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Global Standards and recommended practices to accomplish sustainability in spacecraft operations

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Abstract

Ever since the first spaceflight was launched in 1957, the space industry has grown significantly in line with advancements in technology. There has been a surge of activities in spacecraft operations in the recent years. This rapid growth creates sustainability challenges in space, as well as on earth, due to increasing orbital debris and emissions of greenhouse gases. The rise in space activities has been attributed to the reduced costs of launching spacecrafts. Owing to the cheaper access to space which leads to an increase in spacecraft population, especially in the low earth orbit up to an altitude of 2000 km, resulting risks of collisions. It will be difficult or impossible to operate spacecrafts due to congestion in future if no harmonization efforts are made. It is important to note that there is a deficit of global standards to operate and dispose of spacecrafts at present.

This paper aims to explore the feasibility of establishing global standards and recommended practices that states, and private institutions should comply with to achieve sustainable and safe spacecraft operations. Using empirical evidence, this study examines the general standards and recommended practices necessary to maintain a sustainable space environment, ensuring it remains viable for future generations.

Keywords: standards, practices, sustainability, operations, governance, policies,

Acronyms/Abbreviations

ADR: Active Debris Removal
CONFERS: Consortium for Execution of Rendezvous and Servicing Operations
COPUOS: Committee on the Peaceful Uses of Outer Space
EOL: End of Life
ESA: European Space Agency
IADC: Inter Agency Space Debris Coordination Committee
ICAO: International Civil Aviation Organization
ISO: International Standard Organization
ITAR: International Traffic in Arms Regulations
ITU: International Telecommunication Union
LEO: Low Earth Orbits
LCA: Life Cycle Assessments
LTS: Long-Term Sustainability Guidelines
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SDA: Space Data Association
STM: Space Traffic Management
SSR: Space Sustainability Rating
SWF: Secure World Foundation
UN: United Nations
UNOOSA: United Nations Office for Outer Space Affairs

1.0 Introduction

1.1 Background on sustainable spacecraft operations and increasing importance

Sustainable spacecraft operations have become more challenging than ever owing to the accelerated space exploration and satellite deployment. It is important to ensure a long-term sustainable space framework globally for

the safety of the spacecraft as well as the environment. Several key factors contribute to the growing concern over sustainability in spacecraft operations. These include the accumulation of orbital debris, environmental impacts, resource limitations, and evolving international regulatory frameworks.

There are over 30,000 trackable objects which are larger than 10cm and millions of smaller debris fragments [1] that can be considered as the most pressing sustainability challenge for spacecraft operations. A growing number of rockets launching is impacting the sustainability on earth due to greenhouse gas emissions. Chlorine gas releases from rocket motors deplete the stratospheric Ozone layer [2] and Aluminum Oxide particles contribute to climate change by altering the atmospheric composition [3]

Sustainable resource management in space for long-term missions should be self-sufficient without endangering the finite resources on earth. International regulatory bodies urge for long-term sustainability by advocating for more responsibility in the space domain. Certain states, institutes and private companies push for adherence to sustainable measures for funding and approvals.

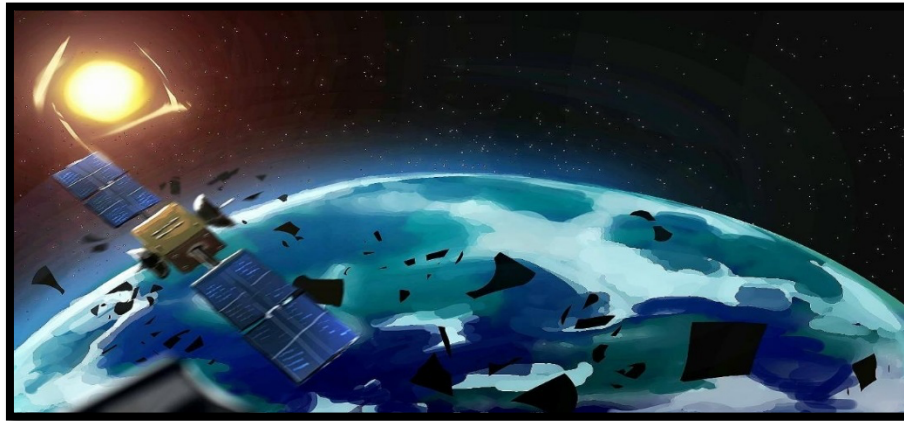


Figure 01. Space is not a landfill

1.2 Research gap on harmonized global standards and practices

Despite the rapid expansion of space exploration, the space industry continues with lack of harmonized global standards and universally accepted practices. In contrast, the civil aviation industry benefits from a well-established governance structure through the International Civil Aviation Organization (ICAO), which enforces the safe, secure, sustainable, and efficient air travel to its 193-contracting states. However, the governance in the space industry remains fragmented due to the different intentions of space actors with space law enforcement primarily regulated at an individual country level. The lack of global regulatory framework creates huge challenges to ensure sustainable space for future generations.

Despite this, certain agencies like the United Nations Office for Outer Space Affairs (UNOOSA) and the Inter Agency Space Debris Coordination Committee (IADC) provide non-binding guidelines to mitigate space debris. However, compliance isn't mandatory and the risk for satellite operations persists. Furthermore, there is no universally agreed standards among space actors to mitigate the environmental consequences caused by rocket emissions and to prevent overcrowding satellites potentially leading to Kessler Syndrome [4].

The need for a Space Traffic Management (STM) system is critically important to avoid potential collisions in Low Earth Orbits (LEO) due to increasing congestion. At present, there is no authoritative international body overseeing management of space traffic. The United Nations has taken some measures to open a discussion for STM, however the progress remains limited, and other institutions such as Space Data Association (SDA) and Space Sustainability Rating (SSR) have no law enforcement power as they are industry led initiatives [5,6].

1.3 The objective of accessing the role of global standards and practices

The requirement for effective global standards and recommended practices is essential to ensure safe, secure, and sustainable spacecraft operations as space exploration has become more complex. Establishing harmonized enforcement remains a challenge due to the lack of intent among the space actors. The objective of the paper is to explore effective practices in space operations while evaluating the role of a global standard for lasting space operations for the years to come.

