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RESEARCH ARTICLE

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The quest for sustainability in lower orbit: Conceptual models for space tourism

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1 | INTRODUCTION AND PLAN OF THE ARTICLE

From the day Dennis Tito became the first private citizen to travel to space for no other reason but the sake of the experience itself, space tourism stops being a chimaera and became a reality, albeit an elitist one. And if only seven passengers flew to the International Space Station (ISS) on board of Russian Soyuz rockets during the new millennium's first decade, other modalities of space tourism—such as sub-orbital travel—are increasingly getting commercialised due to its growing technological and financial accessibility (Chang, 2020).

After years of hiatus, the sub-orbital commercial flights resumed in 2019, propelled by the combined contribution of the public (e.g., NASA) and private companies (such as Virgin Galactic and Blue Origin) in the main spacefaring countries. New entrants in the launching segment, even countries with no previous spacefaring history, such as New Zealand, have enhanced the potential for further development (Zhang & Wang, 2020). 2021 saw the record number of 14 civilians who experienced space travel (Space Foundation, 2022), almost doubling the number of all previous years combined.

1.1 | More ambitious objectives loom ahead

The vision of SpaceX (2020) to commercialise space flights to Mars by 2050 is regarded a distant but increasingly possible with the recent technological development and economic interest in space. Other endeavours, such as the building of orbiting space hotels (the Voyager Station due to open as early as 2027; CNN, 2021) are other, visionary on-going efforts to expand the remit of extreme tourism. And if until recently the market dimensions were limited, they are rapidly peaking up pace. A report from Northern Sky Research (2021) estimates at US $ 385 million revenues from orbital tourism, projected to grow as high as US$ 605 million by 2029. The suborbital segment looks even more dynamic, with an estimated compound annual growth rate (CAGR) of 24.5% in the decade 2021–2031.

All this raises important questions about its sustainability and even the case for space tourism in the first place. Some consider it environmentally costly when not ethically unsavoury (Cohen, 2017; Guerster et al., 2019), and requiring overcoming formidable regulatory challenges (Padhy & Padhy, 2021). Especially for what concerns the costing side of space tourism, there is no breakthrough in sight, even though reusable rockets have done considerable progress in lowering the budget requirements for space missions (CSIS, 2020).

Until the entire space adventure is dominated by the so-called 'tyranny of the rocket equation' (Petitt, as cited by Young, 2015, p.45), which translates in 90% of the weight of a rocket being just the fuel to lift it off the planet's surface, the economic burden will remain, and so will the associated environmental costs. Hence, the need to critically evaluate whether space tourism can indeed be made sustainable and ethical and, if so, what are the preconditions for making this happen.

Interestingly, while any sustainability discourse for space is derived from the sustainable tourism frameworks, the applicability of sustainability indicators to space tourism remains unclear and never clearly defined before, a clear gap in the knowledge we have identified in this study. Although most authors are optimistic about the economic sustainability of space tourism, the predictions for social and environmental sustainability are not as promising. The moral dilemma of the equal distribution of space tourism generated wealth and its environmental impact are sensitive areas that require robust conceptualisation and empirical analysis. Moreover, the growing interest in space tourism research makes the absence of a theoretically grounded and robust analytical framework to enhance sustainability even more remarkable. This is the second, evident knowledge gap this article intends to address: devise a conceptual model that, building on the sustainable tourism framework and Dubin's (1970) theory building two-stage approach, is adapted to space tourism as an example of 'frontier' tourism with unique peculiar characters.

Section 2 offers a working definition of space tourism, discusses how it fits in the overall debates about ethical tourism and sustainability, and is instrumental for what comes next: a systematic review of the literature of sustainable tourism from Dennis Tito's travel in 2001 up to 2021, aiming at identifying relevant indicators for sustainable tourism and evaluate their applicability to space tourism.

Section 3 briefly covers the methodological aspects of both systematic reviews and conceptual models and identifies the above-mentioned indicators.

Building on the critical analysis of 101 indicators, Section 4 designs a brand-new conceptual model for sustainable space tourism. As it stands, there is a fourth field (technology) altogether missing in the traditional model by White et al. (2006) and derived studies. Adopting Industry 4.0 (I4.0 afterwards; Sun et al., 2012; Baldwin, 2019; Schwab, 2015; Kagermann et al., 2011; Lasi et al., 2014) framework in relation to the space sector (Cristians & Methven, 2017; Forcina & Falcone, 2021; Vaidya et al., 2018), the analysis demonstrates why technology represents the cornerstone of the conceptual model presented in this article.

Section 5 concludes that sustainability can be fully achieved in space tourism only when technology takes the front seat, with Industry 4.0 and its nine pillars unleashing their revolutionary capabilities. Due to the nature and scope of this study, we have focused mainly on sub-orbital tourism, although its conclusions can be opportunely expanded to include outer space activities. The final section also explores the potential of the conceptual model herein developed for empirical research, paving the way for next steps, future research, and proof of concept.

2 | SPACE TOURISM. THE STATE OF THE DEBATE

2.1 | Legal definition and economic dimension

There is still ambiguity about what qualifies as space tourism (Johnson & Martin, 2016). The European Space Agency (ESA 2008, p. 19) defines it as an "*activity that will encompass the execution of sub-orbital flights by privately-funded and/or privately-operated vehicles and the associated technology development driven by the space tourism market*". Chang (2017) and Cohen and Spector (2019a) define commercial space travel as leisure and recreation, allowing tourists to experience zero-gravity and celestial observation.

Spector (2020b) categorises space tourism into three broad subcategories, i.e. sub-orbital, orbital, and beyond-orbital (ie, outer space, such as in a lunar base or a Martian outpost) and so do Friel (2020), Cohen and Spector (2019a), Chang (2015) and Webber (2013). On the other hand, Ma et al. (2020); Soleimani et al. (2019), and earlier Weaver (2011) include spacecraft launching observation as such. Damjanov and Crouch (2018), Frischauf et al. (2018) Weeks and Faiyetole (2014) add digital components (EVR, enhanced virtual reality) to the definition.

2.1.1 | Things become more complex when it comes to the requirements

From a legal point of view, that the definition of an astronaut (there is still no legal counterpart to ESA's industry definition of a space tourist; Failat, 2012) consist of two main aspects: the training required for the task and distance from Earth's surface they reach.

Requirements vary a great deal, and if 6 months are generally considered necessary to visit the ISS (UNOOSA, 2022b), Virgin Galactic asks for only 1 week of preparatory training for suborbital flights (Virgin Galactic, 2022).

Still, the non-professional personnel in space are considered 'visiting crewmembers' by the Inter-Governmental Agreement ('IGA') in an agreement reached between the space agency's participating to the ISS project (NASA, 2002). Although without binding legal value beyond the ISS, it constitutes nonetheless a 'trendsetting, if not an industry standard' (Von der Dunk, 2013).

