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Review Article

An Inevitable Technological Disaster Type: Space Debris

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Abstract

The rapid accumulation of space debris has emerged as a critical threat to global satellite infrastructure, jeopardizing essential services such as communications, navigation and real-time weather forecasting, which are fundamental to effective disaster management. This paper provides a comprehensive review of the multifaceted challenges posed by space debris, focusing on collision risks, Kessler Syndrome and the inherent vulnerabilities of satellite networks. It highlights significant gaps in existing international regulatory frameworks, underscoring the urgent need for stronger global coordination. While technological interventions such as Active Debris Removal (ADR) and enhanced Space Situational Awareness (SSA) show promise, they fall short when applied alone. A sustainable solution requires an integrated approach that combines innovative technologies such as on-orbit manufacturing and self-destruction systems with policy reforms that enforce stricter debris management protocols and encourage compliance with economic measures such as debris removal credits and orbital parking fees. China, European Union, the United States and some other countries have already begun the work needed to coordinate space activities, but the breadth of these efforts and rules varies from country to country, and the lack of ownership or control of space is a problem. Given the important role of satellites in disaster response, the protection of space assets is essential to sustaining global resilience. Ensuring long-term sustainability will depend on international cooperation, binding agreements and a collective commitment to preserve the orbital environment for future generations.

Keywords

Space Debris, Active Debris Removal (ADR), Space Situational Awareness (SSA), Kessler Syndrome, Technological Disaster.

1. Introduction

In the era of rapid technological advancement, space activities have become integral to modern civilization, supporting essential services such as communication, navigation, weather forecasting, and defence. There is however a paradox that exists with the increased use of space infrastructure systems, the increasing problem of space debris. This debris typically includes spent satellites, rocket stages, and fragments from objects that have collided or exploded. This represents a significant hazard for both operational satellites and crewed space missions. The threat extends beyond outer space, affecting critical disaster-mitigation activities like emergency communication, weather services, and satellite navigation systems.

As of 2024, there are an estimated 130 million mini debris objects (less than 1 cm), 1.1 million objects (between 1 cm and 10 cm) and 40,500 objects (greater than 10 cm) in polar orbit around the earth in low earth orbit (European Space Agency [ESA], 2024). Even small objects travel at speeds of up to 28 km/h, hence even a small piece can turn into a destructive instrument that can cause major damage and even obliterate satellites (Swope et al., 2024). Also, the situation in LEO is worsened by the launching of mega constellations such as Starlink and OneWeb that plan to place thousands of satellites to ensure the availability of worldwide internet coverage. These constellations, while being of great economic and technological advantages, create a serious threat of impact collision which may destabilize the environment and, in effect, cause the Kessler Syndrome – a system of debris (Buchs, 2021). Based on 'Orbiting Now' (NanoAvionics, 2024), more than 7,000 Starlink satellites have been launched into orbit, while an estimated 9,900 operational satellites exist. Although these projects have many advantages, the risk factors from their 'end-of-life' phase heighten worries of the how these will perform in space.

The implications of space debris are profound, not only for spacefaring nations but for global disaster management capabilities. In the event of a possible disaster, activities to return life to normal are addressed in four stages: disaster response, rescue, recovery, mitigation and disaster preparedness (Öcal, 2019; 2021). Satellites play a crucial role in providing real-time data for monitoring natural disasters such as hurricanes, earthquakes, floods, and wildfires (Ryan et al., 2022). For instance, in the case of a disaster and especially within a vast area, the satellites help maintain critical telecommunication systems and help in locating the injured using satellite-based systems (ESA, 2016; Dukiya&Banji Adeleye, 2022). Unfortunately, if these services are disrupted by a collision with debris, efforts to respond to and manage the effects of a disaster will be greatly hampered in terms of saving lives and properties.

Despite these well-documented risks, global efforts to mitigate space debris remain inadequate. The existing mechanisms like the guidelines of the Inter-Agency Space Debris Coordination Committee (IADC) and the recommendations of the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) constitute soft law provisions on debris mitigation (Lambach& Wesel, 2021). These guidelines include principles like the 25-year rule, which requires that satellites be deorbited or moved to a disposal orbit within 25 years after mission completion (Virgili et al., 2016). However, several challenges hinder adherence to these recommendations, particularly among commercial satellite network providers, where economic factors and rising operational costs often take precedence over environmental concerns (Maclay& McKnight, 2021). Furthermore, the existing SSA Space Situational Awareness systems only keep track of a very small percentage of debris, primarily those objects that are over ten centimetres in size, while a few million even more hazardous pieces of debris remain untracked and unmeasured (ESA, 2024).

The obligation to maintain cleanliness and order in the orbits of the Earth is shared by every nation and commercial enterprise that launches and operates in space. Those who do not participate in such activities but depend on the services provided by satellites are not immune to the potential consequences of their inaction (OECD, 2026). This is yet another example of the tragedy of the commons; here, the actors involved are rationally self—interested and act in their own short—term — in fact, the less each of them cares about the resources, the more degraded they are (Lambach & Wesel, 2021). In the absence of adequate measures to reduce space debris, the increase in space activities, which is uncontrollable at this point, has already resulted in serious incidents such as that of Iridium and Cosmos in 2009, which destroyed over 2000 pieces of defined debris (Buchs, 2021).

To tackle the problem of space junk, a wide range of interventions including technology, regulations, and financial motivations is necessary. One such development relates to the creation of Active Debris Removal (ADR) systems which has technological promise. Companies such as Astroscale as well as regional players like the European Space Agency (ESA) are already experimenting with ways to incorporate nets, robotic arms, and even harpoons in a bid to capture and remove large objects of debris from the earth's orbit (Degrange, 2019). Widespread fragmentation of such larger debris, however, commendable as it may be, will not address the raise many problems financial and technical that ADR face today, bringing into a need for cooperation among the countries of the earth (ESA, 2016). Along with these technologies however, there is a great realization that there is need for stricter international laws to make such measures effective. The persistent lack of effective, legally enforceable treaties that address the issue of space debris removal still impedes progress, and the establishment of such a system is imperative due to the lack of regulations governing Outer Space Operations, including a Space Traffic Management (STM), which would be regulated by an organization to ensure compliance (Maclay & McKnight, 2021). Or, alternatively, economic tools, for example, the credits for the removal of debris, or the fees for orbital parking, could motivate the private sector to consider more seriously their commitments to protecting the orbits (Carroll, 2019).