1.4 Implications for sustainable space activities

In the absence of globally accepted regulations and environmental protection, long-term space operations and operational efficiency constitute significant risks in space exploration. However, establishing global standards can help to mitigate the challenges in space activates while ensuring sustainable space exploration.

2.0 Literature Review

2.1 Evolution of sustainable space operations

Sustainable spacecraft operations can be considered as one of the growing areas of research owing to the concern on space debris mitigation, resource limitation and environmental impact. Sustainable practices in space operations have evolved over the years from the basic waste management up to comprehensive policies on de-orbiting mechanisms, in-orbit servicing, debris mitigation and green propulsion systems. However, the early industrial policies focused on technological innovation along with economic gains rather than sustainability concerns [7]. Negligence on sustainability assessments impacted significant environmental deterioration as well as socio-economic costs.

Wilson [8] has shown that sustainability focusing on space operations came into being in the 21st century as life cycle assessments (LCAs) were not included in early mission planning. Orbital debris from early space exploration were largely neglected until it caused a collision risk for spacecraft as well as manned missions, where certain space agencies like NASA and ESA implemented space debris mitigation policies.

Long-Term Sustainability Guidelines (LTS) of the United Nations Office for Outer Space Affairs (UNOOSA), which is an agreement on space sustainability, were published several decades after the beginning of space race. Nevertheless, a rise in sustainable space practices came into being in the late 20th century due to the development of sustainable policies which ensure safe, secure, and efficient space exploration. Due to the increasing consideration of sustainability, innovative policies are shifting towards transitioning into sustainable technologies [9]. Prominent space agencies like NASA, ESA as well as private companies, SpaceX, Blue Origin have given precedence to perform space operations sustainably by implementing orbital debris mitigation strategies, disposal of spacecraft at the end of life and reusable launch systems. Both NASA and ESA demonstrate that they are actively integrating sustainable mission planning into their space missions as per Artemis Accords [10] and Clean Space Initiative [11].

The future of sustainability in space operations appears to be promising as there is a trend in the application of circular economic principles. Tan et al. [12] explores reuse and recyclability in space operations while minimizing waste and maximizing resource efficiency. Astroscale, a private space company has provided long term sustainability guidelines for End Of Life (EOL) and Active Debris Removal (ADR) procedures and planning to offer EOL and ADR services in the future. [13]. Durrieu and Nelson [14] emphasized the development and adoption of green design and green technologies for future space missions, after an evaluation of carbon footprints of various space operations.

2.2 International Treaties and Guidelines

There are several treaties, technical regulations and voluntary guidelines that have been developed by several international organizations. As of 2024, there are five major international space treaties that have been established by the United Nations to ensure peaceful and sustainable space for all nations. The International Telecommunication Union (ITU) has established four important regulations to ensure efficient, fair, no-interference and sustainable satellite communications use in broadcasting, navigation and telecommunication.

The International Organization for Standards (ISO) has developed quality, technical safety and sustainability standards for global space operations. ISO supervises operational standards, space systems design, space debris mitigation and sustainability. These ISO standards enhance the reliability of space operations and reduce the collision risks as well as environmental damage while promoting international collaboration in space activities. There are several other guidelines and frameworks also available from various international institutions and industry groups. These are supplement to the UN, ISO and ITU regulations on space exploration.

Key frameworks, international treaties and guidelines on space governance were illustrated below, in table 1.

Organization	Framework	Description (Key Points)	Reference
UN	The Outer Space Treaty <ul style="list-style-type: none"> • Year 1967 • Signatory or with ratification countries 132 	<ul style="list-style-type: none"> • Space exploration is for all nations. • No sovereignty claims. • No nuclear weapons in space • Promotes Intermarital corporations 	[15]

	The Rescue Agreement <ul style="list-style-type: none"> Year 1968 Signatory or with ratification countries 124 	<ul style="list-style-type: none"> Assist astronauts in distress. Return the space debris to its owners 	[16]
	The Liability Convention <ul style="list-style-type: none"> Year 1972 Signatory or with ratification countries 119 	<ul style="list-style-type: none"> Absolute liability for the damage caused by space objects. Damage claim mechanism among states 	[17]
	The Registration Convention <ul style="list-style-type: none"> Year 1976 Signatory or with ratification countries 76 	<ul style="list-style-type: none"> Register space objects with UN Launch notification to UNOOSA 	[18]
	The Moon Agreement <ul style="list-style-type: none"> Year 1979 Signatory or with ratification countries 22 	<ul style="list-style-type: none"> Declaration of Moon/Celestial bodies as common heritage of humankind 	[19]
ITU	ITU Radio Regulations <ul style="list-style-type: none"> Year 1906 29 members and Currently 193 member states 	<ul style="list-style-type: none"> Allocate and Manage radio frequency spectrum for satellite communication Ensure fair and free use of frequency 	[20]
	ITU Constitution and Convention <ul style="list-style-type: none"> Year 1992 Treaty Countries 194 	<ul style="list-style-type: none"> Defines obligations and rights of members states International cooperation by means of efficient telecommunication 	[21]
	ITU Coordination procedures <ul style="list-style-type: none"> Year 1963 Member countries 193 	<ul style="list-style-type: none"> frequencies for terrestrial or satellite services must notify the ITU 	[22]
ISO	ISO 24113 Space Debris Mitigation	<ul style="list-style-type: none"> Reduce space debris generation Satellites to be deorbited after mission completions 	[23]
	ISO 14620 Space System Safety Requirement	<ul style="list-style-type: none"> Establish protocols for launch vehicles and spacecrafts 	[24]
Other	ESA Convention <ul style="list-style-type: none"> Year 1975 Year 2003 (Amended) 22 member states 	<ul style="list-style-type: none"> Promote space research, technology development Members states should comply regulations and contribute financially 	[25]
	UN Long-Term Sustainability guidelines (LTSG) <ul style="list-style-type: none"> Year 2019 	<ul style="list-style-type: none"> Establish 21 voluntary guidelines, developed by UN COPUOS 	[26]
	Artemis Accords <ul style="list-style-type: none"> Year 2020 	<ul style="list-style-type: none"> Set standards for lunar exploration 	[27]
	ESA Clean Space <ul style="list-style-type: none"> Year 2012 22 member states 	<ul style="list-style-type: none"> Minimize space debris, reduce pollution and promote sustainable practices Promote eco-friendly spacecrafts and launch vehicles design 	[28]

Table 01: Key frameworks, Treaties and Guidelines on Space Governance

2.3 Emerging issues and challenges in space exploration

As a result of growing space activities in recent years, sustainability in space operations faces severe challenges. Therefore, the requirement for effective governance and policies on space sustainability is urgently needed in order to mitigate space debris accumulation, resource limitations and inconsistencies in space law.

