Space Economy and Sustainability: A Systematic Review

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Space Economy and Sustainability: A Systematic Review

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ABSTRACT

The space economy is booming thanks to the increasing investment of government agencies, private companies, and venture capitalists. From the beginning of the New Space era, the array of actors involved in the development of technologies for extra-terrestrial activities has increased, as well as the downstream applications that foster innovations on Earth. Space technologies promote growth and prosperity: they pose challenges and opportunities in terms of sustainability from multiple perspectives. In outer space, several issues can hinder launches or the capabilities of observing and collecting data (e.g., presence of debris, regulatory and legal issues), while there is room to improve the technical and economic efficiency of operations; on Earth, technologies developed to support space missions and satellite data provide support to human development and help monitoring climate change. The literature dealing with space sciences is extremely varied, from materials and physics for the launch of probes, to management of missions, or the coordination of international activities. The aim of this study is to investigate whether and how studies in the space economy area addressed the topic of sustainability through a systematic literature review. This article analyses 254 articles along multiple dimensions, including the three pillars of sustainability and the sustainable development goals. The studies are categorized according to their main locus of research (i.e., in Space and on Earth) and then grouped in thematic clusters. In doing so, this article provides an overview of the state of the art, highlights potential gaps, and proposes fruitful avenues for future research.

1 | Introduction

The space economy is experiencing a significant transformation, characterized by the emergence of the new space economy (NSE), which is disrupting traditional activities by leveraging innovations in technology and business models (Paravano, Locatelli, and Trucco 2023). In general, Space Economy refers to "the full range of activities and the use of resources that create and provide value and benefits to human beings in the course of exploring, understanding, managing and utilizing space" (OECD 2022). In the last 20 years, this industry has changed significantly, reshaped into the so-called NSE. Major technological achievements (e.g., development of reusable launch systems, satellite miniaturization, setting up of experimental labs on orbiting space stations) have lowered the barriers that companies face to enter the sector (Denis et al. 2020; Mazzucato and Robinson 2018). Consequently, space-related commercial activities have expanded, which are characterized by an increasing number of operating firms and private organizations, a higher provision of value to customers, and a growing relevance of venture capitalists financing space start-ups (OECD 2019). The impact of the NSE extends beyond the Space Economy: for example, satellite data can improve decision-making processes and enhance the business services and products of non-space end users (Paravano, Locatelli, and Trucco 2023).

The NSE is fueled by private investments and entrepreneurship, leading to the emergence of numerous start-ups and new players in the industry (Denis et al. 2020). This new ecosystem is expanding beyond government-driven space exploration, and it includes applications as Earth Observation and satellite communications (Paravano et al. 2024). The NSE is expected to grow significantly in the next years, with revenues likely to more than double and exceed 1 trillion $ by 2040 (Bank of America Institute 2023; Euroconsult 2023; OECD 2019). The diversification of actors in the NSE fostered economic growth through collaboration and competition and, at the same time, raised the awareness on the impact of space activities in terms of sustainability (Denis and Pasco 2015; Paravano et al. 2024). The challenges related to sustainability are crucial to ensure the long-term benefits of space exploration and utilization of resources without compromising the environment or the interests of future generations. Generalizing the approach in Buchs and Bernauer (2023), who distinguished between "the sustainability of the space infrastructure" and "the space infrastructure for sustainable development", the concept of sustainability in the Space Economy can be examined with respect to the focal locus of interest: sustainable activities in outer space and sustainability on Earth. On the one hand, sustainability in outer space refers to the responsible and efficient use of space resources without depleting or damaging them. The space industry is becoming increasingly important in the context of achieving Sustainable Development Goals (SDGs), as mitigating climate change and protecting the environment. The United Nations (U.N.) Economic and Social Council (2020) has recognized the potential of space technologies for sustainable development and has called for international cooperation to ensure equitable access to these technologies, especially for developing countries. In this context, the role of collaboration in the development of national and international policies is key to support sustainability (Ansdell, Ehrenfreund, and McKay 2011). It is crucial to develop a comprehensive framework for the sustainable management of space resources to ensure that future space activities do not negatively impact the environment or create the so-called space debris that can threaten future operations. The issue of space debris refers to the accumulation of defunct satellites, spent rocket stages, and other fragments from previous space missions. While there is limited evidence on the actual impact of the proliferation of debris on Earth, either in terms of air pollution or loss of services (Undseth, Jolly, and Olivari 2020), they pose a significant hazard to operating spacecraft, satellites, and stations[1].

On the other hand, the use of space-derived data and technologies can support the challenges to sustainability on Earth. Remote sensing, satellite communication, and navigation systems have revolutionized various industries and terrestrial activities, as agriculture, disaster management, and natural resource management (Durrieu and Nelson 2013; Yap and Truffer 2022). For example, space technologies have helped to monitor crop growth, predict natural disasters, and track deforestation: these activities impact the resilience and sustainability of economies positively, especially in developing countries that often lack the infrastructure and resources to manage these challenges effectively (Lamba, Rani, and Kumar 2021). Hence, the application of space technologies and the responsible use of resources and of satellite data have the potential to play a significant role in achieving the SDGs on Earth (Paravano et al. 2024).

In this context, tracking the development of the literature dealing with the sustainability of the space activities can provide an overview of the existing status and highlight gaps, in terms of type of sustainability and the locus, that is, if the focus is on outer space or on the impact of space operations, technologies and data on Earth.

With regard to the type of sustainability, typically three dimensions or pillars are distinguished: environmental, social, and economic (Purvis, Mao, and Robinson 2019). All the pillars refer to the main concept of sustainable development that points to satisfying present needs without compromising future generations' ability to meet their own needs (the Brundtland Commission for UN Secretary-General and World Commission on Environment and Development 1987). Environmental sustainability entails the conservation of natural resources and preservation of global ecosystems to support well-being and health. This dimension primarily focuses on long-term approaches, as environmental impacts may not manifest immediately. Social sustainability refers to the active support of current and future generations in creating liveable and healthy communities through formal and informal structures, relationships, and systems that are diverse, equitable, democratic, and interconnected (McKenzie 2004). Finally, economic sustainability refers to the long-term economic development of firms, countries or societies and their resilience.

The variety of fields dealing with space sciences is extremely wide, ranging from Materials science and Physics for the launch of probes, to management of missions, Astrobiology, or the coordination of international activities. The purpose of this study is to conduct a systematic literature review to examine whether and how studies in the field of Space Economy (e.g., policies, industry, technologies) have addressed the sustainability challenge. The sample examined contains 254 articles that are examined and organized along multiple dimensions, as, among others, the locus of deployment or application (i.e., in outer space or on Earth), the sustainability pillar and the SDGs. This analysis improves the understanding of the current body of knowledge and highlights potential gaps. On this basis, promising paths for future research are suggested.

2 | Method

2.1 | Systematic Literature Review

The systematic literature review (SLR) is a rigorous and comprehensive approach that aims to identify, evaluate, and synthesize existing research on a specific topic, especially when it covers multiple disciplines. In this study we follow the method described in recent studies (e.g., Agostini and Nosella 2019; Allen, Metternicht, and Wiedmann 2021; Garzaniti et al. 2021; Moro et al. 2023), consisting of the following main steps (Figure 1):

1. Preliminary search and screening: this step consists in the definition of a starting search query, which is applied on

FIGURE 1 | Schema of the applied method.

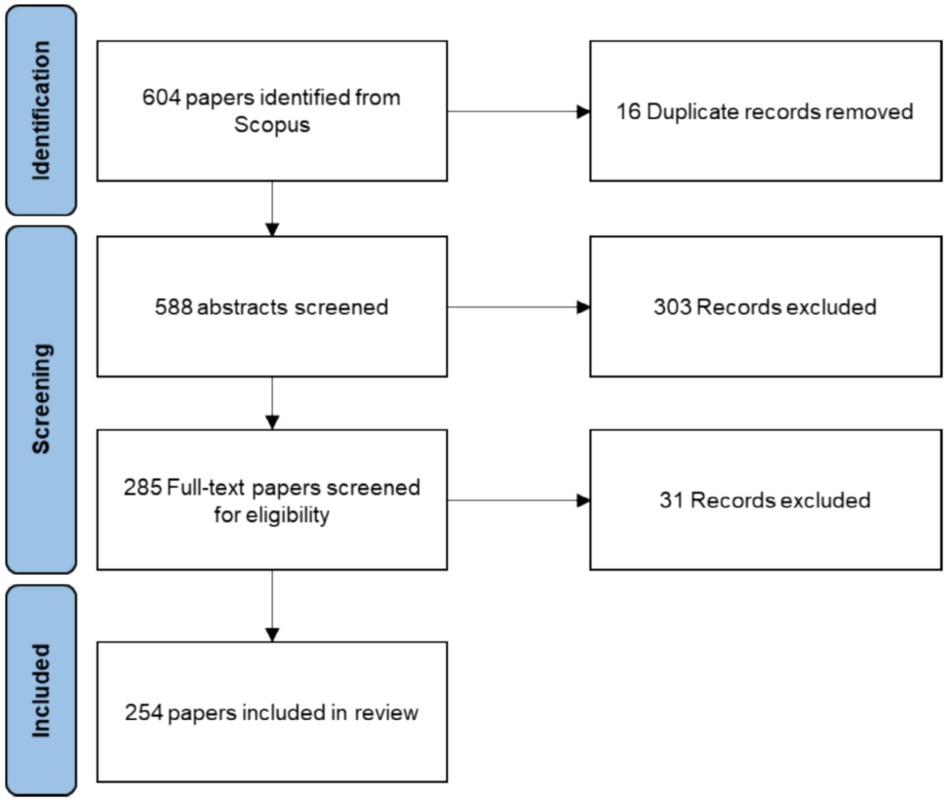

FIGURE 2 | PRISMA diagram for SLR.

a source database for the retrieval of articles and bibliographic data; the identified articles are screened to exclude false positive matches, and the search results are checked for relevant missing research areas (false negative).

2. Refined search and screening: The search query is updated from the preliminary analyses and an extended data collection is performed. Exclusion of false positive results (see Figure 2 below for further details).
3. Generation of the classification of the articles in the identified sample through a combination of manual and automated techniques.
4. Analysis of the resulting database.

The source of the scientific publications is the Scopus database, which is commonly considered as having a wide coverage of disciplines and publishers with scientifically sound journals (Wohlin 2014). The scope of the selection is limited to journal articles and reviews written in English[2]. The first step in our SLR aims to provide a preliminary identification of the perimeter of the topic. The main concepts that we aim to include in our investigation deal with the space economy/sector and sustainability. A scientific publication is included in the examined sample if both the space and the sustainability concepts are found in either its title, abstract, or set of keywords provided by the authors or by Scopus. We assume that in general if an article provides sufficient focus on sustainability issues, then the authors do mention sustainability in the searched fields.

To reduce the inclusion of false positive results from the search query, we excluded the articles with terms related to sub-orbital Aeronautics and ground operations[3] and those journals focusing on regional and urban development, where the term "space" is intended with a different meaning (i.e., spatial dimension or geographical location)[4]. The following query was searched in Scopus in February 2023.

TITLE-ABS-KEY(sustainable OR sustainability OR SDG) AND TITLE-ABS-KEY({space industry} OR {new space} OR {space economy} OR {space science} OR {space technology} OR {space technologies} OR {space sector}).

This preliminary query returned 241 articles, which were examined with the aim to exclude out-of-scope articles. The screening process started from reading the abstracts of the articles. Articles were excluded for the following reasons: (i) the word "space" refers to the spatial dimension (e.g., Lee and Kim 2007; While, Littlewood, and Whitney 2000), (ii) they do not perform a thorough analysis nor a discussion on sustainability issues. To clarify the latter, an article was excluded if sustainability is neither the core topic nor sufficiently debated or measured. For example, articles focusing on a new initiative or the application of a new technology for which sustainability considerations were not sufficiently assessed were excluded: these articles provide generic hints to long-term sustainable returns with no thorough discussion nor a quali-quantitative assessment of the claimed improvements in terms of sustainability (e.g., Challagulla et al. 2020). This criterion determined also the removal of those articles that merely summarize an event or initiative, as the work of Balogh and Haubold (2009), who propose an initiative for capacity building in space technology development within the U.N. Programme on Space Applications framework, and the article of Yehia (2008), who summarizes the discussions held at a conference organized by the European Space Policy Institute. Furthermore, to minimize the potential for subjectivity, the researchers cross-checked their decisions regarding the exclusion of articles from the final sample.

