oxidizers for solid rocket propulsion promise safer substitutes for ammonium perchlorate used in traditional chemical rockets, mitigating environmental concerns such as thyroid cancer and acid rain (Trache et al., 2017). These systems, which use ionized gas and electric fields to generate thrust, consume far less fuel and produce minimal emissions. Solar-electric propulsion, already used in some spacecraft, harnesses solar energy to power propulsion systems, reducing both the fuel required and the environmental impact. Additionally, it provides an appealing interim solution for expedited human transit in outer space, using the swift advancements in solar array technology (Chang Díaz et al., 2019). On the other hand, hybrid-electric propulsion may be seen as a superior ecologically friendly option to fuel propulsion systems in specific scenarios (Ribeiro et al., 2020). The advent of reusable rockets has been a game-changer in reducing the environmental cost of space launches. By reusing components of rockets, companies like SpaceX have significantly lowered the number of new rockets required for missions, cutting down on the resources consumed and emissions generated.

Another critical factor in the drive toward sustainability in space is the integration of renewable energy sources. Solar energy has long been a cornerstone of space exploration, powering satellites, space stations, and deep-space missions. III-V multijunction solar cells (MJSCs) represent the conventional commercial technology for spaceship power, although emerging technologies such as Cu(*In*,*Ga*)Se2 (CIGS) and perovskite solar cells (PSCs) exhibit potential for aerospace power systems (Verduci et al., 2022). The International Space Station (ISS), for instance, relies heavily on solar panels to meet its energy needs (Gietl et al., 2000; Oman, 2003; Cheng et al., 2016). Expanding the use of solar power in ground operations, spacecraft construction, and satellite systems could further reduce the reliance on carbon-intensive energy sources. Moreover, the concept of space-based solar power (SBSP) has captured the imagination of scientists and policymakers alike. This involves collecting solar energy in space, where sunlight is constant and unimpeded by atmospheric interference, and transmitting it back to Earth. Though still in the experimental stages, SBSP holds the potential to revolutionize clean energy on Earth while reducing the energy demands of space activities. Additionally, it represents a significant advancement in scientific research, providing enhanced collection efficiency and extended collection duration for solar energy (Bhagat and Joy, 2021; Chowdhury, 2023; Guo et al., 2023).

Space exploration's contributions to sustainability are not limited to reducing its own carbon footprint. The industry plays a pivotal role in helping to monitor and mitigate climate change on Earth. Space exploration can enhance sustainable development on Earth by incorporating policy and strategic elements related to global health, water, energy, and urban development (Ferretti et al., 2020). Space exploration influences the UN's Sustainable Development Goals via remote sensing, Earth observation satellite data, alien circumstances, spinoff technologies, and societal ramifications (Macias et al., 2022). Satellite projects such as NASA's Orbiting Carbon Observatory-2 (OCO-2) and Japan's Greenhouse Gases Observing Satallite (GOSAT) have established a comprehensive long-term record of atmospheric greenhouse gas concentrations, including data from China's TanSat mission (Boesch et al., 2021). TanSat, China's inaugural greenhouse gas monitoring satellite, supplies critical data for comprehending and mitigating carbon emissions, hence enhancing the monitoring and verification capabilities of the Paris Agreement (Boesch et al., 2021). This real-time data is invaluable for scientists and policymakers working to understand and address the impacts of climate change. As satellite technology continues to evolve, new generations of smaller, more efficient satellites, like CubeSats, can be deployed at a lower cost and with less environmental impact than their predecessors. These innovations not only support the space industry's sustainability goals but also enhance the global community's ability to respond to environmental crises on Earth.

1.1. *Statement of problem, rationale, and objective of the review*

The global pursuit of net-zero emissions presents unique challenges for space exploration, particularly given its energy-intensive operations and environmental impact. Recent analyses reveal that only 19.8 % (152 of 769) of organizations with net-zero targets meet basic robustness criteria, highlighting the need for more rigorous frameworks and implementation strategies (Hale et al., 2022). This challenge is particularly acute in space exploration, where activities affect the global commons regardless of the operating entity.

While international bodies such as the United Nations Office for Outer Space Affairs (UNOOSA) and the International Telecommunication Union (ITU) have initiated guidelines for sustainable space operations, including the United Nations Committee for the Peaceful Uses of Outer Space (UN COPUOS) working group's non-binding recommendations for long-term space sustainability (Martinez, 2018), more stringent regulatory frameworks are required. These frameworks must address both emissions management and space debris mitigation through standardized carbon accounting systems and emission trading schemes. Emerging technologies, particularly renewable and regenerative fuel cells, show promise for sustainable space missions due to their high-power density, specific energy density, and zero environmental impact characteristics (Pu et al., 2021). However, significant barriers persist, including high implementation costs, technical challenges in deep-space renewable energy systems, and regulatory gaps.

This narrative review examines the intersection of net-zero objectives and space exploration, with particular emphasis on:

- Environmental impact of space exploration
- Technological pathways for reducing the carbon footprint of space activities
- Policy mechanisms and international collaboration frameworks

The review's significance lies in its comprehensive analysis of emerging sustainable space technologies and regulatory frameworks, contributing to both environmental science and space policy discourse. It aims to identify viable pathways for aligning space exploration with global sustainability objectives while acknowledging the sector's unique technological and operational constraints.

2. The environmental impact of space exploration

Space exploration, while providing numerous technological and scientific advancements, comes with significant environmental consequences. The environmental footprint of space missions includes the emissions from rocket launches, the growing problem of space debris, and the energy-intensive nature of manufacturing and ground operations. Space launch vehicles release combustion gases and particles into the atmosphere, affecting ozone chemistry and Earth's energy equilibrium via radiative forcing (Sirieys et al., 2022). These aspects, often overlooked in the public discourse around space, are increasingly being examined as the global community pushes toward sustainability and net-zero carbon emissions. Fig. 1 illustrates a spacecraft ascending into the atmosphere, emitting a plume of smoke and particle matter that ascends through multiple atmospheric strata. The smoke plume ultimately ascends to the stratosphere, where it may engage with the ozone layer. The emissions produced during the launch, comprising ozone-depleting chemicals and nitrogen oxides, may contribute to the degradation of ozone molecules, potentially resulting in detrimental environmental effects.

2.1. Launch emissions

The carbon footprint of space exploration is heavily influenced by the emissions produced during rocket launches. Rockets burn vast quantities of fuel, releasing carbon dioxide (CO_2), water vapor, black carbon (soot), and other pollutants into the atmosphere. Rocket exhaust emissions generate thermal nitrogen oxides and carbon dioxide at altitudes reaching 67 km, hence contributing to air pollution (Kokkinakis and Drikakis, 2022). A fleet of 1000 annual launches of suborbital rockets might establish a continuous layer of black carbon particles in the northern stratosphere, resulting in substantial alterations in global atmospheric circulation, as well as in ozone and temperature distributions (Ross et al., 2010). It is important to note that the type of fuel used plays a significant role in determining the scale and type of emissions. For instance, liquid-fueled rockets, which often use a combination of liquid oxygen and refined kerosene, tend to release fewer harmful particles compared to solid-fueled rockets, which produce higher levels of toxic substances, such as aluminum oxide (Dallas et al., 2020). Studies show that while the global emissions from space launches are relatively small compared to industries like aviation, their environmental effects are disproportionately significant due to the altitude at which these emissions are released (Dallas et al., 2020).