Inoperable spacecrafts, modules, remains of rocket stages and collision fragments have grown in number over the years and formed a belt of debris around earth which poses risk to operational spacecrafts [4]. Through a series of cascading debris collisions described as Kessler Syndrome [29], this belt has the potential to make space completely

inaccessible for hundreds, if not, thousands of years to come. NASA's Orbital debris mitigation guidelines as well as ESA's Clearspace – 1 mission [30] for Active Debris Removal (ADR) can be considered as significant step towards debris mitigation efforts. However, the high costs of debris mitigation procedures, legal issues as well as lack of international enforcement of space law, these mitigation efforts become more challenging [31].

3.0 Method of analysis

A research method can be interpreted as a technique, a process or a strategy that is used to interpret data and/or evidence for analysis in order to unfold new information or refine a better understanding of a topic. A comprehensive research methodology comprises of philosophies, which include ontological and epistemological aspects, inductive, deductive and adductive approaches [32]. The strategies used in these research methods include primary/secondary case studies, surveys, experiments, systematic review, archival research and grounded research and the methodological approach. This study will be on qualitative, evidence based secondary research.

3.1 Research approach

Among the three principal research approaches, the deductive approach will be used, as this research targets specific interrelated concepts with verifiable assumptions. In the deductive research approach, a theory will be explored and verified under the prevailing circumstances. This approach will be used to evaluate the global standards and recommended practices to accomplish sustainable spacecraft operations. The evaluation is narrowly focused owing to assumptions such as the key attributes of global standards, recommended practices and their relationship with sustainable spacecraft operations. As per the above assumptions, 12 journal articles were selected through a rigorous filtering process using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) model [33], and the data in the findings chapters of those selected articles will be systematically extracted for the evaluation process which are in line with the assumptions, which are made. This method can be classified as deductive as it is line with the “theory-to-data” approach.

3.2 Research Strategy

There are many alternate research strategies used by scholars. However, a good research strategy gives an overall direction of the research with the processes that are being used. The author relies solely on already published research materials and gathers data directly for this research, called “secondary research”, in order to carry out systematic investigation with the existing data. A systematic review approach for research has the following important aspects as per Bearman et al. [34]. (i) A set of narrowly focused objectives with the pre-defined suitability requirements, (ii) An approach which is explicit and reproducible, (iii) The search criteria extracts all the relevant journal articles based on the suitability requirement and (iv) A critical assessment about the validity of the key findings from the selected journal articles.

Owing to the sensitive nature of the research, as it linked with society, governance and sustainability, the author believes that the most appropriate research strategy would be primary research such as survey or a case study. However, it is not practical to do so due to the time constraints and associated costs. Besides the pros and cons of the research technique, the author decided to execute the systematic review as the data collection and analytical strategy for this study.

3.3 Scope

The scope of the study is limited to the global standards and practices required for sustainable spacecraft operations. However, the author has visually illustrated the boundaries of the research criteria as per the Venn diagram in figure 2 below.

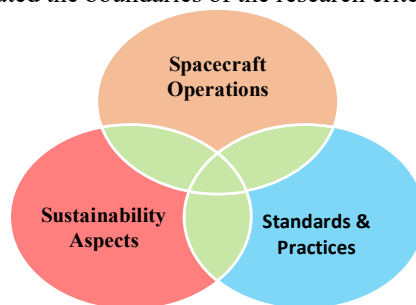


Figure 02: Boundaries of research criteria

3.4 Search criteria

The search process of the journal articles includes a careful selection of key words and phrases in order to find the most appropriate journal articles published within the last 15 years. The journal search terms were entered into popular academic databases such as Emerald, Elsevier, Research Gate and Willy by utilizing search tools ProQuest and Google Scholar. The selected articles were illustrated in the above Venn diagram (Figure 2) representing the area belonging to the intersections of three circles which is highlighted in green.

3.5 Quality evaluation

The initial search generated several hundred journal articles. The author applied further filtering process for the search parameters in order to narrow it down to a feasible list for quality evaluation based on relevance, effectiveness and quality of the sources. This process of screening resulted a list of 48 journal articles.

3.6 Inclusion and exclusion

The main difference between the systematic review and the literature review is a rigorous screening mechanism that is used to select the journal articles in a systematic review. This process is called the “inclusion and exclusion” criteria [34], depending on the characteristics of the mandatory prospective subject area for the study. Researchers have been using various “inclusion and exclusion” criteria for their scholastic work. However, the Preferred Reporting Items for Systematic Review and Meta Analysis (PRISMA) - a transparent framework [32,35] widely used among scholars for systematic review. The summary of the search results is included in the PRISMA flow chart and 12 qualitative journal articles, which meet the inclusion criteria. The figure below illustrates the “inclusion and exclusion” exercise for the 12 selected articles, which will be used for thematic analysis and for the discussion in order to achieve the desired aims and objectives of the study.