The analysis of abstracts led to a sample of 131 articles. All of these were then examined in their full texts to apply the same exclusion criteria and reach a final sample of 110 articles (46% of the initial sample).

More importantly, this preliminary analysis highlighted some additional keywords that were not included in the initial search query, which might have led to the exclusion of relevant articles (false negative results). The search query was thus modified as follows:

TITLE-ABS-KEY(sustainable OR sustainability) AND TITLE-ABS-KEY({space industry} OR {space economy} OR {space science} OR {space technology} OR {space technologies} OR {space sector} OR {spaceborne} OR {spaceflight} OR {space flight} OR {outer space} OR {orbital space} OR {spacecraft} OR {space exploration}).

This new search returned a total of 604 articles, including 363 additional documents which were not found in the prior approach. Figure 2 provides the PRISMA flow diagram (Page and Besco 2021) of the sample identified from the refined search query. The articles were assessed by applying the previous exclusion criteria, first from reading the abstracts and then from full-text analysis. The final sample that combines the selections from the preliminary and the extended queries is made of 254 articles (42% of the Scopus results).

2.2 | Clusters and Tagging

We analyzed the identified sampled articles along multiple dimensions. The first classification allocates the articles to the loci “In space” or “On Earth.” This dimension derives from the distinction between “the sustainability of the space infrastructure” and “the space infrastructure for sustainable development” (Buchs and Bernauer 2023), and considers the concept of sustainability in the Space Economy with respect to the focal locus of interest: sustainable activities in outer space and sustainability on Earth. From reading the full texts we distinguished the publications that focus on missions, operations, and cooperation in outer space, from those describing space-related activities that take place or have a significant impact on the Earth's surface, such as the use of satellite data for Earth Observation, the development of space agencies or programs in a country, and the application of space technologies. A more in-depth analysis has been conducted on space location. By utilizing specific keywords, the articles are distinguished depending on whether their primary focus is on the Moon, Mars, Orbit (Low Earth Orbit, LEO, or Geostationary Earth Orbit, GEO)[5], or space in general respectively. Note that these categories are not mutually exclusive.

The second classification assigns each article to one or more pillars of sustainability, that is, economic, environmental, and social, and follows the increasing attention on the identification of the impact of space activities in terms of sustainability (Denis and Pasco 2015; Paravano et al. 2024; United Nations Economic and Social Council 2020). The three pillars are derived from the literature on sustainability (Purvis, Mao, and Robinson 2019). The characterization of the examined publications was performed through full-text reading and considering the main type(s) of sustainability addressed. To further investigate the dimension of sustainability, we have also associated the SDGs to the collected articles. The SDGs, also known as the Global Goals, are a set of 17 interconnected goals adopted by the U.N. General Assembly in 2015 as part of the 2030 Agenda for Sustainable Development (United Nations 2015). The SDGs aim to address global challenges such as poverty, inequality, climate change, environmental degradation, peace, and justice, among others. The association of SDGs to scientific articles was performed through the specific search queries available in Scopus, for each of the SDGs (Jayabalasingham 2019). Articles that fall within the queries are marked with the corresponding SDG. We controlled if each of the articles in our selection appeared among the results of those queries and retrieved the corresponding SDG. This approach limited the subjectivity of a classification relying exclusively on the researchers' evaluation.

Finally, the selected articles were grouped according to their main research topic. This classification was performed in two steps with the aim to assign each article to a single group. The first step relied on an automated clusterization through the application of the k-means algorithm[6] on title, abstract and keywords of the examined articles. K-means clustering is an iterative process that considers texts as vectors and starts allocating the analyzed items to an initial set of k clusters and then minimizes the distance between the cluster centroid and the elements in the cluster. The process ends when the clusters have reached a stable state (see for example: Na, Xumin, and Yong 2010). We did some preliminary tests on the target number of clusters and set it to 15, a relatively large number of groups to provide a sufficient granularity to start from. We then performed a manual validation that led to the following five groups: Policy, Law and regulation, Debris, Life Support Systems (LSS) and habitat, Remote sensing and data handling. It is worth noting that some articles could have been assigned to more than one cluster, since they are covering more than one topic, and we assigned them following their main perspective/argument. The application of this criterion required particular attention when approaching the articles dealing with the debris problem and potential regulatory solutions. In those cases, we gave priority to the Debris cluster over Law and regulation (as for example in the cases of Abashidze, Chernykh, and Mednikova 2022 and Mocrei-Rebrean 2022). This decision has been made considering that the "debris" issue is one of the most acknowledged topics with respect to sustainability and that the inclusion of all the articles dealing with this subject in a single group would improve their analysis and discussion. Finally, 17 recent articles were included in a residual category labeled Emerging topics that might flourish in upcoming years.

3 | Overview of the Sampled Articles

The identified sample of publications contains mostly articles (87%) and some reviews (13%). Figure 3 shows the publication activity over the years up to February 2023. We observe few articles until 2009 (11%), an increase in the years from 2010 to 2019 (44%), and a sharp surge in the recent few years from 2020 (45%). Several reasons for the changes observed in the publication rate can be argued. One possible factor is the emergence of the New Space trend, as well as the growing awareness of sustainability issues, particularly in recent years. Governments worldwide have implemented different initiatives to promote sustainability, as the Sustainable Development Agenda 2030 (United Nations 2015).

The articles have been published in 101 journals (Figure 4 shows the journals with more than three articles in our sample). Acta Astronautica (58) and Space Policy (36) jointly represent 37% of the sample, highlighting the interest of these journals for sustainability in the space sector. 44% of the article was published by journals having each less than four publications in the sample, suggesting that the topic is extremely spread across outlets, and even those that are not specifically dedicated to space activities are starting to cover the topic from multiple angles.

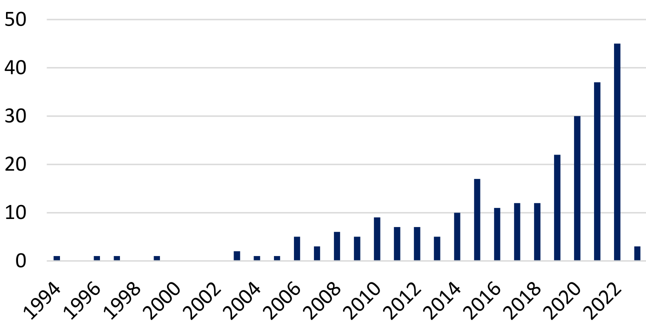

FIGURE 3 | Year publication frequency from 1994 to February 2023.

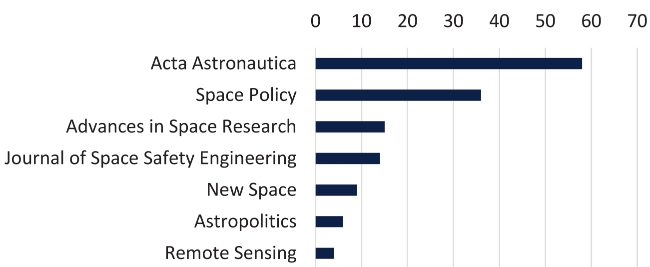

FIGURE 4 | Publication frequency across journals.

The articles in the identified sample were authored by 160 individuals. On average, there are 3.6 authors per article. 35% of the articles have only one author, whereas 53% have between 2 to 5 authors. Only 12% of articles are written by more than five authors.

Figure 5 shows the geographical scope of the research activities by ranking the number of articles by the affiliation country of the authors. The United States (71 articles), France (35), United Kingdom (24) and Germany (24) are the most frequent source countries. The presence of BRICS countries (Brazil, Russia, India, China, and South Africa) among the top 15 is not negligible: they account for a total of 48 documents in the sample. In general, African and Middle Eastern countries are represented by a very small subset of articles (12 articles). The participation of BRICS countries and other emerging nations in the space sector, especially in recent years, underscores the global interest and collaboration in space activities, creating opportunities for new entrants to contribute to space technology and exploration.

Figure 6 displays the organizations associated with the articles and lists only those with four or more articles. There are a total of 160 different affiliations, and, among them, the U.S.

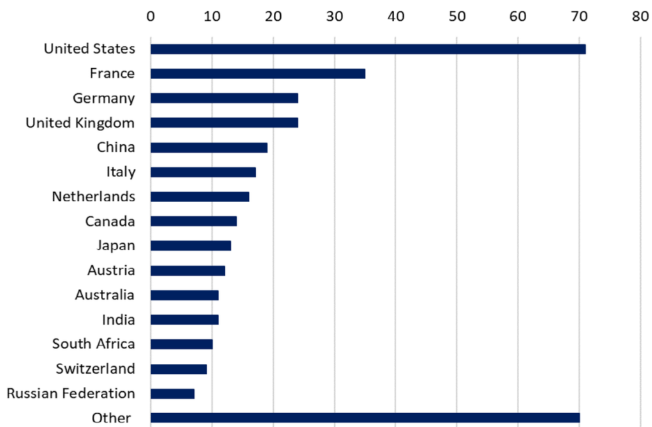

FIGURE 5 | Count of documents by affiliation country of the authors.

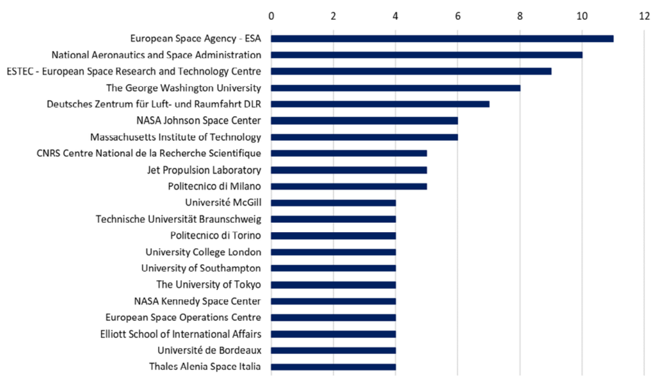

FIGURE 6 | Documents by author's affiliation.

National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have the most articles (18). Government agencies have the highest number of publications, followed by universities and research centers.

4 | Analysis of the Classifications

4.1 | Locus and Sustainability Pillars

All articles have been classified along different dimensions of analysis as explained in Section 2.2: the locus of the article content (i.e., in space and/or on Earth), the sustainability focus, the specific research cluster, and their SDGs.

Tables 1 and 2 show the distribution of the identified articles across the dimensions representing the locus (in space and/or on Earth) and the sustainability pillars. The Appendix 1 reports detailed information on each article (Table A1). Most of the documents (66%) deals with sustainability in space, whereas 53% of them focus on Earth. 19% of the sample jointly discusses sustainability in both loci, exploring mainly policies, economic aspects, and legal and regulatory considerations that are relevant to both space and Earth applications (e.g., Ansdell, Ehrenfreund, and McKay 2011; Hofmann and Bergamasco 2020; Paladini, Saha, and Pierron 2021). The analysis of the space locus is detailed across the sub-categories Orbit (20%), Moon (11%), Mars (5%), and outer space in general (33%). We observe an increasing presence of articles inversely proportional to the distance from ground activities.

In terms of sustainability pillars, the environmental aspects are the most extensively studied (58%), followed by the economic (47%) and the social ones (45%). The majority of the sample (61%) focuses on a single pillar (e.g., Bohlmann and Koller 2020; Takeuchi 2019; Williamson 2012); 28% of the documents addresses two pillars concurrently (e.g., Profitiliotis and Loizidou 2019; Yan 2019); and only 11% of the sample discusses all the three pillars, mainly in terms of policies aimed at promoting a comprehensive sustainable development (e.g., Froehlich, Ringas, and Wilson 2022; Losch 2020; Sarkissian 2006).

The comparison between the two main loci indicates that the articles focusing "on Earth" are more concerned on the social dimension of sustainability (33%) than those "in space" (26%), while the opposite is true for the environmental aspects that are addressed more often for the "in space" locus (44%) than for "on Earth" (22%). Regarding the social dimension, the higher share "on Earth" is not surprising and it can be explained by two main reasons: (i) policy, international cooperation, and regulation are inherently linked to terrestrial organizations (e.g., Laurini and Gerstenmaier 2014; Sagath et al. 2018); (ii) the sample contains articles that discuss the social impact of space-derived technological applications or data on human communities on Earth (e.g., Asiyanbola et al. 2021; Jason et al. 2010). The higher share of the environmental dimension for the space locus is instead unexpected. It can be partially explained by the large number of articles dealing with the issue of space debris, but nonetheless the environmental dimension of sustainability is the least represented for the On Earth locus. These articles are mainly about the use of data collected by satellites for smart agriculture,

TABLE 1 | Locus/pillar matrix for papers from 1994 to February 2023.