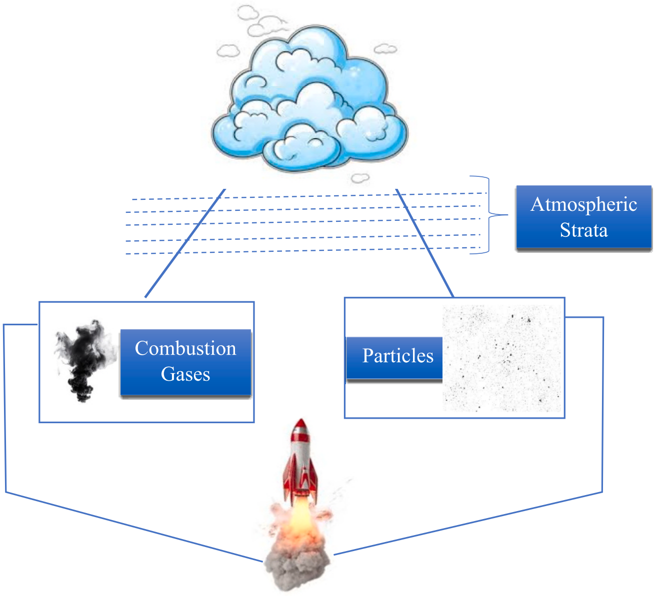

Fig. 1. Representing the environmental impact of space launch vehicles.

Upon reaching the stratosphere, the black carbon particles (soot) emitted by rockets can persist in the high atmosphere for several years. Rockets emit pollutants directly into the stratosphere, where natural meteorological phenomena, such as rain, that could mitigate these particles are limited. Consequently, black carbon particles collect, exerting a significantly bigger influence on climate than particles released nearer to the Earth's surface. Recent studies indicate that soot emitted from rockets is up to 500 times more effective at contributing to global warming than soot from sources such as aeroplanes. The extended presence of black carbon in the stratosphere adds to global warming and probable ozone depletion (Ross et al., 2010). This suggests that as space exploration increases, so too will the need to mitigate the unique environmental effects of high-altitude emissions.

The environmental impact is further amplified by water vapor emissions in the upper atmosphere (Platov et al., 2011; Kolle et al., 2021). Water vapor at these altitudes leads to the formation of persistent clouds that reflect infrared radiation back toward the Earth's surface, further amplifying the warming effect (Palchetti et al., 2015). This effect, combined with the increasing frequency of commercial space flights and raising significant concerns about long-term impacts on global climate patterns.

2.2. Manufacturing and ground operations

The environmental impact of space exploration is not confined to the upper atmosphere; significant emissions and resource consumption occur on the ground during the manufacturing of spacecraft and rocket components. Ground operations in space manufacturing include a variety of preparatory tasks such as topology optimization, incorporating additive manufacturing constraints, design verification, fabrication, and verification/qualification testing are all required to support the manufacturing process in space (Orme et al., 2018). These procedures demand significant energy for rocket fuel manufacture, powering machinery, and cooling systems, which contribute to CO_2 emissions (Jozič et al., 2020). Between 2009 and 2018, 140 kt of carbon dioxide were emitted from rocket launches, with 65 % from Russian and American launches (Pradon et al., 2023). Furthermore, energy-intensive facilities on the ground add to emissions through constant power usage. These operations, when combined, provide a significant carbon footprint, raising concerns about sustainability in the growing space economy.

The production of rockets, satellites, and associated infrastructure is fuel and energy-intensive (Jozič et al., 2020). The materials used, including rare metals like aluminum alloys and composite materials like advanced carbon, reinforced carbon, and flexible insulation blanket, often require extensive mining, refining, and fabrication processes that consume large amounts of energy and emit greenhouse gases (Tiwary et al., 2021). For instance, the carbon footprint of manufacturing a single satellite can be substantial due to the precision engineering and high-performance materials required.

Ground operations, including the maintenance of launch facilities, control centers, and testing sites contribute to the environmental impact of space missions (Dallas et al., 2020). These facilities are often powered by conventional energy sources, predominantly fossil fuels, which add to the carbon emissions associated with space exploration. The water consumption for cooling systems, rocket testing, and other ground activities is another environmental concern. Large amounts of water of about 400,000 gal (NASA, 2020) are needed to suppress heat and sound during rocket launches to a level of 6.92 dB (Xing et al., 2022), and the depletion of local water resources can be significant, especially in arid regions where many spaceports are located (Van Foreest et al., 2009; Zhou et al., 2022; MEREU and ISVORANU, 2023).

Water injection can significantly reduce jet noise during rocket liftoff with appropriate injection angles and mass flow rates.

Furthermore, the environmental costs of transporting rocket components and spacecraft to launch sites are considerable. Given the global nature of the space industry, parts are often manufactured in different countries and then transported over long distances to launch using trailers, with vibrations controlled by varying air spring stiffness, tire stiffness, transportation speed, ballast weight, and sudden acceleration/braking (Diwakar and Balaguru, 2020), these space crafts which could weigh as much as 5000 kg (Li and Zhou, 2023) add to the carbon footprint through logistics and supply chain activities. As the space industry continues to expand, there is a growing recognition of the need to adopt more sustainable practices in both the manufacturing and operational phases. Space exploration emission mitigation encompasses renewable energy adoption in manufacturing and ground operations alongside advanced materials development for efficient spacecraft. While renewable energy could meet two-thirds of global energy demand by 2050, achieving net-zero emissions requires technological innovations in transportation and industry, particularly in emissions-free electricity and carbon-neutral fuels (Davis et al., 2018; Gielen et al., 2019). Green supply chain management further reduces environmental impact through optimized transportation systems, including slow steaming and improved operational efficiency (Mohtashami et al., 2020; Saada, 2021).

2.3. Evaluating the environmental consequences of reusable rockets

The emergence of reusable rocket technology has transformed space exploration by markedly decreasing launch expenses and enhancing flight frequency. SpaceX's Falcon 9 has exemplified the feasibility of booster recovery and refurbishing, facilitating several flights per rocket (Reddy, 2018). Nevertheless, discourse regarding the sustainability of reusable rockets frequently emphasises launch efficiency and cost reduction, neglecting the environmental consequences of production and refurbishing. An exhaustive assessment of reusable and expendable rockets must take into account emissions from manufacturing, refurbishment energy expenditures, and overall lifecycle effects.

