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Space Debris: Assessing Risks and Strategic Mitigation for Sustainable Space Operations: A Qualitative Study

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Abstract: As scientific inventions make significant strides in modern times, humans have made considerable progress in scaling worlds beyond our own. This has resulted in our species exploring outer space, wherein each day brings along novel avenues of planetary exploration. However, with each innovation directed towards it, there has risen a continuous threat of increasing space debris beyond our immediate atmosphere [1].

Space Debris can be defined as a byproduct of humans' expanding presence in outer space. Although normal human vision cannot see space debris in the sky, it often marks its presence in low Earth orbit (LEO) [2]. This has emerged as a highly concerning challenge in the current times. Beyond being an eminent threat to planet Earth and its residents, it also poses a hurdle to sustainable space operations [3]. Space debris comprises objects such as inactive satellites, spent rocket stages, fragments from collisions, and other defunct objects. This poses a significant threat to various extra-terrestrial entities such as operational satellites, human-crewed missions, and future space exploration [4]. This exponential increase in orbital debris, along with the growing dependency of mankind on space-based technologies has amplified concerns over the long-term sustainability of Earth's orbital environment [4] [3].

This paper aims to examine the plethora of risks space/orbital debris poses. It further explores the current and futuristic strategies that can be applied for its mitigation. Building on the same, the paper will also elaborate upon the critical threats posed by space debris, such as significant financial losses, hurdled communication networks, and cascading debris creation which is also known as the Kessler Syndrom [5]. Another crucial threat that such significant debris accumulation causes is its re-entry into the Earth's atmosphere. This poses a risk to terrestrial safety [6].

What makes these risks more critical are the scientific and technological limitations in tracking, predicting, and managing the growing debris population. Even though the current detection systems are highly advanced, they often fall short in monitoring smaller debris fragments that are highly hazardous due to their high velocities [7].

Moving further, we will look into the various efforts that are being made to mitigate space debris. These include both active and passive strategies, which not only focus on preventing debris generation through improved satellite design, end-of-life disposal protocols, and adherence to international guidelines, but also include key aspects of debris removal techniques such as robotics arms, nets, and lasers deployment [8]. Even though these solutions are innovative and promising, they are still in their nascency and thus face key technological, financial, and legal challenges.

Lastly, as we consider the regulatory frameworks, international organizations such as the United Nations Office for Outer Space Affairs (UNOOSA) and other space agencies like NASA and the European Space Agency (ESA) have put forward various guidelines. These frameworks aim to address the growing challenge related to space debris. However, the implementation of these guidelines is also impacted occasionally owing to the lack of binding agreements and enforcement mechanisms. This results in a lack of global compliance [9] [10].

The paper will also shed light on case studies of successful debris management missions and as a result highlight emerging technologies that could impactfully transform space debris mitigation. Moreover, the paper will further explore the importance of establishing international collaboration to advance research and increase debris management investments. Thus, it can be seen that space debris presents a critical challenge that requires immediate coordinated attention from not just governments and space agencies, but also from the private sector entities. Once the risks associated with the same are meticulously analysed, strategic mitigation measures can be implemented. This will allow humans to safeguard the orbital environment for future generations. It will also enable them to ensure the sustainability of space operations better.

Keywords: *Space Debris, Orbital Sustainability, Collision Risks, Mitigation Strategies, Active Debris Removal, International Collaboration, Kessler Syndrome.*

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I. INTRODUCTION

A. Importance of Studying Space Debris for Future Space Missions and Sustainability

The foremost reason why space debris needs to be studied is because it paves the way for future space explorations. Moreover, it also ensures the long-term sustainability of outer space activities [1] [3] [4]. As humans today prepare themselves for ambitious space-bound missions, it is critical to understand and address the challenges posed by space debris. The growing accumulation of debris not only threatens the future of space operations but also jeopardizes the use of low Earth orbit (LEO) as a resource for scientific, commercial, and exploratory purposes [4] [3]. The safety of Earth's orbital environment plays a significant part in future space missions to the Moon, Mars, and beyond. However, with the constantly existing challenges posed by space debris, there lies a critical threat to spacecraft during launch, transit, and operation in orbit. Collisions with debris can lead to intense damage to spacecraft, which will endanger both robotic and crewed missions [1] [11].

Another key reason why space debris needs to be studied is humans' growing interest in satellite constellations. These satellites are deployed for a range of activities right from global internet connectivity, weather monitoring, and Earth observation [12]. Global technology firms such as SpaceX, Amazon, and OneWeb are deploying thousands of satellites in LEO to provide these services. However, with each new launch, there comes an increasing probability of collisions, which could generate more debris, [11] [12] and even render parts of LEO unusable. This will limit humanity's ability to access and utilize space resources.

Lastly, a dire necessity to study space debris comes from not just supporting future missions but also preserving the space environment as a shared, yet finite resource [13]. Space is often regarded as a global commons, where activities by one nation or organization can pose far-reaching consequences for others as well. Resultantly, international cooperation and policy development are integral to the sustainable use of space [14]. By studying the nature, behaviour, and impact of debris, researchers and policymakers can develop guidelines and best practices to prevent further debris generation. Moreover, as space activities become more sustainable, the cost of collisions, repairs, or replacements of damaged assets could become significantly lower [13] [3].

Thus, a meticulous study of space debris could not only mitigate costs but also foster innovation in areas such as active debris removal, tracking technologies, and spacecraft design [4]. By giving space debris mitigation research and action, its due priority, humanity can safeguard the orbital environment, promote sustainable space exploration, and continue to harness the benefits of space for science, society, and industry [15].

B. Objectives of the Paper

This paper seeks to address the issue of space debris and provide a comprehensive understanding of the same. It will explore the definition, significance, and implications of managing space debris to ensure sustainable space exploration in the future. The paper aims to provide a detailed understanding of the origins of space debris, its characteristics, and the threats it poses to operational satellites, crewed missions, and the overall usability of LEO.

Complementing this, the paper will shed light on how the proliferation of debris impacts current and future space missions, particularly in the context of increasing satellite deployments, space tourism, and interplanetary exploration. The paper also aims to explore the potential consequences of scenarios such as the Kessler Syndrome, underscoring the urgency of proactive debris management strategies.