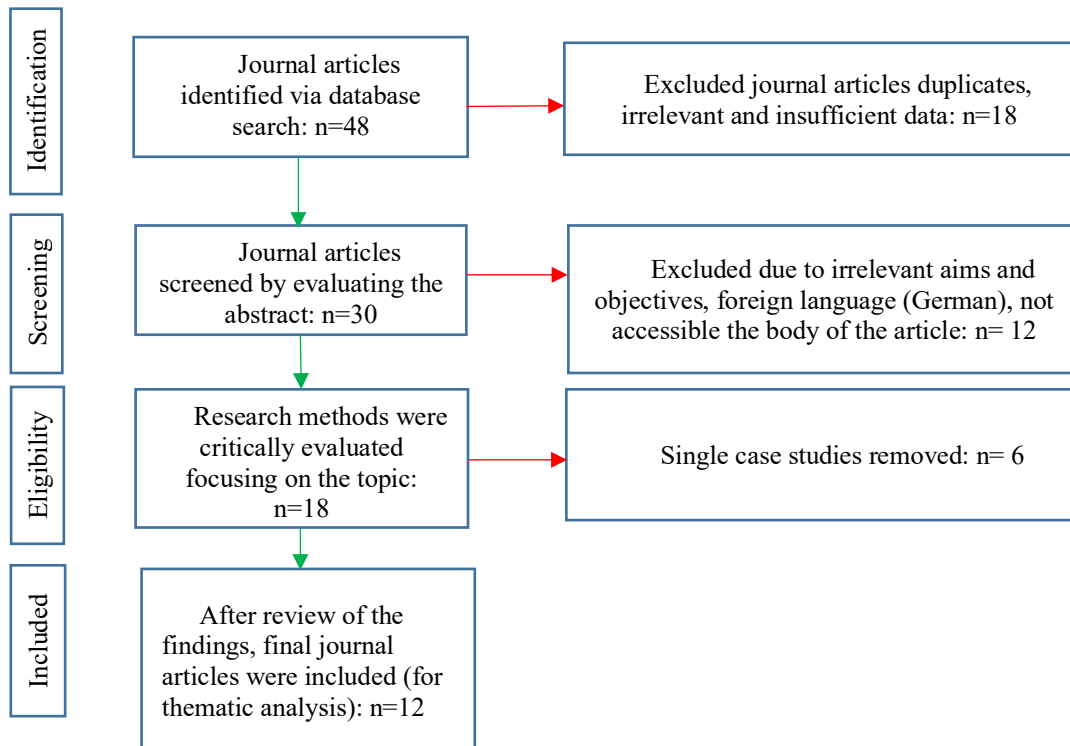


Figure 03: PRISMA Flow

3.7 Descriptive summary

The author has carried out an analysis on the selected 12 articles and organised a summary table based on the author, topic, research methodology and the key findings. This table enables the author to understand the important aspects, such as when the research was done, how it was done and the key outcome of the respective research. The key outcomes or findings will enable the author to formulate the current research. The table below illustrates the descriptive summary of the research.

No.	Author	Topic	Methodology	Key Findings
1	Oltrogge, D.L. and Christensen, I.A., [36]	Space Governance in the New Space Era	Literature review with comparative analysis	<ul style="list-style-type: none"> • Four levels of space governance • Regulatory gaps • Stronger international cooperation for sustainability • Identified key areas for future space governance
2	Gleason, M.P., [13]	Establishing space traffic management standards guidelines and best practices	Literature review with policy and gap analysis	<ul style="list-style-type: none"> • Importance of effective Space Traffic Management (STM) • Identified gaps in the current STM frameworks. • Requirement for global STM polices. • Encourage to improve space situation awareness (SSA) • Space sustainability is at risk
3	Decardi, A., [38]	Development of global safety orientations for space exploration regulations and bridging with aviation standards	Comparative analysis with policy review	<ul style="list-style-type: none"> • Lack of global safety standards • Propose safety assessment process. • Need for a unified international space safety standard like in aviation. • Challenges in establishing space safety standards
4	Weeden, C. et al., [13].	Industry implementation of the long-term sustainability guidelines: An Astroscale perspective	Policy Review with case study	<ul style="list-style-type: none"> • Background of Long-term sustainability (LTS) of UNCOPUOS guidelines • Compliance of LTS isn't legally binding. • Astroscale's effort on adopting LTS and creation of industry standards. • Identified gap on LTS

5	Sharma, T. et al., [39].	A global space policy that would review space exploration	Comparative Analysis	<ul style="list-style-type: none"> • Despite global reliance space-based technologies, only few have the ability to make the best use • Identified the challenges for space collaboration. • Proposed a global space policy for sustainable and peaceful space exploration
6	Murtaza, A. et al., [40].	Orbital debris threat for space sustainability and way forward	Comparative analysis	<ul style="list-style-type: none"> • Space debris threat to space operations and its cascading effects • Update of space debris situation • Regulatory and policy challenges in mitigating debris • Proposed a Satellite Information Network (SIN) for dual or multi-mission satellites
7	Som, S., [41]	An international symbol for the sustained exploration of space	Historical review with comparative analysis	<ul style="list-style-type: none"> • A need for global identity in space exploration • Critiquing the space race between Russia and America • Propose a new space symbol and a global space philosophy in space exploration
8	Dey, A and Jagadanandan, J., [42]	Balancing commercialization and sustainability in outer space: Addressing new challenges	Policy reviews with comparative analysis	<ul style="list-style-type: none"> • Adopt supporting policies for private sector involvement in space activities. • Lack of clear regulations on space sustainability • Need for an international regularity framework for space
9	Martinez, N., [43]	The development and implementation for international UN guidelines for the long-term sustainability of outer space activities	Historical review with a comparative assessment	<ul style="list-style-type: none"> • Need for a long-term sustainability (LTS) in space • Challenges in implementing LTS due to the non-binding nature of UN guidelines

				<ul style="list-style-type: none"> • Requirement for high level political agreement on cooperative governance of space
10	Yang, K. and Wu, Y., [44]	Improving international governance of space debris in the era of large constellations of small satellites and China's response	Policy Analysis with technical assessment	<ul style="list-style-type: none"> • Ineffectiveness of space debris mitigation policies due to large rise in debris • Unavailability of international standards de-orbiting satellites • National policies, frameworks and technology usage for space debris crisis in China • Methods to improve space governance
11	Trur, A., [45]	Governance aspects of space sustainability: The role of epistemic actors as enablers of progress	Historical Analysis and Theoretical assessment	<ul style="list-style-type: none"> • Evolvement of space governance • Gaps in international space treaties • The role of epistemic actors • Developing binding international agreements based on scientific consensus
12	Gallagher, N., [46].	Space governance and international cooperation	Policy analysis and comparative study	<ul style="list-style-type: none"> • Lack of clear, consistent strategy for space governance • Strategic approaches for space cooperation • Challenges in implementing global space governance and recommendations for effective governance