This review aims to provide a comprehensive analysis of what is the space debris problem, what can be its possible dangers focusing on its implications for disaster management, the current challenges in debris mitigation, and the potential solutions that could lead to a sustainable space environment.

2. Challenges of Space Debris

One of the most important hurdles in maintaining the viability of space activities as well as services performed on Earth is the increasing amount of space debris orbiting the planet. This is due to the fact that many active satellites have been launched particularly the launching of large constellations of satellites in low earth orbit. The number of such incidences has drastically increased due to the increase in a number of objects within the space. The problems created by these phenomena in turn cause other problems by creating more debris which in turn can lead to the destruction of the entire orbital ecosystem and the systems that go with it such as when there is a catastrophe. Given that there is a rapid increase in spatial capabilities of both individual countries and commercial entities, there is no need to re-emphasize the importance of solving the problem of space debris.

2.1. Collision Risks and Orbital Congestion

With over 130 million debris objects currently in orbit, ranging from fragments smaller than 1 cm to larger defunct satellites and rocket stages, the risk of collisions in LEO has increased significantly (European Space Agency [ESA], 2024). Even small debris fragments, traveling at velocities of 28,000 km/h, can cause catastrophic damage to operational satellites, rendering them useless and generating even more debris. Mega-constellations like SpaceX's Starlink and OneWeb have increased congestion in low Earth orbit (LEO), raising the risk of accidental collisions between satellites and debris. (Virgili et al., 2016). With SpaceX alone planning to deploy over 12,000 satellites, the task of collision avoidance has become far more complex, and as of 2024 it reached the target of 7,000. (Maclay& McKnight, 2021). Also, sending satellite to the space and space business is not just dependent on SpaceX, which is also funded by many venture capitals and small companies. The logic of business model is "renting slots". One company is producing satellite, and it allocate some slots to rent very small companies to fund itself for the satellite project. This makes to funding new space projects easier.

The threat of collisions is ever-present. A good illustration is the 2009 incident involving the collision of Iridium 33 satellite with an old Russian satellite, Cosmos 2251, which resulted in more than 2000 trackable pieces of debris. Evidence that one episode may greatly worsen the issue of space debris. (Buchs, 2021). Moreover, this example serves to demonstrate the risk that such legacy orbital debris that is not tracked presents to functioning spacecraft, even in a state of inaction. The continued expansion of satellite constellations into densely packed orbital regimes will lead to more incidents of on-orbit collision unless the issues of tracking and mitigation are addressed. Not only active satellites but also spent upper stages of rockets and other big space objects which are no longer in use add to the space debris. Such enormous space debris can break up due to collisions and form numerous small debris pieces that are still dangerous. Satellites located in geostationary orbit (GEO) are also at risk of this kind of events, as they perform critical functions including those for weather monitoring and telecommunication services. Disruption of such geostationary satellites might bring about serious effects to the systems on earth especially for systems responsible for disaster management and crisis communication (Ryan et al., 2022).

2.2. The Kessler Syndrome: A Self-Perpetuating Cascade

The Kessler Syndrome remains one of the most significant long-term threats posed by space debris. First proposed by NASA scientist Donald Kessler, this scenario suggests that as the density of objects in orbit increases, the likelihood of collisions will rise exponentially. Each collision will generate more debris, leading to a self-sustaining cascade that could render entire regions of LEO unusable for future operations (Buchs, 2021). The threat of the Kessler Syndrome is particularly concerning in the context of mega-constellations, where thousands of satellites occupy the same orbital region. The 775 km, 850 km, and 975 km altitudes of LEO are already hotspots for debris, and any major collision in these areas could trigger a cascading effect. This would have devastating consequences as means of technological disaster, as the loss of key satellites could cripple communication networks and disrupt navigation services that are essential for coordinating relief efforts during natural disasters (ESA, 2024).

2.3. Disaster Management and Space Debris

A collision between satellites in outer space can be defined as a crisis not only in the spatial context but also in terms of the earthly systems which are satellite-dependent. Satellites are vital elements in the prediction and mitigation of hazards. Key satellites that are primed in geosynchronous earth orbits (GEO) or those that are low tend to provide services such as weather forecasting, communication and navigation which are needed on the ground for the healthcare systems in the event of a probable disaster. A major impact could render critical satellite resources unusable when quick response actions are needed hence hampering communication and satellite-based forecasting of the disaster. For instance, when a debris crash causes damage to a weather satellite, such a weather forecast would be done after the scheduled time, which pushes the estimation of the potential flood seasonal hurricane casualties to a later and more treacherous time. Hence, in this way, the collision of space objects can escalate a natural calamity into a worldwide disaster. In addition, meteorological satellites furnish timely notice of the development of hurricanes, typhoons and floods; extending governments and people the chance to take appropriate measures to reduce the impact of the monster. Again, such satellites, which provide video images, are necessary to assist rescue activities after a disaster strikes, particularly in areas where land phone services have been disrupted (ESA, 2016). Therefore, the greatest risk to the operation of such satellites is space debris. In 2020, the incident of the OneWeb and Starlink satellite constellation demonstrated how active avoidance activity also shows the downside of satellite operation, where such nearness leads to service disruption and also raises issues on the safety of space (Buchs, 2021). As satellite constellations become larger and more complex, the risk of losing key satellite capabilities due to debris-induced collisions becomes a serious concern for disaster preparedness and response strategies. Each day this threat is increasing because of an increasing number of satellites. During disaster relief efforts, rescue crews depend on navigation satellites, including those in the Global Navigation Satellite System (GNSS), for guidance. The capacity of relief workers to get to affected areas promptly and effectively could be significantly impacted by any disruption in GNSS services brought on by debris collisions. Therefore, the issue of space debris is a worldwide concern that has a direct impact on the welfare of people on Earth and is not limited to spacefaring states (Maclay & McKnight, 2021).