Building on the same, the paper will examine existing measures for mitigating space debris. Via it, it will contribute to the ongoing discourse on maintaining the orbital environment as a sustainably shared resource. Lastly, the paper will underscore the necessity of international collaboration in addressing space debris. It aspires to encourage the development of unified and effective strategies to tackle the growing debris problem, which will eventually benefit science, industry, and humanity.

II. UNDERSTANDING SPACE DEBRIS

A. Overview of Space Debris: Definition and Significance

Space debris, which is often referred to as orbital debris or space junk, includes a range of non-functional objects within Earth's orbit. Some of the commonly identifiable debris includes defunct satellites, discarded rocket stages, fragments resulting from collisions or explosions, and smaller paint chips or metal shards [2]. Ever since the first artificial satellite, Sputnik 1 was launched in 1957, debris accumulation has increased significantly [16]. This has created an ongoing challenge for modern space operations, which results in significant implications for the safety and sustainability of outer space initiatives.

Fig 1: Sputnik 1
[Image Source – NASA Photo Gallery] [17]

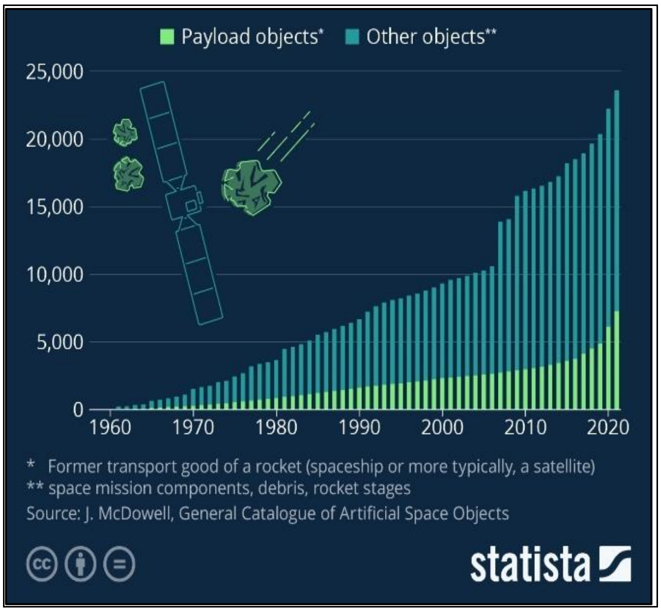

Fig 2: Artificial Objects in Earth's Orbit by Year of Launch/Separation
[Image Source – Statista.com] [18]

Furthermore, as per the recent estimates conducted by various space agencies, it has been identified that millions of objects, ranging in size from a few millimetres to several meters, are currently orbiting our planet [19]. While it has been ascertained that larger objects pose an obvious threat to our planet, even small debris which travels at orbital speeds, often exceeding 28,000 kilometres per hour, can also cause serious damage [7]. The reason behind this is, that the kinetic energy which these high-velocity particles carry makes them capable of penetrating not just spacecraft shielding but also causing catastrophic collisions with operational satellites [20] [19]. This further adds to the already accumulating debris, which amplifies the issue, of manifolds.

What makes this issue more challenging is the vulnerability of operational satellites that provide critical services such as global communication, GPS navigation, weather forecasting, and scientific research [12]. If any of these satellites collide with space debris, it could disrupt these essential services. This, in turn, impacts both individual users and even entire industries and can hamper economic progression [12].

Another evident impact that such collisions can have is the economic costs associated with repairing or replacing damaged satellites [13]. Last but not least, such debris poses risks to human life as well. However, compared to the many dangers we encounter daily, the risk posed to any one person by falling space debris is negligible. Experts estimate the chance of injury to be less than one in a trillion [20]. The International Space Station (ISS) Orbital Debris Collision Avoidance Process seeks to mitigate the threat these orbital debris pose [21]. However, this is both resource-intensive and operationally challenging.

Fig 3: International Space Station with Earth in the Background
[Image Source – NASA] [22]

Another pressing concern related to space debris is the potential onset of the Kessler Syndrome. This phenomenon was proposed by NASA Scientist Donald J. Kessler in the year 1978 [23]. As per this, a collision between debris results in a chain reaction that generates further debris and leads to an exponential increase in orbital density. Over time, such a scenario could render certain orbits unusable, effectively blocking access to space and hindering future exploration and development [24].

Thus, as evidenced, addressing the issue of space debris is quintessential for ensuring the sustainability of space as a shared resource. This, in turn, will enable continued advancements in space exploration and technology.

B. Classification of Space Debris

Space debris can be broadly classified into three primary categories: fragments, inactive satellites, and rocket stages, with each contributing uniquely to the growing population of orbital debris.

- ***Fragments:*** Fragments constitute the most numerous category of space debris. These comprise small pieces of collided, exploded, or breakup satellites within the LEO. These emerge as a consequence of events such as anti-

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satellite (ASAT) weapon tests or accidental collisions between spacecraft, which result in thousands of debris fragments. However, the size of these fragments may range from a few millimetres to several meters, either of which can cause significant damage upon impact with operational spacecraft or satellites. For instance - The destruction of FengYun-1C by China in January 2007 alone led to a 25% surge in trackable space objects [5] [25].

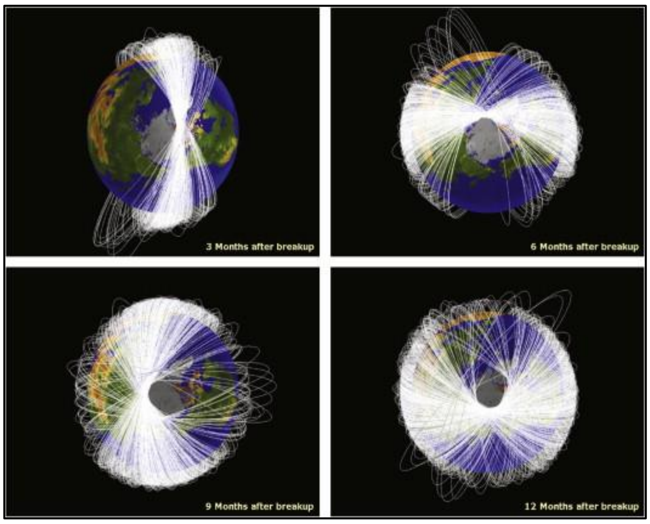

Fig 4: Spread of Fragmented Debris in Orbit after a Satellite Collision
[Image Source – From Johnson et al (2008)] [25]

- ***Inactive Satellites:*** Of the objects catalogued in space, 24% are satellites, less than one-third of which are still active, while 11% are composed of spent upper stages and mission-related elements such as launch adapters and lens covers. Those spacecraft that have completed their operational life, yet are bound to remain in orbit owing to the absence of any deorbiting mechanisms from inactive satellites [5]. Despite not being able to perform their intended functions these elements continue to occupy valuable orbital slots, particularly in low Earth orbit (LEO) and geostationary orbit (GEO). They pose significant collision risk and also generate further debris in the event of any collision [5].
- ***Rocket Stages and Mission-Related Debris:*** Rocket stages, another major source of debris, are remnants of launch vehicles that are left in orbit after delivering payloads. These include booster stages and upper stages, which often contain residual fuel that may explode, further contributing to the debris population [5]. Additionally, mission-related debris, such as jettisoned covers, bolts, and discarded equipment from space missions, also contributes to the growing number of orbital objects.