Table 02: Descriptive summary

3.8 Thematic analysis

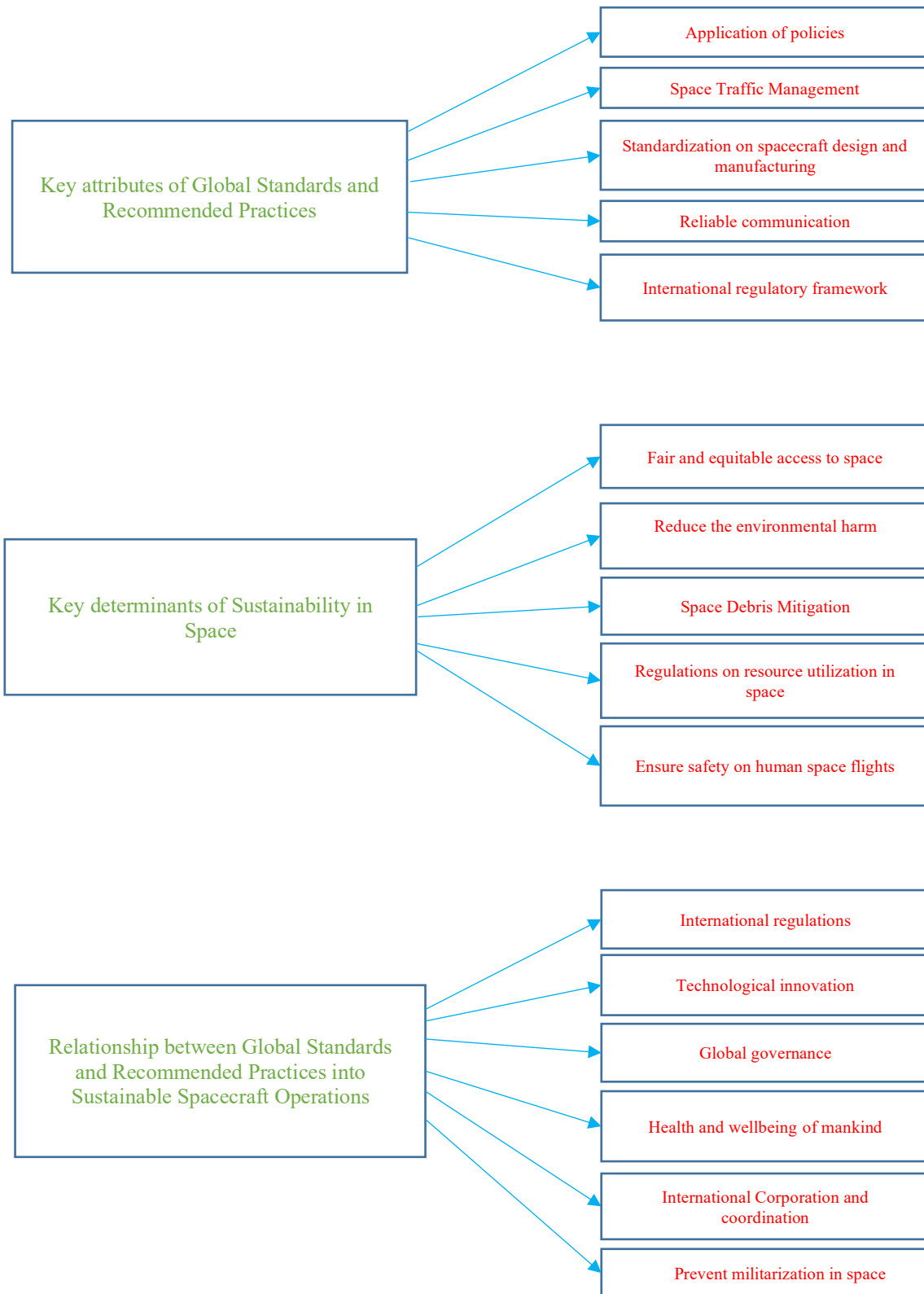


Figure 04: Thematic Structure

4.0 Discussion

This chapter consists of an evaluation of the key findings and how it relates to the research question. The findings from the thematic analysis will be used to develop relationships and patterns and synthesize them. The author attempts to evaluate the key findings from the descriptive summary, along with the thematic analysis, in order to achieve the desired objectives of the study.

4.1 Key attributes of global standards and recommended practices

The initial literature review suggests that there are five factors of key attributes in global standards and recommended practices in space operations. Those factors are application of space policies, space traffic management, standardization on spacecraft design and manufacturing, reliable communication, and international regulatory framework. From the thematic analysis, it is evident that three factors are more significant than the others, which are the application of policies, standardization of spacecraft design and manufacturing and international regulatory frameworks.

4.1.1 Application of space policies

Oltrogge and Christensen [36] emphasized that developing an effective legal policy regime requires coordination of multiple stakeholders with good understanding between the commercial sector and the multilateral space governance. Dey and Jagadanandan [42] affirmed the same view with the addition of formulating an international space policy through a regularity framework. The Global consensus on space policy implications defers from aviation industry, which is the safety criteria [38]. The author agrees that safety constitutes the backbone of aviation operations due to the presence of human factor. However, human spaceflight operations constitute the same precedence. Weeden et al. [13] stated the objective of developing a long-term sustainable national and international framework with emphasis on space policy with best standards and practices as it recognises equality. Sharma et al [39] revealed that all the states active in space exploration have their national space policy, whereas EU member states have a dedicated “One-Space-Policy” with common objectives. They argued that international involvement of UN or SWF programs shouldn’t overshadow the requirement of a global space programme and implement a global umbrella space policy ensuring sustainable development of space exploration. Trur [45] revives the norms of peaceful space exploration and emphasizes that the purpose of international policy coordination should be to keep outer space peaceful.

4.1.2 Standards on spacecraft design and manufacturing

It is critical to promote UN COPUOS long-term sustainability guidelines in order to harmonize the national regulations on spacecraft design, operations and disposal [36]. Recommended design and operational practices published by CONFERS, collaborates on research which includes spacecrafts design to facilitate safe and sustainable operations with effective spacecraft servicing [37,13]. Decardi [38] proposed a similar idea stating that spacecraft should be designed without complexity, enabling in-space repair and servicing. It is important to envision opportunities to optimize a spacecrafts design to avoid spacecraft vulnerabilities. Murtaza et al. [40] state that shielding the spacecraft must be incorporated into the design as a necessity to protect from millimetre size debris. A delegate from Venezuela proposes that spacecrafts should be designed with adequate fuel to deorbit them at the end of their life at the UN COPUOS 58th session [44]. However, Gallagher [46] argued that the vague language of UN COPOUS guidelines allows the space user to decide the design of the spacecraft, allowing the production of long-lived space debris.