This matters, because the definition of the phenomenon affects its perception as feasible, ethically sustainable, and economically viable. Tourism is a significant contributor to many national economies, directly contributing on average 4.4% of national GDP and 21.5% of service exports in OECD countries (OECD, 2020). Even as a niche subsector (Friel, 2020), space tourism is rapidly becoming attractive for its high-skill job creation and revenue spillovers (Zhang & Wang, 2020). The economic multiplier of such developments will be higher than other industries (Cole, 2015), whereas the knowledge and skill base will facilitate space infrastructure construction (Komerath et al., 2007; Zhang & Wang, 2020). Friel (2020) and Spector (2020a) predict that space tourism will benefit terrestrial tourism destinations in the launching countries, facilitating all types of space flights and (Webber, 2013) becoming a pivotal sector of the economy due to economy of scale.

Finally, space as a study subject enhances the attractiveness of STEM disciplines, as the ISS-related *Principia Initiative* sponsored by ESA and the UKSA during the tenure of UK astronaut Tim Peake (UK Principia, 2017) demonstrated.

Space tourism can help develop alternative financing methods. Venture capital, angel capital, and public financing have already created a new sub-sector away from the traditional state-sponsored space research (Beery, 2012) Such private partnership is present even in China, where the government role is otherwise predominant (IDA, 2019). Launch infrastructure through private financing promotes economic growth (Ingle, 2011) with potential for empowerment for local communities, while supporting initiatives such as space mining.

Space tourism will still face challenges, from modelling to consumer behaviour and operational challenges.

Conceptual models on the potential size of the space tourism market (Chang, 2020; Cohen & Spector, 2019a; Cole, 2015; Komerath et al., 2007; Le Goff & Moreau, 2013) are of difficult assessment in terms of reliability (Zhang & Wang, 2020).

Predictive modelling (Komerath et al., 2007) shows a prospective profit stream for hoteliers serving the space tourism market. However, Reddy et al. (2012) identified safety, training requirements, duration of travel, design of the spacecraft, accommodation facilities as the most critical components; insurance costs is another (Crouch et al., 2009). Laing and Crouch (2004, 2005, 2011) concur with such findings. More recent studies (Olya & Han, 2020; Platt et al., 2020; Wang et al., 2020) shows who risk perception also plays a role, overriding enthusiasm and adventurous motivations.

The industry will require a highly trained workforce to serve tourists in an entirely alien environment of space (Goehlich et al., 2013; Strickland, 2012). Lyall (2010) and Pizam (2008) suggest that HRM and hospitality management as important areas of academic research in the next decade.

2.1.2 | The need of a regulatory framework cannot be overlooked

The so-called international space law (the five Treaties of the 1970 s, starting from the 1967 OST), not meant to apply to companies but only to nation-states, is unsuitable for commercial enterprises, tourism included, as the analysis of interplays between national and supranational institutions (Hobe, 2010), their deliberations and collaborations (Aganaba-Jeanty, 2015; Forganni, 2017) and spheres of authority (Masson-Zwaan & Freeland, 2010) demonstrates. The existing regulations only cover the commercial aviation industry, or extreme tourism (the Antarctic, maritime and adventure tourism; Abaydeldinov & Kala, 2016; Spennemann, 2007). A targeted legal framework, now in its infancy, will soon become a requirement.

Aviation planning and the legal system of commercial aviation establish the precedence for the space tourism industry's health & safety, and risk management practices Rosa (2013). Kaul (2019) recommends considering outer space and traditional aviation management together in future aviation management studies. Standardisation (Orme, 2017; Yehia & Schrogl, 2010) and specialised insurance (Ferreira-Snyman, 2017) must ensure the economic sustainability of space tourism operators, together with the legal status and licence for tour operators and tourists (Masson-Zwaan & Freeland, 2010). Governance of the space tourism supply chain (Dunk, 2013), investment guidelines (Blount, 2010), accident and emergency response policies (Beamer-Downie, 2013) for the sector will also need applicable procedures.

2.2 | Sustainability and sustainable tourism

Back in 2012, Buckley was already counting about '5,000 relevant publications' attempting at evaluating the global tourism sector in terms that reflected 'global research in sustainable development' (Buckley, 2012, p. 1). Still, 10 years down the line, the industry is not close(r) yet to achieve sustainability.

Meta-analysis and systematic literature review (SLR) have outlined the evolution of sustainable tourism (Pan et al., 2018), emergent themes and their policy implications (Zolfani et al., 2015), measurement indicators (Agyeiwaah et al., 2017; Nesticò & Maselli, 2020; Rasoolimanesh et al., 2020), challenges and barriers to sustainability and competitiveness (Pan et al., 2018; Streimikiene et al., 2021). Kapera (2018), Muangasame and McKercher (2014), Ocampo et al. (2018) and Tseng et al. (2018) have applied such concepts to the world tourism industry, from Poland to the Philippines and Vietnam.

A common theme is the need for a set of sustainable performance indicators, which have grown in number and variety over the years, creating a 'choice overload' (Agyeiwaah et al., 2017:26) problem for the industry and making it difficult to select, measure, and assess their effectiveness (Schwartz, 2014). Larson & Poudyal, 2012 and Marzo-Navarro et al., 2015, summarise the lack of funding, commitment, institutional support, implementation, action plans, and vague objectives as the key reasons for such failure. Muangasame and McKercher (2014) and Tseng et al. (2018) provide empirical evidence that long lists obscure primary sustainability concerns and prevent greater awareness and implementation.

There is the complex and often controversial debate of what constitutes a valuable—read, applicable—indicator for sustainability, starting from definitions lifted from United Nation's Agenda 21 (UN, 1993) to Bellagio Principles for standard measurement practice (Bell & Morse, 1999). And when it comes to space tourism, sustainability becomes a particularly controversial point.

2.3 | Space tourism and sustainability. An oxymoron?

The high-cost, high-risk characteristics of the space sector (Gurtuna, 2013; Paladini, 2019; Vedda, 2009) are well known, including the astronomical (pun intended) carbon footprint of the space missions and their related environmental risks. While those are justified in the name of a superior interest of the space exploration and humankind progress (although stunts like Musk's orbiting Tesla have been criticised due to contamination risks; Davis, 2018), when it comes down to initiatives such as tourism, things become less defensible.

A few studies question the ethics of private space initiatives, both in terms of equality of access and social justice (Aganaba-Jeanty, 2015). Williamson (2003) points out the ethical dilemma for commercial space exploration. In the same tradition, Peeters (2018) discusses the moral ground of using scarce planetary resources for non-scientific space travel. Other contributions explore the requirement for the colonisation of outer space (Brown, 2004), health and safety issues of tourists in space (Lyall, 2010; Marsh, 2006), and the necessity of an equal distribution of gains from space tourism (Toivonen, 2020). Weeks and Faiyetole (2014) proposed a wider access to space education to raise public awareness and participation on sensitive social welfare issues.