Each of the aforementioned debris categories presents unique challenges to space operations. For instance, while large objects such as inactive satellites and rocket stages are easier to track, they still pose significant risks in the event of collisions [20] [19]. On the contrary, even though smaller fragments are harder to detect, they are also equally dangerous owing to their high velocities [19] [6]. Together, these forms of debris create a densely populated orbital environment, especially in critical regions such as LEO, which hosts most satellites and the International Space Station.

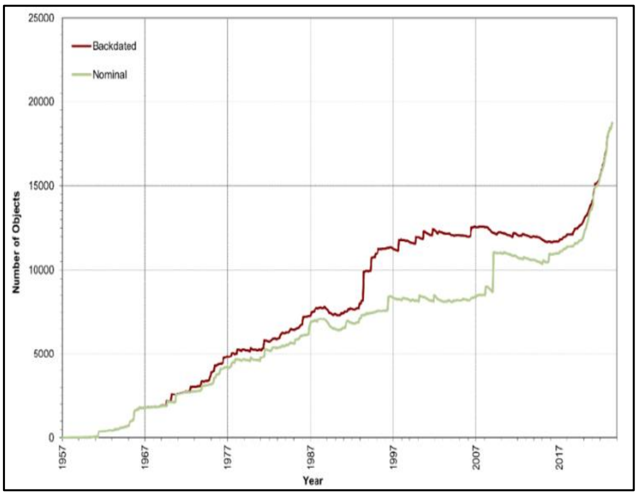

Fig 5: Statistical Chart Tracking the Accumulation of LEO Objects from 1957 to 2023, with Adjustments Excluding Fragments from Intentional Destruction and Reassigning Breakup Debris to Initial Launch Dates
[Image Source – researchgate.net] [26]

By aiming to categorize space debris, researchers, space agencies, and policymakers can prioritize interventions. This will ensure a safer and more sustainable orbital environment for future space activities.

C. Causes of Space Debris Accumulation

One of the primary reasons for space debris accumulation is the constantly growing human activity in Earth's orbit over the last few decades. This includes debris from various sources such as satellite collisions, rocket launches, and other mission-related activities [4] [18] [20]. These causes, often interrelated, exacerbate the already concerning state of Earth's orbital environment and threaten the sustainability of space operations.

Among these collisions between active and inactive satellites are one of the most prominent contributors to space debris. As the density of objects in orbit increases, particularly in low Earth orbit (LEO), the likelihood of accidental collisions rises [27]. Such collisions can create thousands of debris fragments, each travelling at high velocities and capable of further collisions, leading to a chain reaction known as the Kessler Syndrome [24] [23]. One notable event was the collision between the Iridium 33 and Cosmos 2251 satellites in 2009 [28], which aptly highlighted the destructive potential of these incidents.

Another contributing factor to space debris is rocket launches. These launches are associated with placing satellites and other payloads into orbits. During a typical launch, components such as upper stages, booster stages, and fairings are discarded, often remaining in orbit. These objects,

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often large and containing residual fuel, pose a risk of explosion, which can create additional debris [4]. Alongside this, explosions of satellites and rocket stages, which often result from residual fuel or faulty components are another major source of space debris [20]. Owing to such unplanned events, thousands of fragments are released, which range from millimetres to several meters in size.

Another key factor that contributes towards space debris is the Anti-Satellite (ASAT) Test, which is a result of the deliberate destruction of satellites via ASAT weapon testing. These tests are primarily conducted by nations to demonstrate military capabilities and create large amounts of debris in shorter durations [29]. For instance – the ASAT tests conducted by China and India in 2007 and 2019 [30] respectively, produced significant debris fragments, many of which still pose risks to operational satellites and other space assets.

Lastly, space missions too create debris that adds to the already existing issue of debris accumulation. At times, discarded equipment such as lens covers, bolts, and adapter rings, are often left in space after their deployment [31]. Despite many of these objects being smaller in size, their high velocities make them dangerous to operational spacecraft [20] [19].

Resultantly, one needs to understand the root causes of space debris accumulation to develop a critical understanding of effective mitigation strategies. This way, governments, space agencies, and private entities can focus on implementing preventative measures, such as better spacecraft design, active debris removal technologies, and stricter regulations for satellite launches and operations.

D. Current Statistics and Trends in the Space Debris Population

The space debris population has witnessed a concerning increase over the past few decades, reflecting the intensifying pace of human activities in Earth's orbit. According to data from international space agencies and organizations such as NASA and the European Space Agency (ESA), the number of objects in orbit, both functional and non-functional, has grown exponentially, with a significant proportion constituting space debris [18] [4] [16].

As of 2024, there are over 36,000 catalogued objects in orbit larger than 10 cm [32] [33]. These majorly include non-functional satellites, rocket stages, and large fragments resulting from collisions or explosions. Even though these are actively tracked by space surveillance networks, they still pose an ideal threat to orbital entities [1] [27]. Moreover, the count increases immensely when one takes into consideration smaller debris particles. It is estimated that there are approximately 1 million objects ranging between 1 cm and 10 cm and over 130 million objects smaller than 1 cm [34]. These objects are capable of causing severe damage to operational satellites and spacecraft.

The most susceptible to these debris particles is the low Earth orbit (LEO). This space is defined as altitudes up to 2,000 kilometres.