Locus/sustainability pillar		Environmental	Economic	Social	Total
On Earth		57	75	83	135
In space		112	73	65	167
	Orbit	36	16	11	50
	Moon	19	18	12	28
	Mars	6	6	7	12
	Other	52	36	38	82
Total		146 (24)	119 (29)	115 (33)	254 (48)

Note: The "Total" values in brackets indicate the number of articles that address both loci.

TABLE 2 | Locus/pillar matrix for paper from 1994 to February 2023 in percentage.

Locus/sustainability pillar		Environmental	Economic	Social	Total
On Earth		22.4%	29.5%	32.7%	53.2%
In space		44.1%	28.7%	25.6%	65.8%
	Orbit	14.2%	6.3%	4.3%	19.7%
	Moon	7.5%	7.1%	4.7%	11.0%
	Mars	2.4%	2.4%	2.8%	4.7%
	Other	20.5%	14.2%	15%	32.3%
Total		57.5%	46.9%	45.3%	100%

monitoring the climate change, and water and land resources optimisation (e.g., Aleksieva-Petrova et al. 2022; Chabrillat et al. 2019; Zhuang, Liu, and Liu 1999). This suggests that studies assessing the environmental impact of space activities on Earth (e.g., linking data or technologies to a quali-quantitative measurement of short/long term impact on land, crops, urbanization, etc.) have potential to grow.

In addition to the locus and sustainability pillar categories, Figure 7 exhibits the distribution across the identified research clusters. The largest group is Policy (27.2%). In the subsequent section each research cluster will be investigated more in details, also taking the locus and the sustainability pillars into account.

4.2 | Analysis of the Identified Research Clusters

4.2.1 | Policy

Policy is the largest cluster, containing 69 articles that share homogenous research topics (Table 3). These articles provide indications to national and international bodies on how to favor access to space (e.g., Argoun 2012) to develop or improve a space program (e.g., Sridhara Murthi and Madhusudan 2008; Walker and Granjou 2017) or space agencies' operations (Brunner 1994). The scope of the analyses ranges from specific space projects (Gil et al. 2014), to governmental (Brunner 1994) and non-governmental organizations (Reibaldi and Grimard 2015), to agencies and initiatives involving multiple countries (Yan 2021) or invoking a global coordination effort (e.g., Ansdell, Ehrenfreund, and McKay 2011; Di Pippo 2019). The selected articles indicate a need to strengthen international cooperation to make space activities more sustainable. Many space programs include bilateral or multilateral collaborations; however, deep space exploration that is beyond Earth's atmosphere (Moon, Mars, and further) requires global-scale cross-disciplinary initiatives (Ansdell, Ehrenfreund, and McKay 2011). Ansdell, Ehrenfreund, and McKay (2011) stressed the importance of when ESA introduced a new policy that granted access to some of the time reserved to ESA itself on the International Space Station (ISS) to other actors that were not usually involved in the ISS experiments and activities. This led to the participation of space and non-space organizations from a wide array of groups, such as academic institutions, agencies in emerging

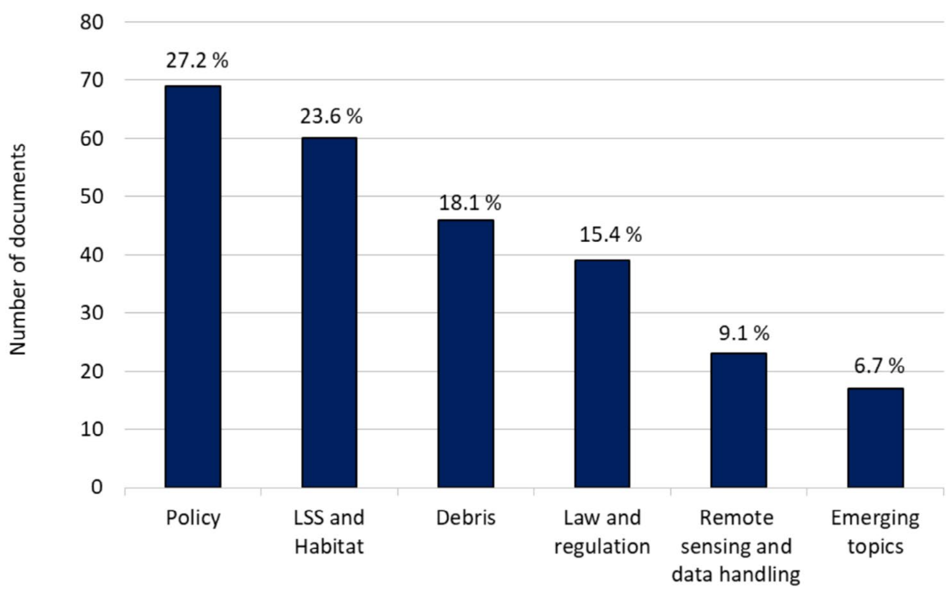

FIGURE 7 | Distribution of articles by clusters.

TABLE 3 | Locus/pillar matrix for the cluster policy.

Research topic: Policy		Environmental	Economic	Social	Total
On Earth		15	43	44	60
In space		11	17	12	25
	Orbit	3	2	3	6
	Moon	2	4	4	5
	Mars	0	2	2	2
	Other	6	11	5	14
Total		20 (4)	49 (6)	47 (8)	69 (11)

Note: The "Total" values in brackets indicate the number of articles that address both loci.

countries, and private companies. This collaborative approach promotes faster technological innovation and progress in space activities, while supporting long-term success and sustainable development. Public and private stakeholders can jointly develop sustainable products and implement strategies to address social and environmental challenges (Paravano, Locatelli, and Trucco 2023; Varughese et al. 2023).

Some of the articles in this group examine the characteristics and the challenges faced by space agencies and emerging space programs with respect to sustainability and highlight additional opportunities. Concerning the largest space agencies, governance seems the main challenge to future sustainability. Mazzucato and Robinson (2018) highlight the evolution of NASA's activities with the increased involvement of the private sector and the related issues about leadership and control. Sagath et al. (2018) delve into the challenges ESA has faced, in particular the deployment of shared space policies across all the member states. Focusing on smaller agencies and programs, Martinez (2009) and López (2016) analyzed the African and the South American space activities respectively, while Sridhara Murthi, Bhaskaranarayana, and Madhusudana (2010) the Indian Space Agency. In these studies, the authors suggest that the sustainability of the space agencies of these emerging countries would benefit from: the participation to international initiatives such as the working group on long-term sustainability of the U.N. Committee on the Peaceful Uses of Outer Space, part of U.N. Office for Outer Space Affairs (UNOOSA 2024); the development of policies and guidelines to reduce the problem of space debris; the promotion of international scientific cooperation through exchange programs to improve capacity building. With respect to the African context, Froehlich, Ringas, and Wilson (2022) assert that space activities present a potential avenue for reducing digital technology disparities by facilitating enhanced access to satellite-based services, including internet connectivity in remote and underserved regions. Large constellation, which necessitates a minimum level of infrastructure, can narrow the digital divide, enabling more balanced access to information and technology, which is crucial for economic and social advancement. However, space policies in emerging countries may also face sustainability issues. The construction of spaceports, launch sites, and ground facilities has the potential to generate economic returns; nonetheless, it also presents the risk of environmental degradation with a negative impact on the local population (Varughese et al. 2023).

Moreover, U.N. have formally acknowledged the value of projects on small satellites[7] to favor the development of wider space programs in emerging countries (e.g., Ansdell, Ehrenfreund, and McKay 2011; Argoun 2012). This type of projects has a positive impact on partners with less expertise in fundamental space technologies. First, emerging countries without an established space program can benefit from the data and services provided by existing small satellites (e.g., Earth Observation data or telecommunication and geolocation services) and enhance their local infrastructures. Second, the involvement in the technical development of new satellites is key to reach further independence, with own spacecraft and thus improve economic and social sustainability. Interestingly, no article was found describing in detail the Chinese space activities, even though some studies do mention them as part of the Asia Pacific Space Cooperation Organisation—APSCO (Liao 2020) or for reference and comparison (Di Pippo 2019). Despite China's advancements in space technology and exploration in the last 20 years (Solomone 2006), their analysis is still not sufficiently disclosed and updates are needed.

By definition this cluster of studies is more oriented toward the On Earth locus, where organizations are established and funded, than the space locus: the latter is discussed in 25 articles that address policies to support the sustainability of initiatives with a predominant focus on the outer space. For example, Mankins (2009) examined the feasibility and the economic sustainability of the construction of an outpost on the Moon. With the technical state of the art at that time, the analysis concluded that such an endeavor would not be economically viable. This is in quite contrast with the current "Artemis" program that aim to establish an orbiting station around the Moon and the technological advancements that try to find solutions to sustainable lunar settlements. The few articles addressing the governance of colonization processes do not focus on the Moon but on a generic celestial body. For instance, Schmidt and Bohacek (2021) highlighted the importance of incorporating science and technology into decision-making processes due to the inhospitable space environment. Similarly, adapting to the new environment will necessitate different moral and ethical assumptions, as well as broader adjustments in human collective behavior.

The identified articles tackle more frequently the economic and the social dimension of sustainability, whereas the presence of an environmental perspective is very limited and almost always considered jointly with the other two pillars. For example, Bohlmann and Koller (2020) analyse the activities of ESA in the Arctic region, one of the most rapidly and severely areas affected by climate change. Some of the ESA satellite programs (e.g., Sentinel, Copernicus, and CryoSat) actively monitor the Arctic environment. At the same time, the developments in satellite technologies improve telecommunication capabilities and push the progress in the use of space data. These activities are not only beneficial for the Arctic region, but they can also find applications to support all the dimensions of sustainability all over the world.

4.2.2 | Life Support Systems and Habitat

The research cluster LSSs and Habitat includes studies characterized by a primary focus on human survival in space. The studies in this cluster place significant emphasis on innovative energy sources (e.g., Gruber 1996; Zidanšek et al. 2011), on the development of new techniques that rely on in situ resource utilization (ISRU) to build and maintain habitat (e.g., Hinterman et al. 2022; Isachenkov et al. 2021), and on the advancement of closed-loop systems (e.g., Brown et al. 2021; Tikhomirov et al. 2007). ISRU refers to the processes to exploit local natural resources at mission destinations instead of transporting all the necessary supplies from Earth. Closed-loop systems facilitate the recycling of resources and the minimization of waste, in contrast to open-loop LSSs that consume materials, predominantly originating from Earth, and generate waste. Closed-loop systems are typically more complex and expensive than open ones, due to the sophisticated technology employed in the recycling of resources.

Nevertheless, closed-loop systems are indispensable for long-duration missions or settlements on other planets. Therefore, the improvements in ISRU and closed-loop LSSs are claimed to be fundamental to support the sustainable development of space exploration (Tang et al. 2021).

The studied technologies for enhancing human adaptability when leaving Earth refer to both other celestial bodies (e.g., Irons and Irons 2021; Thomas, Weislogel, and Klaus 2010) and space stations/ships (e.g., Brown et al. 2021; Mammarella et al. 2017). While this cluster primarily focuses on the In space locus (Table 4), in few cases it also addresses the impact of LSSs when deployed on or adapted to Earth to improve living conditions (e.g., water management in hot deserts in Polyakov, Musaev, and Polyakov 2010) or to develop alternative energy production methods (Zidanšek et al. 2011).

The articles dealing with the environmental dimension of sustainability represent the largest group among the three pillars (72%). Many provide details on the extraction and use of in situ resources to reduce the environmental impact on the host planet (e.g., Gumulya, Zea, and Kaksonen 2022; Sanders and Larson 2013; Wager et al. 2022). Other studies analyse the effects of space-specific agriculture techniques (e.g., Kaplan, Shapiro-Ilan, and Schiller 2020; Mortimer and Gilliham 2022; Tang et al. 2021) on providing fresh food to astronauts and reducing the number of supply launches from Earth. Some articles address closed-loop systems and find beneficial effects from the reduction and recycling of waste, either of human origin (Walker and Granjou 2017) or from cultivations (Brown et al. 2021).