The initial fabrication of a reusable rocket incurs higher material and engineering expenses which ranges from $6 to $10 M for light and heavy rockets respectively than that of single-use variants (Koenigsmann et al., 2003). This is mainly attributable to the utilization of sophisticated materials, design optimization, transition from expendable to reusable and the use of advanced technologies necessary to guarantee the lifetime and functionality of reusable systems (LI et al., 2021; De Freitas Bart et al., 2023).

Reusable boosters necessitate further structural reinforcements, heat-resistant coatings, and landing apparatus, all of which result in increased carbon emissions during production and ozone column loss (Larson et al., 2017). In contrast, disposable rockets are engineered for single use, frequently utilizing lighter materials that diminish initial production emissions but require continual replacement. Although reusability diminishes waste and lowers material prices per launch, refurbishing procedures include supplementary energy expenditures. Post-flight inspections, component substitutions, and reassembly necessitate substantial industrial energy consumption, hence augmenting the overall carbon footprint of a reusable rocket. SpaceX's Falcon 9 boosters undergo a refurbishment procedure that includes cleaning, structural integrity assessments, and possible component replacements, necessitating manufacturing resources and logistics. The emissions linked to these activities must be measured to ascertain if reusability genuinely provides an environmental benefit compared to single-use options.

A comprehensive evaluation of reusable and single-use rockets necessitates a lifecycle analysis that incorporates manufacture emissions, refurbishment energy expenditures, launch emissions, and end-of-life factors. For instance, the Falcon Heavy reusable booster system significantly reduces environmental and cost impacts compared to the Falcon 9 rocket launch system, saving over $6000 per kilogram and reducing environmental impact potential by over 40 % (Harris and Landis, 2019). Manufacturing emissions arise from the carbon dioxide footprint associated with the production of a new rocket, regardless of its reusability. The energy expenses associated with refurbishment contribute to this footprint, as the processing and preparation of a booster for reflight necessitate industrial resources. Launch emissions, encompassing propellant combustion and atmospheric effects, exacerbate the total environmental burden. Rocket exhaust gases produce considerable thermal nitrogen oxides and carbon dioxide at altitudes up to 67 km, which could have a significant cumulative effect on climate (Pradon et al., 2023). Furthermore, the sustainability of disposal techniques for decommissioned boosters compared to the continuous production of expendable rockets must be considered. Initial research indicates that following numerous flights, reusable rockets could realise a net decrease in emissions relative to the production of an equivalent quantity of expendable rockets. Nonetheless, information regarding refurbishment emissions is scarce, necessitating a more comprehensive analysis to ascertain a conclusive environmental advantage.

2.4. Space debris and its contribution to environmental degradation

Space debris, comprising defunct satellites, spent rocket stages, and orbital fragments, poses a critical environmental and operational challenge to space exploration. Even microscopic debris, such as paint flecks, presents significant hazards to satellite networks and the International Space Station, necessitating robust international policies and guidelines (Norberg, 2013; Greenbaum, 2020; Yozkalach, 2023). The increasing density of orbital debris has become a major concern for both current space operations and future missions, as these objects travel at velocities exceeding 27,000 km per hour in LEO, making even small impacts potentially catastrophic (Park, 2018).

The exponential growth of orbital debris is predicted to trigger Kessler syndrome—a cascade of collisions generating increasing amounts of debris—within 200–250 years (Hudson, 2023). This phenomenon occurs when the density of objects in orbit becomes so high that collisions between objects create a self-sustaining chain reaction of further collisions. While this scenario could potentially render LEO unusable, it may be mitigated through passive disposal, collision avoidance, and active debris removal strategies (Shekhar and Verma, 2023; Hudson, 2023). The implications extend beyond space operations to affect critical Earth-based services, including climate monitoring, disaster management, and global communications (Drmola and Hubik, 2018). The challenge is particularly acute in popular orbital bands where communication and Earth observation satellites operate, as these regions already show signs of congestion. Chronopoulos (2023) points to specific events, such as the 2007 Chinese anti-satellite test and the 2009 Iridium-Kosmos collision, which generated thousands of pieces of trackable debris, further contributing to the risk of Kessler Syndrome. These events underscore the potential for both intentional and accidental actions to exacerbate the debris problem and increase the likelihood of future collisions. Moreover, NASA estimates that there are millions of pieces of debris in LEO, including over 26,000 objects larger than a softball, over 500,000 objects larger than a marble, and over 100 million objects larger than a grain of salt (NASA, 2020). These objects pose a significant threat to operational satellites and spacecraft, with even small debris capable of causing catastrophic damage due to the high orbital velocities involved. The growing volume of debris also threatens the loss of vital space-based services, such as weather forecasting, telecommunications, and global positioning systems.

Debris proliferation models, such as the NASA Orbital Debris Engineering Model (ORDEM), the European Space Agency's MASTER model, and the Space Debris Environment Engineering Model (SDEEM), simulate the evolution of the space debris environment, taking into account factors such as launch traffic, satellite deployments, fragmentation events, and natural decay processes (Horstmann et al., 2017, 2021; Matney et al., 2023; LIU et al., 2024). These models provide valuable insights into the future debris environment and the likelihood of collision events, enabling a quantitative assessment of the risk of Kessler Syndrome. Studies using these models have projected a significant increase in the number of debris objects in the coming decades, particularly in heavily used orbital regions like LEO. This increase raises concerns about the growing risk of collisions and the potential for Kessler Syndrome to occur, which could severely limit access to space and disrupt vital satellite services. The differences in predictions between models, such as those observed between ORDEM and MASTER at SSO altitudes, highlight areas where further research and data collection are needed (Horstmann et al., 2021). For example, Pardini and Anselmo (2021) provide insights into the limitations of current tracking capabilities, noting that the US Space Surveillance Network catalogue is estimated to be only 66 % complete for objects 10 cm or larger, with even lower completeness for smaller debris using the MASTER model. This incompleteness highlights the challenges in accurately assessing and managing the debris population, particularly for the smaller but still hazardous objects.

Current mitigation efforts encompass both technological and policy solutions. Advanced technologies being developed include netting systems for capturing larger debris, robotic arms for controlled removal of defunct satellites, and laser ablation techniques for altering the trajectories of smaller fragments (Aglietti et al., 2020). Companies such as Astroscale and ClearSpace are pioneering active debris removal initiatives, demonstrating the growing commercial interest in space sustainability. The ReDSHIFT project exemplifies comprehensive approaches through deorbitable spacecraft development, satellite miniaturization, and international debris management standards (Rossi et al., 2018). These efforts are complemented by international guidelines for debris mitigation, such as the Inter-Agency Space Debris Coordination Committee (IADC) recommendations and the United Nations' Long-term Sustainability Guidelines (Mejía-Kaiser, 2020; Martinez, 2021).

However, the high costs and technical complexities of debris removal underscore the importance of preventive measures. Key preventive strategies include designing spacecraft with end-of-life deorbiting capabilities (Valmorbida et al., 2023), implementing more stringent international regulations on space debris creation (Greenbaum, 2020), and promoting responsible space operations through improved tracking and collision avoidance systems (Sarkar et al., 2022). The success of these initiatives requires unprecedented international cooperation and commitment from both traditional space agencies and emerging commercial space entities to ensure the sustainable use of Earth's orbital environment.