The impact of space tourism on culture and heritage is part of social sustainability. Categorising space as heritage tourism, Weibel (2020) brings faith and religion into the context. For her and other like-minded space travellers, exploring the universe is a form of human emancipation. Collins and Autino (2010) predict that space tourism would preserve and foster peace on Earth. Similarly, Spector and Higham (2019) expect utopian transhumanism and so do Cohen and Spector (2019b), discussing prospective human activities in outer space.

Nonetheless, the environmental sustainability of space tourism remains a highly contested area.

Tourism scholars such as Cohen (2017), Peeters (2018), Wallacher et al. (2019) asked if space tourism can be sustainable at all. Sceptics such as Collins and Autino (2010), Peeters (2018) and Spennemann (2006) considered the negative impact of the tourists' presence in the space due to carbon emissions, which have the potential to create further environmental damage to the Earth. Debris in space is another area of growing concern (NASA Orbital Debris Program Office, 2021; Gopalaswamy & Kampani, 2014; Liou, 2011).

According to Peeters (2018), space tourism would make the Earth's resources scarcer and more expensive, as the resulting extraction of resources devoted to space tourism will contribute to damage the Earth's fragile ecosystems. A recent study by Scott (2020) went further, assessing the prospective impact of spaceport development on local environments and cultures. Advocates of space tourism such as Iliopoulos and Esteban (2020) and Spector (2020b), believe that the solution lies in the sector's growth, which can address resource scarcity on Earth with space mining, NEOs (Near-Earth Asteroids) and the lunar soil being the natural targets.

3 | BUILDING A NEW FRAMEWORK FOR SUSTAINABLE TOURISM

In our effort to build a new framework for sustainable space tourism, specialised consumption tourism provides the overall theoretical underpinning (Carvalho et al., 2019; Richards, 2011), highlighting components such as self-development and identity construction. Space tourism is such a stimulating and exciting experience that exposes participants to skill sets otherwise impossible to acquire (Platt et al., 2020), escaping the banality of mass tourism (Olya & Han, 2020). More specifically, more than exploring the motivators for people to venture into space tourism (Reddy et al., 2012; Wang et al., 2020), we intend to define in which way an experience that most people would label as not environment-friendly can be reframed and reconducted to a sustainable dimension.

To this extent, we have systematically reviewed the current literature on space tourism to identify the factors affecting tourism sustainability (Nesticò & Maselli, 2020; Sardianou et al., 2016; Tseng et al., 2018), exploring three dimensions of sustainability, namely: (i) economic, (ii) environmental, and (iii) socio-cultural.

These three dimensions were chosen for a reason: they were derived from the triple bottom line theory of Elkington (1994) and previously used as an interpretative framework to build a sustainable tourism model (White et al., 2006), from which our own conceptual model for sustainable space tourism starts from.

3.1 | The methodology

Conceptual models are a popular method in social sciences, counting more than 60 definitions (Creswell, 1994; Thalheim, 2018; Delcambre et al., 2018; Mylopoulos, 2020). They guide "experimentation by expressing the modelling objectives, and model inputs and outputs" (Robinson et al., 2015) and have been previously used in tourism and hospitality (Bec et al., 2019; Lagiewski et al., 2019; Watson, 2008) although they have not been applied to model sustainable space tourism so far.

As much as conceptual models, systematic reviews are widely used. The framework adopted in this article is the PRISMA method (Gøtzsche et al., 2009; Liberati et al., 2009; Moher et al., 2009), i.e., identifying all the sources, (Rodríguez-López et al, 2020; Zupic & Čater, 2015), screening them for quality and eligibility, and making decisions about inclusions.

A number of platforms have been used for this review on space tourism, that is, EBSCO, SCOPUS, Web of Science, and the Chartered Association of Business Schools (CABS) journal list. The keyword search used in the query was TITLE-ABS-KEY string 'space tourism' by publication type—journals, language (English), subject area (business & management, economics, social science, environmental science, engineering, arts & humanities), and time (year 2001–2021), returning 126 documents.

3.2 | Indicators of sustainable tourism: A comparative view

Bossel (1999) provided some criteria to develop indicators for sustainability in general, and the general validity of the framework is essential in the selection process itself (White et al., 2006). We also agree with Stoeckl et al. (2004) when they suggest that sustainability per se is not measurable, and that the role of indicators is limited to offering indications of direction and change. They still can, however, or should provide information about trends and help in setting goals (Castellani et Sala, 2010; Crabtree & Bayfield, 1998).

Finally, and convincingly in our view, 'although it seems paradoxical to develop indicators for sustainable tourism when no satisfactory definition of the concept exists, the process of developing the indicators does help in determining the important tenets of the concept," (Miller, 2001, p. 361).

Agyeiwaah et al. (2017) and Ocampo et al. (2018), both identified a total of 39 sustainability indicators. Nesticò and Maselli (2020) included 23. Our first selection of 101 single sustainability indicators (Appendix) includes 23 economic indicators, 40 environmental, and 38 socio-cultural indicators, selected them according to their applicability, measurement data availability, and appraisal by empirical literature. Table 1 shows them in a synthetic form.

Table 2 presents instead our second selection from the first series, according to what emerged as the most relevant after cross-checking them in the sources.

Our review shows that employment, tourism intensity, operational cost, profitability are the most common single economic indicators. Air, water, land quality, pollution and recycling level, green energy consumption, greenhouse gas (GHG) emission, preservation of biodiversity, statutory protection of forest and endangered species, build-up areas and their impact on the ecosystem are statistically the ones used more often as parameters for environmental sustainability.

In terms of socio-cultural sustainability measurement (the social and cultural components have been merged in this article following White et al., 2006's conceptual model), parameters such as tourist-local ratio, visitors' and local satisfactions, locals' involvement in the tourism development and management process, tourism education to promote local heritage and preservation of such cultural aspects, safety, and access are prevalent in existing studies. Some of them (e.g., tourism education to promote local heritage and preservation of such cultural aspects) are, however, of limited practical utility due to

TABLE 1 Synthetic table of indicators of sustainable tourism.

Indicators of sustainable tourism	Nesticò and Maselli (2020)	Agyeiwaah et al. (2017)	Ocampo et al. (2018)	Total
Economic	3	12	8	23
Environmental	17	9	14	40
Socio-cultural	3	18	17	38
Total	23	39	39	**101**

Source: Authors' elaboration.