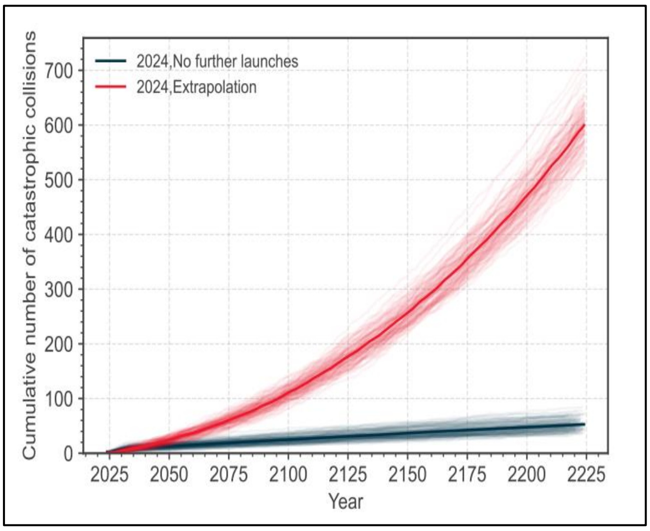

Fig 6: Simulated Long-Term Evolution Scenarios Depicting Cumulative Collisions in LEO
[Image Source – Space Environment Report] [34]

Within this region a range of active satellites, such as those within mega-constellations like SpaceX's Starlink, which alone comprises over 5,500 operational satellites as of early 2024. Such constellations have resulted in an increased satellite population which in turn increases the likelihood of collisions and further debris generation [35].

Beyond this, the geostationary orbit (GEO) which is located at an altitude of approximately 36,000 kilometres is also heavily used. However, debris here tends to accumulate in "graveyard" orbits following end-of-life disposal manoeuvres. As per the reports generated in April 2017, up to 290 breakups, collisions, and explosions have been recorded since the beginning of the space age [36]. In the year 2007, the Chinese ASAT test alone created over 3,000 pieces of trackable debris when it destroyed the Fengyun-1C weather satellite [37] [25]. Similarly, the 2009 collision between the Iridium 33 and Cosmos 2251 satellites resulted in approximately 2,300 trackable fragments, further exacerbating the debris issue [28].

The increased number of small satellites, specifically from commercial operators, also contributes significantly to the growing accumulation of debris in LEO and GEO. While these provide opportunities for scientific research and commercial applications, their rapid deployment often outpaces the implementation of effective debris mitigation measures. As a result, greater efforts are being made to develop debris removal (ADR) systems and ensure enhanced satellite design for better end-of-life disposal. However, if a consensus is not achieved on the issue at a global level and no stringent frameworks are defined, the accelerating growth of space debris will continue to threaten the sustainability of Earth's orbital environment.

III. THREATS POSED BY SPACE DEBRIS

A. *Risks to operational satellites and spacecraft*

One of the growing concerns of space debris accumulation is the escalating risk to operational satellites and spacecraft. This threatens the safety, functionality, and sustainability of activities in Earth's orbit [27] [11].

When any collision with debris, even with smaller fragments occurs, it has the potential to cause catastrophic damage owing to the high velocities at which these objects orbit [19] [20]. These risks not only pose a serious threat to individual missions but also create mammoth challenges to the long-term usability of critical orbital regions.

- ***Collision Risks:*** Collisions are among the most severe threats posed by space debris to operational satellites and spacecraft. At orbital speeds exceeding 28,000 km/h, even small debris fragments can release enough kinetic energy to disable or destroy a satellite [20] [19]. For instance, a 1 cm fragment could cause as much damage as a hand grenade upon impact [38]. Larger debris, such as defunct satellites or discarded rocket stages, presents even greater risks, as collisions involving these objects can generate thousands of additional debris fragments, compounding the problem through a phenomenon known as the Kessler Syndrome [23] [24].
- ***Damage to Critical Systems:*** Operational satellites rely on delicate systems such as solar panels, antennas, and thermal protection structures, all of which are vulnerable to impacts from debris. Even minor damage to these components can degrade satellite performance, shorten mission lifespans, or disrupt vital services such as communication, navigation, weather forecasting, and Earth observation [27] [4] [31].
- ***Threats to Human Spaceflight:*** Space debris poses a particular danger to crewed missions. Spacecraft transporting astronauts, such as the ISS, are at risk from debris impacts. Protective shielding, like Whipple bumpers, provides some defence, but it is not effective against larger debris or clusters of fragments [11].
- ***Economic and Operational Impacts:*** The economic costs of collisions or damage caused by debris are substantial. Replacing or repairing satellites damaged by debris involves significant financial and logistical challenges. Furthermore, collisions can disrupt the services provided by these satellites, such as global positioning systems (GPS), satellite television, internet connectivity, and climate monitoring [13].
- ***Compromising Future Space Activities:*** As the density of debris increases, accessing and operating in Earth's orbit becomes increasingly hazardous. Launch windows must be carefully planned to avoid debris, and the probability of damage to spacecraft during ascent rises [11]. This adds complexity and cost to space missions and may eventually make certain orbits inaccessible, restricting scientific research, exploration, and commercial activities.

Thus, it is evident that the risks posed by space debris to operational satellites and spacecraft are multifaceted. These may range from direct physical damage to broader operational and economic consequences. Moreover, it can be ascertained if no proactive measures are taken for debris mitigation and management, increasing threats from them will continue to undermine the safety and sustainability of space operations.

B. *Potential Consequences for Earth*

As the space debris gets accumulated in Earth’s orbit it results in far-reaching consequences not just for space operations but also for the planet itself. Some of these threats include the re-entry of debris into the Earth’s atmosphere and the catastrophic implications of the Kessler Syndrome [39].

One of the foremost consequences of higher space debris accumulation is its re-entry into the low Earth orbit (LEO). This is, however, subject to gradual orbital decay owing to atmospheric drag. While a major percentage of debris burns up upon re-entry into the earth, larger objects such as non-operational satellites or rocket stages can survive to reach the surface. This, in turn, results in significant threats to life, infrastructure, and the environment.

One such instance has been the re-entering of fragments of China’s Long March 5B rocket stages in recent years. Many of its large components have survived and landed in the Indian and Pacific oceans [40] [41]. Even though no significant casualties have been reported to date, the chances of damage infliction increase as the debris population grows. Additionally, many of these elements that re-enter Earth consist of hazardous materials such as leftover rocket fuel or toxic substances, which can contaminate soil and water sources, leading to environmental damage.