4.1.3 International regulatory frameworks on standards and practices

The development of international space traffic regulations in the form of standards, guidelines and best practices is required to address the rapid growth of space activities [37] to ensure a safe and secure space environment. Decardi [38] emphasized that the ultimate objective of safe space exploration is to impose standards and regulations backed by the international treaties. However, Som [41] stated that sustainable collaboration between space actors may provide the opportunity to achieve a new form of international regulations which will stimulate competition, allowing access to new frontiers in the private sector.

Murtaza et al. [40] argued that current space debris mitigation guidelines are ineffective due to the non-binding nature and any such guidelines must be an international regulation for everyone rather than following them on a voluntary basis. Gallagher [46] argued that voluntary self-regulation for space activities is inadequate and an international regulatory agreement is needed to outlaw the destructive activities in the space environment. Dey and Jagadanandan [42] reaffirmed the necessity of an international regularity framework, governing the registration of satellites and managing the space debris to ensure sustainable utilization of space environment. Development of International regulatory framework promotes the long-term sustainability of outer space activities [43]

According to the thematic analysis, international regularity framework is the most significant key theme amongst all. However, the author believes that there is a clear interdependency between all the key themes.

Enforcing international regulations through standards and recommended practices in space operations is deemed necessary to ensure safe, secure and sustainable space activities. The unique challenges in space operations such as technical complexity, risk factors and high costs make international regulations enforcement critical.

4.2 key determinants of sustainability in space

According to the literature review, there are five factors of sustainability in space that have been identified, which includes fair and equitable access to space, reducing environmental harm, space debris mitigation, resource utilization in space and safety of human spaceflight. As per the thematic analysis, the first precedence will be given to reducing environmental harm as it is the main predictor for sustainability in space.

4.2.1 Reduce environmental impact on space operations

Oltrogge and Christensen [36] emphasized the fact that when there isn't adequate financial motivation to protect the space environment, regulations are likely to be needed. They further state that governments and the private actors in space industry have a fundamentally different focus when it comes to space environmental protection. Developing consensus-based standards and best practices for space operations encourages the protection and sustainability of the space environment [37]. A private company, Astroscale has made certain efforts to protect the space environment by its end-of-life servicing as well as active debris removal [13]. Murtaza et al. (2019) highlighted the threat and the risk to operational satellites as well as the space environment because of space debris accumulation. Yang and Wu [44] affirmed that the rapid increase of space debris has become a great threat to the space safety and space environment.

It is critically important to establish minimum standard criteria for commercial industry operations in order to safeguard the environment. [42]. Martinez [43] argued that it took several decades world leaders to react to climate change issues, the same situation has arisen for space activities in Earth's orbital environment and the scientific community is sounding the alarm for world leaders to take immediate action. Global leaders and private industry should forego short-term gains and look for lasting solution to protect the space environment [46].

4.2.2 Space debris mitigation for space sustainability

Due to the surge in space activities in the recent years, the problem of space debris continues to rise, posing a significant threat to operational satellites and long-term sustainability of space activities. Owing to the high orbital speeds of 8-10Kms⁻¹, a debris of 10cm can destroy an operational satellite and further create thousands of smaller debris [40]. A feasible space traffic management system prevents collisions and effectively slow down the growth of space debris [44]. Yang and Wu [44] argued that the current space debris mitigation mechanisms fail to address the space debris issue caused by large constellation of satellites as international governance mainly focus on mitigation rather than prevention of space debris. There are different opinions among space actors about space debris accumulation. Martinez [43] states that certain states don't consider space debris as a problem for space exploration while others are more concerned about the environmental harm as a pretext to retain their position in the space business. Space debris mitigation standards were incorporated into legislation by the US, ESA and IADC member states [37]. Murtaza et al. [40] pointed out that leading space actors such as Australia, Japan and Germany (being an ESA member state), opposed making Space Debris Mitigation guidelines legal at the UN COPUOS meeting, as they were linked with evolving technologies considering the cost-benefit trade-offs. Even though UN COPUOS has initiated procedures for space debris management, the complexity of implementing these procedures has led to a focus on promoting responsible space use rather than enacting binding laws to address the issue. [43]

4.2.3 Ensure safety on human spaceflight operations

Crewed spaceflights began in 1961 with the flight of Yuri Gagarin aboard Vostok1. Safety is paramount in human spaceflight missions and safety standards and practices differ from spaceflight providers. However, The United States Joint Space Operations Center (JSpOC) provides high accuracy screenings for crewed flights to cover all active spacecraft [40]. Nevertheless, there are several limitations in the Space Surveillance Network (SSN) as objects smaller than 10cm cannot be tracked [46]. Timely coordination between space flight operators and effective action on orbital events reduce the risk of collisions in spaceflight [43]. Decadi [38] states that a human rating space system accommodates human requirements and controls hazards to manage safety risks on crewed spaceflight through NASA Procedural Requirements (NPRs). Basic situational awareness data provided by US military is available for all the space operators as safety of the spaceflight considered as a public service [36]. There are many standards and practices that have been developed by organizations to ensure the safety of space exploration. However, Gleason [37] stated that there isn't any need for new standards to be developed just for human spaceflight.

4.3 The relationship between the global standards and recommended practices in sustainable spacecraft operations

The literature review indicated that there are six factors which lead to the relationship between the global standards and recommended practices in sustainable spacecraft operations. International regulations, technological innovation, global governance and international corporation can be considered more important than others according to the thematic analysis.

4.3.1 Impose international regulations

The need for international standards, guidelines and practices are driven by the dramatic rise of space operations. Hence, Gleason [37] emphasized that a rise in space traffic regulations is unavoidable, which may lead to an increase in the designing cost of spacecrafts. National level regulations are becoming more and more redundant and adherence to the international law becoming more prominent [42]. Decadi [38] states that international regulations concerning the safety of a space mission are underdeveloped. Therefore, any mission must adopt several risk mitigation strategies. Increased regulations are deemed necessary to ensure sustainable spacecraft operations. However, Gleason [37] argued that innovations in the private sector will be constrained and the investment in the space industry will be discouraged. Som [41] argued that sustainable international collaboration is required to develop corporate regulations which will incentivize private companies to access new horizons in space exploration.