TABLE 2 Selected indicators for economic, environmental, and socio-cultural sustainability

Economic	Environmental	Socio-cultural
Number and quality of employment creation	Tourism density	Tourist–local ratio
Revenues and profitability	Transport usage	Frequency, the capacity of services, or level of use of local medical and transportation systems and living quality
Numbers of tourist arrival	Coastal erosion	Promotion and education of conservation and sustainable concepts that leads to awareness and implications
Accommodation quality, capacity and occupancy	Endangered species and their conservation	Protection and understanding of local culture and heritage sites
Local ownership in business	Area of built-up land	Safety and security
Length of stay and repeat visit	Green buildings	Resident's attitude and complaints
Operational cost	Energy consumption	Crime rate and harassment
Tourist satisfaction with related activities	Greenhouse gas emissions	Retention of local customs and language
	Share of renewable energies	Actions and events taken to promote indigenous culture
	Annual water consumption	Satisfaction with local integrity
	Water reused	Training and development of local tourism personnel and provision of educational opportunities
	Quality of air, water, and land	The attitude of the locals toward satisfaction, service, quality, and training mechanisms
	Air, water and noise pollution due to tourist activity	Local interaction and development toward tourists
	Waste management and recycling capacity and quality	Local residents and community involvement and participation in the management of tourism
	Animal biodiversity, Plant biodiversity, Wetland biodiversity experience	
8	16	14

Source: Authors' elaboration.

the time scale required to observe them for a meaningful understanding (Sardianou et al., 2016).

The literature (Kapera, 2018) indicates that there are conflicting priorities between tour operators and sustainability advocates as they seem to have focused more on environmental and socio-cultural sustainability compared to economic. Data availability and benchmarking is critical (Blancas et al., 2011; Booth et al., 2020) for our analytical framework for the space tourism industry, while other indicators separate central and peripheral issues for prioritisation (Keeble et al., 2003).

The suitability of such indicators for sustainable space tourism is, of course, a critical and debatable point.

First of all, single indicators by themselves are of limited usefulness due to their high specificity of the space medium, which differs a great deal from Earth-based tourism. They are in general better combined in wider categories, as macro-indicators, both for in terms of theoretical framework and explanatory function.

It is, however, possible to establish a connection between the single indicators in Table 2 and the macro-indicators developed for the conceptual framework of space tourism.

The linkage is shown in Table 3 in detail and discussed in detail in the next Section 4.

4 | A CONCEPTUAL MODEL FOR SUSTAINABLE SPACE TOURISM

In order to build the actual conceptual model for sustainable space tourism, we have combined Dubin's theory building (1970) as applied

TABLE 3 Macro-indicators for sustainable space tourism

Economic	Linkages with Table 2	Theoretical basis for CM1/2 (sources)
Circular Economy [6 R]	Operational cost; Water reused; Green buildings; Local residents and community involvement and participation in the management of tourism	Paladini et al., 2021; Tamponnet & Savage, 1994; Kelman et al., 2015
Private–public partnership (PPP)	Number and quality of Employment creation; Local ownership in business	Gurtuna, 2013; Paladini, 2019
Distribution	Revenues and profitability; number and quality of Employment creation	ESA, 2020a; Beery, 2012
Venture/private capitals	Revenues and profitability; Local ownership in business	Weinzierl & Sarang, 2021; Vedda, 2009
Environmental		
Resource consumption	(equivalent to:) coastal erosion and water consumption; biodiversity	ESA, 2020b
Aerial/orbital traffic protection	Transport usage	EU GNSS, 2022
Debris Control	[a]	NASA Orbital Debris Program Office, 2021; Gopalaswamy & Kampani, 2014; Liou, 2011
Energy requirement	Share of renewable energies, energy consumption; transport usage	Sharmina et al. 2021; Bows-Larkin, 2015
Carbon Footprint	Greenhouse gas emissions	Higham et al., 2022
Mitigation strategies	Quality of air, water, land; waste management; share of renewable energies	Budeanu et al., 2016; Polido et al., 2014
Socio-cultural		
Education	Promotion and education of conservation and sustainable concepts that leads to awareness and implications; training and development of local tourism personnel and provision of educational opportunities	UK Principia, 2017; ESA/EC 2016
Scientific research	[b]	
Gender equality	[b]	WIA, 2022
Local communities	Community involvement; local interaction; tourist attitude	Ingle, 2011

Source: Authors' elaboration.

[a]Medium specific: debris relates to the Earth's orbits situation explained in the text and it has no obvious counterpart on planet except general pollution of the seas.

[b]The linkage here is more with general sustainability targets, such as SDGs.

by Meredith (1993) to business studies and constructed a model which derives from 'conceptually and logically connected ideas,' (Watson, 2008).

And if traditional theory building distinguishes between the theoretical modelling and the empirical research as two different, although connected, stages, here we are clearly focusing on the first one, leaving the proof of concept to future studies (more about this in Section 5). Here we have developed the conceptual model at a theoretical construct, specifying its framework and linking it with the relevant underlying theories, also explaining in which way these 'building blocks' have been assembled in practice.

The starting point is the already referenced and widely cited conceptual model of sustainable tourism first presented by White et al., 2006, simplified and adapted in the diagram presented in Figure 1.

4.1 | Technology as the fourth component of the model

The first conceptual model developed here – labelled CM1—builds on White et al. (2006) and adapts it to the specific characteristics of space tourism as detailed in Sections 2 and 3.

If there is anything the extensive literature on sustainable tourism on one hand and space tourism on the other showed is that there are three major components --economic, socio-cultural, and environmental--although there is no agreement in the literature about which one is the most relevant.

While the three components are essential for sustainable tourism as well, White et al. (2006) as it stands is not sufficient to model space tourism, and it is easy to understand why: a fourth component, technology, is missing, and, in its absence, it becomes impossible to enable a sustainable dimension for tourism, no matter the way sustainability has been defined.

Figure 2 shows how to integrate technology in the conceptual model of sustainable space tourism.

Some scholars (Davidian, 2020) have defined space tourism industry as a 'technological niche protomarket' (Geels, 2006), where a dominant design of innovation pattern has yet to emerge.

Regardless the specific shape this innovation path will lead to, however, it is not possible to discuss the existence of space tourism without its technological angle, which is a fundamental enabler of anything related to space.

Without technology, we could not have space tourism –by design.

Before 1957 (the year of the launch of Sputnik 1), there was no way for humankind to reach the Karman line (i.e., one of the acknowledged frontiers of outer space). This is the reason why technology has to be included in the diagram as the fourth essential component to make space tourism not only sustainable but even possible.