Another consequence of higher space debris accumulation is the Kessler Syndrome which was first proposed by NASA scientist Donald Kessler in the year 1978. It describes a hypothetical scenario in which the density of space debris in Earth’s orbit reaches a critical threshold. At this point, collisions between debris objects would trigger a self-sustaining cascade of further collisions, exponentially increasing the number of debris and rendering entire orbital regions unusable [23] [24].

If set in motion, the Kessler Syndrome will have far-reaching implications on Earth and humanity. Among these, the most significant would be the disruption or loss of key satellite-based services, such as communication, navigation, weather forecasting, and Earth observation. Moreover, it would also hamper our ability to safely access and operate in space, which would lead to delayed exploration missions and non-continuation of ambitious projects such as Mars Colonization or Asteroid Mining [24]. This would eventually lead to severe economic impacts. The global space industry which is valued at hundreds of billions of dollars would collapse, which would further impact industries reliant heavily on satellite technology.

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Lastly, beyond the evident risks of space debris accumulation, accumulation of debris in large quantities can have long-term consequences for Earth's environment and sustainability [15] [3]. Over time, it has been observed that a failure to address this issue could set a precedent for unsustainable practices in other domains, undermining global efforts toward environmental preservation and resource management. Thus, there is a dire necessity for the implementation of effective policies, thought-after technological advancements, and international collaboration to mitigate its risks and ensure sustainable space exploration and usage for future generations [7] [14].

C. Case studies of Significant Space Debris Events

The study of significant space debris events is critical to understanding the scope and severity of the issue, as well as the potential risks to operational satellites and spacecraft. Among the notable events that have shaped our understanding of space debris dynamics are the Iridium-Cosmos collision, the intentional destruction of satellites, and the Fengyun-1C anti-satellite (ASAT) test. These cases highlight the consequences of space debris and emphasize the need for international coordination and mitigation measures.

- ***The Iridium-Cosmos Collision (2009):*** The Iridium-Cosmos collision is one of the most significant accidental space debris events to date. On February 10, 2009, an operational Iridium 33 communications satellite collided with the defunct Russian satellite Cosmos 2251 at an altitude of approximately 800 km in low Earth orbit (LEO). The collision occurred at a relative speed of over 42,000 km/h and resulted in the fragmentation of both satellites into thousands of debris pieces. Moreover, it generated over 2,000 trackable fragments and countless smaller pieces that could not be detected but still posed risks to other satellites and spacecraft in LEO. This collision was the first recorded incident of an accidental collision between two intact satellites. Moreover, it portrayed the growing risks of operating in congested orbits and emphasized the limitations of existing collision avoidance systems [28] [42].
- ***Fengyun-1C ASAT Test (2007):*** The intentional destruction of the Fengyun-1C weather satellite by China during an anti-satellite (ASAT) test in January 2007 remains one of the largest single contributors to the space debris population. The test, conducted at an altitude of approximately 865 km, involved a kinetic impact that shattered the satellite into more than 3,400 trackable debris fragments and tens of thousands of smaller pieces. The debris which resulted from this test remains in highly dense-traffic orbits. Resultantly, it poses a significant threat to operational satellites and spacecraft. This event further reflected how deliberate satellite destruction can have far-reaching consequences. Moreover, it further brought to attention the need for responsible behaviour in space and the development of agreements/frameworks that could prevent similar incidents [25] [43].

Beyond these aforementioned events, many other incidents have occurred through time, which have contributed significantly to the growing population of space debris. Among this, a noted event was the breakup of a Briz-M rocket stage, which resulted in over 1,000 pieces of debris [44]. These events have time and again highlighted the diverse sources of space debris and the eminent need to manage them properly.

Debris mitigation methods such as end-of-life disposal plans, active debris removal technologies, and stricter international regulations governing satellite operations needs to be deployed in order to address the global challenges posed by space debris. Moreover, through a study of these cases, the space community and governments can better comprehend the intricate technicalities of debris generation. This will allow them to work towards sustainable solutions for preserving the usability of Earth's orbits.

IV. SCIENTIFIC AND TECHNOLOGICAL CHALLENGES

A. Tracking and Monitoring Space Debris:

Tracking and monitoring space debris is vital for mitigating the risks posed by them to Earth and its population [1] [45]. To ensure this, several measures need to be undertaken. These involve but are not limited to identifying, cataloguing, and predicting the movements of debris to prevent collisions with operational satellites, spacecraft, and the International Space Station (ISS) [27] [7]. Advanced technologies, including ground-based radars, space-based sensors, and laser ranging systems, play a critical role in these efforts.

- ***Ground-Based Radars:*** Among the various methods deployed for active debris tracking, ground-based radar systems for the backbone of these efforts [45]. These systems deploy high-frequency radio waves to detect and track objects in Earth’s orbit. These objects may fall anywhere from large defunct satellites to smaller fragments that may pose a serious threat to orbital space elements. Some of the noted radar systems include the U.S. Space Surveillance Network (SSN), which operates a global network of sensors to monitor objects larger than 10 cm in low Earth orbit (LEO) and larger than 1 meter in geostationary orbit (GEO). Furthermore, phased-array radars, such as the Space Fence radar system, provide continuous coverage of orbital regions and can detect objects as small as 5 cm in LEO [46]. However, these systems come with their limitations, which may arise owing to atmospheric interference and coverage gaps at higher altitudes.

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Fig 7: A Ground-Based Radar - EISCAT Svalbard Radar
[Image Source – The European Space Agency] [47]

- ***Space-Based Sensors:*** Space-based sensors complement ground-based radar systems by providing continuous and unobstructed coverage of orbital debris [48] [49]. These sensors are mounted on satellites and thus allow for the detection and tracking of smaller debris which may be untraceable from the ground. Some of the commonly used space-based debris monitoring techniques include optical sensors, infrared imaging systems, and onboard radars. A notable feature of these radars is that they can track objects in GEO and beyond. This ensures critical data access which enhances situational awareness. Lastly, space-based sensors also play a pivotal role in identifying debris generated by recent fragmentation events, enabling rapid response and risk assessment. Some key examples of such sensors include projects such as the European Space Agency's (ESA) Space Debris Telescope and the U.S. Department of Defense's Geosynchronous Space Situational Awareness Program (GSSAP) [47] [50].
- ***Laser Ranging Systems:*** Laser-ranging systems are another valuable tool for tracking space debris. These systems make use of ground-based lasers to measure the distance to debris objects with immense accuracy. They further analyze the time taken for laser pulses to reflect off objects and return to the source. This allows researchers to accurately gauge the objects' orbital parameters [51, 52].
- ***International Collaboration and Data Sharing:*** One of the key aspects of tracking and monitoring space debris is the necessity to ensure global collaboration. This is due to the shared nature of the orbital environment. Various space agencies and organizations like the ESA, NASA, and the U.S. Space Force have established programs that share tracking data and improve coordination among stakeholders. This enables these groups to facilitate the exchange of orbital data, enabling better collision avoidance strategies and debris mitigation planning.