52% of the studies in this cluster deals with the economic sustainability theme. Many researchers have simultaneously addressed both economic and environmental sustainability, focusing on the benefits and drawbacks of adopting a closed-loop system (e.g., Tikhomirov et al. 2007; Yamashita 2003) and achieving a balance between costs and profits when utilizing in situ resources in habitat design (e.g., Ellery 2022; Landgraf 2021). Although the costs in R&D for closed-loop systems are high, there are advantages coming from the adoption of such systems, since they minimize the payload of resources transported from Earth (e.g., Nelson, Dempster, and Allen 2013; Yamashita 2003). The available “cargo” can be directed to other types of payloads (e.g., scientific experiments, other secondary resources) with the same amount of fuel. When designing new missions, the size of the launch vehicles and the required amount of fuel can be reduced (see for example: Wertz, Everett, and Puschell 2011).

The discussion of social aspects encompasses various perspectives on human health. For example, Ghidini (2018) delved into regenerative medicine to enhance astronauts' well-being in space, while Bijlani et al. (2021) investigated the effects of radiation and microgravity on microbial life aboard the ISS. Additionally, some articles explore the social benefits stemming from the establishment of outposts on both the Moon (e.g., Fuller et al. 2022; Wager et al. 2022) and Mars (e.g., Barker 2015; Kim 2022), as well as the utilization of in situ resources for societal development (e.g., Chavy-Macdonald et al. 2021; Dallas et al. 2020). Moreover, particularly noteworthy is the emphasis on the mental health of astronauts and the analysis of social effects during extended missions or within hypothetical colonies (e.g., Boy and Doule 2014; Cerro 2017).

4.2.3 | Debris

The articles in the Debris cluster offer a comprehensive overview of the problem, which is considered one of the main concerns to the sustainability of space activities (Durrieu and Nelson 2013). Due to the inherent focus of this studies, “space” is the main locus (Table 5): most of the articles in this group discusses the environmental sustainability in space (87%) and they address, in particular, the Orbit sub-locus (71%), where almost all the debris and the potential threats are located.

As a consequence, authors focus on the means to mitigate debris issues adopting multiple approaches: tracking and cataloging known objects (from software and data processing improvements), developing technologies to capture, remove or deorbit debris, and implementing regulations to minimize the creation of new debris through responsible practices.

Starting from the latter sub-group of articles, some of the authors were interested in the regulatory framework and the knowledge repositories that have been built and could be improved to mitigate the issue of debris. Some have documented the efforts of UNOOSA over the past decade in creating and

TABLE 4 | Locus/pillar matrix for the cluster Life Support System and Habitat.

Research topic: Life support system and habitat		Environmental	Economic	Social	Total
On Earth		8	9	5	11
In space		42	29	21	56
	Orbit	3	4	2	6
	Moon	15	14	6	21
	Mars	6	4	5	10
	Other	19	8	9	22
Total		44 (3)	32 (2)	23 (3)	61 (3)

Note: The “Total” values in brackets indicate the number of articles that address both loci.

TABLE 5 | Locus/pillar matrix for the cluster debris.

Research topic: Debris		Environmental	Economic	Social	Total
On Earth		2	0	3	3
In space		40	9	4	46
	Orbit	27	7	3	33
	Moon	0	0	0	0
	Mars	0	0	0	0
	Other	13	2	1	13
Total		40 (2)	9 (0)	4 (3)	46 (3)

Note: The "Total" values in brackets indicate the number of articles that address both loci.

managing a the U.N. Register of object launched into outer space (e.g., Brachet 2012; Porras 2019). The articles under examination agree on the importance of a worldwide registry for launched objects in outer space. This would facilitate the creation of a tool to map debris and objects in space and avoid accidents. Moreover, it would promote international partnerships to assess ownership and responsibility among partners such as ISS. However, the authors acknowledge the limitations of the current system, as there is no penalty for filing late. Furthermore, only nations can register objects (Hertzfeld 2021). Private companies should, therefore, work with their respective foreign ministers to notify the U.N. of the registration. Despite the availability of a standard form, not all nations respect it. To address these shortcomings, the authors propose that, on the one hand, the U.N. be granted (i) the authority to implement penalties for non-compliance or late filing, (ii) the authority to investigate submissions for accuracy and completeness; and (iii). be staffed with sufficient personnel to handle and post the registration information and serve as a point of contact for every nation. On the other hand, all nations should be required to send their information in real time to the U.N.

Another group of authors focus on guidelines and regulations that help mitigating the debris problem (e.g., Morin and Richard 2021; Palmroth et al. 2021; Popova and Schaus 2018). They emphasize the critical need for government, institutions, and space agencies to collaboratively develop a regulatory framework that outlines rights and responsibilities. Specifically, they prioritize the impact of international agreements to reduce the generation of new debris with respect to the potential of technical solutions to remove them. There seems to be a general consensus in demanding that nations and space agencies take responsibility and adopt a more sustainable code of conduct, establish guidelines and best practices for space activities which can promote responsible behaviors, reduce debris generation, and ensure a safer space environment for all (Plattard 2015).

An alternative organizational and/or technological perspective is adopted by other authors who consider the advancements in preemption and removal of debris. With respect to the former, the design and planning phases of the new missions could be more effective in considering the solutions to limit the generation of debris and the threats posed by space objects at their end of life (Pardini and Anselmo 2021). Post-mission disposal guidelines represent a valid method for reducing the impact of satellites if required and properly implemented. In addition, an active space traffic management has the potential to bring order to near-Earth space in the future (Chen 2011). With respect to the latter, a small group of works focus on the technological developments for active and passive removal of the debris. The development of innovations for tracking and removal is of critical importance, because some regions of space (e.g., LEO) have already reached relevant densities of debris and prevention measures could be of limited efficacy. The removal of existing objects from orbit is necessary to prevent further escalation (Crowther 2003). However, the involved technologies are mainly at a conceptual or prototypal phase; hence, only few works were identified in our sample. Ben-Larbi et al. (2022) investigated the development of micro-adhesive materials to remove very small-sized debris, representing a particularly dangerous debris class due to its unpredictability. This approach creates an active debris removal system with low technological complexity and cost. Instead, Serfontein et al. (2021) focused on passive systems that aim to increase debris drag and lead to a faster deorbiting and make the objects fully burn when crossing the atmosphere. Furthermore, to address the issue of debris, recent developments have focused on extending the operational life of satellites in GEO, as proposed by Letellier and Lizy-Destrez (2022). This approach aims to reduce the number of targets in graveyard orbits. However, these systems are still in the early stages of design and mission analysis. The costs and benefits of extending satellite life, including potential loss of performance, durability, and additional maintenance requirements, are still being evaluated.

This cluster of articles is notably characterized by a lack of attention given to the economic and social sustainability aspects, as well as the possible impacts on Earth. These impacts include the reduction of the capacity to observe the sky and the potential loss of satellites due to debris impacts, which can compromise indispensable services such as telecommunications and GPS satellites (Undseth, Jolly, and Olivari 2020).

4.2.4 | Law and Regulation

In the Law and regulation cluster (Table 6), particular attention is given to the sustainability effects and challenges of treaties and frameworks regulating space activities. Both loci were discussed, with a slightly larger presence of articles addressing the locus in space. There seems to be room to improve the current

TABLE 6 | Locus/pillar matrix for the cluster law and regulation.

Research topic: Law and regulation		Environmental	Economic	Social	Total
On Earth		8	11	18	23
In space		15	11	19	28
	Orbit	3	2	3	4
	Moon	2	0	2	2
	Mars	0	0	0	0
	Other	10	9	14	22
Total		17 (6)	16 (6)	26 (11)	39 (12)

Note: The "Total" values in brackets indicate the number of articles that address both loci.

definitions of the space law (Stubbe 2018), especially regarding the issue of long-term sustainability: the identified articles suggest that this issue has not been sufficiently addressed so far (e.g., Deva Prasad 2019; Yan 2022). Within the sub-loci of space, Orbit, and Moon appear underdeveloped, especially considering the need for a coordinated effort in satellite deployment and traffic management and the upcoming ARTEMIS missions to our satellite[8].

Social sustainability is the most investigated dimension concerning the locus "On Earth." Most of the articles deal with commercial regulation in diverse contexts, such as access to satellite constellations (e.g., Giannopapa, Staveris-Poykalas, and Metallinos 2022; Tanaka 2017). The authors described the recent initiative in Europe with the objective of fostering a digital transformation within its member nations. This has been done with the intention of ensuring the continent's continued connectivity, regardless of external circumstances. Furthermore, there has been a growing demand for the implementation of high-speed broadband services. However, to enhance the competitiveness of these endeavors on the global stage and reduce Europe's dependence on external suppliers, it is imperative to establish a European mega constellation. Furthermore, this could help safeguard the telecommunications manufacturing industry within the European region. Intellectual property rights are also discussed in this cluster (Chen and Zhao 2022). The authors analyzed the conflict between the principles of territoriality as they relate to intellectual property (IP) and the prohibition against exercising territorial sovereignty in outer space, as set forth in Article II of the Outer Space Treaty. He concluded that the conflict between the legal regimes of outer space and IP is largely theoretical rather than having any significant practical implications. This is because it is possible to utilize space objects as a connecting factor to link space activities with the existing laws of the State of Registry, thereby realizing functional sovereignty (Article VIII of the Outer Space Treaty).

The topic of security is frequently addressed in the context of cybersecurity (Housen-Couriel 2016), underscoring the significance of international law in protecting satellite communication from cyberattacks and the necessity of enhancing sanctions against states that fail to uphold and implement legal norms. Security is also discussed in the context of the militarization of space-related activities (e.g., Su 2013; Su and Lixin 2014). The authors underscored the necessity to reinforce space law against the weaponization of space, which has resulted in environmental contamination, increased debris, and the destabilization of international equilibrium. They proposed the establishment of an international treaty to prohibit the testing, deployment, and use of orbital weapons. On the contrary, the publication output dealing with the environmental impact on Earth appears quite limited (e.g., Hoyhtya et al. 2022; Yan 2019), although improved management of Earth Observation data in terms of shared and equitable access could benefit the society at large (Giannopapa, Staveris-Poykalas, and Metallinos 2022).

4.2.5 | Remote Sensing and Data Handling

The Remote sensing and data handling cluster accounts for 9% of the sample. Almost all the articles concern Earth Observation; hence, the "in space" locus is not investigated, and the main sustainability pillar is environmental (Table 7). Two main streams can be identified: agriculture and land. Several studies deal with harnessing the potential of satellite data in enhancing agricultural practices. The advancement of smart and precision agriculture promises to optimize field efficiency by minimizing waste and facilitating informed decisions on crop management (e.g., Chabrillat et al. 2019; Hank et al. 2019; Tziolas et al. 2021). This research area is crucial for emerging countries (e.g., Dewitte et al. 2012; Goel et al. 2021; Lamba, Rani, and Kumar 2021).

The second main research stream focuses on the use of satellite data to monitor land in its diverse types (i.e., grassland, wetland, forest, desert, etc.) to understand the environmental transformations of our planet (e.g., Ali et al. 2016; Moomen et al. 2022; Zhuang, Liu, and Liu 1999) and in particular with respect to climate change concerns (e.g., Coleman et al. 2020; Huo et al. 2021) and the sustainable use of natural resources (Dwivedi et al. 2006).

Both research streams on agriculture and land can benefit from the policies supporting data democratization (Kojima 2016). Increasing the opportunities and the actors that can access data from satellites would accelerate both the developments in their processing and the applications in a variety of scientific fields. For example, some types of satellite

TABLE 7 | Locus/pillar matrix for the cluster Remote sensing and data handling.

Research topic: Remote sensing and data handling		Environmental	Economic	Social	Total
On Earth		20	3	3	22
In space		0	0	0	0
	Orbit	0	0	0	0
	Moon	0	0	0	0
	Mars	0	0	0	0
	Other	0	0	0	0
Total		20 (0)	3 (0)	3 (0)	22 (0)

Note: The "Total" values in brackets indicate the number of articles that address both loci.

data as the observation of nighttime lights have been recently employed to study the economic development of urban areas and to assess the impact of conflicts in war zones (e.g., Eun and Skakun 2022; Li et al. 2018).

The cluster includes only few articles that discuss remote sensing for specifically monitoring urban areas (e.g., Maktav and Erbek 2005; Musakwa and Van Niekerk 2015)[9]. Urban development is tightly connected to social sustainability. Hence the results suggest that there is room to expand the body of knowledge tackling remote sensing in the context of urbanization with a specific analysis of the impact in terms of sustainable social development.