2.5. Long-duration and deep-space missions

While sustainability efforts in Low Earth Orbit (LEO) have gained significant attention, deep-space missions—such as lunar, Martian, and interplanetary exploration—present unique sustainability challenges that require distinct solutions. Unlike LEO operations, where solar power is a reliable energy source and where deorbiting mechanisms can mitigate space debris, deep-space missions face limitations in energy generation, power system capabilities, propulsion efficiency, resource utilization, and waste management due to their prolonged duration and distance from Earth (Lei et al., 2023).

One of the primary challenges is the feasibility of solar-electric propulsion (SEP) in deep-space environments (Chang Díaz et al., 2019). While SEP is an effective technology for LEO and some interplanetary missions, its efficiency diminishes as spacecraft move farther from the Sun, where solar irradiance is significantly weaker. For missions to Mars, Jupiter, or beyond, alternative propulsion methods such as nuclear thermal propulsion (NTP) and radioisotope thermoelectric generators (RTGs) become necessary. However, these systems pose environmental and safety concerns due to the handling, disposal, and potential accidental release of radioactive materials. Developing cleaner, more sustainable deep-space propulsion technologies remains a major hurdle in aligning long-duration missions with net-zero objectives.

Another significant concern is in-situ resource utilization (ISRU) and waste management. Unlike short-term LEO missions, deep-space missions cannot rely on frequent resupply from Earth (Pischulti et al., 2024), necessitating the efficient use of available resources. The extraction of oxygen and water from lunar or Martian regolith, as well as closed-loop life-support systems that recycle air and water, are being explored as sustainable solutions. However, these technologies are still in the experimental phase, and their large-scale implementation requires further development to ensure reliability. Additionally, waste generated during long-duration missions, including non-recyclable materials and hazardous byproducts, presents logistical and environmental challenges, as conventional disposal methods such as atmospheric reentry are not feasible beyond Earth's orbit.

Space debris and end-of-mission disposal strategies also become more complex in deep-space environments. While debris in LEO can be managed through controlled deorbiting, spacecraft sent to the Moon, Mars, or interplanetary space often lack clear disposal pathways (Heilala, 2023). Abandoned landers, spent boosters, and orbiting debris around celestial bodies could pose long-term sustainability risks, similar to the space debris issue in LEO. The development of planetary protection protocols and sustainable end-of-life strategies for deep-space missions is crucial to prevent contamination and environmental degradation on extraterrestrial surfaces.

Finally, the carbon footprint of deep-space exploration extends beyond launch emissions and onboard energy consumption (Ryan et al., 2022). Between 2009 and 2018, launch vehicles emitted 140 kt of carbon dioxide, 79 kt of water vapor, 5 kt of chlorine, and 8 kt of alumina, contributing to climate change and ozone depletion (Pradon et al., 2023). The infrastructure required to support deep-space missions—including deep-space tracking stations, ground-based manufacturing, and mission control operations—demands substantial energy inputs, much of which still comes from non-renewable sources. Transitioning mission operations to renewable energy-powered ground facilities and improving the sustainability of space hardware manufacturing will be essential to reducing the overall environmental impact of deep-space exploration.

As humanity pushes further into space, ensuring sustainability in long-duration missions will require a combination of technological advancements, international policy frameworks, and mission design innovations. While some progress has been made, achieving net-zero emissions for deep-space exploration remains a formidable challenge that must be addressed as part of the broader movement toward sustainable space activities.

3. Pathways toward net-zero in space exploration

Net-Zero in Space Exploration encompasses the entire lifecycle of space missions, including launch emissions, spacecraft manufacturing, operational sustainability, and end-of-life disposal. While launch emissions are a major contributor to space-related carbon output (Kokkinakis and Drikakis, 2022; Pradon et al., 2023), a comprehensive net-zero approach also addresses the energy consumption of satellites and space stations, the resource intensity of spacecraft production, and sustainable decommissioning strategies. Achieving net-zero requires a combination of green propulsion systems, renewable energy adoption, and circular economy principles in spacecraft design, ensuring that emissions are minimized at every stage (Staszewski, 2023). Additionally, self-sustaining space habitats and in-situ resource utilization (ISRU) reduce reliance on Earth-based resupply missions, further decreasing the environmental impact of long-term space exploration. By integrating these elements, net-zero in space moves beyond launch emissions to create a sustainable, low-impact space industry that aligns with global climate goals.

3.1. Green propulsion systems

The transition to green propulsion technologies represents a crucial advancement in reducing space exploration emissions. Hydroxyl-free hydrazine exemplifies this shift, offering reduced environmental impact while enabling sophisticated propulsion systems (Gohardani et al., 2014). Unlike traditional chemical propulsion systems that rely on carbon-intensive fuels, electric propulsion systems utilize ionized gas to generate thrust, achieving higher energy densities and optimized thrust levels (Mazouffre, 2016).

SEP further advances sustainable space operations by harnessing solar energy for both spacecraft operations and propulsion. SEP has demonstrated success in direct flight missions and shows promise for expedited human deep space transportation, benefiting from advances in solar array technology (Phillips, 1980; Chang Díaz et al., 2019). Notable applications include NASA's Dawn mission, which validated the technology's efficiency for long-duration missions.

As illustrated in Fig. 2, green propulsion technologies offer multiple environmental and technical advantages. These systems significantly reduce CO_2 and NOx emissions, supporting climate change mitigation efforts while enhancing energy efficiency, particularly in electric and hydrogen-based systems (Du et al., 2019; Tiwari, 2021; Varga et al., 2020; Palies, 2022). The technologies deliver lower operational costs, and high performance through optimized design and reduced fuel consumption while simultaneously decreasing dependence on fossil fuels through renewable energy integration (Nosseir et al., 2021; Soni et al., 2024). Additional benefits include reduced noise pollution, especially relevant for atmospheric applications, simplicity, and better storability, and minimized use of hazardous propellants (Park et al., 2019; Nosseir et al., 2021). These advancements not only improve compliance with environmental regulations but also foster innovation and create new economic opportunities in the clean energy and transportation sectors.