2.4. Lack of Global Coordination and Regulatory Gaps

The lack of international coordination and enforcement systems that guarantee compliance with debris reduction guidelines makes managing space debris more difficult. Although non-binding guidelines, such as the widely recognized 25-year rule for satellite deorbiting, have been developed by international organizations like the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) and the Inter-Agency Space Debris Coordination Committee (IADC), these frameworks lack the teeth required to enforce compliance (Lambach & Wesel, 2021). The 25-year rule recommends that defunct satellites be moved to a graveyard orbit or deorbited within 25 years of the end of their mission, but adherence to this guideline is inconsistent, particularly among private operators of large satellite constellations (Virgili et al., 2016). This lack of enforcement creates a scenario where private companies may prioritize short-term economic gains over long-term environmental stewardship. Without global regulatory bodies capable of holding operators accountable for debris mitigation failures, space actors are often left to self-regulate. As a result, the pace of debris generation outstrips mitigation efforts, particularly as the space industry becomes more privatized and competitive. The deployment of mega-constellations in LEO further complicates matters, as commercial operators may launch thousands of satellites without sufficient planning for end-of-life disposal (Maclay& McKnight, 2021).

Compounding this problem is the lack of a comprehensive Space Traffic Management (STM) system. Unlike air traffic control, which coordinates the movement of aircraft to prevent collisions, STM systems are still in their infancy and largely operate on an ad-hoc basis. Satellite operators rely on tracking data from independent Space Situational Awareness (SSA) systems to predict potential collisions, but these systems can only track larger debris objects (those greater than 10 cm), leaving millions of smaller, yet still dangerous, debris fragments unmonitored (ESA, 2024). The absence of a unified STM system increases the likelihood of accidental collisions, as operators must independently decide when to maneuver their satellites based on limited and sometimes conflicting data. The 2020 near-collision between OneWeb and Starlink satellites underscores the urgent need for better coordination and shared SSA data to prevent future accidents (Buchs, 2021).

2.5. Economic Impacts of Space Debris

Space debris isn't just a problem for the space industry; it affects many other sectors that rely heavily on satellite technology. With the cost of launching satellites dropping and companies racing to put up massive constellations, the number of objects in orbit is growing fast, which raises the risk of collisions and orbital traffic jams. This makes it essential to balance economic growth with efforts to manage space debris, as doing so can prevent potentially huge financial losses, whereas ignoring it could stall the entire space economy.

Collisions in space are costly, not just for the space industry but for industries that depend on services like GPS, Earth observation, and telecommunications. Research shows that interruptions in satellite communication can disrupt everything from financial transactions to aviation and disaster response. (Nozawa et al., 2023). Several economic models have been put out to alleviate the financial strain. Insurance models that could reduce the financial risks connected to satellite crashes are one strategy. According to these models, satellite operators must have insurance that covers possible debris-related damages. This creates a safety net that covers the financial effects of crashes and incentivizes businesses to adopt safer practices by offering lower-risk operators lower rates. By putting this approach into practice, operators may be encouraged to incorporate collision avoidance and end-of-life disposal systems into their satellites, which would promote a more responsible operational culture (Buchs, 2021). Other proposed ideas include Pigouvian taxes or tradable permits that would set limits on satellite numbers and make operators pay fees based on their potential to generate debris. These concepts are similar to tools already used in environmental protection, like carbon credits, designed to build sustainability into the economic equation (Rao et al., 2020).

Another approach focuses on Active Debris Removal (ADR), which means actually capturing and deorbiting large, defunct objects. Right now, ADR tech is still emerging and expensive, but government partnerships with private companies could help make it more accessible. For instance, the European Space Agency and ClearSpace are working together on a mission to remove debris, and both Japan and the U.S. are exploring national programs for similar goals. With governments covering part of the cost and sharing the risk, these projects become more feasible. Expanding this effort, international bodies like the United Nations could establish a global fund to provide subsidies for ADR, ensuring that both established and emerging space nations participate in keeping orbits safe and clean. Governments could support the commercialization of ADR through public-private partnerships (PPPs), co-financing projects with private companies to lower the initial financial barrier and accelerate technological development. By co-financing debris removal missions, governments can not only encourage private sector participation but also help distribute the economic burden of debris management across multiple stakeholders. Such partnerships could be further enhanced by international bodies like the United Nations establishing a global fund dedicated to debris removal, which would provide subsidies to operators engaging in clean-up activities. This would also encourage participation from emerging space-faring nations, ensuring that all countries contribute to and benefit from a cleaner orbital environment (Nozawa et al., 2023).

The economic impact of unregulated space debris could be substantial. A study by Nozawa et al. (2023) estimates that the global GDP could decline by up to 1.95% over the next two centuries if no active remediation measures are implemented. This loss is attributed to reduced satellite operations, disruptions in services, and increased costs for collision avoidance and risk mitigation. The study also highlights that the implementation of debris remediation measures, such as ADR, can significantly mitigate these losses. By maintaining the functionality of critical satellite networks, global economic stability can be preserved, demonstrating the long-term economic benefits of investing in space sustainability.

3. Some Solutions to Space Debris

As the threat of space debris continues to grow, a multi-faceted approach that combines technological innovations, regulatory reforms, and international cooperation is necessary to prevent further degradation of the orbital environment. Current mitigation efforts, while crucial, are insufficient to fully address the escalating risk posed by debris, particularly in Low Earth Orbit (LEO) where a majority of the world's satellites operate. The path forward includes both preventive measures to stop the generation of new debris and active interventions to remove existing debris from space. This section explores the key solutions being implemented, focusing on debris mitigation, Active Debris Removal (ADR), and the critical role of global collaboration.

3.1. Mitigation and Passivation Techniques for Preventing Future Debris

The first line of defense against space debris is mitigation, which involves designing and operating satellites and space missions in a way that minimizes the creation of new debris. One of the most widely adopted mitigation strategies is the 25-year rule, which requires that satellites and other space objects deorbit or move to graveyard orbits within 25 years of the end of their mission (Virgili et al., 2016). While the rule is a step forward, its implementation has been inconsistent, particularly among commercial satellite operators. Many private companies face economic pressures that discourage adherence to best practices in debris mitigation, further complicating global efforts to address the issue (Maclay& McKnight, 2021). ESA's Zero Debris Approach by 2030 outlines a broader strategy for both mitigation and removal, incorporating technologies to reduce new debris creation, enhance tracking, and ensure that space objects are safely deorbited or relocated to graveyard orbits after their mission's end (European Space Agency, n.d.).

Passivation techniques, which involve removing residual energy sources such as fuel or charged batteries from defunct satellites, are another critical mitigation method. Passivation prevents explosions that can generate new debris fragments, reducing one of the main sources of additional debris. The European Space Agency (ESA) has pioneered the use of passivation valves in its satellite designs, allowing fuel to be safely vented at the end of a satellite's mission (ESA, 2016). However, like the 25-year rule, the widespread adoption of passivation techniques remains uneven across the global space industry.