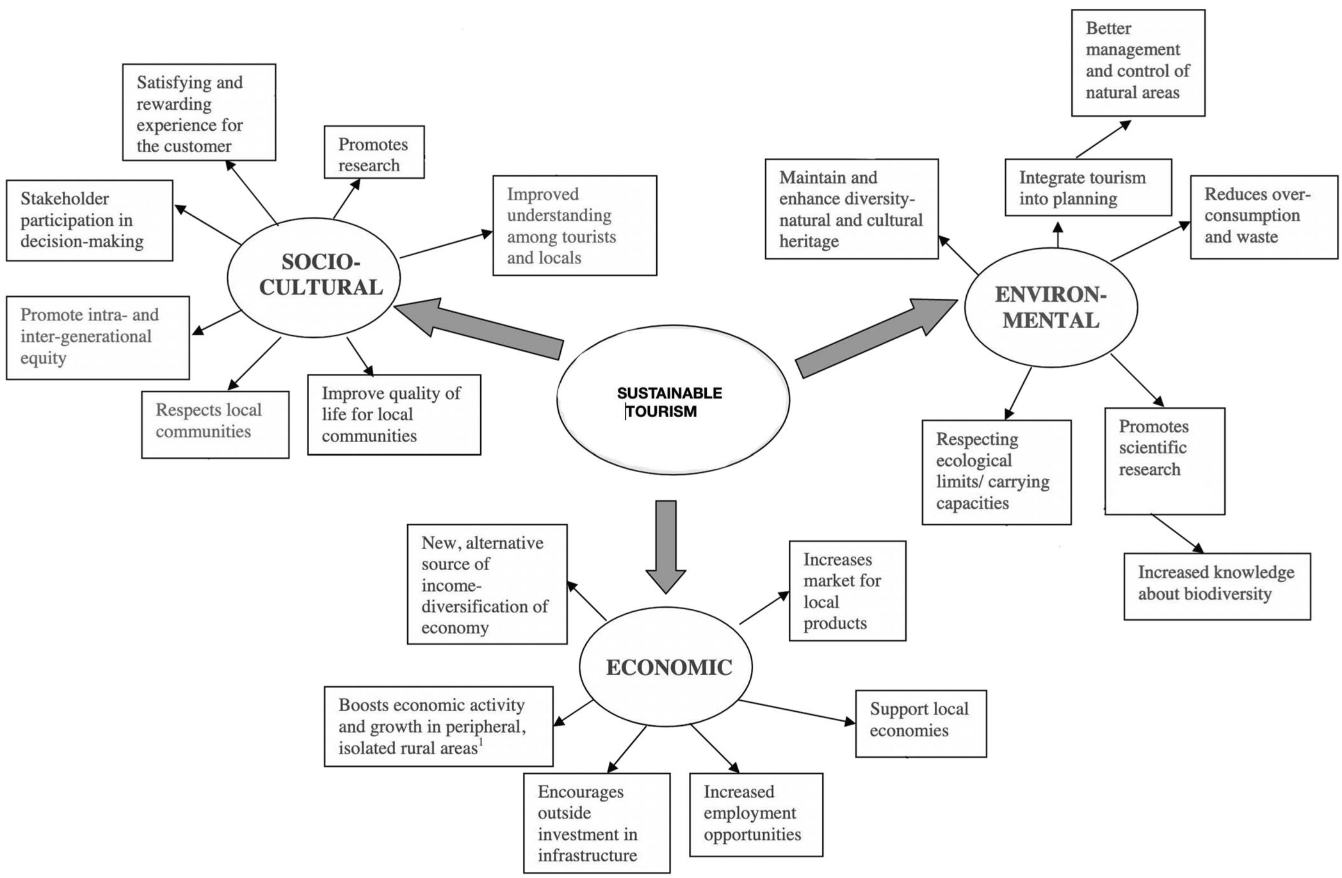

FIGURE 1 Sustainable tourism diagram. *Source:* Author's adaptation on original by White et al. (2006).

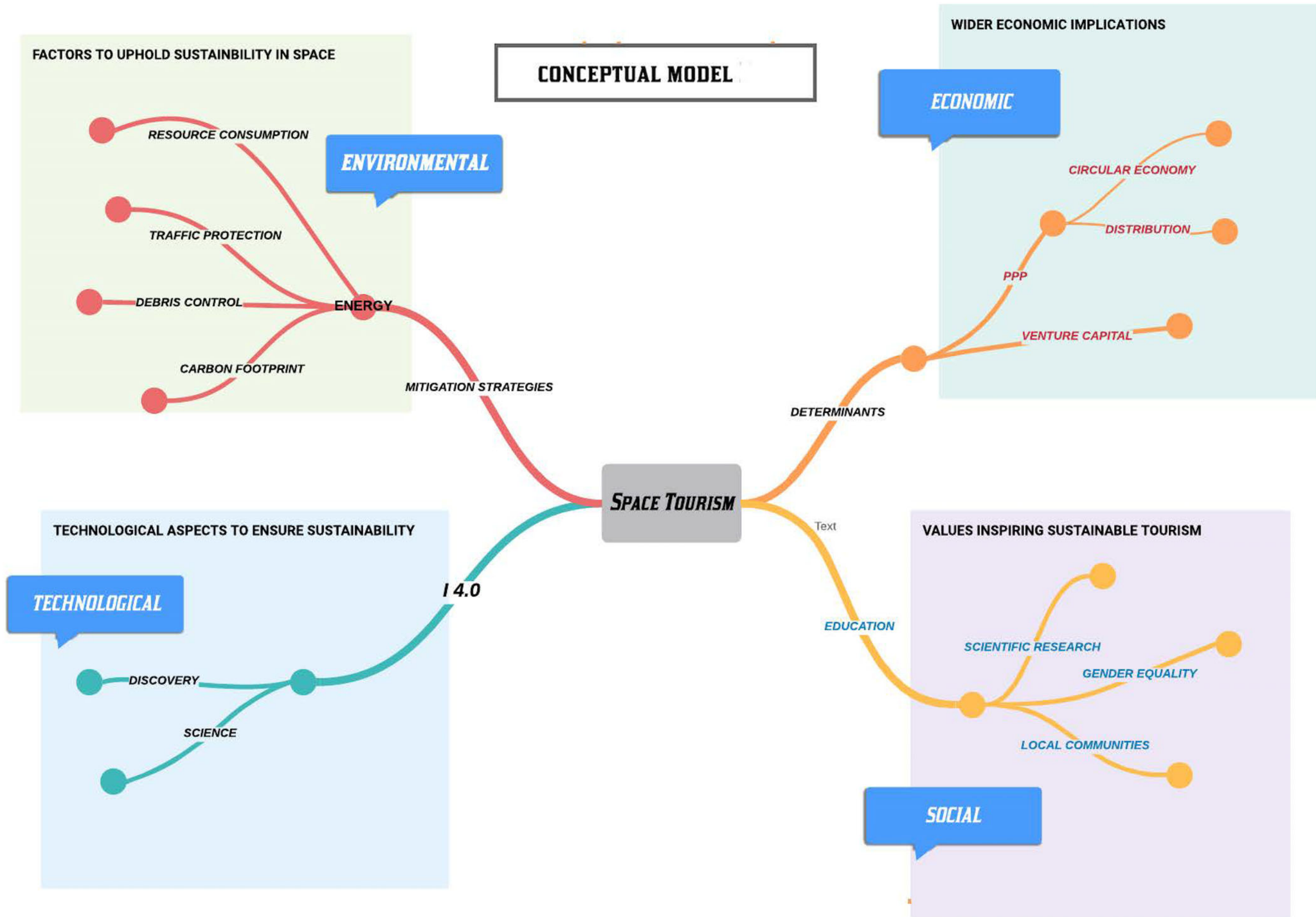

FIGURE 2 Conceptual model #1 for sustainable space tourism. *Source*: Authors' elaboration [Colour figure can be viewed at wileyonlinelibrary.com]

But we can actually go further than that, because, to discuss sustainability, we need to understand the way sustainability can be enabled by a certain kind of technology.