Another major leap toward net-zero emissions comes from the development of reusable rockets. The SpaceX Falcon Heavy reusable launch vehicle uses a variety of strategies such as varying the mass flow rate of fuel during different stages of the flight to optimize fuel consumption and minimize environmental impact during launch (Jozič et al., 2020). Traditionally, rockets have been single-use vehicles, with components either burned up in the atmosphere or left as debris after

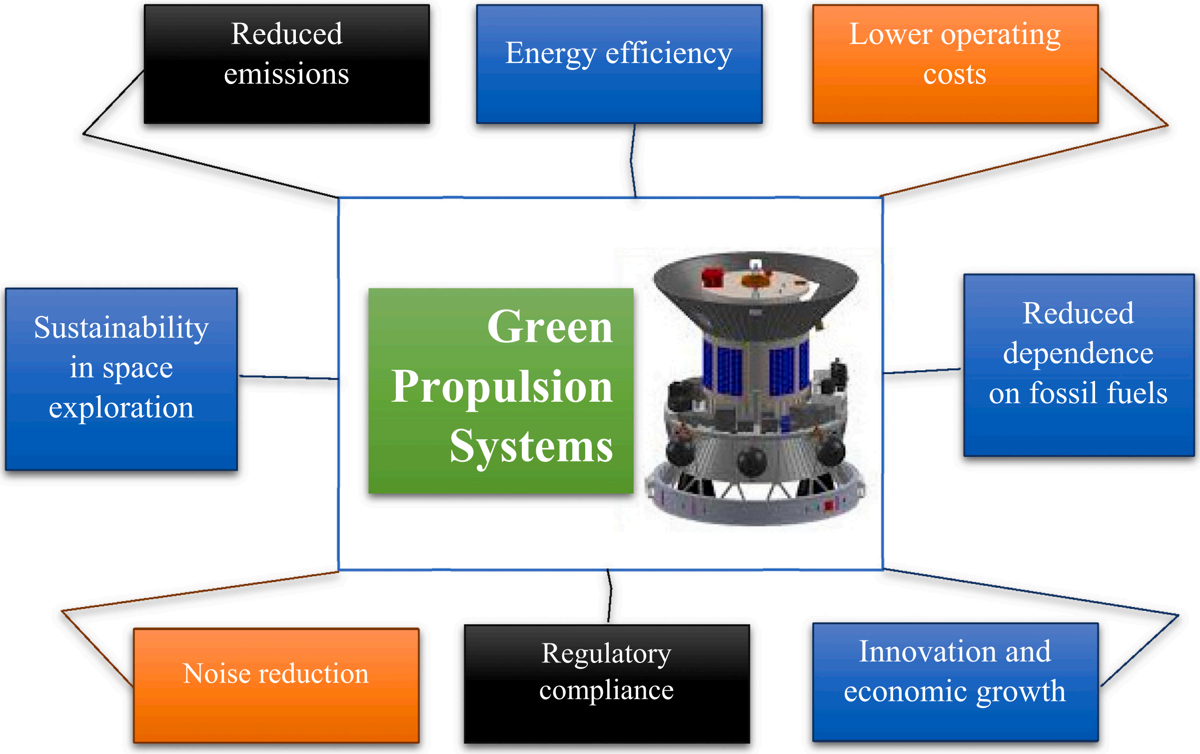

Fig. 2. Benefits of green propulsion systems in sustainable and technological progress.

launch. The introduction of reusable rockets, such as SpaceX's Falcon 9 and Blue Origin's New Shepard, has significantly reduced the need for manufacturing new rockets for each mission. This not only lowers costs but also decreases the overall environmental footprint by reducing the consumption of materials and energy involved in rocket production. Reusable rockets are increasingly becoming the norm in commercial spaceflight, with more companies investing in this technology to align with sustainable practices.

3.2. Renewable energy sources

The integration of renewable energy sources represents a critical pathway toward net-zero space exploration, with solar energy serving as a cornerstone for powering spacecraft, satellites, and space stations like the ISS. Optimal attitude control for solar-powered spacecraft enhances net energy acquisition during maneuvers, reducing fuel dependency (Kristiansen et al., 2021). While solar-powered satellites offer reliable, cost-effective energy generation, their widespread adoption requires reduced launch costs, improved solar panel efficiency, and international collaboration (Meftah et al., 2022). Beyond spacecraft applications, solar energy powers ground-based operations at launch facilities and manufacturing plants, offering thermal energy storage capabilities that reduce utility consumption and enhance operational profit in multipurpose batch facilities (Simão et al., 2022).

SBSP represents a transformative development in renewable energy for space exploration. This technology, which traps solar energy and generates electric power using photovoltaic cells, converts it to DC power, stores it in a battery reserve, and transmits it to an earth station via microwave beam (Boddu et al., 2019), could provide continuous clean energy to nations with constrained energy resources (Cash, 2019; Pelton, 2019). SBSP systems, as described by Wood and Gilbert (2022), generally comprise three primary components: the generation apparatus, the beam-forming and direction system, and the receiver. The generation component typically consists of a vast array of photovoltaic (PV) cells, converting sunlight directly into electricity. However, these PV panels, often made of thin silicon wafers, face significant challenges in the harsh environment of space. Deep space radiation can degrade their performance more rapidly than ground-based systems, and impacts from space debris or micrometeorites pose a constant threat (Wood and Gilbert, 2022). One promising approach to mitigating these challenges is presented by Abiri et al. (2022), who propose a novel design for a lightweight SBSP system using high-efficiency III-V photovoltaics and a modular configuration of small, repeatable unit cells called "tiles." This modular design enhances resilience against damage from space debris, as individual tile failures would have minimal impact on the overall system output (Abiri et al., 2022). Furthermore, their design incorporates lightweight parabolic concentrators to focus sunlight onto the PV cells, potentially increasing efficiency and reducing the required surface area. This aligns with the findings of Giorgio et al. (2024), who highlight the potential of refraction mirrors to enhance the efficiency of solar energy collection in SBSP systems.

Rodgers et al. (2024) highlight the significant costs associated with SBSP, particularly the expenses related to launching materials into orbit. Their analysis of two SBSP designs, the Innovative Heliostat Swarm (RD1) and the Mature Planar Array (RD2), reveals that launch costs account for 71 % and 77 % of the total lifecycle cost for each design, respectively (Rodgers et al., 2024). This underscores the need for more cost-effective launch solutions to make SBSP economically viable. Furthermore, the study indicates that manufacturing costs, including the development and production of spacecraft modules, contribute significantly to the overall expenses. The lightweight design proposed by Abiri et al. (2022), with an areal mass density of 160 g/m2, could potentially alleviate these cost pressures by reducing the mass requiring launch. Giorgio et al. (2024) acknowledge the challenge of the large size of SBSP systems and the associated launch costs but suggest that reusable space transportation vehicles could offer a solution. Ambatali and Nakasuka (2024) further address this challenge by proposing a thin-film SSPS design that utilizes foldable membrane satellite modules. This approach reduces weight and allows for compact stowage, potentially lowering launch costs.

The beam-forming and direction system is crucial for efficient energy transmission. In one study, two power transmission systems for SBSP were explored: laser and radio frequency (RF) (Cougnet et al., 2004). While lasers are suitable for long distances and smaller receivers, they are susceptible to attenuation in planetary atmospheres, particularly due to dust storms. RF systems, on the other hand, are advantageous at shorter distances and less affected by atmospheric conditions (Cougnet et al., 2004). The choice between laser and RF transmission depends on the specific application and environmental factors. For instance, in the case of Mars, it was suggested that RF systems may be preferable due to their robustness against dust storms. Giorgio et al. (2024) emphasized the importance of further research and experimentation to ensure the safety and efficiency of microwave transmission, including minimizing energy losses and preventing harm to humans, wildlife, and aircraft navigation. Another study also emphasized the need for further research and development in wireless power transmission technologies to ensure efficient and reliable energy transfer over long distances (Alam et al., 2024).