4.3.2 Utilization of technological innovation for space sustainability

Technological innovation is a key driver which opens new frontiers in space exploration. The successful evolution of space technology benefits not only individual nations and private institutes, but also all space stakeholders [40]. However, in order to achieve long-term sustainability in space, it is necessary to limit the number of spacecraft launches which will prevent debris accumulation. In contrary, spacecraft operators such as SpaceX, OneWeb and Boing plan to launch high number of satellites. Sharma et al [39] argued that ITAR needs to radically change its stance to reflect the technological innovation in space which will depend upon the US defence and security budget. Decadi [38] argued that imposing regulations on designing space vehicles are likely to hinder technological innovation. However, it is important to impose global regulation to prevent the overcrowding of satellites in graveyard orbits, while optimizing usage and mechanisms to return to base (Earth) at the end of the mission.

4.3.3 Global governance for space exploration

The policies, laws and agreements that regulates human activities in outer space can be named as space governance. Space governance mechanisms comprise of international treaties, national regulations and corporate law that ensures safe and sustainable of space activities for peaceful purposes. Oltrogge and Christensen [36] divided space governance into two, one is binding and other is non-binding. Binding space governance means that legally enforceable international treaties, agreements and law for space activities, whereas non-binding refers to not legally enforceable and voluntary compliance. Dey and Jagadanandan [42] emphasized those alternative ways of global governance to develop clear standards for space exploration and space resource utilization. However, binding national governance promotes space sustainability while sympathizing the states's own interpretation of international common space law [36]. Dey and Jagadanandan [42] describe that the current trend of global space governance is to promote selective policies by The United States and ESA, which will be implemented through soft-law mechanisms like the Artemis Accords.

4.3.4 Requirement of International cooperation and coordination for sustainable space

Space exploration is inherited globally and no one state can take ownership. Space operations affect all nations, not just one. Therefore, international cooperation and coordination is necessary for peaceful, sustainable and equitable access for all countries. Som [41] emphasized the requirement of a new symbol of international cooperation in order to promote peace and collaboration in space exploration. The United Nations (UN) showcases its commitment to establish international cooperation to enable developing nations to benefit from space-based technologies for peaceful purposes [43]. Although space is vast, there are certain concerns over the irresponsible usage and crowding of low earth orbits creating risks to space operations. However, COPUOS long-term sustainability (LTS) guidelines address the space activities that could disrupt naturally as well as man-made causes, while promoting international corporation [13]. Dey and Jagadanandan, [42] state that COPUOS also expects to establish a forum which provides creative solutions to businesses while establishing international coordination of their operations with global standards. Yang and Wu [44] and Trur [45] emphasize the necessity of having international cooperation when dealing with the accumulation of space debris, especially with large constellations of satellites. Murtaza et al. [40] point out the benefits of having international cooperation for establishing legal frameworks to cope with the financial, strategic and security

aspects of Automatic Debris Removal (ADR). Nevertheless, Sharma, T. et al. [39] argues that space technology developed for dual-use and the skills often become hinderance for international cooperation. Prominent spacefaring nations keep a weak stance for international cooperation and self-governance as they need flexibility rather than compliance with equitable rules [46]

From the thematic analysis, it is evident that a strong relationship between global standards and recommended practices is crucial to achieve sustainable space operations. It assures that the space environment remains a safe, accessible, and viable for space exploration, scientific research, and commercial usage for prolonged period.

4.4 Strategic framework to accomplish sustainable spacecraft operations.

Based on the thematic analysis, the author has developed a strategic framework considering the factors relevant to global standards and practices, space sustainability and spacecraft operations. The framework ensures a well-balanced coexistence of the above factors for long-term sustainable space exploration. The author emphasizes the fact the Triple Bottom Line (TBL) approach in the key in the framework (Figure 5) to achieve sustainability in spacecraft operations.