A key advancement in debris mitigation is the development of self-disposal technologies, which allow satellites to autonomously deorbit at the end of their operational lives. SpaceX's Starlink satellites, for example, are equipped with autonomous propulsion systems that enable them to perform controlled re-entries, reducing the risk of becoming long-term debris (Maclay& McKnight, 2021). As more companies adopt such technologies, the overall risk of generating new debris will decrease. Additionally, innovations in satellite design for demise, which involve using materials that disintegrate completely upon atmospheric re-entry, offer a promising way to ensure that defunct satellites do not contribute to the debris population (ESA, 2024).

3.2. Active Debris Removal (ADR)

While mitigation techniques focus on preventing the creation of new debris, Active Debris Removal (ADR) technologies aim to reduce the number of existing debris in orbit. ADR is particularly important for addressing large debris objects, such as defunct satellites and rocket stages, which pose the greatest risk for catastrophic collisions. By removing these larger objects, ADR can prevent them from fragmenting into smaller debris, which is harder to track and avoid. Several ADR systems are currently in development, with Astroscale's ELSA-d mission standing out as one of the most promising. ELSA-d uses a magnetic docking mechanism to capture and deorbit defunct satellites, reducing the risk of further debris generation (Degrange, 2019). The success of this technology demonstrates the feasibility of ADR systems and has paved the way for future missions capable of removing multiple debris objects per mission.

The European Space Agency (ESA) is at the forefront of efforts to develop Active Debris Removal (ADR) technologies, recognizing that the long-term sustainability of space depends on actively removing existing debris. According to ESA, even if all space launches were stopped today, the amount of space debris would still increase due to collisions between existing objects, leading to a "cascade" effect. This highlights the necessity of ADR for stabilizing the orbital environment. One of ESA's key initiatives is the ClearSpace-1 mission, set to launch in 2025, which will be the world's first commercial debris removal mission. ClearSpace-1 aims to capture and deorbit a defunct ESA object in Low Earth Orbit (LEO). The mission involves the use of robotic arms to capture debris and safely guide it back into Earth's atmosphere, where it will burn up. This is a crucial step toward establishing a regular market for in-orbit servicing, including refueling and repair of satellites, and more importantly, preventing future collisions by removing large, high-risk objects from key orbits. Moreover, ESA emphasizes the importance of removing 5-10 large debris objects per year to stabilize debris levels in critical orbits. The removal of large, intact objects like defunct satellites and rocket stages is seen as the most effective way to prevent further fragmentation, which could exacerbate the debris problem.

Other ADR technologies include nets, robotic arms, and harpoons designed to capture and deorbit large debris objects. The RemoveDEBRIS mission, led by the Surrey Space Centre, successfully tested these techniques in 2018, demonstrating that they can be effective at capturing debris in orbit (Degrange, 2019). Another innovative approach is the use of laser systems to nudge small debris into lower orbits, where it will burn up upon re-entry. While still in the experimental phase, laser-based debris removal offers the potential to deal with debris fragments that are too small to be captured using traditional ADR methods (Maclay& McKnight, 2021). To give an example to the companies that has been working on ADR method, "ClearSpace" is a well-known startup, originally a spin-off from EPFL (École Polytechnique Fédérale de Lausanne), focused on solving the space debris problem. ClearSpace is pioneering efforts in Active Debris Removal (ADR) with a mission to capture and deorbit defunct satellites and large debris objects from orbit. Their innovative approach involves using a robotic arm to "grasp" and safely deorbit debris, reducing the risk of collisions in space. ClearSpace is contracted by ESA (European Space Agency) for its first mission.

ADR still faces several obstacles in spite of these encouraging developments. ADR is a complicated and costly solution because of the high cost of debris removal missions and the technological challenge of catching and deorbiting items in orbit. Furthermore, issues of accountability and liability have not been settled. For instance, it is unclear who should pay for the removal of outdated satellites from now-dissolved agencies or debris left behind by closed businesses (Ryan et al., 2022). Concerns regarding the possible militarization of space are also raised by the possibility that some ADR technologies, especially those that use robotic arms or lasers, could be modified for use as anti-satellite (ASAT) weapons (Carroll, 2019).

3.3. Strengthening Global Cooperation

"Effective communication and collaboration among the government, non-governmental organizations, community leaders, and the public are essential for reducing the risk of natural disasters and promoting sustainable development in landslide-prone regions" (Baruah et al., 2023).

Although these words are mentioned for the Dima Hasao region in India, it's a general approach for natural disasters and a critical aspect of solving the space debris problem is the need for stronger international cooperation. Space is a shared global resource, and the actions of one country or private company can have far-reaching consequences for others. Currently, there is no binding international treaty that mandates space debris mitigation or active debris removal (ADR). The lack of enforceable regulations leaves room for inconsistent practices across the globe, with some spacefaring nations and private operators taking minimal responsibility for their space activities. While voluntary guidelines such as those from the IADC and UN COPUOS provide a starting point, they are not sufficient to address the scale of the problem (Lambach& Wesel, 2021).

One potential solution to enhance global cooperation is the establishment of an international Space Traffic Management (STM) system. STM would serve as the space equivalent of air traffic control, ensuring that satellites and debris are closely monitored and that operators are informed of potential collisions in real time. The development of a global STM system would require significant investment and collaboration between governments and private industry, but it is essential to reducing the risk of debris-related collisions. Some initiatives toward STM are already underway, with agencies such as NASA and ESA working on improving Space Situational Awareness (SSA) systems. However, for STM to be truly effective, it will need to be embraced and integrated by all spacefaring nations (Maclay& McKnight, 2021). Sharing SSA data on a global scale would be a significant step toward improving collision avoidance. Currently, SSA systems are operated independently by different countries and private companies, leading to fragmented data and inefficiencies in tracking debris. A unified global SSA network, where all space actors share tracking data, would greatly improve the safety of space operations by ensuring that operators have access to the most accurate and up-to-date information on debris movements (ESA, 2024). This would also enable better coordination for satellite maneuvers to avoid potential collisions.

Additionally, developing nations and emerging spacefaring countries must be brought into the fold of international space debris mitigation efforts. Many of these nations are eager to enter the space economy but may lack the resources to fully implement debris mitigation technologies or adhere to SSA standards. International bodies such as the United Nations Office for Outer Space Affairs (UNOOSA) can play a key role in facilitating technical assistance and funding to help these nations comply with best practices for space debris management (Lambach& Wesel, 2021).