The receiver, or rectenna, is a ground-based structure designed to capture the incoming energy beam and convert it back into electricity for distribution to the grid. The sheer size of the rectenna required to capture the dispersed energy beam raises concerns about land use and potential environmental impacts. Additionally, ensuring the safety of people, animals, and infrastructure in the vicinity of the rectenna requires careful design and operation (Wood and Gilbert, 2022). Rodgers et al. (2024) further emphasized the environmental considerations associated with SBSP, noting that while the lifecycle greenhouse gas emissions of SBSP are lower than those of fossil fuels, they fall within the range of emissions from terrestrial renewable energy sources. Abiri et al. (2022) address these concerns by designing their system to operate within the 1–10 GHz frequency range and ensuring that the power intensity at the ground level does not exceed that of ambient sunlight. In addition, there is a need for careful consideration of the orientation systems and potential impacts on aircraft and satellites (Giorgio et al., 2024).

Each of these components presents unique challenges to the feasibility of SBSP. Overcoming these challenges will require significant advancements in materials, engineering, and operational strategies. For example, developing more radiation-resistant PV materials and robust protection mechanisms against space debris will be crucial for the long-term viability of SBSP systems. The advancements in battery technologies, such as photo-rechargeable nanocomposites, have significantly enhanced storage efficiency (Singh P. et al., 2024). The CASSIOPeiA system exemplifies SBSP's potential, proposing a scalable approach from sub-megawatt to gigawatt systems that could simultaneously address Earth's energy needs and reduce space operations' carbon footprint (Cash, 2019). Unlike terrestrial solar installations, SBSP systems operate independently of weather conditions and daylight cycles, offering consistent renewable energy generation while supporting both orbital and Earth-based activities with sustainable power on an unprecedented scale.

3.3. Satellite technology and environmental monitoring

Satellites serve as critical tools in monitoring Earth's environmental systems and supporting global climate change initiatives. Advanced satellite sensors provide comprehensive data on key climate indicators, including deforestation patterns (Finer et al., 2018; Hadi et al., 2018; Reiche et al., 2018), sea-level variations (Vignudelli et al., 2019; Adebisi et al., 2021; Mangan, 2023), ocean temperature fluctuations (Minnett et al., 2019; O'Carroll et al., 2019; Jung et al., 2022), and atmospheric greenhouse gas concentrations (Müller et al., 2021; Wang et al., 2023).

This real-time environmental data enables evidence-based policymaking and conservation efforts.

The evolution of satellite technology itself contributes to net-zero objectives through enhanced efficiency and environmental considerations. The emergence of CubeSats exemplifies this progress, offering reduced fuel requirements for launch and operation compared to conventional satellites (Al-Hemeary et al., 2020). These miniature satellites, deployable in clusters, provide cost-effective and rapid development cycles while utilizing solar and magnetic sensors for economical navigation (Nurgizat et al., 2023). The reduced mass of roughly one kilogram (Kuntanapreeda, 2019) and size of these systems measuring 10 cm along each axis (Monkell et al., 2018), minimizes environmental impacts during production and deployment, while the integration of efficient technologies, including advanced solar panels which can generate up to 9.62 % of the energy generated by conventional solar panel systems, and energy-conscious components (Ostrufka et al., 2019), extends operational lifespans. This longevity reduces replacement frequency and associated launch emissions, further advancing sustainability goals in satellite operations.

3.4. *Circular economy in spacecraft design*

The adoption of circular economy principles in spacecraft design represents a transformative approach to space sustainability. The space industry inherently serves as a ‘natural environment’ for implementing circular economy concepts, offering valuable insights for terrestrial applications (Paladini et al., 2021). Unlike traditional linear economies that follow an extract-use-dispose model, circular economy approaches minimize waste through systematic reuse, recycling, and repurposing of materials throughout the spacecraft lifecycle. As illustrated in Fig. 3, the circular economy framework encompasses multiple integrated phases. Spacecraft are engineered with an emphasis on longevity, modularity, and recyclability, utilizing sustainable materials to reduce resource extraction. This approach extends to production efficiency, distribution systems, and operational longevity through repair and upgrade capabilities rather than replacement. The implementation of reverse logistics systems enables material recovery and repurposing (Ayyaz and Görener, 2019), while innovative waste management transforms inevitable waste into energy or ensures secure disposal (Farooq et al., 2022).

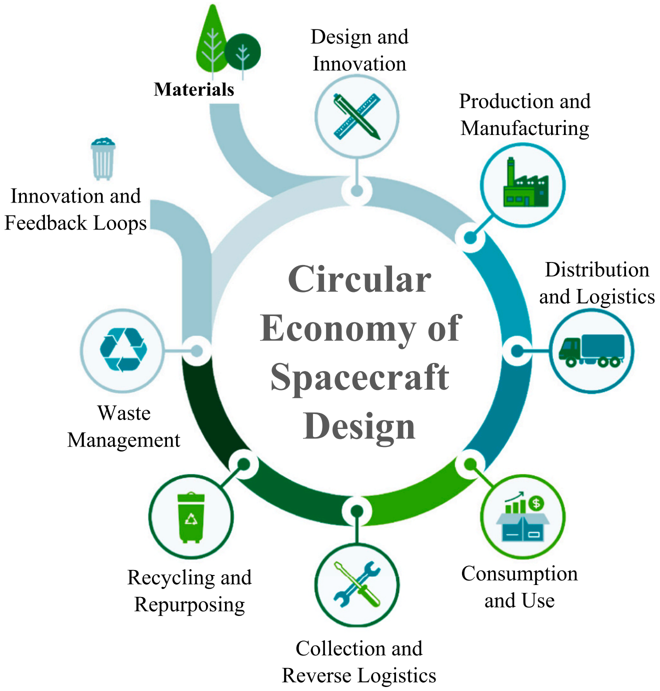

Fig. 3. Phases of the circular economy in sustainable product lifecycle management.

The application of these principles significantly reduces the environmental footprint of space missions (Velenturf and Purnell, 2021). Modular spacecraft designs facilitate component repair and upgrade, extending operational lifespans while reducing material demand and waste. Similarly, innovative satellite systems incorporate end-of-life considerations, such as the DEORBITSAIL project, which provides an economical de-orbiting mechanism using solar sails for safe atmospheric incineration of spacecraft under 500 kg (Lappas et al., 2011). These advancements in circular design principles not only minimize space debris but also establish a more sustainable framework for long-term space exploration.