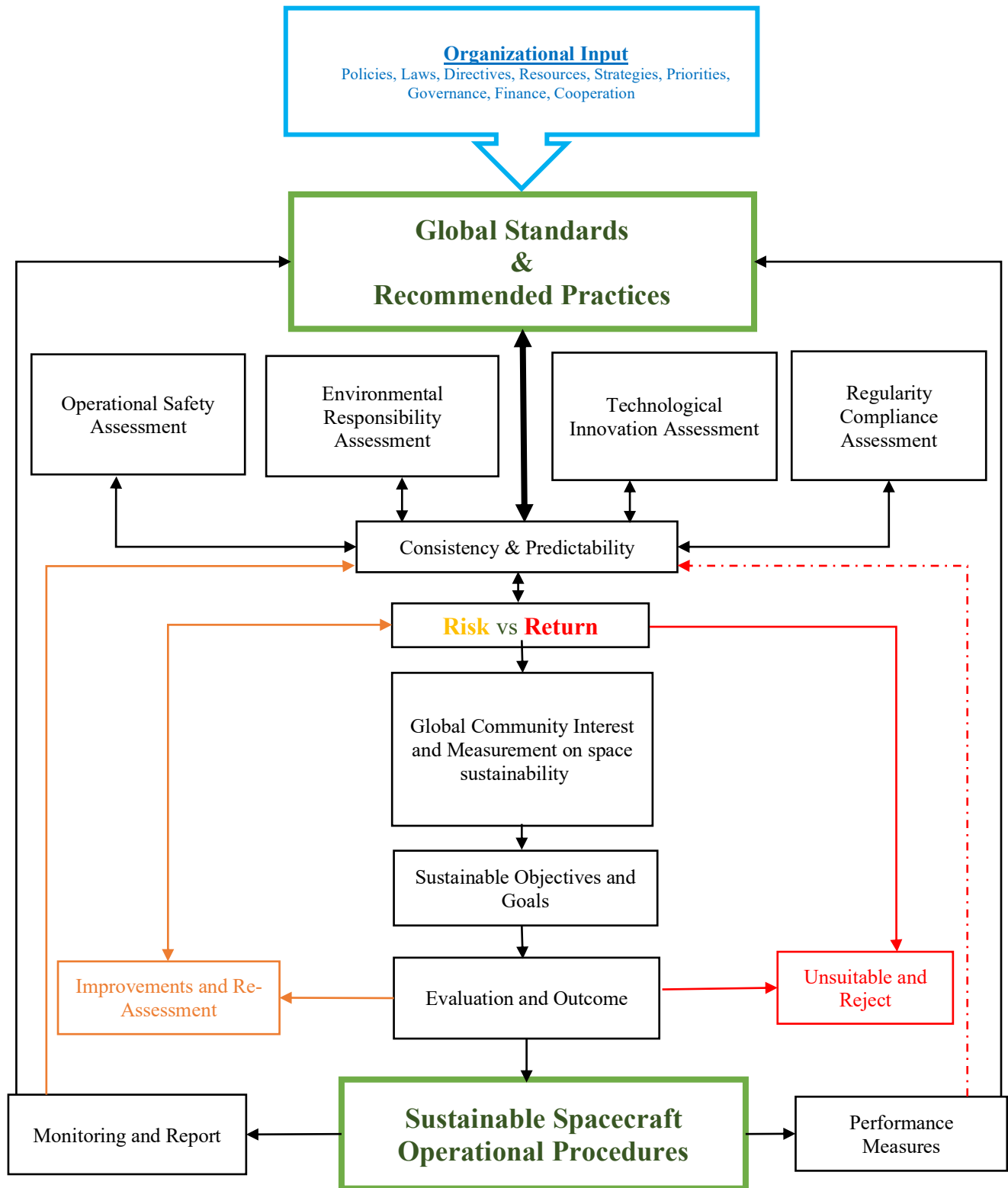


Figure 05: Strategic Framework for Sustainable Spacecraft Operations

5.0 Conclusion and Recommendation

The rapid expansion of space exploration, which, driven by government agencies and private enterprises, emphasizes the importance of implementing global standards and recommended practices to ensure sustainable spacecraft operations.

The aim of this study is to critically evaluate the key attributes of global standards and recommended practices and the key determinants of sustainability in space. Furthermore, the author attempts to critically evaluate the relationship between global standards and practices in sustainable spacecraft operations, and additionally, to develop a strategic framework to achieve sustainable spacecraft operations with compliance of global standards and recommended practices.

This study highlights the key challenges in establishing global standards and practices for sustainable spacecraft operations, including application of global space policy, international regularity frameworks, space debris reduction, global governance and international cooperation. Legal instruments currently available from the United Nations such as the Outer Space Treaty (OST), Rescue Agreement, Registration Convention and Moon agreement provide certain fundamental structures for global standards. However, owing to the non-binding nature and lack of enforcement mechanisms, these fail to address the emerging issues that hinder sustainable spacecraft operations. Various voluntary agreements and collaborative initiatives by various governmental agencies and institutions contribute an integral part of sustainability in space operations. However, the lack of enforcement exacerbates sustainable space exploration and threats remain. The thematic analysis suggests that a unified consensus on global standards and practices are deemed necessary to ensure sustainable, safe, equitable access to space operations.

This research is based on a systematic review due to time limitations and difficulties in obtaining ethical approvals. The author believes that apart from the systematic review, a survey would have been very useful for this research, as sustainability is a “hot” theme, and data can be analysed from a larger data sample. In-person interview and online surveys can be used depending on the feasibility.

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Appendix A –Thematic Analysis

	Key themes	Oltrogge, D.L. and Christensen, I.A., 2020	Gleason, M.P., 2011	Decardi, A., 2018	Weeden, C. et al., 2019.	Sharma, T. et al., 2011.	Murtaza, A. et al., 2019.
Key attributes of Global Standards and Recommended Practices	Application of policies	Relevant	Relevant	Relevant	Relevant	Relevant	
	Space Traffic Management	Relevant	Relevant		Relevant		
	Standardization of spacecraft design and manufacturing	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant
	Reliable communication	Relevant	Relevant		Relevant		Relevant
	International regulatory framework		Relevant	Relevant	Relevant		Relevant
Key determinants of Sustainability in Space	Fair and equitable access to space		Relevant			Relevant	Relevant
	Reduce the environmental harm	Relevant	Relevant	Relevant	Relevant		Relevant
	Space Debris Mitigation	Relevant	Relevant	Relevant	Relevant	Relevant	
	Resource utilization in space	Relevant					Relevant
	Ensure safety on human space flights	Relevant	Relevant	Relevant	Relevant		Relevant
Relationship between Global Standards and Recommended Practices into Sustainable Spacecraft Operations	International regulations		Relevant	Relevant		Relevant	
	Technological innovation	Relevant		Relevant		Relevant	Relevant
	Global governance					Relevant	Relevant
	Health and wellbeing of mankind						
	International Corporation and coordination	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant
	Prevent militarization in space						

Appendix B –Thematic Analysis

	Key themes	Som, S., 2010	Dey, A and Jagadanandan, J., 2025	Martinez, N., 2022	Yang, K. and Wu, Y., 2022	Trur, A., 2020	Gallagher, N., 2010
Key attributes of Global Standards and Recommended Practices	Application of policies	Relevant	Relevant				Relevant
	Space Traffic Management			Relevant	Relevant		
	Standardization of spacecraft design and manufacturing					Relevant	Relevant
	Reliable communication	Relevant					
	International regulatory framework	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant
Key determinants of Sustainability in Space	Fair and equitable access to space		Relevant			Relevant	Relevant
	Reduce the environmental harm		Relevant	Relevant	Relevant	Relevant	Relevant
	Space Debris Mitigation		Relevant	Relevant	Relevant	Relevant	
	Regulations on resource utilization in space		Relevant	Relevant	Relevant	Relevant	Relevant
	Ensure safety on human space flights			Relevant	Relevant		Relevant
Relationship between Global Standards and Recommended Practices into Sustainable Spacecraft Operations	International regulations	Relevant	Relevant			Relevant	
	Technological innovation						Relevant
	Global governance	Relevant	Relevant				Relevant
	Health and wellbeing of mankind						Relevant
	International Corporation and coordination	Relevant	Relevant	Relevant	Relevant	Relevant	Relevant
	Prevent militarization in space	Relevant					Relevant

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