Space technology has been long recognised as one of the keys to achieve the 17 UN Sustainable Development Goals on Earth by 2030 (UNOOSA, 2022a), in countless ways, from EO (Earth Observation) systems (UN, 2022) to satellites and engineering applications (EU GNSS, 2022).

Even one of the most intractable aspects, the aviation's environmental impact, has recently seen efforts to 'decarbonise' the sector' (Bows-Larkin, 2015; Higham et al., 2022; Sharmina et al., 2021) to enhance the drive toward sustainability.

More importantly, Space 4.0, as it is now defined in the public debate (ESA/EC, 2016; ESA, 2016), is characterised by a native connection between Industry 4.0 and circular economy, whose principles, if not the name, have been long used in the space sector (the already mentioned concept of 'spaceship Earth'; Fuller, 1963; Paladini et al., 2021) in a brand-new dimension of the sector itself, which enhances the very concept of sustainability at its core.

Before looking at this specific aspect and the way technology changes radically the space tourism sustainability model, however, it is worth looking at the other, more traditional categories and their indicators.

4.2 | Sustainability dimensions: From single indicators to macro-indicators

Once the fourth pillar, technology, has been inserted in the model, it is possible to reconfigure and link a substantial part of the single indicators listed for sustainable tourism in Table 2 to the new model for space tourism and relative indicators.

Table 3 lists our own set of indicators as included in CM1, together with providing sources for specific space tourism indicators (absent from Table 2) as emerging from the literature considered in Section 2 and 3 and the theoretical justifications for their selection.

A cursory look to Table 3 will show that not all the single indicators previously identified have been included, as explained in the table notes.

This is due to the specificity of the medium 'space'. Some otherwise crucial indicators, such as Debris (Control), play no role in the environmental component of Earth-based tourism, while they are an area of growing importance in space activities, tourism included. Others, such as Education as included in the Socio-Cultural components of Table 3, refer specifically to strong ties between space and STEM subjects in all scholastic curriculum at all levels, as detailed in Section 2, as so does Scientific Research.

Both Tables 2 and 3 indicators, however, function in a similar fashion in the construct.

If anything, our indicators are macro-indicators, which was expected to be, given the still initial stage of development of space tourism (e.g. an indicator for 'number of tourists' would not make a lot of sense when the total number is less than 30) and their applicability is often more theoretical and predictive at this stage than explanatory. It will, however, be in the future years, once space travel becomes more frequent.

In other cases, the connection between Tables 2 and 3 indicators is immediately evident.

Island states tourism indicators (Nesticò & Maselli, 2020) of Table 2 and the spaceship earth philosophy recently applied to understand circular economy-based sustainability (Paladini et al., 2021) are pertinent to this analytical framework, and it is not by coincidence that circular economy features prominently as one of the macro-indicators of Table 3.

Close-loop systems (Kelman et al., 2015) are prevalent both island states and spaceships. A similar kind of close-loop system (or, following Tamponnet & Savage, 1994, CES—closed ecological systems) will also operate in the space tourism industry, and some examples of the way this could happen already exist (as the water purifying system ESA-MELiSSA in use on the ISS. Paladini et al., 2021; Poughon et al., 2009).

This is not without risks: close-loop systems are vulnerable (hence the need to recycle and re-input) and constitute a fragile and sensitive (alien in the case of space) ecosystem. The orbital location of space tourism will make it less resilient to environmental disasters and catastrophic events (Budeanu et al., 2016; Polido et al., 2014).

Technology, however, is not just the enabler for the space sector as a whole and one of the essential components of sustainable space tourism. It has the potential to radically modify the three other components of sustainable tourism in a way that probably is not even recognisable if we compare them to past approaches. Taking all this into account, the conceptual model should therefore be modified and rewritten, debating the pivotal role of technology and its potential for change.

4.3 | Putting technology in the front seat. A I4.0-enabled conceptual model

The next chart (Figure 3) shows how the model has been reconfigured (CM2) to account for the centrality of technology as the cornerstone of the entire construct.

4.4 | To space tourism, space 4.0 and industry 4.0 look crucial

The epochal transformations it entails, both at a conceptual level (Sun et al., 2012; Baldwin, 2019; Schwab, 2015; Kagermann et al., 2011; Lasi et al., 2014) and through the application of its 'nine pillars' (Cristians & Methven, 2017; Vaidya et al., 2018; Forcina & Falcone, 2021; Fettermann et al., 2018) are going to change the sector beyond recognition. This is evident when looking at the way the nine pillars themselves (e.g., artificial intelligence, big data, IoT, and smart manufacturing) taken individually and as a whole are already transforming the space sector, and, inevitably, space tourism itself.

The literature on Industry 4.0 conceptualisation shows that, while its nine innovation-enabler fundamental pillars (i.e., Big Data &AI, Horizontal &Vertical Integration, Cloud Computing, AR, IoT, Additive Manufacturing &3D Printing, Autonomous Robot, Simulation, Cyber-Security; Rüssmann et al., 2015) make smart systems viable, it is only when they are all used together that Industry 4.0 unleashes its potential for transformation (SAP, 2020; Haskel & Westlake, 2018). If this is true for industry in general, this is even more valid in cutting-edge fields such as space industry (therefore space tourism) that would not exist without high-investment, high-risk, research-intensive technology, which has characterised the sector since the onset (Gurtuna, 2013; Vedda, 2009).

Again, the most authoritative forecasts on space industry support this interpretation.

The space industry's Cycle 5 (OECD, 2016, 2019), begun in 2018 to continue for at least a decade, has already brought in new space actors, taking the sector away from the traditional upstream and downstream divide and steering it toward a different configuration, enabling endeavours such as space mining prototype and 3D printing for a prospective lunar base.