3.5. *Environmental considerations*

Recent studies have provided quantitative data on the environmental impact of various space propulsion systems. Deroo et al. (2024) conducted a life cycle sustainability assessment (LCSA) of four monopropellant systems, surprisingly finding that those using ASCENT and LMP-103S had a significantly larger environmental impact than traditional hydrazine systems. This was primarily attributed to the substantial resource use and ecotoxicity associated with iridium and rhenium extraction, key components in ASCENT and LMP-103S thrusters. Conversely, Pettersen et al. (2016) found that chemical-electric propulsion systems, while offering high specific impulse (Isp), have a larger environmental footprint due to the energy-intensive production of xenon propellant. These findings underscore the importance of considering the full life cycle impacts of different propulsion technologies when evaluating their sustainability.

The environmental impact of space propellants is further compounded by the need for high purity. Pettersen et al. (2017) highlighted that the purification of space-grade propellants, such as hydrazine and liquid hydrogen, significantly increases their environmental impact due to the energy required and the use of solvents. This is exemplified by space-grade liquid hydrogen produced in Kourou, which generates an order of magnitude more environmental impact than conventional liquid hydrogen. However, research also indicates potential for improvement. Cardiff et al. (2014) demonstrated that green propellants like AF-M315E and LMP-103S can offer mass and volume benefits compared to hydrazine, potentially leading to reduced launch emissions. Furthermore, their analysis showed that these green propellants can increase the ΔV capability of spacecraft by 24.9 % to 35.6 %, enhancing mission efficiency and potentially reducing the need for additional launches. These findings suggest that while challenges remain, there are pathways toward reducing the environmental impact of space propulsion through careful material selection and technological advancements.

Beyond individual technologies, a more integrated approach to evaluating sustainable propulsion is necessary. Lily et al. (2024) advocate for a holistic framework that considers multiple factors, including environmental impact, performance, cost, and reliability. Their case study comparing different bipropellant options demonstrates that greener alternatives can be selected without necessarily compromising performance or cost-efficiency, particularly for less demanding missions. This highlights the importance of a comprehensive evaluation approach that aligns with specific mission objectives to promote the adoption of sustainable propulsion solutions.

3.6. *The role of artificial intelligence in sustainable space exploration*

As space activities continue to expand, the integration of Artificial Intelligence (AI) has emerged as a transformative tool for enhancing sustainability in space exploration. AI-driven solutions are increasingly being applied to orbital debris tracking, predictive modeling for launch emissions, and AI-optimized propulsion systems, all of which contribute to achieving net-zero emissions and mitigating the environmental impact of space missions. Machine learning-based approach improves orbit prediction accuracy of space debris by at least 50 %, showing its potential in enhanced space situation awareness (Li et al., 2020). By leveraging machine learning algorithms and advanced computational models, AI enhances the efficiency, accuracy, and sustainability of space operations (Furano et al., 2020).

One of the most pressing challenges in space sustainability is the growing threat of orbital debris, which poses collision risks to operational satellites and spacecraft. Traditional methods of tracking debris rely on ground-based radar and optical telescopes, for instance, THz radar can effectively achieve high-resolution 3-D imaging of spinning space debris (Yang et al., 2018), but AI-driven orbital debris tracking systems have significantly improved real-time monitoring and prediction capabilities. Machine learning algorithms analyze vast datasets from space surveillance networks (Nguyen et al., 2019), enabling more accurate tracking of debris movement and potential collision risks. AI-powered systems, such as those developed by NASA and the European Space Agency (ESA), use historical debris patterns to predict future debris trajectories (Shen et al., 2022), allowing space agencies to design collision-avoidance maneuvers that minimize fuel consumption and mission disruptions. Additionally, AI facilitates automated debris removal strategies, optimizing the deployment of robotic systems designed to capture and deorbit hazardous space junk (Sharma and Sinha, 2022).

Beyond debris tracking, AI-driven predictive modeling plays a crucial role in reducing launch emissions (Shankar, 2023). By analyzing environmental data, propulsion system parameters, and atmospheric conditions, AI can forecast the carbon footprint of rocket launches with greater precision. These models enable space agencies and private companies to optimize launch windows, fuel efficiency, and trajectory planning to minimize emissions. AI-based simulations can also assess the long-term atmospheric impact of different rocket fuels (Casalino et al., 2024), contributing to the development of greener propulsion alternatives. This data-driven approach aligns with sustainability goals by promoting informed decision-making that reduces the environmental impact of space activities.

AI is also revolutionizing propulsion systems, leading to more sustainable space travel. Traditional propulsion technologies rely on fixed operational parameters, often resulting in inefficient fuel consumption. AI-optimized propulsion systems use real-time data analysis and adaptive algorithms to dynamically adjust engine performance, optimize fuel usage (Zheng et al., 2022), and enhance thrust efficiency. For example, deep reinforcement learning models have been used to fine-tune ion thrusters, allowing for more precise control of thrust levels based on mission needs (Federici et al., 2023; Brandonisio et al., 2024). AI-enhanced propulsion not only reduces fuel consumption but also extends the lifespan of spacecraft, reducing the frequency of replacement launches and lowering the overall carbon footprint of space exploration.

Furthermore, AI contributes to mission autonomy, reducing reliance on Earth-based control centers that require significant energy resources. AI-powered spacecraft can make real-time navigation and operational decisions without constant human intervention, leading to more efficient fuel management and resource utilization. This capability is particularly crucial for deep-space missions, where communication delays make real-time human control impractical. By integrating AI into mission planning and execution, space agencies can further enhance sustainability in both near-Earth and interplanetary exploration.

The integration of AI into space sustainability efforts represents a paradigm shift in how missions are designed, executed, and maintained. From tracking orbital debris to predicting and mitigating launch emissions and optimizing propulsion systems (Li et al., 2020), AI-driven innovations play a critical role in advancing net-zero space exploration. As AI technology continues to evolve, its potential to enhance sustainability in space activities will only grow, offering new opportunities for reducing environmental impact while expanding humanity's reach into the cosmos.

4. Policy and international collaboration

The path to achieving net-zero emissions in space exploration goes beyond technological advancements; it also requires significant developments in policy and international collaboration (Zhang et al., 2021; Perri et al., 2022, 2023; Tiwari et al., 2024). As space is a global commons, the environmental consequences of space activities—whether emissions, space debris, or resource depletion—are shared by all nations. Therefore, addressing these challenges demands coordinated efforts that transcend national boundaries. International policies and regulatory frameworks must evolve to ensure that sustainability becomes an integral part of space exploration. Likewise, collaboration between public and private entities can accelerate the adoption of sustainable practices and technologies within the industry.