3.4. Regulatory Reforms and Policy Recommendations

A comprehensive strategy that incorporates targeted measures and regulatory reforms across several stakeholders, including national space agencies, commercial satellite operators, and international regulatory bodies, is required to address the ongoing problem of space debris. These parties must work together and implement transparent, doable regulations to lower the danger of collision and the current debris population to guarantee the long-term viability of space activities.

At the international level, there is an urgent need for a unified framework to address space debris. Current efforts are fragmented, with many nations adhering to non-binding guidelines that lack enforcement mechanisms. The United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) should lead efforts to create a binding global framework for standardizing debris mitigation and cleanup. This framework could provide clear directives on post-mission disposal (PMD), the integration of Active Debris Removal (ADR) technologies, and protocols for space traffic management (IRGC, 2021. An international agreement, akin to the Zero Debris Charter promoted by the European Space Agency (ESA), could encourage collaboration between space-faring nations, fostering a unified approach to debris management that emphasizes both prevention and active cleanup efforts. Moreover, economic incentives can play a pivotal role in encouraging compliance. Financial tools, such as subsidies or tax benefits, could be introduced to reward nations and companies that invest in advanced debris removal technologies or demonstrate consistent adherence to international mitigation standards (Buchs, 2021)(IRGC, 2021). Such incentives would not only encourage broader adoption of sustainable practices but also stimulate technological innovation, making space operations safer and more efficient. Similar to how environmental funds have been used to address pollution on Earth, an international fund could be created to finance large-scale debris removal projects, especially benefiting emerging space nations that may lack the resources to tackle this issue independently (IRGC, 2021).

National space agencies have a crucial role in reinforcing these international guidelines through domestic regulations. For example, agencies should enforce stringent end-of-life disposal requirements, mandating that all future satellites include autonomous deorbiting mechanisms. This would ensure that defunct satellites are removed from critical orbits, thereby reducing the risk of collisions and further debris generation (IRGC, 2021). In addition to enforcing compliance, governments can strengthen their Space Situational Awareness (SSA) capabilities by investing in infrastructure that enables more accurate tracking of space objects, including smaller, currently untracked debris. Enhanced SSA networks can provide precise data that is vital for collision avoidance, helping operators make informed decisions to prevent potential accidents. Some countries, like the United States and Japan, have already initiated national programs focused on debris removal, exploring technologies that can capture and deorbit large, defunct satellites. These programs can serve as models for other nations, illustrating how national initiatives can contribute to a broader, global effort. Furthermore, international bodies could provide funding mechanisms to support such projects in other countries, ensuring that space sustainability is a collaborative, inclusive effort (Buchs, 2021)(IRGC, 2021).

It is also important to note that commercial satellite operators are part of this ecosystem, and their collaboration is necessary for efficient management of space debris. They need to follow these practices regarding collision avoidance: they need to be capable of sharing relevant trajectory data in real time and operate under collision avoidance guidelines which minimize the chances of inadvertent collision. Enhanced coordination between commercial operators, especially those with many satellites in the same orbits, can also reduce the likelihood of disastrous consequences owing to orbital overcrowding. Furthermore, regulatory measures should encourage new satellite designs to include means of deorbiting the satellites. This enabled satellite systems at the end of their services lifetime to avoid remaining in orbit and become a threat later on. The high costs associated with debris removal can be an impediment to action, but working together can help counter this issue. This Collaborative way of working will reduce the economic restraints regarding active debris removal, thus enhancing the autonomy of operators in keeping the outer space safe for every user. For example, the ClearSpace-1 technology that is designed to retrieve and deorbit the space debris that poses high risk is an innovation that demonstrates how creativity to solve the challenges of sustainability of space can be achieved through harnessing the resources of both the public and private sector. The repealed statute needs to provide for tougher obligations on satellite users, such as being required to provide for self-disposal apparatus and postmortem measures against debris creation (ESA, 2016). The treaty could also introduce penalties for non-compliance, such as restrictions on future launches for operators who fail to deorbit their satellites or contribute to debris generation. Additionally, the establishment of debris removal quotas, where countries and private companies are required to remove a certain number of debris from orbit each year, could incentivize proactive participation in debris removal efforts (Carroll, 2019).

3.4.1. Ethical and Liability Issue

Liability is another highly controversial topic in the management of space debris. Although governments are held accountable for the harm caused by their space objects under the Liability Convention, it is unclear who is responsible for clearing debris and covering related expenses (Degrange, 2019). Because of this, there isn't a clear legal precedent that holds operators responsible for debris left by abandoned rocket stages or satellites. To guarantee that all parties contribute to the sustainability of space, a redesigned liability structure might place accountability for debris cleanup on the original operator or launch state. The problem of orphaned debris—debris left behind by entities that are no longer in existence or are not functioning in space—would likewise be resolved by this. And, in the annual report of the 2023 United Nations Office for Outer Space Affairs, the same issues were reported, and the same technological solutions were repeated.

Current international law, particularly the Liability Convention of 1972, holds states responsible for damage caused by their space objects, but it does not sufficiently address the complexities of debris removal or the costs associated with it. Accountability gaps have resulted from this, especially in the management of defunct satellites and abandoned rocket stages that still endanger orbital safety (Degrange, 2019). The idea of space stewardship is one of the main ethical issues. It is the ethical duty of all space-faring organizations, whether they are commercial businesses, national space agencies, or developing space nations, to make sure that their activities do not jeopardize the orbital environment. This involves not only adhering to current debris mitigation guidelines but also proactively taking steps to prevent the creation of new debris. However, this sense of shared responsibility is not always reflected in the actions of operators, especially when the cost of implementing debris mitigation measures is perceived as too high. Ethical stewardship demands that entities prioritize long-term sustainability over short-term gains, recognizing that space is a shared resource that must be preserved for future generations.

