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# Space bioprocess engineering as a potential catalyst for sustainability

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Investment in spacefaring enterprises must offer transformative solutions to Earth-based challenges. Providing for the future health of our home planet is possibly the greatest return on investment. Therefore, ensuring that the large costs of astronautics also yield benefits on Earth is critical. The goal of space bioprocess engineering is the design, realization and management of biologically driven technologies for supporting off-world human exploration. Here, we outline several technologies with high dual-use potential, argue that continued investment in such technologies is justified, and offer insight into specific research and development strategies that will increase sociological, political and technological benefits for sustainable development on Earth.

Less than a year after the triumph of the 1969 Moon landing under the Apollo program of the National Aeronautics and Space Administration (NASA), Gil Scott-Heron's spoken-word poem 'Whitey on the Moon'[1] struck a resounding chord with the American populace by calling out social and economic disparities in the allocation of public funds. NASA's budget was over 4% of total federal spending in 1965 and 1966 and over 3% in 1964 and 1967; the cost of the Apollo program added up to US$25.4 billion in 1973, which is equivalent to US$178 billion in 2022. Now, more than 50 years after the debut of the album 'Small Talk at 125th and Lenox'[1], the world is preparing once again to put human footprints on Earth's largest natural satellite. In response to the announcement of the Artemis program[2]—which is supported by the Artemis Accords, an understanding of spacefaring nations under the leadership of NASA—many have echoed Scott-Heron's concerns and argued that funding used for space exploration should instead be spent to address problems on Earth[3,4]. Equitable allocation of taxpayer money is indeed critical, and the societal benefit of space exploration must be maximized. The operational costs alone for a single Artemis launch are close to US$4.1 billion for just the rocket, spacecraft and ground systems[5]. Estimates for a human exploration campaign to Mars range from US$150 billion to US$1 trillion[6] (representing ~5% of the gross domestic product (GDP) of the United States and ~1% of the world's GDP). To provide a return on investment (ROI), most national space agencies (for example, NASA, the European Space Agency (ESA) and the Japanese Aerospace Exploration Agency (JAXA)) explicitly aim to explore the universe for the good of all humankind. Space technologies developed via public funding should therefore offer both cross-cutting cost solutions and dual-use applications towards addressing paramount sociocultural and environmental challenges on Earth. It is also a fact that space technologies perpetually find terrestrial applications with seminal impact—economic as well as societal[7–9]. ESA, for example, has explicitly recognized the 'socio-economic impact of space activities'. We argue that meaningful societal advantages and benefits are achievable through equitable distribution gains engendered specifically by space bioprocess engineering (SBE)[10] technologies.

The challenges of delivering critical supplies in space, such as food, pharmaceuticals and materials, along with providing primary life support, are extraordinary[11]. Reliably delivering these necessities in an exceptionally austere environment with troublesome supply chains requires the de-risking of methods and substantial innovation to achieve maximum resource efficiency. Whereas on Earth a natural aversion to upfront costs often results in a rather incremental approach to change[12], the profound constraints of space provide a powerful impetus: requisite technologies developed to further off-world exploration may bear the implementation cost in pursuit of truly transformative solutions that transcend extant technologies[13]. From among the myriad of astronautical platforms, biotechnology and integrated biomanufacturing[10] paradigms have pivotal potential to support human health[14],

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as well as to reduce mission costs and increase operational resilience[15]. Whereas there is currently a strong financial motivation to advance space-related technology, including biological approaches, promoting the integration of sustainability principles into these innovations could bridge the gap between financial gain and environmental responsibility[16]. Only recently codified, SBE[10] presents game-changing possibilities for the future of space exploration in ways that also potentiate solutions to pressing planet-side problems, including climate change, sustainable development and equitable economic growth.

Recognizing the need for dedicated advancements in biological and physical sciences in space, the National Academies of Sciences, Engineering, and Medicine have made strategic recommendations for the next decade of research[17]. The two flagship campaigns—'Bioregenerative Life Support Systems' (BLiSS, previously called BLSS when referring to the field itself) and 'Manufacturing mATeRIals and proCEsses for Sustainability in space' (MATRICES)—are prime exemplars of the intertwined journey of space exploration and Earth sustainability. Aiming to provide a holistic understanding of biological systems for the development of sustainable life support, BLiSS directly relates to SBE. This underscores the importance of and need for self-reliant (closed-loop) systems to ensure food provision, air and water purification, and waste management—crucial elements for long-duration space missions as well as sustainability on Earth. MATRICES aims to navigate the dual challenges of the finite resources that can be launched from Earth and the conundrum of effectively reusing both terrestrial and extraterrestrial materials, which is a testament to the symbiotic relationship between space exploration and sustainability.

## Space bioprocess engineering

SBE integrates synthetic biology, metabolic engineering, and bioprocess design under extreme conditions to enable and sustain a biological presence in space through delivery of the nutritional, medical, and incidental material requirements that will ward astronauts from the harsh conditions of interplanetary transit and residence off-world[10]. The enabled technologies are integral to the maintenance of clean water and air with the highest resource efficiency, as well as for the minimization and recycling of waste streams that are produced throughout a mission, as is compulsory for self-sufficiency[15].