4.1. *Regulatory frameworks for sustainable space activities*

International regulatory frameworks are critical to aligning space exploration with global sustainability goals. While organizations like UNOOSA and ITU have established guidelines for space activities and resource sharing (Pritchard-Kelly, 2023), current frameworks require enhancement to adequately address carbon emissions from launches and environmental risks from space debris. The development of comprehensive carbon accounting systems for space activities represents a crucial regulatory advancement. Such systems, modelled on terrestrial industry standards, would encompass both stocks and flows, connecting human activities with biospheric and atmospheric responses to facilitate climate mitigation assessment (Keith et al., 2021; Kaur et al., 2024). Implementation of emission trading schemes in the space sector offers another promising approach. Evidence from China's emission trading pilots demonstrates the potential effectiveness, showing an average annual carbon intensity reduction of 0.026 tons per 10,000 yuan in pilot regions (Zhou et al., 2019).

Space debris management demands particularly robust regulatory attention. While current guidelines promote responsible satellite disposal and deorbiting technology adoption, stronger enforcement mechanisms are essential (Lappas et al., 2011; Rossi et al., 2018). These should include mandatory end-of-life disposal plans for spacecraft and stringent penalties for non-compliance. The transnational nature of space debris necessitates international collaboration in establishing and enforcing clear standards supported by effective monitoring mechanisms. This regulatory framework must balance innovation and exploration with environmental protection, ensuring sustainable practices across all space activities while maintaining accountability through measurable standards and enforcement protocols.

4.2. *Public-private partnerships*

Public-private partnerships are increasingly vital in advancing sustainable space exploration as the industry shifts toward commercialization. Public-private research and development partnerships (PPRDPs) promote open-source research, generating beneficial information spillover effects and agglomeration externalities (Rausser et al., 2023). While such collaborations have proven successful in the U.S. and Great Britain, implementation challenges persist in regions like Russia due to limited high-tech production capabilities and bureaucratic constraints (Zavarukhin et al., 2022).

Government support through financial incentives, including green credit guarantee programs and tax reallocation from energy supply sectors, can stimulate private engagement in sustainable space technologies (Taghizadeh-Hesary and Yoshino, 2019). The development of reusable rockets exemplifies successful public funding impact on environmental innovation in space launches (Jozič et al., 2020). Beyond financial incentives, joint research initiatives between space agencies and private companies address complex sustainability challenges, with organizations like NASA establishing communities of practice within their Engineering Network to enhance information transfer (Topousis et al., 2012).

Private sector competition significantly drives sustainable innovation. The relationship between private investment and advancements in small satellite technology fosters industry growth while enhancing societal benefits (Plugar et al., 2021). Companies like SpaceX, Blue Origin, and Rocket Lab demonstrate how competition can accelerate developments in reusable technology and cost-effective launches. Government agencies further influence sustainability through contract requirements and environmental standards, while international forums like COPUOS facilitate global collaboration on emission reduction and debris management. These partnerships ensure commercial space activities align with broader environmental protection goals while maintaining technological innovation and economic viability.

5. Challenges and limitations

The pursuit of net-zero emissions in space exploration faces multiple interconnected challenges across technological, economic, and regulatory domains. A primary obstacle is the substantial cost of developing and implementing green space technologies. While initiatives like SpaceX and Blue Origin's reusable rockets demonstrate progress, the high initial investment requirements create significant barriers for smaller companies and emerging space programs. This challenge necessitates comprehensive frameworks for managing prolonged space missions' programmatic aspects and expenses, particularly as current initiatives focus primarily on solar system exploration (Wilson et al., 2023).

Technical limitations present additional hurdles, particularly in deep-space missions where renewable energy implementation becomes increasingly complex. As spacecraft venture farther from the Sun, the diminishing solar intensity compromises the viability of solar power, often necessitating reliance on traditional chemical fuels or nuclear power sources. This challenge is compounded by the complexity of managing sustainability in extended missions, where resource recycling and component reuse become logistically challenging. The regulatory landscape presents further complications, characterized by fragmented international frameworks and inconsistent compliance with existing guidelines.

Additionally, a significant challenge lies in the fragmented regulatory landscape governing space sustainability. While international organizations such as UNOOSA provide overarching guidelines, enforcement and implementation vary significantly at the national level. For example, UNOOSA's Space Debris Mitigation Guidelines offer recommendations on limiting space debris, yet compliance remains voluntary, leading to inconsistent adherence across nations (Portelli et al., 2010). In contrast, some national policies, such as the United States' Space Policy Directive-3 (SPD-3) and the European Space Agency's Clean Space Initiative, impose stricter sustainability measures, including mandatory end-of-life disposal plans and active debris removal programs (Bohlmann and Koller, 2020). However, discrepancies between national regulations and the lack of legally binding international agreements create loopholes that allow certain entities to operate with minimal environmental accountability. A comparative analysis of existing treaties and national policies highlights the need for a harmonized global framework that enforces sustainability standards uniformly across all space-faring nations. Without such cohesion, space exploration risks continued environmental degradation, as regulatory gaps enable some actors to prioritize economic and strategic interests over long-term sustainability. Strengthening international cooperation and developing enforceable global treaties will be essential in ensuring that space exploration aligns with net-zero objectives (Pankova et al., 2021).

The challenge is further exacerbated by uneven technological development and adoption rates between established space programs and emerging ones, creating disparities in environmental impact mitigation capabilities. Additionally, geopolitical competition often supersedes environmental considerations, as nations prioritize strategic space capabilities over sustainability goals. These multifaceted challenges underscore the need for enhanced international cooperation, standardized regulatory frameworks, and innovative solutions to achieve sustainable space exploration while maintaining technological progress and economic viability.

6. Conclusion

The integration of sustainability principles into space exploration represents a critical imperative for human progress. The environmental impacts of space activities—from launch emissions to orbital debris—demand comprehensive solutions that align technological advancement with environmental stewardship. Achieving net-zero emissions in space exploration encompasses both technological innovation and ethical responsibility, particularly given space's status as a global commons. Significant progress in green propulsion systems, including electric and solar-electric technologies, alongside the development of reusable rockets, demonstrates the feasibility of reducing space operations' carbon footprint. The continued evolution of solar power applications, both in spacecraft systems and ground operations, coupled with research into space-based solar power (SBSP), presents promising pathways for clean energy solutions benefiting both space exploration and terrestrial applications.

The success of sustainable space exploration hinges on robust international collaboration and regulatory frameworks. Given the borderless nature of space, emissions and debris management require coordinated global responses. The implementation of comprehensive regulatory systems, supported by public-private partnerships that drive sustainable innovation, is essential for industry-wide progress toward net-zero goals. The adoption of circular economy principles in spacecraft design and operation offers additional sustainability benefits through material reuse, recycling, and repurposing, reducing manufacturing demands and extending component lifecycles.

Despite facing significant technological, economic, and regulatory challenges, sustainable space exploration offers transformative potential. Beyond environmental protection, a sustainable space sector catalyzes innovation, generates new industries, and contributes to addressing terrestrial challenges through enhanced climate monitoring and renewable energy development. This approach ensures that humanity's space aspirations advance in harmony with Earth's environmental preservation, creating a legacy of responsible exploration for future generations.

CRediT authorship contribution statement

David Bamidele Olawade: Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization. **James O. Ijiwade:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation. **Ojima Zechariah Wada:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization.

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