The responsibility for "Orphaned" Another particularly controversial topic is debris. Orphaned debris is the term used to describe satellites and other space objects that have been abandoned in orbit by companies that have ceased operations or are no longer in existence. Since there is currently no clear legal framework for determining who is responsible for these objects, it is difficult to enforce cleanup activities. Thousands of discarded items exist in orbit around the earth because of carelessness, and they all run the risk of colliding with operational satellites. Without a revised responsibility framework, operators might keep acting irresponsibly since they won't be held accountable for any debris that is left behind. To address these challenges, a revised liability framework could assign responsibility for debris cleanup to the original operator or launch state, ensuring that all actors contribute to the sustainability of space. This could involve mechanisms such as "polluter pays" principles, where operators are financially responsible for the removal of debris they generate. For instance, if a satellite becomes non-operational and poses a risk to other objects, the original operator or the state that authorized the launch would be obligated to finance its removal. This would not only incentivize better design and operational practices but also ensure that companies factor in end-of-life disposal when planning their missions.

Additionally, the United Nations Office for Outer Space Affairs (UNOOSA) has highlighted the need for improved legal frameworks in its 2023 annual report, reiterating that current technological solutions, such as Active Debris Removal (ADR), are only effective if supported by clear regulatory measures. The report stresses the importance of international cooperation in establishing guidelines that go beyond mitigation, urging countries to adopt practices that facilitate the removal of existing debris. This includes creating incentives for companies to develop and deploy ADR technologies, as well as establishing shared funds that can be used to address the issue of orphaned debris. By having a centralized fund, managed by an international body, resources can be allocated more efficiently, ensuring that even debris left by defunct or inactive entities can be addressed without a disproportionate financial burden on any single nation (United Nations, 2023).

3.4.2. Business Impact and Responsibility in Space Debris Mitigation

Due to their growing reliance on satellite-based services, many businesses indirectly contribute to the buildup of space debris even if they are not directly participating in space activities. Businesses put pressure on service providers to extend satellite constellations in order to accommodate the growing demand for high-speed internet and smooth international communication. As a result of this expansion, more satellites are frequently launched, which adds to orbital congestion and, eventually, the debris issue when the satellite reaches the end of its useful life. For instance, the need for fast internet around the world has prompted internet service providers to set up massive constellations of satellites, which, although advantageous from a technological standpoint, increase the possibility of orbital debris when the satellites eventually cease to exist. To address these indirect contributions, businesses could adopt the concept of a provision fund, modeled after principles found in International Accounting Standards (IAS) 37 on environmental provisions, which guides companies in setting aside funds for anticipated future liabilities (Deloitte, 2024.). Similar to environmental liabilities on Earth, these provision funds would let businesses to set aside monies expressly for managing space debris, acknowledging its indirect influence on orbital sustainability. Businesses could guarantee they have set aside funds to address future expenses, like those related to debris removal or satellite deorbiting, by implementing a provision for space debris mitigation. As suggested by IAS 37, regular evaluations and modifications of these funds would maintain their alignment with the true costs of debris reduction, allowing them to adjust to shifting space operations and technical developments.

Drawing inspiration from Canadian practices, a collective industry fund could also be introduced. In Canada, various sectors, particularly those involving resource extraction, pool resources to manage the environmental impact of their operations collectively. As an example to those funds from Canada are Environmental Damages Fund (Environment and Climate Change Canada, 2024) and Canadian Mining Association’s TSM initiative (Mining Association of Canada, 2024). Applying a similar approach to space sustainability, satellite-dependent industries could establish an industry-wide fund, distributing the financial responsibility for debris management across multiple stakeholders. This model could provide a scalable, sustainable funding source for Active Debris Removal (ADR) initiatives, enhancing the ability to address debris generated by inactive satellites effectively. Moreover, Governments could also offer tax breaks to businesses that make contributions to these provision funds. Businesses would find it financially advantageous to take part in space sustainability programs thanks to such incentives, which would also allow their contributions to be seamlessly integrated into regular accounting and financial frameworks. Businesses would have a real incentive to integrate sustainable practices into their satellite operations if tax breaks were provided for money spent on space debris mitigation. This supports proactive investment in sustainability by supporting the notion that provisions can be recognized as expected liabilities, as described in IAS 37.

Through these proactive financial and operational measures, businesses can play a significant role in fostering a sustainable orbital environment. By acknowledging their indirect role in space debris accumulation, businesses not only contribute to the resilience of the space sector but also ensure the longevity and reliability of the satellite services on which they depend.

3.5. Global Approaches to Space Debris Management

The science of risk management is considered one of the modern sciences that government institutions and international bodies are interested in; through developing guidelines, regulations, and legislation that strengthen the safety system, prevent risks, and reduce their effects (El Mougher, Abu Sharekh, Abu Ali, & Zuhud, 2023). The challenge of space debris has led to varied responses across the globe, with countries and regions implementing unique strategies based on their technological capabilities and regulatory frameworks. In the United States, the approach is guided by the

U.S. Space Policy Directive-3, which emphasizes Space Situational Awareness (SSA) and the development of a Space Traffic Management (STM) system. This policy outlines measures to improve debris tracking, encourage data sharing among international partners, and promote practices that minimize the creation of new debris. Additionally, the U.S. has partnered with private companies like Astroscale to advance Active Debris Removal (ADR) technologies, aiming to develop practical methods to deorbit defunct satellites and large debris objects (Maclay & McKnight, 2021). The Federal Communications Commission (FCC) also plays a regulatory role by setting guidelines that require satellite operators to deorbit their satellites within a specific timeframe, reducing the risk of long-term debris generation (Swope et al., 2024).

The European Union has adopted a similarly proactive stance, with the European Space Agency (ESA) spearheading efforts through its Zero Debris Charter. This initiative commits ESA and its partners to ensure that no debris-producing object remains in orbit beyond 2030, setting a clear framework for sustainability in space operations. Europe's approach also involves the development of ClearSpace-1, the world's first dedicated mission to actively remove debris, which will use robotic arms to capture and deorbit large, high-risk objects. Additionally, the European Commission has introduced the EU Space Regulation, which requires satellite operators to comply with strict end-of-life disposal guidelines and encourages innovation in debris mitigation technologies (Degrange, 2019; ESA, 2024). This regulatory environment underscores Europe's commitment to maintaining a sustainable orbital environment and advancing the global discourse on space sustainability.

In China, space debris management is integrated into the country's broader space development strategy. China regularly engages in international forums, such as the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS), to coordinate debris reduction activities and has created its own orbital debris mitigation guidelines that comply with international norms. In recognition of the dangers associated with an increase in satellite launches, the China National Space Administration (CNSA) has also entered into collaborations to test technology for debris removal and monitoring (Ryan et al., 2022). The quick growth of Chinese satellite constellations, however, has sparked worries despite these initiatives. If mitigation measures are not strictly enforced, this could lead to orbital congestion (Carroll, 2019).