NASA's Space Technology Mission Directorate (STMD) exists as a framework to precipitate, vet and fund innovations; its Technology Transfer program[18] works to secure funding for dual-use industry applications of promising technologies[19]. In 2010, the STMD released the 'Space Technology Grand Challenges' (STGCs): 13 calls for new technologies to address gaps across human presence, management of space resources, and scientific progress and exploration[11]. The more recent STMD Strategic Framework of 2022 organizes the goals and objectives that NASA will pursue to fulfil its mission into a strategic plan with 18 capability areas that are categorized into four thrusts: Go, Land, Live and Explore[20]. SBE grew in part from these needs, and relevant technological outcomes include advances in crop production, wastewater management and resource recovery/recycling, as well as advancements in biofabrication[21].

The effectiveness of SBE relies on essential efficiencies for end-product recycling (loop closure), maximizing the use of strictly limited resources and optimizing resilience and sustainability during long-term missions with nominal logistical support. These efficiencies could surpass the effectiveness of current Earth-side analogues. Enhanced plant-based carbon fixation[22], for example, could be of high dual-use, making for direct translations towards addressing climate and environmental challenges[23]. Specific examples of technological maturation or efficiency breakthroughs with high potential for dual-use are bioadditive manufacturing for tissue regeneration[24], bioregenerative life-support systems[25,26], engineered high-performance crops that provide nutritional and medicinal victuals[27,28], biofuel production[29,30] and electrical power generation[31], as well as the bioproduction of chemicals and materials for manufacturing[32–34], and bioremediation for targeted metal recapture and extraction[35,36]. Moreover, SBE-driven solutions can contribute to educational and workforce training initiatives that are aimed at cultivating sustainable and inclusive economies while generating academic and economic co-benefits for promising new fields of study[10]. Prioritizing secondary considerations—such as size- and mass-efficiency, self-contained and modular operation, autonomy and adaptability—is crucial for achieving minimum viability in integrated space biomanufacturing systems. These considerations, often of lesser importance in Earth-based industrial biomanufacturing[37], can facilitate the creation of transportable, sustainable and self-supporting biotechnological systems. These are powerful drivers for integrated biomanufacturing technologies that can deliver hyper-efficient, distributable and logistically independent food, materials and pharmaceutical production systems that are suitable for decentralized deployment.

## Space technology driving sustainability

Whereas the intensification of resource extraction on Earth during the Anthropocene epoch has resulted in environmental problems that threaten the persistence of humankind, space exploration and exploitation have been viewed as a possible remedy[38]. By contrast, sustainability for the purpose of space science and technology has often been considered to be the de-risking of potential negative impacts of space exploration to planetary protection[16]. This can be assessed by analysing the flow of assets to minimize the environmental footprint and maximize resource efficiency[10]. Recent efforts to transfer the concept of sustainability in the context of societal and economic development to spaceflight have focused on in situ resource utilization for low-Earth orbit, Moon and Mars missions. A study by the German Aerospace Center (DLR)[39,40] elucidates how this approach has manifested and evolved and discusses the implications of these perspectives. The DLR's distillation of gaps in existing concepts (such as disregard for social or environmental aspects) calls for the adoption of 'space in situ sustainable development' and suggests ways to establish this idea further to enable a comprehensive evaluation of mission scenarios concerning their sustainability. More recently, specific microbial biotechnologies that bear high potential for sustainable space exploration through in situ resource utilization and loop closure have been outlined[16]. The roadmap also identifies the relevance of these emerging technologies to Earth-based applications and identifies the specific United Nations (UN) Sustainable Development Goals (SDGs) that could benefit.

### Sustainability and climate mitigation

In 2015, the same year in which the Paris Agreement on climate change was signed, all 193 members of the UN also adopted the SDGs, which are 17 challenges of the modern era across a wide range of areas that include environmental, economic and societal issues. Specifically, the SDGs cover poverty alleviation and hunger eradication, health and education, social and gender equality, clean energy and environmental protection, as well as peace and justice, to promote a more equitable and sustainable world by 2030[41,42]. Many of the identified problems are caused or aggravated by climate change; therefore, science-driven solutions must be at the heart of any plans to achieve the SDGs[43]. For example, it is impossible to adequately fight global warming without also fighting for public health[44] and social equity[45]. In acknowledgement of their responsibility to promote sustainable development, ESA has identified specific programmes related to the SDGs. We aspire to complement a perspective from 'across the pond' and analyse in further depth how space technology guided by SBE can contribute to the SDGs. For this purpose, we have identified the specific SDGs whose fulfilment could be advanced by SBE (Table 1). Within this framework, both the technological deliverables and the innovative concepts explored by SBE may offer new avenues towards sustainable development, whether as optimized iterations of regnant