However, despite the technological advancements that have enhanced tracking procedures, challenges remain. Smaller debris fragments are often hard to detect and pose significant risks to space operations [6]. Thus, it is necessary to develop more sensitive tracking systems and active debris removal technologies. This could be achieved through the integration of technologies like artificial intelligence (AI) and machine learning (ML) algorithms to enhance tracking accuracy and predictive capabilities.

B. Limitations in Current Detection and Avoidance Technologies:

Despite significant advancements in detection and avoidance technologies, several limitations hinder their effectiveness in addressing the challenges posed by space debris. One of the major limitations occurs in the inability of debris detection mechanisms to detect smaller debris [53]. These elements fall typically below 10 centimetres in size diameter. While large debris pieces can be tracked effectively using ground-based radars and space-based sensors, smaller fragments remain undetectable due to their size and limited radar resolution [27] [6]. These small debris objects can still cause significant damage upon collision, posing a critical threat to operational satellites and spacecraft.

Another drawback is the challenge of providing consistent global coverage by the tracking systems. Ground-based radars are limited by geographical constraints, such as the curvature of the Earth, while space-based sensors are restricted by power, data bandwidth, and operational lifespan [45]. Furthermore, the reliance of many of these systems on outdated data or incomplete information also impacts their ability to make precise predictions [54]. Alongside this, as mentioned above, atmospheric drag variability, solar radiation pressure, and the gravitational pull of celestial bodies like the moon and the sun, further contribute to uncertainties in modelling. This makes collision avoidance decisions less reliable [55].

Finally, technological and operational constraints, including the high cost of deploying and maintaining advanced tracking systems, limit the widespread implementation of these technologies. Even though nations and organizations have consistently undertaken collaborative efforts, these are still deemed insufficient which leads to gaps in global debris management.

V. INTERNATIONAL REGULATIONS AND POLICIES

A. Overview of International Treaties and Agreements Related to Space Debris:

The governance of space activities, including the management of space debris, is primarily guided by international treaties and agreements established under the auspices of the United Nations. These treaties form the foundation on which sustainable and responsible outer space activities are carried out [56]. However, while existing frameworks shed light on some aspects of space debris, they often lag behind in enforcement mechanisms and specificity. This leaves considerable gaps in global debris management.

The cornerstone of international space law is considered to be the Outer Space Treaty signed in 1967. The treaty aims to outline key principles for the peaceful use of outer space. It also holds nations responsible for activities conducted by their governmental and non-governmental entities. Moreover,

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this treaty also mandates that activities needs to be conducted to avoid harmful contamination of space [57].

In this regard, the Liability Convention of 1972 complements the OST by establishing a framework for liability related to damage caused by space objects. It holds launching states accountable for damages, whether on Earth or in outer space [58]. Furthermore, the Registration Convention of 1976 elaborates that the states are required to provide comprehensive information about launched objects. This information also needs to include their purpose and orbital parameters [59]. However, despite such detailed guidelines, the convention does not impose strict enforcement mechanisms.

Beyond such treaties, non-binding international guidelines also play a vital role in addressing space debris. Among these, the United Nations Guidelines for the Long-Term Sustainability of Outer Space Activities, adopted in 2019, encourage member states to adopt measures to reduce debris generation, enhance debris monitoring, and promote active debris removal [60].

However, despite such extensive measures, current treaties and agreements face several limitations. Firstly, weakened compliances owing to a lack of binding obligations pose a heightened threat. Complementing this, the rapid growth of private sector space activities and the increasing number of debris-producing events challenge the adequacy of existing frameworks. There is a pressing need for updated international agreements that address the complexities of space debris in the modern era [61], emphasizing proactive measures, global cooperation, and stricter enforcement.

B. Role of Organizations like NASA, ESA, and UNOOSA in Space Debris Mitigation:

Space debris, a growing concern in Earth's orbital environment, poses significant threats to satellites, spacecraft, and even future space exploration. With the rapid expansion of space exploration activities via governments and private entities, the challenges associated with debris accumulation have intensified [2] [1] [20]. This has resulted in an evident need for collaborative global efforts to mitigate its impacts. Various space agencies like the National Aeronautics and Space Administration (NASA), the European Space Agency (ESA), and the United Nations Office for Outer Space Affairs (UNOOSA) have taken critical steps to address this issue through research, policy advocacy, and tech-centric advancements.

For instance – NASA's Orbital Debris Program Office meticulously studies the generation, behaviour, and mitigation of debris in Earth's orbit. The organization works towards developing robust models that can track existing debris and predict potential collisions, such as the Orbital Debris Engineering Model (ORDEM) [62] [63]. By implementing guidelines for satellite operators and fostering innovation in active debris removal (ADR) technologies, NASA ensures that the U.S. space sector remains accountable while contributing to global solutions.

Likewise, the ESA also lays significant stress on both mitigation and remediation strategies. Through its Space Debris Office at its European Space Operations Centre, the agency focuses on monitoring orbital debris, conducting collision avoidance manoeuvres, and developing sustainable policies [64]. Moreover, via its Clean Space initiative, the organization aspires to promote eco-friendly practices throughout a satellite's lifecycle, including preventing debris creation and designing spacecraft for eventual deorbiting [65].

Similarly, UNOOSA plays a complementary and equally critical role by fostering international collaboration and developing regulatory frameworks to address space debris [56]. As it is a United Nations body, it works actively to ensure equitable access to outer space. Simultaneously it promotes long-term sustainability and provides member states with a framework to mitigate debris generation. All this is being achieved through its adoption of the 21 Guidelines for the Long-term Sustainability of Outer Space Activities [60].