4.2.6 | Emerging Topics

A total of 17 articles (6.7%) do not properly fit in the other clusters: they focus on two main topics. A group of studies discusses some ethical concerns related to space exploration and sustainability (e.g., Beisbart 2019; Cohen and Spector 2022; Rodyn 2019). In particular, Beisbart's work introduces the term "transplanetary sustainability" and proposes the creation of the 18th SDG for sustainability in the space environment. This is to be achieved with respect to the unique characteristics of the space environment, including extreme conditions, the absence or different gravity, the presence of resources in outer space and on other planets, and the massive presence of debris caused by human activities.

The second topic is space tourism which is analyzed in its market and commercial aspects (e.g., Kaltenhäuser et al. 2017; Peeters 2010; Spector, Higham, and Doering 2017), the legal and the environmental dimensions (e.g., Padhy and Padhy 2021; Frost and Frost 2022). The global space tourism market was valued 851.4 million U.S. dollars in 2023 with an expected compound annual growth rate of 44.8% up to 2030 (Grand View Research, 2024). Despite the expected economic growth, the identified articles suggest the need of future developments in the legal framework and of research assessing the environmental impact. The analysis of Padhy and Padhy (2021) emphasizes the limitations of the current framework, where uncertainty and weak enforcement can harm the growth of the space tourism sector. The authors call for clearer and stronger environmental rules and property rights, internationally shared procedures, and regulatory bodies for space tourism in a similar fashion to what the International Civil Aviation Organization does for the corresponding sector. Frost and Frost (2022) deal with the environmental aspects of space tourism and the often-overlooked impact on Earth, which should be better regulated by space law.

4.3 | Sustainable Development Goals

The articles were further classified according to the SDGs provided by Scopus. The SDGs cover a broad range of issues, from economic growth and social inclusion to environmental sustainability and peacebuilding. Figure 8 displays the distribution of articles within the sample. The most frequently addressed SDG is Partnership for the goals (SDG 17), with a primary focus on Earth-related aspects (70 articles). The other most represented SDGs are the number nine Industry, innovation, and infrastructure (47 articles) and the number 12 Responsible consumption and production (30 articles). No article was found specifically discussing Gender Equality (SDG 5). A similar outcome was found by Cruz Rambaud, López Pascual, and Meléndez Rodríguez (2021)[10]. They asserted that the most addressed SDGs, in Aerospace industry, were 12, 9, 7, and 13. Furthermore, the Remote Sensing and Data Handling cluster reveals that SDGs 2, 15, and 11 are the most prevalent. These findings align with those of Paravano et al. (2024), who conducted a similar investigation into the ESA project and its impact on the SDGs. Their study concluded that Earth observation projects primarily influence SDGs 2, 15, and 11.

A group of 60 articles is not associated to any SDG: 50 of them address the space locus. This could be attributed to the fact that the SDGs were primarily developed for on Earth applications.

The analysis of the distribution of the SDGs across the research clusters reveals some correlations (Table 8). For instance, the Debris cluster is strongly aligned with the SDG 9 and 12, while LSS and habitat with SDG 9, 12, and 15. Conversely, the research topic Remote sensing and data handling displays a fragmented distribution due to its diverse applications in various contexts, contributing to a wider array of SDGs. Notably, clusters focused on the industrial and technical aspects of space activities are most closely associated with SDG 9, 12, and 15.

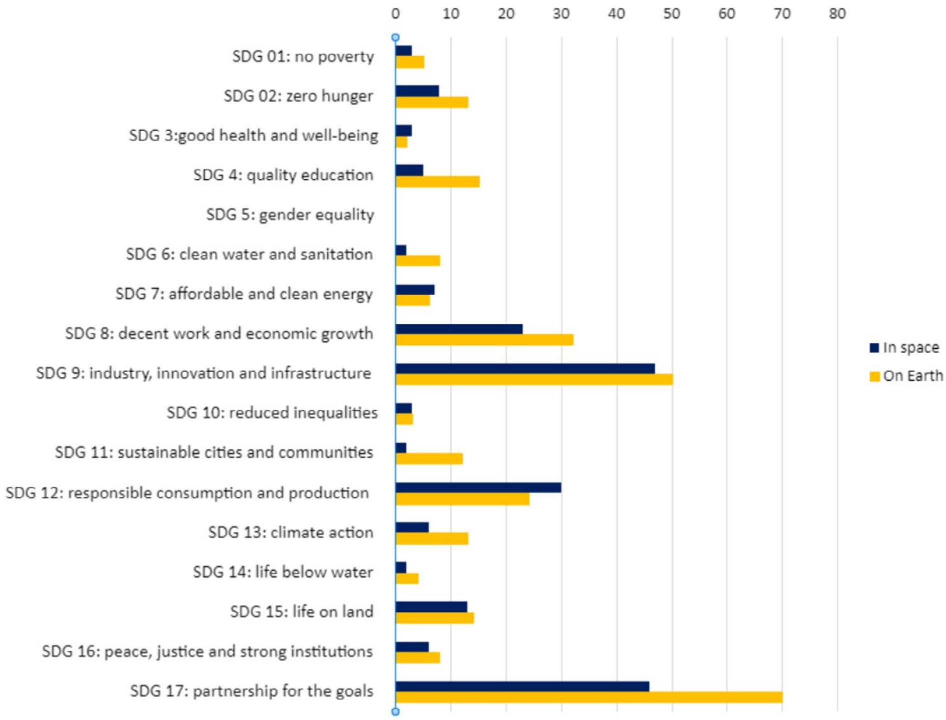

FIGURE 8 | Papers distribution by sustainable development goals and loci.

TABLE 8 | Percentage Distribution of SDGs across the identified clusters.

	Debris	Law and regulation	LSS and Habitat	Policy	Remote sensing and data handling	Emerging topics
SDG 01			4.3	4.3	2.2	2.2
SDG 02			15.2	10.9	13.0	
SDG 03	4.3					4.3
SDG 04	2.2	2.2	6.5	15.2		8.7
SDG 05						
SDG 06	2.2		6.5	4.3	6.5	
SDG 07	4.3	4.3	10.9	4.3	2.2	
SDG 08	13.0	13.0	10.9	45.7	8.7	8.7
SDG 09	21.7	23.9	43.5	67.4	6.5	10.9
SDG 10			4.3			4.3
SDG 11			6.5	6.5	13.0	
SDG 12	17.4	8.7	23.9	21.7	8.7	13.0
SDG 13	2.2	2.2	2.2	15.2	8.7	2.2
SDG 14			2.2	2.2	4.3	2.2
SDG 15	2.2	2.2	23.9	10.9	13.0	
SDG 16	2.2	6.5	2.2	10.9	2.2	2.2
SDG 17	32.6	47.8	8.7	84.8	23.9	8.7
No SDG	37.0	21.7	41.3	26.1		4.3

5 | Gaps and Future Research Avenues

The analysis of the identified literature reveals the presence of gaps and areas with potential for further development. The first evidence is the relatively limited number of studies addressing the impact of the space-related activities on the environmental sustainability of Earth. These are almost entirely in the clusters with direct relationship with the terrestrial environment, for example, remote sensing (Maktav and Erbek 2005), or that suggest new applications of space technologies, for example, the use of LSSs on Earth scenarios (Polyakov, Musaev, and Polyakov 2010). However, there seems to be potential to develop studies also in some of the other clusters, with the aim to include the perspective of environmental sustainability on Earth, for example, when considering international space programs and the organization of national agencies: an increased awareness could act as a flywheel to further address such dimension.

Focusing on the "In space" locus of research, the economic and social dimensions of sustainability are less addressed than the environmental one. Concerning the economic pillar, one area that shows potential for future research is the Debris cluster as we discuss in the next paragraphs. The economic dimension could also be expanded in the LSSs and habitat group, which seems to have room for further addressing the social challenges of living in orbiting stations, spaceships, and colonies on other celestial bodies. The scarcity of resources, the confined nature of the environment, the distance from Earth, and the hazardous conditions pose significant threats to the teams of astronauts and future inhabitants. These issues are particularly relevant for scholars and practitioners, given the imminent missions to return to the Moon and the planned future missions to Mars.

The analysis of the identified clusters provided evidence of underdeveloped research areas: in some cases, this comes from the intrinsic definition of the theme (e.g., the Earth locus is not tackled in the Debris cluster), while in other cases, new studies could improve the understanding of the topic.

The Policy group predominantly focuses on terrestrial activities and the policies required to foster new space programs, to ensure equitable access to space for emerging nations, and to stimulate the growth of space agencies. International collaboration is of crucial importance for space exploration. Access to space necessitates a global effort, including the incorporation of emerging countries into the space context. Resources must be distributed equitably, thereby promoting technological innovation in numerous nations and developing more launch sites and ground facilities, especially at the equator, where launch costs are lower. In this context, sustainability can be a cost-saving measure rather than an additional expense (Argoun 2012) if measures to prevent environmental deterioration resulting from the excessive exploitation of natural resources are implemented (Varughese et al. 2023). The involvement of additional partners facilitates the streamlining of space access management, particularly given that the countries developing the technology are often distinct from those providing the launch sites. Furthermore, international collaboration is essential due to the scale of projects. Past endeavors and anticipated developments in new space stations, such as Axiom Space or the Lunar Gateway, underscore the necessity of a global ecosystem (Ansdell, Ehrenfreund, and McKay 2011). These new spacecraft and space stations are privately led initiatives involving a global network of diverse partners and suppliers, including agencies, research institutions, and companies. While the literature acknowledges the relevance of a smooth collaborative effort (e.g., Sagath et al. 2018; Sridhara Murthi, Bhaskaranarayana, and Madhusudana 2010; Yan 2021), further analyses including sustainability are required. From the analyses in this study, we suggest four main avenues of research. First, a more comprehensive examination of the past and ongoing initiatives aiming at fostering collaboration is essential to identify the most successful and their characteristics, through case studies and qualitative analyses. In particular, the research could focus on the outcome of mechanisms in place to involve emerging countries or to suggest new ones. For example, future research could investigate initiatives such as the working group on long-term sustainability of UNOOSA (2024) with the aim to understand their efficacy and areas of improvement. Second, studies should point out whether new international organizations are required, or it would be more effective to enhance the existing ones. Third, new research could further assess the sustainability of space programs of governmental organizations in order to evaluate their impact along classifications such as the SDGs. For instance, a recent study of Paravano et al. (2024) analyzed ESA's business programme portfolio between 2014 and 2022 and its impact on the SDGs. ESA developed this platform of activities to promote the development, testing and validation of products, services and businesses enabled by space technologies. Their findings reveal that the most impacted SDGs are 2 and 3, namely Zero hunger and Good health and well-being, as well as 11, which concerns sustainable cities and communication (Paravano et al. 2024). As a final avenue for this cluster, current studies seem to have not sufficiently covered the Chinese context despite the significant investment and the recent results obtained in space exploration[11].

The studies in the LSS and habitat cluster have just started to investigate the potential applications on Earth of such technologies developed to assist life in space. In general, the economic impact of developing and implementing LSSs has been explored to a limited extent in both terrestrial and extraterrestrial contexts. From a technological perspective, some articles investigate the costs and benefits of developing closed-loop systems but without an in-depth analysis of their sustainable impact. However, these studies are relatively dated (e.g., Nelson, Dempster, and Allen 2013; Yamashita 2003), and there is a lack of recent research on the topic. Future research could investigate further the potential of LSS, both as a fundamental technology in space exploration and as a resource on Earth (e.g., Polyakov, Musaev, and Polyakov 2010). New findings could have a positive impact on the SDGs, for example, studying the evolution of parasites in microgravity could develop more resistant crops and support the achievement of SDG 2, Zero Hunger (e.g., Kaplan, Shapiro-Ilan, and Schiller 2020). In addition, studying water management systems could solve the problem of clean water in emerging economies, supporting the achievement of SDG 6, Clean water and Sanitation (e.g., El-Shawa et al. 2022). Furthermore, the literature contains a significant number of articles on ISRU and LSS, but they do not address the sustainable aspects. In this cluster, the social aspect of sustainability is under-addressed, especially within the domain of Mars exploration and with respect of astronauts' lives, either in spaceships, stations, or hypothetical colonies: further studies drawing from sociological and psychological fields could contribute to improve our understanding.