The efforts of emerging spacefaring states to address space sustainability are also increasing. Debris mitigation and space traffic management are two topics covered in national space plans created by nations like the Philippines, Nigeria, and Rwanda. These countries are eager to implement sustainable practices right away, even if they are still developing their space infrastructure. For example, the Artemis Accords, an international agreement that encourages ethical activity in space, including debris control, have been signed by Rwanda and Nigeria (OECD, 2024). The Asia-Pacific Space Cooperation Organization (APSCO) and the Asia-Pacific Regional Space Agency Forum (APRSAF) encourage member nations to collaborate on space sustainability by exchanging best practices and creating cooperative projects. These platforms have enabled emerging nations to align their space activities with international standards and contribute to global sustainability efforts (Lambach & Wesel, 2021).

The African Union has established the Africa Space Agency, which aims to coordinate space activities across the continent and develop a cohesive strategy for addressing space sustainability. This includes initiatives to enhance Space Situational Awareness (SSA) and support the implementation of national space policies that prioritize debris mitigation. Similarly, the European Space Agency and Japan have partnered on joint missions, such as testing laser-based technologies for nudging small debris into lower orbits, where it can burn up upon re-entry (Degrange, 2019). These collaborative efforts underscore the importance of shared responsibility and international cooperation in managing the risks associated with space debris.

Despite these efforts, challenges in international coordination persist. Established space nations like the United States, Europe, and Japan have well-developed regulatory frameworks. Under these frameworks they coordinate "How satellite operators should handle their satellites at the end of their operational life" and restrictions such as "Measures to minimize the creation of new debris", and "Tracking and managing existing debris through SSA and STM systems". However, there remains a need for more robust enforcement and greater alignment of national policies. Emerging space nations are actively building their capabilities, but resource limitations can hinder their ability to implement comprehensive debris mitigation strategies. A more integrated global approach, which draws from these diverse regional strategies, is essential to effectively address the growing threat of space debris and ensure the sustainability of space operations (ESA, 2024; Maclay & McKnight, 2021).

3.6. Enhancing Space Situational Awareness (SSA)

One of the critical aspects of managing space debris is improving Space Situational Awareness (SSA) systems. SSA refers to the ability to detect, track, and predict the movement of objects in space, including active satellites and debris. Current SSA systems, such as those operated by the United States Space Surveillance Network (SSN), focus on tracking objects larger than 10 cm in diameter (ESA, 2024). However, this leaves millions of smaller debris fragments, many of which are still large enough to cause significant damage to satellites, untracked. Enhancing SSA capabilities to detect smaller debris is crucial for improving collision avoidance and minimizing the risk posed by Lethal Non-Trackable (LNT) debris.

Recent advancements in radar and optical tracking systems have made it possible to detect smaller objects with higher accuracy. Companies like LeoLabs, for instance, are developing commercial tracking systems that can monitor objects as small as 2 cm in Low Earth Orbit (LEO) (Maclay& McKnight, 2021). These improved tracking capabilities allow satellite operators to better predict potential collisions and take evasive actions. Furthermore, the integration of artificial intelligence (AI) into SSA systems can help process large amounts of tracking data more efficiently, enabling quicker and more accurate predictions of debris paths.

International cooperation in sharing SSA data is also essential for creating a comprehensive global debris tracking network. Currently, many SSA systems operate independently, with national space agencies and private companies maintaining separate databases of debris tracking information. A more unified approach, where SSA data is shared among all space actors, would significantly improve the safety of space operations by ensuring that all operators have access to real-time data on potential collision threats (OECD, 2024). The development of a global Space Traffic Management (STM) system, overseen by an international body, could help facilitate this level of cooperation, preventing collisions and improving the overall management of space traffic. This would not only improve the safety of space operations but also reduce the likelihood of future debris-generating collisions (Maclay& McKnight, 2021). International bodies such as the United Nations Office for Outer Space Affairs (UNOOSA) could play a key role in overseeing the development and implementation of a global STM system, ensuring that space remains accessible and sustainable for all actors.

4. The Path Forward

One of the most promising avenues for the future of space debris management lies in emerging technologies. While Active Debris Removal (ADR) systems are already being tested, future technologies will need to focus on making ADR more scalable and cost-effective. Current ADR systems, such as Astroscale's ELSA-d mission, have demonstrated the potential to capture and remove defunct satellites, but these systems need to evolve to handle multiple objects in a single mission to make debris removal more economically viable (Degrange, 2019). The development of autonomous robotic systems, which can identify, capture, and deorbit debris without human intervention, is a critical next step (Jovičić, 2024). These systems could significantly reduce operational costs and increase the efficiency of ADR missions.

Looking further into the future, on-orbit manufacturing could revolutionize how we approach debris management. By recycling debris into raw materials that can be used to construct new satellites or space infrastructure, on-orbit manufacturing addresses both the debris problem and the logistical challenges of launching materials from Earth (Carroll, 2019). This technology is still in its infancy, but research and development in this area could open up new possibilities for long-term sustainability in space operations. For example, defunct satellites and spent rocket stages could be repurposed into building blocks for space stations or other large-scale structures, reducing waste and optimizing the use of existing resources. Although in the literature on-orbit manufacturing seems as a “future method”, the last review board report for the On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1) project of NASA says that “IRB recommends the OSAM-1 project be discontinued.” The reason seems to be the high cost of operation (National Aeronautics and Space Administration, 2024).

In addition to debris recycling, advancements in self-disposal technologies will play a crucial role in preventing future debris generation. Satellites equipped with autonomous propulsion systems or other end-of-life disposal mechanisms can ensure that they safely deorbit or move to graveyard orbits once their missions are complete (Maclay & McKnight, 2021). Combined with design for demise—the use of materials that completely burn up upon re-entry—these innovations will help reduce the number of defunct satellites left in orbit, lowering the risk of collisions and further debris creation (ESA, 2024).

4.1. Sustainability in Space Operations

Future space operations must be centred on sustainability. Sustainable methods that put the long-term health of the orbital environment first must be adopted by commercial businesses and spacefaring nations. This involves using materials that disintegrate upon re-entry and implementing autonomous deorbiting capabilities, two examples of best practices in satellite design. Operators must also make sure they adhere to current debris mitigation regulations, such the 25-year rule, and make investments in technology that allow them to prolong the operating lifespans of their satellites through repairs and on-orbit servicing (IOS) (Virgili et al., 2016).