Thus, it can be seen that NASA, ESA, and UNOOSA collectively form the foundations of international space debris mitigation efforts. While the former two focus on advancing technological solutions and operational guidelines, the latter's diplomatic efforts ensure widespread adoption and adherence to these practices. Furthermore, it is also evident that in the coming future, robust partnerships, stringent enforcement of guidelines, and continued innovation will be crucial in mitigating the risks of space debris and safeguarding the future of space exploration.

C. Compliance Issues and Challenges in Enforcing Debris Mitigation Guidelines:

Enforcing space debris mitigation faces major challenges due to fragmented global regulations, technological limits, and rapid commercialization. Most international guidelines, like the UN's sustainability framework and IADC standards, are voluntary, leading to inconsistent compliance. Emerging space nations and private firms often lack incentives or resources to implement these measures, worsening the issue.

National regulatory differences further complicate enforcement. Some countries mandate debris mitigation, while others have minimal rules, creating an uneven playing field. Jurisdictional conflicts arise when multiple nations are involved in debris incidents, making accountability difficult.

The rise of commercial space activities, especially mega-constellations, increases debris risks. Many private operators, particularly small satellite developers, see compliance as costly and challenging. Technological gaps, such as limited tracking of small debris and costly disposal solutions, further hinder adherence.

Without a global enforcement authority, oversight remains weak. Organizations like UNOOSA promote cooperation but lack enforcement power, leaving regulation to individual nations, often resulting in insufficient oversight.

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To ensure space sustainability, binding regulations, compliance incentives, and cost-effective mitigation technologies are crucial. Only coordinated global action can effectively address these challenges.

VI. MITIGATION STRATEGIES

A. Active Debris Removal Techniques:

The growing threat of space debris has made active debris removal (ADR) essential for ensuring a safe orbital environment. Unlike passive measures, ADR directly removes debris using harpoons, nets, and laser systems, each with distinct advantages and challenges. To begin with, Harpoons are one of the many direct measures deployed to remove debris. They work by piercing and securing large, non-cooperative objects like defunct satellites, allowing controlled deorbiting. ESA's RemoveDEBRIS mission successfully demonstrated this method, though challenges remain in precise targeting and preventing fragmentation during capture [66].

Fig 8: The Harpoon Mechanism on the Remove Debris Satellite is Engineered to Spear and Pull in Floating Debris from Earth's Orbit. [Image Source: Airbus/the RemoveDebris Consortium] [67]

Another effective method for debris removal is Nets. These provide a more flexible approach by enveloping debris, making them ideal for irregular or fragile objects. ESA also tested this technique, proving its effectiveness. However, ensuring accurate deployment and avoiding secondary collisions remains a challenge.

On the contrary, laser systems offer a non-contact solution by ablating debris surfaces to alter their orbits, slowing them down for safe re-entry. While this method is effective for smaller debris, high energy demands, alignment issues, and geopolitical concerns pose significant hurdles. Although, one of the advantages of laser systems is that they do not require direct interaction with debris [68]. Ultimately, it can be concluded that the choice of ADR technique depends on the size and nature of the debris. As space activities expand, ADR will be crucial for maintaining a sustainable and secure orbital environment.

B. Passive Mitigation Methods:

Passive mitigation plays a crucial role in addressing space debris by preventing its generation rather than focusing on removal. This approach relies on two key strategies, designing spacecraft to minimize debris and implementing end-of-life (EOL) disposal measures. Together, these methods ensure the long-term sustainability of space operations.

To begin with, designing spacecraft for debris prevention involves using durable materials that can withstand the harsh conditions of space, thereby reducing the risk of fragmentation. Additionally, shielding technologies protect against micrometeoroids and small debris, further minimizing potential damage [69]. Another important aspect is the development of modular spacecraft, which allows for in-orbit upgrades and repairs, extending their operational lifespan and reducing the need for frequent launches [70]. Moreover, satellite manufacturers now incorporate features like venting residual fuel at the end of a mission, preventing explosions that could generate debris. These proactive measures align with international guidelines, such as those set by the Inter-Agency Space Debris Coordination Committee (IADC).

In addition to preventive design, EOL disposal strategies are equally critical. Once a spacecraft completes its mission, it must be safely removed from operational orbits. For satellites in low Earth orbit (LEO), controlled deorbiting ensures they burn up in the atmosphere, preventing long-term clutter [71] [72]. On the other hand, geostationary satellites are moved to designated graveyard orbits, keeping active orbital paths clear [73]. Notably, many spacefaring nations now mandate compliance with EOL guidelines, requiring satellite removal within 25 years of mission completion.

However, despite their effectiveness, passive mitigation methods come with challenges. The cost of implementing these measures can be high, especially for smaller satellite operators. Furthermore, the rise of mega-constellations adds complexity to large-scale debris management [35] [12]. Therefore, ensuring widespread adoption requires technological advancements, regulatory enforcement, and international cooperation.

Thus, it can be ascertained that passive mitigation is essential for the sustainable future of space exploration. By prioritizing debris prevention and safe disposal, these strategies offer a cost-effective, scalable solution to the growing space debris problem. However, their success depends on continuous innovation, global collaboration, and strict adherence to international guidelines.

C. Emerging Technologies and Prospects in Debris Mitigation

With the constantly increasing issue pertaining to space debris, there has been a continuous innovation in emerging technologies that aim to mitigate risks and ensure the sustainability of space operations.

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One promising avenue is the development of autonomous robotics for active debris removal (ADR). The development of robotic arms and capture mechanisms, which are equipped with AI-driven navigation and precision targeting systems, will be able to retrieve non-functional satellites and large debris fragments [8]. Various organizations such as ClearSpace and government initiatives such as ESA's ClearSpace-1 mission are sound examples of the ongoing advancements in this domain, focusing on removing high-risk objects from orbit [74]. Another key technology is the deployment of advanced propulsion systems to enable self-removal capabilities [75]. Satellites equipped with electric or chemical propulsion systems can manoeuvre to deorbit themselves or transition to graveyard orbits at the end of their operational lifespans [73]. These innovations are particularly relevant for mega-constellations, where thousands of small satellites require efficient and cost-effective disposal mechanisms.

Alongside this, the integration of artificial intelligence and machine learning is transforming debris tracking and collision avoidance systems. Enhanced tracking technologies, including improved radar and optical sensors, coupled with predictive algorithms, enable real-time monitoring and proactive collision mitigation [68]. This ensures better coordination among operators in increasingly crowded orbital regions.