The Debris cluster strongly emphasizes studies promoting international collaboration by creating information-sharing systems for orbital debris and developing more effective and stringent guidelines, particularly for the disposal phase. Policymakers could benefit from considering new research outcome for the implementation of comprehensive strategies that balance economic growth in the space sector with environmental sustainability. Currently, one of the main approaches to solve the issue of space debris is through the definition of policies that shape the regulatory and collaborative frameworks with clearer responsibilities. From improved analyses, decision makers could support the characterization of international agreements that go beyond the current non-binding guidelines and promote enforceable treaties that hold nations and private entities accountable for debris management. Furthermore, legal measures that engage all stakeholders in the space sector, coupled with a more comprehensive analysis of the economic impact of debris on space activities, would support solutions to these issues. Under this perspective, there seems to be a lack of studies addressing the liability for potential damages caused by debris on other space vehicles. From a technological perspective, many authors prioritize passive or tracking system improvements over active devices for debris removal. The analyses of the mitigation strategies are currently not conclusive. This is in part due to the embryonic stage of development of many of them and the lack of available data. However, a qualitative (or if data allows it, a quantitative) comparison across technological and organizational approaches in terms of effectiveness and sustainability would support the understanding of the debris issue. In addition, it would be advantageous for future research to focus on the socioeconomic consequences of space debris on life on Earth, which have not yet been sufficiently investigated. The uncontrolled proliferation of debris leads to reduced visibility, impairing sky observation, and poses a tangible risk to satellite loss due to debris impacts, thereby imperiling essential services such as telecommunications and GPS satellites (Undseth, Jolly, and Olivari 2020). The above-mentioned potential lines of research could be linked to several SDGs. SDG 9, Industry, innovation, and infrastructure, is particularly relevant in this context, given that the uncontrollable growth of space debris has a detrimental effect on active satellites. Furthermore, the need for international cooperation, regulation, and shared responsibility, as outlined in SDG 17, Partnerships for the Goals, is a crucial aspect in addressing the issue of space debris.

The Law and Regulation cluster is characterized by a general concern about the need to improve space treaties and regulatory frameworks, especially in terms of sustainability (e.g., Stubbe 2018; Deva Prasad 2019; Yan 2022) and, in particular, environmental sustainability on Earth. Furthermore, the articles collectively indicate the necessity for the improvement of international space laws and international collaboration in a multitude of areas, including access to space and the regulation of mega-constellations (e.g., Giannopapa, Staveris-Poykalas, and Metallinos 2022; Tanaka 2017). Additionally, a significant focus is placed on examining security aspects, which profoundly impact the environment and geopolitical landscape (Su 2013). One critical issue is the lack of a clear distinction between airspace and outer space. Airspace is typically considered a sovereign territory under the jurisdiction of individual nations, while outer space is governed by international agreements prohibiting national sovereignty and appropriation. However, the boundary between these two domains is unclear, creating ambiguity in applying national and international laws to space activities (Bhatnagar and Dey 2024; Housen-Couriel 2023). This uncertainty underscores the need to update legal frameworks to address modern challenges, such as defining territorial boundaries and private property rights in space. Concerning the space locus, further attention should be directed toward the Moon and Mars as well, with the aim of safeguarding environmental sustainability and establishing economically and socially sustainable colonies.

Moreover, within the Remote sensing and data handling cluster, there seems to be the potential for future developments, both expanding some of the existing areas of study (e.g., agriculture and land) and exploring new fields (e.g., economic impact, aviation). With respect to the former group, the current findings in this review suggest that there is room for employing “space-derived” data for further regional and urban-level analyses, especially concerning the social dimension of sustainability (e.g., Maktav and Erbek 2005; Musakwa and Van Niekerk 2015). In this context, a wide array of topics could be further developed, ranging from the enhancement of green spaces and precision agriculture to the monitoring of urban heat islands, the tracking of migration flows, and the assessment of urbanization. Additional studies can investigate the positive impact of space data and extend the existing findings on climate change and related mitigation strategies in risky areas (e.g., Ali et al. 2016; Coleman et al. 2020; Moomen et al. 2022) by trying to perform an economic assessment of the use of satellite data. Finally, new areas of application could emerge and require dedicated analyses, e.g., the monitoring of the changes in wind gusts and turbulence and the consequences for the Aviation sector. These research lines have the potential to impact several SDGs. Specifically, remote sensing techniques in the agricultural sector could contribute to achieving SDG 2 (Zero Hunger) and SDG 6, (Clean Water and Sanitation). Additionally, the application of satellite data to monitor climate change is expected to enhance the realization of SDG 13, (Climate Action), SDG 15 (Life on Land), and SDG 12 (Responsible consumption and production). In this direction, UNOOSA published a report highlighting the potential of space technology and satellite data to support the entire Agenda 2030 (United Nations, Office for Outer Space Affairs 2023).

Concerning the cluster of emerging topics, we note that space tourism is a growing research field but the articles that focus on sustainability aspects are still in an embryonic stage. Consequently, as the space industry experiences growth and a proliferation of new entrants, it becomes imperative to anticipate future challenges from environmental, social, and economic perspectives. This is crucial to ensure that these developments contribute positively to both space and Earth ecosystems.

6 | Conclusion

This study examines the current body of literature dealing with space economy and sustainability. Through a systematic literature review, articles were collected from Scopus, screened, and analyzed along multiple dimensions. Each of the 254 articles in the sample was assigned to the main locus of research, that is, in space or on Earth. The space locus was further characterized (i.e., Orbit, Moon, Mars or Other space) to gain deeper insights. The predominant sustainability pillars, that is, environmental, economic, or social, were assessed in the identified scientific products. To further characterize sustainability, the articles were tagged with the SDGs resulting from the queries available in Scopus (Jayabalasingham 2019). Finally, a mixed approach (automated clustering and manual control) was employed to identify the primary research topic and then assess the presence of potential research gaps. Five groups were identified: "Policy", "Debris", "LSS and habitat", "Law and regulation", "Remote sensing and data handling." A sixth residual cluster was created for "Emerging topics."

The analysis revealed that, in general, there is a slight prevalence of articles that primarily focus on space as the main locus of research rather than Earth. In terms of sustainability pillars, environmental aspects were the most addressed, followed by economic and social considerations. A further finding revealed that studies on environmental sustainability were primarily focused on the space locus, while articles categorized under the Earth locus predominantly addressed social sustainability. As our planet is constantly facing environmental threats, more research on the environmental issues on Earth is also needed when focusing on the sustainability of the Space Economy: new studies could contribute to investigating the potential benefits that Earth could gain, for example, from an improved collaborative framework for technological development, an extended downstream application of space technologies, or a wider diffusion of space data.

When analyzing the literature in detail, some differences emerge across the identified clusters of research. In line with the general trend, the group dealing with Policy issues shows a limited number of studies that address the environmental impact resulting from policy adoption, the establishment of space agencies or the implementation of ad hoc programs. Moreover, only few articles discuss space policies and programs in China (Solomone 2006), despite the country's fast development pace. Practitioners and researchers in the space sector can gain useful insights from comparing the different strategies implemented in different countries and from assessing the impact of policies on long-term sustainability.

Similarly, there seem to be few studies addressing the implications on Earth of the space debris issue, especially economic and social dimensions (Undseth, Jolly, and Olivari 2020). This is of utmost importance in the NSE for two main reasons. First the NSE is characterized by an increased number of players that access space, including private companies providing launchers or satellite constellations. Second, there seems to be consensus in the literature on the call for improvements in the legal and regulatory framework of space in general, and for debris in particular.

Furthermore, there is a gap in the exploration of the potential LSSs when applied on Earth, as pointed out by some studies for reducing waste and enhancing life conditions in challenging environments or resource-constrained settings (e.g., El-Shawa et al. 2022; Gruber 1996). Earth Observation through satellite data shows room for more research on the urban environment, in particular for the assessment of the social sustainability: the several applications for traffic management and city development call for extended analyses of the long-term effects (e.g., Musakwa and Van Niekerk 2015).

The group of articles with Earth as the main locus of research shows, in particular, the need to address the legal aspects to support long-term sustainability. In addition, there is room for new studies specifically addressing the issues of sustainability within the context of lunar and Martian exploration, considering both economic and social dimensions. For example, areas such as risk analysis, economic impact on Earth, and the mental health of astronauts are still relatively underexplored, particularly in the context of Mars exploration (Kim 2022).

Finally, we have observed that too many articles lack proper SDG tags, especially in the space field. This suggests that the assignment of SDGs is ineffective for space-related articles. This is particularly evident for the Debris and the LSS and habitat clusters.

Our study is not exempt from limitations. In particular, our search strategy relies on the Scopus database, which contains journals from a large number of scientific fields. However, the repository does not include all the sources of information (e.g., reports, and books) that might contribute to the body of knowledge, especially in certain fields (e.g., legal disciplines). In addition, the applied search strategy captures the articles that clearly mention "sustainability", but there might be some that fall outside our selection since they are not using the term specifically; the group of such "false negative" results could be related in particular to an under-representation of the pillar of economic sustainability. Moreover, the clustering of articles was carried out through a combination of manual and automated processes, with the aim to limit the subjectivity of the researchers in classifying the articles. Finally, our search strategy is limited to articles written in English. Future research should address these issues.

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Conflicts of Interest

The authors declare no conflicts of interest.

Endnotes

[1] Due to the extremely high velocities, collisions with space debris can cause catastrophic damage.

[2] Scopus search syntax: SRCTYPE(j) AND DOCTYPE(ar OR re) AND LANGUAGE(English).

[3] Stopwords: aircraft, airport, airline, aviation.

[4] Excluded journals: Jane S Defence Weekly, Journal Of Urban Economics, Regional Science And Urban Economics, Cities, Marine Policy.

[5] LEO is a relatively close orbit to Earth, typically ranging from about 160 km to 2000 km above the Earth's surface. Satellites in LEO circle the Earth relatively quickly, completing orbits in around 90 min to a couple of hours. In contrast, GEO is situated at a considerably greater altitude, approximately 35,786 km above the Earth's equator. Satellites in GEO maintain a consistent orbital velocity with respect to Earth, appearing stationary from a fixed point on the Earth's surface.

[6] The web platform Carrot2 was employed (https://search.carrot2.org/, last access in June 2024).

[7] Small satellites are spacecraft of low mass and size. Thanks to miniaturization and technological improvements, smaller satellites can be launched, reducing payload and thus costs. There are several classes according to their weight and size: CubeSats are among the most famous and refer to cubes of 10 cm on sides.

[8] NASA's Artemis mission is comprised of four phases. The initial two phases are dedicated to the testing of the Space Launch System and the Orion spacecraft (launch planned in 2025). The third phase is scheduled for 2026 when humans will land on the Moon's South Pole. The last phase (2028) consists of astronauts living and working in the first lunar orbiting space station, Gateway: it will provide a platform for scientific exploration and preparation for future human missions to Mars and deep space.

[9] Note that we excluded three journals focusing on urban topics in our selection query: however, a specific analysis on their content did not reveal false negative results, that is, we did not exclude articles that contain the concepts "sustainability" and "outer space".

[10] They enhance a project managerial tool to support sustainability in aerospace industry. One of their research goals was to describe recent green initiatives in the aerospace sector by checking its contribution to reaching the well-known sustainable development goals (SDGs).

[11] As reported by ESA (https://space-economy.esa.int/article/102/chinas-space-sector-commercialisation-with-chinese-characteristics, last access in June 2024), the Chinese space sector has undergone significant commercialization over the past decade, with the establishment of over 100 companies and the collection of approximately ¥40B (US$6.5B) in funding by Chinese commercial space companies. The Chinese lunar program commenced in 2007 and saw its inaugural rover touchdown on December 14, 2013. Another notable achievement was the first landing on the moon's dark side on March 3, 2019. Additionally, in recent developments of the Chinese space program, there is the space station Tiangong, comprising the first module launched on April 29, 2021, and completed on November 5, 2022.

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Appendix 1

TABLE A1 | List of the selected publications and their classification.