Thanks to the adoption of I4.0 technologies, (e.g., additive manufacturing, new fuel technology, and robotics) costs and production time have substantially lowered, facilitating the entry of private ventures into space (from SpaceX rockets to RocketLab engines to small cubesats). And, while there is no easy solution to an alternative to Tsiolkovsky's rocket equation that still dominates the industry and condemns all the space missions to the iron rule of 1 per cent of payload for a given weight sent into space (NASA, 2021), the possibilities opened by an orbiting Gateway in cislunar orbit (the forthcoming NASA-ESA project) is just an example of what is to come. After all, reaching the Earth orbit is one of the most energy-intensive steps of space missions, only comparable to reaching Mars. All the rest, from Near-Earth asteroids to cislunar orbit and even the lunar surface, are less demanding.

And if the application of the circular economy principles is essential, as shown above, for the sustainability component of space tourism, the nexus between space, I4.0 and CE all working and reinforcing them together is going to produce even more dramatic effects.

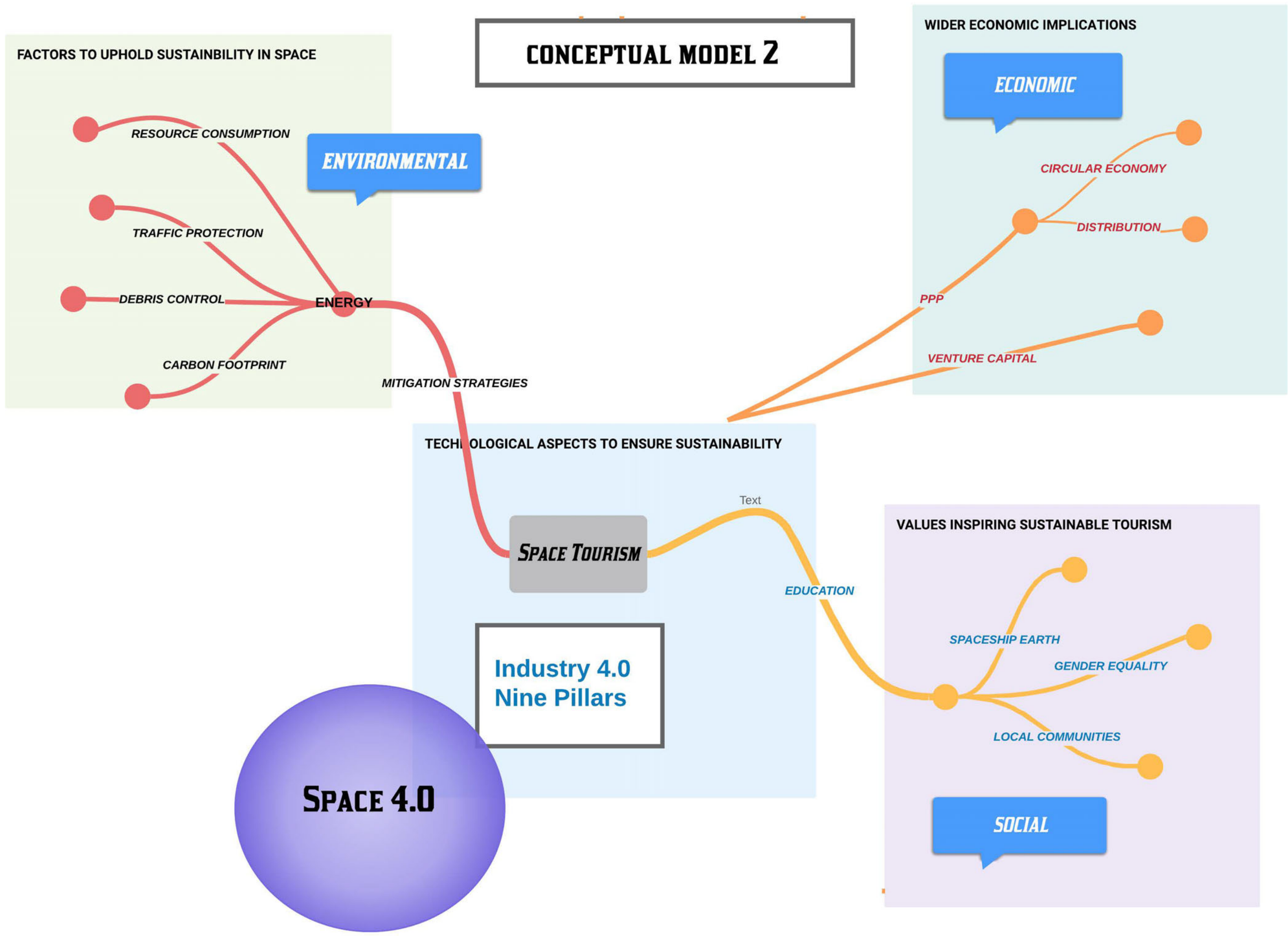

FIGURE 3 Conceptual model #2 for sustainable space tourism. *Source*: Authors' elaboration [Colour figure can be viewed at wileyonlinelibrary.com]

4.5 | There is still work to do in this sense

The debate exploring linkages between Industry 4.0, sustainability, and circular economy is still in its early stage (Dev et al., 2020; Jabbour et al., 2018; Stock et al., 2018; Stock & Seliger, 2016), lying down the foundations for a way forward ("CE-I4.0 nexus"; Dantas et al., 2021). Additional challenges do exist in the application of CE models to extremely complex sectors (Kumar et al., 2019; Matsumoto et al., 2016), as it is certainly the case of the space industry.

But the debate and the possibilities it opens have not gone unnoticed.

Policy-makers have already bridged the gap, including CE as one cornerstone of the EU forward-looking, resource-efficient industrial policy (EC, 2014; 2015; 2016; 2019) and with the formulation of Space 4.0 both by ESA (ESA/EC, 2016) and by the EU (EC, 2013, 2016).

We have just begun glimpsing at the 'enormous potentials' (Hofmann & Rüsch, 2017) I4.0 is going to unleash. As shown by OECD (2019), Cycle 5 will affect the modalities space tourism takes place and together its possibilities to make it sustainable. And if the present is any guide, then the only opportunity to have space tourism that proves environmentally sustainable, economically viable, and socially acceptable is to invest on a radically reshaping technology that breaks present barriers to space.

Finding solutions for a more sustainable, less carbon-heavy fuels as much as addressing the debris issue the overcrowding of the Earth's lower orbit all depend on the advances Industry 4.0 and Circular Economy philosophy can bring to Space 4.0, radically changing the variable of the equations and delivering on their sustainability promises.

5 | CONCLUSIONS, LIMITATIONS OF THE STUDIES, AND FUTURE RESEARCH

If, as Bostrom and Cirkovic (2008, p. 15) claim, 'sustainability should be reconceptualised in dynamic terms, as aiming for a sustainable trajectory rather than a sustainable state', this is even more crucial in a sector in full evolution as space tourism. Where this trajectory will eventually lead us is a fundamental question, and more than one option is open, even though not all of them equally viable or desirable. But to make informed choices, the reconceptualization exercise must be made, and this is our own contribution to that.