Looking ahead, emerging concepts like the deployment of tether systems and drag-enhancing devices could offer cost-effective solutions for passive deorbiting. Additionally, the development of ground-based and space-based laser systems to nudge debris into lower orbits for atmospheric re-entry holds promise, though it raises geopolitical and regulatory concerns.

VII. CASE STUDIES AND SUCCESS STORIES IN DEBRIS MITIGATION

The alarming rise of space debris has prompted significant efforts by space agencies and organizations to implement mitigation strategies. Case studies such as the European Space Agency's (ESA) Clean Space initiative, NASA's Orbital Debris Program, and the RemoveDEBRIS mission have demonstrated effective solutions while providing valuable insights into overcoming the technical and operational challenges of debris mitigation.

ESA's Clean Space initiative represents a holistic approach to addressing the environmental impact of space activities, with a strong focus on debris mitigation [76]. A notable achievement under this initiative is the RemoveDEBRIS mission, which successfully demonstrated multiple active debris removal (ADR) technologies in orbit. The mission tested the use of harpoons to pierce and secure large debris objects, nets to capture tumbling debris, and vision-based navigation for precise targeting. The successful execution of these experiments validated ADR techniques as viable solutions to remove large, inactive objects from orbit [77]. ESA's ClearSpace-1 mission, scheduled for deployment in the near future, aims to remove a Vega rocket payload adapter. This mission will serve as a landmark for operational debris removal, offering a scalable model for tackling larger debris challenges.

Likewise, **NASA's Orbital Debris Program Office** has made significant contributions to debris mitigation through advanced tracking, policy development, and risk assessment [63]. NASA's guidelines, including the widely adopted 25-year rule for end-of-life satellite disposal, have set global benchmarks [72]. The agency's investment in improving radar and optical tracking systems has enhanced the ability to monitor and predict debris movement, enabling timely collision avoidance measures. Furthermore, NASA has fostered partnerships with private operators, promoting compliance with mitigation practices and advancing technologies such as propulsion systems for self-removal.

Several lessons have been learned from past missions and incidents. For instance, the Kosmos 2251-Iridium 33 collision in 2009, which generated thousands of new debris fragments, highlights the importance of real-time tracking and enhanced communication among satellite operators [28].

The impact of mitigation strategies on reducing the debris population is evident. Proactive measures such as passivation techniques, which neutralize leftover fuel to prevent explosions, and the implementation of deorbit systems have reduced the risk of fragmentation events. Active debris removal missions, while still in the experimental phase, hold the potential to remove high-risk objects and prevent the exponential growth of debris. Furthermore, stricter regulatory requirements for satellite launches have incentivized compliance with debris mitigation protocols, fostering a culture of sustainability within the space industry.

VIII. FUTURE DIRECTIONS AND RECOMMENDATIONS

The evolving landscape of space activities necessitates a robust research agenda to address critical gaps in debris mitigation. One prominent research gap is the need for scalable active debris removal (ADR) systems. While experimental technologies such as harpoons, nets, and robotic arms have shown promise in controlled environments, further studies are essential to optimize their performance in real-world orbital conditions.

Any new research in this direction should focus on enhancing precision targeting, improving the structural integrity of captured debris, and developing autonomous navigation systems that can operate reliably in congested orbital regions. Additionally, there is a need for advanced modeling of debris generation and propagation, which would improve risk assessment and inform the design of both active and passive mitigation strategies.

On the policy front, to advance debris mitigation efforts, policy recommendations should focus on transitioning from voluntary adherence to enforceable international treaties that mandate specific end-of-life disposal measures and passivation protocols. It has thus become the need of the hour

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that national regulatory bodies collaborate to standardize technical requirements for satellite design and operation, such as the inclusion of deorbiting systems and controlled re-entry procedures. Incentivizing compliance through a combination of financial benefits, streamlined licensing processes, and punitive measures for non-compliance could further ensure that both governmental and commercial space actors adopt responsible debris mitigation practices. Moreover, establishing a dedicated international regulatory body with oversight capabilities may help harmonize efforts and bridge the gap between emerging and established spacefaring nations.

Lastly, international collaboration and sustained funding are foundational to the success of future debris mitigation initiatives. The shared nature of the orbital environment calls for coordinated global action. Enhanced data-sharing agreements and joint research initiatives can accelerate the development of innovative technologies, while collaborative funding mechanisms can provide the necessary financial support for large-scale demonstration projects. Additionally, integrating emerging spacefaring nations into the global dialogue ensures that mitigation strategies are comprehensive and inclusive, addressing regional disparities in technological capabilities and regulatory frameworks. Such collaboration not only drives technological advancement but also fosters political and economic stability in space governance. Thus, by aligning technological innovation with robust regulatory frameworks and global partnerships, the space community can pave the way for a sustainable orbital environment, ensuring the long-term viability of space operations for future generations.

IX. CONCLUSION

The above paper has examined in detail the various challenges that are posed by space debris. Moreover, it has also looked into the corresponding mitigation strategies that are needed for sustainable space exploration. Key findings underscore the critical need for scalable active debris removal (ADR) technologies, the importance of enforceable international policies, and the role of collaborative efforts in addressing the escalating debris problem. While experimental ADR methods have delivered the expected results, there is a need for future research so that these technologies can be further optimized for real-world applications. Alongside this, there is a need to transition from voluntary guidelines to binding international agreements. This will ensure consistent adherence to debris mitigation practices across all spacefaring entities.

Addressing space debris is paramount for the long-term sustainability of space activities. The proliferation of debris not only endangers operational satellites and manned missions but also threatens the viability of future space endeavours [27] [4] [15]. Without concrete action, the cascading effect of collisions could render certain orbits unusable, severely limiting the potential for scientific discovery, commercial ventures, and international cooperation in space [24] [23]. Owing to these challenges, it has become crucial for researchers and policymakers to intensify efforts in developing and implementing effective debris mitigation measures. Future research should focus on advancing ADR technologies, enhancing debris-tracking capabilities, and understanding the long-term impacts of mitigation strategies on the orbital environment. Furthermore, those who devise new policies should be urged to establish and enforce robust international frameworks that mandate responsible behaviour in space operations. Furthermore, fostering international collaboration and securing dedicated funding is essential to support large-scale mitigation projects and ensure the shared use of space remains safe and sustainable for generations to come.

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