The growing commercial interest in space also presents an opportunity to incentivize sustainable practices through economic mechanisms. Governments could introduce debris removal credits, similar to carbon credits, which reward operators for actively participating in debris mitigation efforts. These credits could be traded or sold, providing a financial incentive for companies to invest in Active Debris Removal (ADR) technologies (Carroll, 2019). Additionally, orbital parking fees could be implemented to charge satellite operators for occupying valuable space in Low Earth Orbit (LEO), encouraging them to adopt more responsible end-of-life disposal practices (Maclay& McKnight, 2021).

4.2. Policy Recommendations for Long-Term Space Sustainability

The future of space sustainability hinges on the implementation of robust policy frameworks that enforce debris mitigation and removal practices. While technological innovations like Active Debris Removal (ADR) and self-disposal technologies offer promising solutions, without strong regulatory backing, the space industry may continue to face challenges in preventing the proliferation of debris. One critical policy recommendation is the establishment of a binding international treaty that obligates all spacefaring nations and private operators to adhere to strict debris mitigation practices, such as the mandatory use of deorbiting mechanisms at the end of a satellite’s life (Maclay& McKnight, 2021).

A convention of this kind might include establish sanctions for noncompliance, such as fines or prohibitions on operators’ ability to deploy satellites in the future if they disregard debris mitigation procedures. Policymakers might encourage more responsible conduct by shifting the financial cost of debris management onto operators by establishing financial disincentives for leaving defunct satellites in space. Governments could also enact tax breaks or subsidies for businesses who make investments in ADR technology or create creative approaches to waste removal (Carroll, 2019).

Another important policy recommendation is the creation of a global debris removal fund, which would be financed by contributions from spacefaring nations and private companies. This fund could be used to support large-scale debris removal projects, particularly in areas of Low Earth Orbit (LEO) and Geostationary Orbit (GEO) that are densely populated with defunct satellites and spent rocket stages (Degrange, 2019). By pooling resources, the international community can tackle the most pressing debris hotspots and prevent further collisions that could lead to a Kessler Syndrome-like cascade of debris events (Buchs, 2021).

4.3. The Role of Emerging Spacefaring Nations

As the space industry grows, more nations are entering the space arena, launching their own satellites, and taking part in multilateral missions. Although these new spacefaring countries are becoming more and more significant to the global space ecosystem, many of them lack the means or know-how to properly execute debris mitigation plans. The long-term viability of space operations depends on these countries being able to take part in international debris management initiatives. International agencies like the United Nations Office for Outer Space Affairs (UNOOSA) should increase the scope of their technical assistance programs to support these new actors. They should offer training and resources to assist these countries in creating their own debris mitigation policies and space situational awareness (SSA) systems (Lambach & Wesel, 2021).

4.4. Long-Term Sustainability Through Public-Private Partnerships

Public-private partnerships (PPPs) will play a crucial role in ensuring the long-term sustainability of space operations. Governments, space agencies, and private companies must work together to develop new technologies and regulatory frameworks that prioritize debris mitigation. For example, governments could provide funding or tax incentives to companies that develop on-orbit servicing (IOS) technologies or other solutions aimed at extending the lifespan of satellites (ESA, 2024). These partnerships could also accelerate the development of next-generation SSA systems, which are essential for tracking smaller debris and providing more accurate collision avoidance data. Private companies, which increasingly dominate the space industry, have a vested interest in maintaining a clean and sustainable orbital environment. As mega-constellations such as SpaceX's Starlink and Amazon's Project Kuiper continue to expand, these companies must lead the way in adopting sustainable practices, such as using autonomous deorbiting systems or participating in Active Debris Removal (ADR) efforts (Maclay& McKnight, 2021). Public-private partnerships can help bridge the gap between government-led initiatives and private sector innovation, ensuring that both sectors contribute to solving the space debris crisis. One promising area for PPPs is the development of debris capture technologies, such as the robotic systems being tested by companies like Astroscale and government agencies like the European Space Agency (ESA) (Degrange, 2019). These technologies are critical for removing large debris objects that pose a significant risk to operational satellites. By combining government funding with private sector expertise, PPPs can help scale these technologies and bring them to market more quickly, addressing the growing debris problem more efficiently.

4.5. Education and Awareness Campaigns

One big piece of solving the space debris problem is simply raising awareness. Although it's a hot topic among space professionals, most people—and even many policymakers—are not as familiar with the issue, especially compared to other global challenges like climate change or pollution. Governments and space agencies could really benefit from investing in outreach efforts to explain why managing space debris is so important. They must invest in education and outreach campaigns to highlight the importance of debris mitigation and the risks associated with inaction (OECD, 2024).

These campaigns could cover the essential roles satellites play in our lives, from global communication to disaster response. For instance, weather satellites help predict storms, giving governments crucial information to prepare for natural disasters, while communication satellites keep emergency responders connected when they're needed most. By showing how a clean, safe orbit directly benefits our daily lives, these efforts could make the importance of space sustainability a bit more real, helping to ensure that both the public and policymakers are motivated to take action.

5. Recommendations and Conclusions

This review study shows that as the threat posed by space debris continues to grow, current mitigation and removal strategies, are not enough to ensure the long-term sustainability of space operations. Several satellites and space operations continue to increase, and many national - international institutions and private companies are working to safeguard the orbital environment. The focus must shift from reactive measures to proactive, preventive strategies that will ensure the continued use of space for the benefit of humanity. For this, total collaboration and social awareness are the key essential methods, because when the satellites disappear into space or have reached their end of life, they become space debris. An increasing number of space debris negatively affects disaster management systems and GPS systems. The recovery of these garbage costs (such as the Active Debris Removal program) more than the cost of the satellite itself.

The solution strategy to new disaster type can be "solution in the source and general control mechanism." Although cleaning space with ADR and similar methods seems interesting, space logic works differently than what we know before from the perspective of cost and time. That is why project durations are extended, and the budget of the projects exceeds the financial plans. This leads to "underperformed" projects, and less willingness to space cleaning. NASA's last committee review report is a good example of this as it states the discontinuation of OSAM-1 project. Cost-effective solutions are required for better space-cleaning applications. That is why, a solution at source is an essential way to deal with this inevitable new generation disaster with the support of educational improvements such as SSA.

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