	# Pillars	Economic	Environmental	Social	# loci	In space	OnEarth	Orbit	Moon	Mars	Other space	Cluster supervised
(Crowther 2003)	1		1		1	1		1	0	0	0	Debris
(Chen 2011)	1		1		1	1		1	0	0	0	Debris
(Brachet 2012)	2		1	1	1	1		0	0	0	1	Debris
(Argoun 2012)	1			1	2	1	1	1	0	0	0	Debris
(Williamson 2012)	1		1		1	1		0	0	0	1	Debris
(Emanuelli et al. 2014)	2	1	1		1	1		1	0	0	0	Debris
(Gheorghe and Yuchnovicz 2015)	1		1		1	1		1	0	0	0	Debris
(Plattard 2015)	1		1		1	1		1	0	0	0	Debris
(Lang et al. 2015)	1		1		1	1		1	0	0	0	Debris
(Bastida Virgili et al. 2016)	1		1		1	1		1	0	0	0	Debris
(Popova and Schaus 2018)	1		1		1	1		1	0	0	0	Debris
(Martinez 2009)	1		1		1	1		0	0	0	1	Debris
(Porras 2019)	1		1		1	1		1	0	0	0	Debris
(Lewis 2020)	1		1		1	1		1	0	0	0	Debris
(Jaehnichen 2020)	2		1	1	2	1	1	1	0	0	0	Debris
(Murtaza et al. 2020)	1		1		1	1		1	0	0	0	Debris
(Rouillon 2020)	1	1			1	1		1	0	0	0	Debris
(Curzi, Modenini, and Tortora 2020)	2	1	1		1	1		0	0	0	1	Debris
(Suchantke et al. 2020)	1		1		1	1		0	0	0	1	Debris
(Pardini and Anselmo 2021)	1		1		1	1		1	0	0	0	Debris
(Morin and Richard 2021)	1		1		1	1		0	0	0	1	Debris
(Haroun et al. 2021)	1		1		1	1		1	0	0	0	Debris
(Pavlova and Voropaev 2021)	1		1		1	1		0	0	0	1	Debris
(Serfontein et al. 2021)	1		1		1	1		1	0	0	0	Debris

(Continues)

TABLE A1 | (Continued)

	# Pillars	Economic	Environmental	Social	# loci	In space	OnEarth	Orbit	Moon	Mars	Other space	Cluster supervised
(Palmroth et al. 2021)	2	1	1		1	1		1	0	0	0	Debris
(Hertzfeld 2021)	1		1		1	1		0	0	0	1	Debris
(Suwijak and Li 2021)	2		1	1	2	1	1	1	0	0	0	Debris
(Clormann and Klimburg-Witjes 2022)	1		1		1	1		1	0	0	0	Debris
(Heinrich et al. 2022)	1		1		1	1		0	0	0	1	Debris
(Zhu 2022)	1	1			1	1		1	0	0	0	Debris
(Ben-Larbi et al. 2022)	1		1		1	1		1	0	0	0	Debris
(Lindsay et al. 2022)	1		1		1	1		1	0	0	0	Debris
(Martinez 2023)	1		1		1	1		1	0	0	0	Debris
(Pardini and Anselmo 2022)	1		1		1	1		1	0	0	0	Debris
(Hatty 2022)	2	1	1		1	1		0	0	0	1	Debris
(Miraux 2022)	1		1		1	1		1	0	0	0	Debris
(Lawrence et al. 2022)	1		1		1	1		0	0	0	1	Debris
(Buchs and Bernauer 2023)	1	1			1	1		1	0	0	0	Debris
(Bernhard, Deschamps, and Zaccour 2023)	1	1			1	1		1	0	0	0	Debris
(Maury et al. 2017)	1	1			1	1		1	0	0	0	Debris
(Maury et al. 2020)	1		1		1	1		0	0	0	1	Debris
(Page and Besco 2021)	1		1		1	1		1	0	0	0	Debris
(Gupta 2016)	1		1		1	1		0	0	0	1	Debris
(Dalledonne 2021)	1		1		1	1		1	0	0	0	Debris
(Abashidze, Chernykh, and Mednikova 2022)	1		1		1	1		1	0	0	0	Debris
(Mocrei-Rebrean 2022)	1		1		1	1		1	0	0	0	Debris
(Padhy and Padhy 2021)	2	1		1	1	1		0	0	0	1	Emerging topics
(Frost and Frost 2022)	3	1	1	1	2	1	1	0	0	0	1	Emerging topics

(Continues)

TABLE A1 | (Continued)

	# Pillars	Economic	Environmental	Social	# loci	In space	OnEarth	Orbit	Moon	Mars	Other space	Cluster supervised
(Weeden and Chow 2012)	1			1	2	1	1	0	0	0	1	Emerging topics
(Calzada-Diaz et al. 2014)	1	1			1		1	0	0	0	0	Emerging topics
(Kojima 2016)	1			1	1		1	0	0	0	0	Emerging topics
(Spector, Higham, and Doering 2017)	2		1	1	2	1	1	0	0	0	1	Emerging topics
(Kaltenhäuser et al. 2017)	2	1		1	2	1	1	0	0	0	1	Emerging topics
(Dietrich et al. 2018)	1			1	1		1	0	0	0	0	Emerging topics
(Rodin, 2019)	1			1	1	1		0	0	0	1	Emerging topics
(Beisbart 2019)	1			1	2	1	1	0	0	0	1	Emerging topics
(Losch 2020)	3	1	1	1	1		1	0	0	0	0	Emerging topics
(Cohen and Spector 2022)	3	1	1	1	2	1	1	0	0	0	1	Emerging topics
(Lucas-Rhimbassen 2022)	1	1			2	1	1	0	0	0	1	Emerging topics
(Doboš 2022)	1	1			1		1	0	0	0	0	Emerging topics
(Kaufman, Lenartz, and Floyd 2022)	1			1	2	1	1	0	0	0	1	Emerging topics
(Toivonen 2022)	2	1	1		2	1	1	0	0	0	1	Emerging topics
(Peeters 2010)	1	1			2	1	1	1	0	0	0	Emerging topics
(Alewine 2020).	1	1			1		1	0	0	0	0	Law and regulation
(Lucas-Rhimbassen 2022)	2	1		1	1	1		0	0	0	1	Law and regulation

(Continues)

TABLE A1 | (Continued)

	# Pillars	Economic	Environmental	Social	# loci	In space	OnEarth	Orbit	Moon	Mars	Other space	Cluster supervised
(Su 2013)	1			1	1		1	0	0	0	0	Law and regulation
(Su and Lixin 2014)	1			1	1		1	0	0	0	0	Law and regulation
(Ahmad 2021)	1			1	2	1	1	0	0	0	1	Law and regulation
(Xiaodan 2015)	2		1	1	1	1		0	1	0	0	Law and regulation
(Giannopapa, Staveris-Poykalas, and Metallinos 2022)	2	1		1	1		1	0	0	0	0	Law and regulation
(Bohlmann and Petrovici 2019)	1		1		1	1		0	0	0	1	Law and regulation
(Hofmann and Bergamasco 2020)	1		1		2	1	1	0	0	0	1	Law and regulation
(Chrysaki 2020)	2	1		1	2	1	1	0	0	0	1	Law and regulation
(Ferreira-Snyman and Ferreira 2019)	1			1	1	1		0	0	0	1	Law and regulation
(Harrington 2020)	1	1			1		1	0	0	0	0	Law and regulation
(Housen-Couriel 2016)	2	1		1	1	1		1	0	0	0	Law and regulation
(Jaramillo 2015)	1			1	1		1	0	0	0	0	Law and regulation
(Chen 2020)	1			1	1	1		0	0	0	1	Law and regulation
(Chen and Zhao 2022)	2	1		1	2	1	1	0	0	0	1	Law and regulation
(Martinez 2021)	2	1	1		1	1		0	0	0	1	Law and regulation
(Iliopoulos and Esteban 2020)	1			1	2	1	1	0	0	0	1	Law and regulation
(Leshinsky 2021)	1	1			1	1		0	0	0	1	Law and regulation

(Continues)

TABLE A1 | (Continued)

	# Pillars	Economic	Environmental	Social	# loci	In space	OnEarth	Orbit	Moon	Mars	Other space	Cluster supervised
(Pheng Low and Ting Goh 2010)	1		1		1		1	0	0	0	0	Law and regulation
(Martinez et al. 2014)	1			1	1		1	0	0	0	0	Law and regulation
(Aganaba-Jeanty 2016)	1			1	2	1	1	0	0	0	1	Law and regulation
(Profitiliotis and Loizidou 2019)	2	1	1		1		1	0	0	0	0	Law and regulation
(Bohacek, Worden, and Grattan 2022)	1	1			1	1		0	0	0	1	Law and regulation
(Stubbe 2018)	2		1	1	1	1		1	0	0	0	Law and regulation
(Takeuchi 2019)	1			1	1	1		0	0	0	1	Law and regulation
(Hoyhtya et al. 2022)	3	1	1	1	2	1	1	1	0	0	0	Law and regulation
(Ishola, Fadipe, and Taiwo 2021)	1		1		1	1		0	0	0	1	Law and regulation
(Su 2017)	2		1	1	2	1	1	0	0	0	1	Law and regulation
(Tanaka 2017)	2	1		1	2	1	1	0	0	0	1	Law and regulation
(Hihara, Nomachi, and Takahashi 2019)	1		1		1	1		1	0	0	0	Law and regulation
(Nie 2019)	2	1		1	1		1	0	0	0	0	Law and regulation
(Deva Prasad 2019)	3	1	1	1	2	1	1	0	0	0	1	Law and regulation
(Yan 2019)	2		1	1	2	1	1	0	0	0	1	Law and regulation
(Stokes et al. 2020)	1		1		1	1		0	0	0	1	Law and regulation
(Deplano 2021)	2		1	1	1	1		0	1	0	0	Law and regulation

(Continues)

TABLE A1 | (Continued)

	# Pillars	Economic	Environmental	Social	# loci	In space	OnEarth	Orbit	Moon	Mars	Other space	Cluster supervised
(Yan 2022)	3	1	1	1	2	1	1	0	0	0	1	Law and regulation
(Nahtigal 2022)	1			1	1		1	0	0	0	0	Law and regulation
(Yan 2023)	1		1		1	1		0	0	0	1	Law and regulation
(Ghidini 2018)	1			1	1	1		0	0	0	1	LSS and habitat
(Wager et al. 2022)	3	1	1	1	1	1		0	1	0	0	LSS and habitat
(Chen et al. 2021)	2		1	1	1	1		0	0	0	1	LSS and habitat
(Barker 2015)	3	1	1	1	2	1	1	0	0	1	0	LSS and habitat
(Paladini, Saha, and Pierron 2021)	2	1	1		2	1	1	0	0	0	1	LSS and habitat
(Cerro 2017)	1			1	1	1		0	0	1	0	LSS and habitat
(Boy and Doule 2014)	2	1		1	1	1		0	0	0	1	LSS and habitat
(Irons and Irons 2021)	1		1		1	1		0	0	0	1	LSS and habitat
(Sanders and Larson 2013)	1		1		1	1		0	1	0	0	LSS and habitat
(Sanders and Larson 2015)	1		1		1	1		0	1	0	0	LSS and habitat
(Levri and Vaccari 2004)	1	1			1		1	0	0	0	0	LSS and habitat
(Hinterman et al. 2022)	2		1	1	1	1		0	0	1	0	LSS and habitat
(Kim 2022)	1			1	1	1		0	0	1	0	LSS and habitat
(Mammarella et al. 2017)	1		1		1	1		0	1	0	0	LSS and habitat
(El-Shawa et al. 2022)	3	1	1	1	1		1	0	0	0	0	LSS and habitat
(Hufenbach 2013)	2	1		1	1	1		1	0	0	0	LSS and habitat
(Ceylan 2020)	2		1	1	1	1		0	0	0	1	LSS and habitat
(Thomas, Weislogel, and Klaus 2010)	1		1		1	1		0	1	0	0	LSS and habitat
(Yamashita 2003)	2	1	1		1	1		0	0	0	1	LSS and habitat
(Tikhomirov et al. 2007)	2	1	1		1	1		0	0	1	0	LSS and habitat

(Continues)

TABLE A1 | (Continued)