There are a few limitations to this study, which we fully acknowledge.

First of all, the study focuses on space tourism and does not address the wider and more complex debate about human colonies in outer space, be their O'Neill-type orbitals, the Moon Village, or Martian settlements. It steers clear of the complex debate of humankind in space in terms of the relationship with the environment, and what would be needed for humans to survive (Cohen & Spector, 2019a, 2019b). The discussion between adapting the environment to human needs (the way Musk intends to terraform Mars; Popular Mechanics, 2020) or changing the human bodies to the medium itself (the transhumanist solution; Launius & McCurdy, 2007; Le Dévédec, 2018; More & Vita-More, 2013) is way beyond the scope of this research.

Similarly, we have not considered the psychological and behavioural aspects that push people to frontier tourism of which space can be considered a subset (Cohen, 2017). There are many insightful studies on the subject (Crouch et al., 2009; Laing & Crouch, 2011) which we considered, but not discussed for a reason: in our scenario, the choice to ‘go-to-space’, for whatever motive it could be, has already been done. The model only attempts to make it sustainable.

The important aspect of the regulatory framework that can sustain space tourism by adapting decades-old legal provisions no longer suitable for the present needs has not been ignored here (Kostenko, 2020; Paladini, 2019). Due to the complexity of the discipline, which would require a stand-alone article by itself, the legal aspects have been conflated into the economic dimension, instead of giving them an autonomous space, as for the relevance they entail for the private and commercial dimensions of the most important space tourism operators.

There is another important limit, which, differently from the others discussed so far, is not in terms of scope but regards the conceptual model: in this paper, we have not presented a case study to test the model itself, for two main reasons.

First, because we believed that what was missing in the first place was a conceptual model for sustainable space tourism on the kind of White et al. (2006), essential to foster the debate. Second, for the sheer lack of space in such an article. This specific limit is to be overcome in future studies. The debate about of a typology space tourism that can be both viable and sustainable, has just started. It is to evolve together with the business itself, although some of the directions they will both take might hold a few surprises.

Discussing if the world should even allow space tourism, given its costs, is crucial, and a positive answer could only come from the demonstration that such tourism can and should be made sustainable. This is our article's contribution, together with offering a conceptual model that combines the literature-identified indicators of sustainable tourism with the specificity of the space sector.

It is both our expectation and our hope that researchers will adopt, improve, and even challenge the model, if this can help the debate progress. Apply the conceptual model to a case study to see in which way the components identified here work in practice, and which kind of data we need for this to happen, are the logical next steps. Empirical studies will be precious to test the extent of the model itself not only in an explanatory function but to evaluate its prescriptive value for the field, if any.

We believe that sustainable and viable space tourism is possible, provided we take into consideration the way technology can develop a sustainable dimension of the space tourism. If technology was the enabler to the space adventure as a whole, then it can and must also be the main enabler to sustainable space tourism. The way we can make it happen is key to our survival as a species and, eventually, as a living planet.

DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study

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APPENDIX: Indicators of sustainable tourism by source and category

	Nesticò and Maselli (2020)	Agyeiwaah et al. (2017)	Ocampo et al. (2018)
Economic	Employment by sector[a]	Revenues and profitability	Cost of maintaining tourism operation
	Economic performance	Employment	The increase of employment opportunities for local residents
	Tourism Intensity (in absolute terms)	Visitor satisfaction	Tourist satisfaction with related activities
		Tourists arrivals, volume and numbers	The volume of tourist, returning tourists and seasonality
		Seasonality	Quality of tourism employment
		Accommodation quality, capacity and occupancy	Carrying Capacity
		Local ownership in business	Overall planning of local tourism industries
		Repeat visit	Management for efficiency for tourism and recreational activities and integration and planning of long-term management tasks
		Expenditure	
		Unemployment rate	
		Economic Leakage	
		Length of stay	
Environmental	Tourism density	Water quality and management solid waste discharge and management	Maintenance of the integrity of the ecological system
	Transport usage	Recycling rate	Treatment and prevention of wastes caused by tourism
	Degree of accessibility in island territories and in territory of the initiative	Air/atmospheric quality	Active remediation and reduction of the damage and interference in areas caused by the tourist activities
	Coastal erosion	Energy consumption	The existence of integrated tourism and environment plan
	Marine habitats and species that have been identified as priorities for conservation	Environmental awareness	Planning and diversification of coastal, land and forest use
	Area of land and sea protected by statutory designations	Air pollution	Cleanliness and quality of tourism facilities
	Area of built-up land	Noise pollution	Population with access to drainage and wastewater treatment system
	Forested land area	Number of endangered species	Protected natural, environmental and wildlife area
	Green buildings	Others	Amount of native, threatened, or endangered species
	Energy consumption		Implementation or application of green design technology and recycling
	Greenhouse gas emissions		Implementation and use of permaculture principles and vegetation areas
	Share of renewable energies		Animal biodiversity, Plant biodiversity, Wetland biodiversity experience
	Waste production		Quality of air, water, and land
	Waste disposal method		Development of nature-based tourists
	Quality of water for human consumption		
	Annual water consumption		
	Water reused		

	Nesticò and Maselli (2020)	Agyeiwaah et al. (2017)	Ocampo et al. (2018)
Socio-cultural	Tourist–local ratio	Residents involvement, participation and awareness	Frequency, the capacity of services, or level of use of local medical and transportation systems and living quality
	Local satisfaction level with tourism	Congestion and overcrowding	Promotion and education of conservation and sustainable concepts that leads to awareness and implications
	Level of satisfaction by visitors	Community satisfaction	Protection and understanding of local culture and heritage sites
		Safety and security	Enhancement of social identification through tourism and environmental protection for local residents
		Access	Training and development of local tourism personnel and provision of educational opportunities
		Community health	The attitude of the locals toward satisfaction, service, quality, and training mechanisms
		Wellbeing and quality of life	Local interaction and development toward tourists
		Residents attitude and complaints	Reinforcement of executive abilities, and ban, and control of available and developed policies
		Education	Assistance and partnerships from local coaches, guides, and advisory through the guidance of offering more tourism and recreation information
		Crime rate and harassment	Local residents and community involvement and participation in the management of tourism
		Gender equality	Crime rates, accidents and visitor safety and security
		Sex tourism and child sex abuse	Legal compliance (prosecutions, fines, etc.)
		Tourists visits to local doctors	Formulates ethics in tourism
		Retention of local customs and language	Performance of tourism academic research and creation of an environmental monitoring system
		Maintenance of cultural sites	Accessibility to recreational facilities
		Actions and events taken to promote indigenous culture	Overall service quality of the amount of local business and potential ones
		Satisfaction with local integrity	
		Loss of authenticity	

[a] *Source*: Authors' elaboration.