	# Pillars	Economic	Environmental	Social	# loci	In space	OnEarth	Orbit	Moon	Mars	Other space	Cluster supervised
(Nelson, Dempster, and Allen 2008)	1		1		1	1		0	0	1	0	LSS and habitat
(Polyakov, Musaev, and Polyakov 2010)	1		1		1		1	0	0	0	0	LSS and habitat
(Nelson, Dempster, and Allen 2013)	3	1	1	1	1	1		0	0	0	1	LSS and habitat
(Walker and Granjou 2017)	1		1		1	1		0	0	0	1	LSS and habitat
(Odawara 2018)	1	1			1	1		0	0	0	1	LSS and habitat
(Kaplan, Shapiro-Ilan, and Schiller 2020)	1		1		1	1		0	0	0	1	LSS and habitat
(Bijlani et al. 2021)	1		1		1	1		0	0	0	1	LSS and habitat
(Brown et al. 2021)	2		1	1	1	1		0	0	0	1	LSS and habitat
(Tang et al. 2021)	1		1		1	1		0	0	0	1	LSS and habitat
(Mortimer and Gilliham 2022)	1		1		1	1		0	0	0	1	LSS and habitat
(Brandić Lipińska et al. 2022)	2		1	1	2	1	1	0	0	0	1	LSS and habitat
(Guibaud et al. 2022)	2		1	1	1	1		1	0	0	0	LSS and habitat
(Häuplik-Meusburger, Sommer, and Aguzzi 2009)	1	1			1	1		0	1	0	0	LSS and habitat
(Hastings, Putbrese, and La Tour 2016)	2	1	1		1	1		1	0	0	0	LSS and habitat
(Vermeulen et al. 2020)	2	1	1		2	1	1	0	0	0	1	LSS and habitat
(Liu et al. 2021)	1	1			1	1		1	0	0	0	LSS and habitat
(Gruber 1996)	1	1			1		1	0	0	0	0	LSS and habitat
(Mulugeta et al. 2009)	1			1	1	1		0	1	1	0	LSS and habitat
(Green 2010)	1			1	1		1	0	0	0	0	LSS and habitat
(Zidanšek et al. 2011)	3	1	1	1	2	1	1	0	1	0	0	LSS and habitat
(Metzger et al. 2013)	1	1			1	1		0	1	0	0	LSS and habitat
(Trisolini, Lewis, and Colombo 2016)	1		1		1	1		0	0	0	1	LSS and habitat
(Lubek 2019)	2		1	1	1	1		0	0	0	1	LSS and habitat

(Continues)

TABLE A1 | (Continued)

	# Pillars	Economic	Environmental	Social	# loci	In space	OnEarth	Orbit	Moon	Mars	Other space	Cluster supervised
(Harris, Eranki, and Landis 2019)	1	1			2	1	1	0	1	0	0	LSS and habitat
(Naser 2019a)	1		1		1	1		0	1	0	0	LSS and habitat
(Naser 2019b)	1		1		1	1		0	1	1	0	LSS and habitat
(Pelle et al. 2019)	2	1	1		1	1		0	0	1	0	LSS and habitat
(Pezent, Sood, and Heaton 2020)	1	1			1	1		1	0	0	0	LSS and habitat
(Braun et al. 2020)	2	1	1		1	1		0	1	0	0	LSS and habitat
(Barker 2015)	3	1	1	1	1	1		0	1	0	0	LSS and habitat
(Dallas et al. 2020)	3	1	1	1	1	1		0	1	0	0	LSS and habitat
(Chavy-Macdonald et al. 2021)	3	1	1	1	1	1		0	1	0	0	LSS and habitat
(Isachenkov et al. 2021)	2	1	1		1	1		0	1	0	0	LSS and habitat
(Landgraf 2021)	1	1			1	1		0	1	0	0	LSS and habitat
(Wilson et al. 2022a, 2022b)	2	1	1		2	1	1	0	0	0	1	LSS and habitat
(Fuller et al. 2022)	3	1	1	1	1	1		0	0	0	1	LSS and habitat
(Bennett and Dempster 2022)	2	1	1		1	1		0	1	0	0	LSS and habitat
(Ellery 2022)	2	1	1		1	1		0	1	0	0	LSS and habitat
(Gumulya, Zea, and Kaksonen 2022)	1		1		1	1		0	0	0	1	LSS and habitat
(Ho-Baillie et al. 2022)	1	1			1	1		0	1	1	0	LSS and habitat
(Santo 2022)	1		1		1	1		1	0	0	0	LSS and habitat
(Kerstens et al. 2019)	2	1		1	1		1	0	0	0	0	Policy
(del Monte and Scatteia 2017)	1	1			1		1	0	0	0	0	Policy
(Kramer 2020)	2	1	1		2	1	1	0	1	0	0	Policy
(Elfes et al. 2006)	1	1			1		1	0	0	0	0	Policy
(Peter et al. 2006)	3	1	1	1	1		1	0	0	0	0	Policy
(Krishen 2011)	2	1		1	2	1	1	0	0	0	1	Policy
(Batkovskiy et al. 2015)	1	1			1		1	0	0	0	0	Policy
(Cahan et al. 2018)	1	1			1		1	0	0	0	0	Policy

(Continues)

TABLE A1 | (Continued)

	# Pillars	Economic	Environmental	Social	# loci	In space	OnEarth	Orbit	Moon	Mars	Other space	Cluster supervised
(Wooten and Tang 2018)	1	1			1		1	0	0	0	0	Policy
(Senthil Kumar et al. 2020)	3	1	1	1	1		1	0	0	0	0	Policy
(Joseph and Wood 2021)	1	1			2	1	1	0	0	0	1	Policy
(Karlsson 2007)	2	1	1		1	1		0	0	0	1	Policy
(Aseno 1997)	2		1	1	1		1	0	0	0	0	Policy
(Martinez 2009)	1			1	1		1	0	0	0	0	Policy
(Jason et al. 2010)	1			1	2	1	1	1	0	0	0	Policy
(Waswa and Juma 2012)	1			1	1		1	0	0	0	0	Policy
(Vedda 2008)	2	1		1	1		1	0	0	0	0	Policy
(Munsami 2014)	2	1		1	1		1	0	0	0	0	Policy
(Asiyanbola et al. 2021)	1			1	1		1	0	0	0	0	Policy
(Froehlich, Ringas, and Wilson 2022)	3	1	1	1	1		1	0	0	0	0	Policy
(Pace 2015)	1			1	1		1	0	0	0	0	Policy
(Balogh, St-Pierre, and Di Pippo 2017)	3	1	1	1	1		1	0	0	0	0	Policy
(Faure, Cho, and Maeda 2018)	1			1	2	1	1	1	0	0	0	Policy
(Reibaldi and Grimard 2015)	2	1		1	1		1	0	0	0	0	Policy
(Adriaensen et al. 2015)	1			1	1		1	0	0	0	0	Policy
(Lehnert, Giannopapa, and Vaudo 2016)	2	1	1		2	1	1	0	0	0	1	Policy
(Sagath et al. 2018)	2	1		1	1		1	0	0	0	0	Policy
(Parragh et al. 2021)	1	1			1		1	0	0	0	0	Policy
(Olla 2008)	3	1	1	1	1		1	0	0	0	0	Policy
(Ehrenfreund and Peter 2009)	2	1		1	1		1	0	0	0	0	Policy
(Ehrenfreund, Peter, and Billings 2010)	2	1		1	1		1	0	0	0	0	Policy
(Ansdell, Ehrenfreund, and McKay 2011)	1			1	2	1	1	0	1	0	0	Policy

(Continues)

TABLE A1 | (Continued)

	# Pillars	Economic	Environmental	Social	# loci	In space	OnEarth	Orbit	Moon	Mars	Other space	Cluster supervised
(Aganaba-Jeanty 2015)	1			1	1		1	0	0	0	0	Policy
(Di Pippo 2019)	3	1	1	1	1		1	0	0	0	0	Policy
(Shabbir, Sarosh, and Nasir 2021)	1			1	1		1	0	0	0	0	Policy
(James, Akinyede, and Halilu 2014)	2	1		1	1		1	0	0	0	0	Policy
(Yan 2021)	1	1			1		1	0	0	0	0	Policy
(Schmidt and Bohacek 2021)	1			1	1	1		0	0	0	1	Policy
(Sridhara Murthi and Madhusudan 2008)	2	1		1	1		1	0	0	0	0	Policy
(Sridhara Murthi, Bhaskaranarayana, and Madhusudana 2010)	1			1	1		1	0	0	0	0	Policy
(Sachdeva 2016)	1			1	1		1	0	0	0	0	Policy
(Otani and Kohtake 2019)	2	1		1	1		1	0	0	0	0	Policy
(Sarkissian 2006)	3	1	1	1	1	1		0	0	0	1	Policy
(Sherwood 2011)	2	1		1	2	1	1	0	1	1	0	Policy
(Peoples 2010)	2	1		1	1		1	0	0	0	0	Policy
(Acevedo et al. 2011)	1			1	1		1	0	0	0	0	Policy
(López 2016)	1			1	2	1	1	0	0	0	1	Policy
(Brunner 1994)	1	1			1		1	0	0	0	0	Policy
(Lehnert, Giannopapa, and Vaudo 2016)	2	1		1	1		1	0	0	0	0	Policy
(Smith and Thompson 2012)	1	1			2	1	1	0	0	0	1	Policy
(Laurini and Gerstenmaier 2014)	2	1		1	1		1	0	0	0	0	Policy
(Logsdon 2015)	2	1		1	2	1	1	0	1	1	0	Policy
(Mazzucato and Robinson 2018)	1	1			1	1		1	0	0	0	Policy
(Baüer, Gérard, and Minster 2006)	1		1		2	1	1	1	0	0	0	Policy
(Broniatowski and Weigel 2008)	2	1		1	1		1	0	0	0	0	Policy

(Continues)

TABLE A1 | (Continued)

	# Pillars	Economic	Environmental	Social	# loci	In space	OnEarth	Orbit	Moon	Mars	Other space	Cluster supervised
(Mankins 2009)	3	1	1	1	1	1		0	1	0	0	Policy
(Maury et al. 2020)	1		1		1	1		0	0	0	1	Policy
(Gil et al. 2014)	3	1	1	1	2	1	1	0	0	0	1	Policy
(Castiglioni et al. 2015)	2	1	1		1		1	0	0	0	0	Policy
(Denis and Pasco 2015)	1	1			1	1		0	0	0	1	Policy
(Colombo et al. 2015)	1		1		1	1		1	0	0	0	Policy
(Sagath et al. 2019)	2	1		1	1		1	0	0	0	0	Policy
(Hoerber, Wenger, and Demion 2019)	3	1	1	1	2	1	1	1	0	0	0	Policy
(Liao 2020)	1			1	1		1	0	0	0	0	Policy
(Bohlmann and Koller 2020)	3	1	1	1	1		1	0	0	0	0	Policy
(Broniatowski and Weigel 2008)	2	1		1	1		1	0	0	0	0	Policy
(Wilson et al. 2022a, 2022b)	2	1	1		2	1	1	0	0	0	1	Policy
(Harris et al. 2022)	1	1			2	1	1	0	0	0	1	Policy
(Anglada-Escudé 2022)	1	1			1	1		0	0	0	1	Policy
(Verspieren 2020)	1	1			1		1	0	0	0	0	Remote sensing and data handling
(Hank et al. 2019)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Chabrillat et al. 2019)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Coleman et al. 2020)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Lamba, Rani, and Kumar 2021)	1		1		1		1	0	0	0	0	Remote sensing and data handling

(Continues)

TABLE A1 | (Continued)

	# Pillars	Economic	Environmental	Social	# loci	In space	OnEarth	Orbit	Moon	Mars	Other space	Cluster supervised
(Tziolas et al. 2021)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Dube et al. 2014)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Huo et al. 2021)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Zhuang, Liu, and Liu 1999)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Dwivedi et al. 2006)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Stuffler et al. 2007)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Hall et al. 2011)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Dewitte et al. 2012)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Ali et al. 2016)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Nautiyal et al. 2017)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Chen et al. 2020)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Aleksieva-Petrova et al. 2022)	3	1	1	1	1		1	0	0	0	0	Remote sensing and data handling

(Continues)

TABLE A1 | (Continued)

	# Pillars	Economic	Environmental	Social	# loci	In space	OnEarth	Orbit	Moon	Mars	Other space	Cluster supervised
(Moomen et al. 2022)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Maktav and Erbek 2005)	1			1	1		1	0	0	0	0	Remote sensing and data handling
(Musakwa and Van Niekerk 2015)	1		1		1		1	0	0	0	0	Remote sensing and data handling
(Argentiero and Falcone 2020)	2	1	1		1		1	0	0	0	0	Remote sensing and data handling
(Goel et al. 2021)	2		1	1	1		1	0	0	0	0	Remote sensing and data handling