**Table 1 | Integration of SBE technologies with NASA's STGCs and the UN SDGs**

| UN SDGs | NASA Space Technology Grand Challenges: EXPAND HUMAN PRESENCE IN SPACE | MANAGE IN-SPACE RESOURCES | ENABLE TRANSFORMATIONAL SPACE EXPLORATION AND SCIENTIFIC DISCOVERY |
|---|---|---|---|
| 2 ZERO HUNGER; 3 GOOD HEALTH AND WELL-BEING | Molecular pharming considers plants as biochemical factories for synthesis of desirable pharmaceutical compounds. In space as well as austere terrestrial environments, molecular pharming could facilitate access to medication. | Advances in space agriculture have led to improvments in vertical farming, which minimizes the spatial footprint as well as inputs of crop cultivation. On Earth, this facilitates access to fresh produce in spatially restricted environments, such as densely populated urban areas. | A biological and physicochemical process using photobioreactors has been studied on the International Space Station (ISS) as a means to establish a hybrid life-support system. Advances in the design of photobioreactors have enabled their use for advanced wastewater treatment as well as for cultivation of nutrient-laden biomass. |
| 6 CLEAN WATER AND SANITATION | The microbial check valve of the Space Shuttle passively neutralized water-borne microorganisms to prevent cross-contamination. Water tanks employing this technology have been installed in water-scarce cities to improve access to clean water. | When processed efficiently, urine could cover more than half of the ISS crew's water demand, while the remaining brine could be used as fertilizer for crop cultivation. On Earth, urine-diversion systems could significantly lower greenhouse gas emissions, energy consumption, and freshwater use of certain communities. | Aquaporins (AQPs) are macromolecular water channels, being considered as biotechnology for energy-efficient water-filtration. Integrating AQPs with extravehicular mobility unit (EMU)-design could enhance astronaut mobility, while aiding the development of improved water purification systems on Earth. |
| 7 AFFORDABLE AND CLEAN ENERGY | The urea bioreactor electrochemical (UBE) unit couples separation of urea from urine to conversion of urea into ammonia, which is subsequently used to generate power. The UBE unit is designed to accept any wastewater containing urine and/or ammonia, and as such could allow energy and resource recovery on- as well as off-Earth. | The offshore membrane enclosures for growing algae (OMEGA) cleans wastewater and forms biomass for production of fuel. This could enable in situ propellant production in space, while facilitating the transition to renewable energy carriers on Earth. | Advanced bioprocesses for production of bio-crude oil that have low-nitrogen requirements have been considered for propellant production at destination to reduce the required resupplies. Technologies like these advance methods for production of petroleum-based energy carriers from renewable feedstocks on Earth. |
| 8 DECENT WORK AND ECONOMIC GROWTH; 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE | Phytoremediation (i.e. the use of plants for remediation of contaminants) can create healthier environments for astronauts in a closed-system. On Earth, the technology has been used to develop low-maintenance living walls, which have natural insulation and promote social and physical health. | Long-term human settlement on the Moon or Mars will necessitate large amounts of construction material, transportation of which from Earth is infeasible. Calcination of limestone for production of concrete can be facilitated microbially, enabling in situ manufacturing in space and lower carbon emissions from concrete production on Earth. | Originally, Biosphere 2 (B2) aimed to miniaturize Earth's ecological environment as a baseline for designing long-term human habituation in space. The B2 experiment informed other analogues that simulated what living on the Moon and Mars could entail. Today, experiments in B2 focus on improving ecology and eco-technology on Earth. |
| 11 SUSTAINABLE CITIES AND COMMUNITIES; 12 RESPONSIBLE CONSUMPTION AND PRODUCTION | The Micro-Ecological Life Support System Alternative (MELiSSA) is an integrated, closed-loop system to provide astronauts with fresh air, water, and food, using microbial recycling of human waste. This system could serve as a blueprint for human-centred urban designs that promote sustainability. | Certain microorganisms form biological polyesters that can be used as biodegradable plastics. These materials have been considered for additive manufacturing on long-duration space-exploration missions. Such bioplastics would also lend themselves to a range of terrestrial applications for sustainable manufacturing. | House plants in conjunction with activated charcoal can efficiently clean indoor air from pollutants. This may be used in conjunction with vertical farming to improve the design of space-based habitation as well as terrestrial buildings, to create liveable environments that are conducive to the good health of their occupants. |
| 13 CLIMATE ACTION | Improved cellulases facilitate the breakdown of cellulosic biomass and advance the valorization thereof for production of fuels. This could allow in situ production of propellants in space, as well as enable a transition to carbon-neutral biofuels on Earth. | Generation of ammonia with the Haber–Bosch process is energy-intense and therefore has a significant carbon footprint. As in situ method for ammonia production in space, nitrogen fixation with microbial biotechnology coud be more compact, while on Earth reducing carbon emissions and thus the environmental impact. | The Surface-Adhering BioReactor (SABR) is a cultivation platform for microalgae that mimics how vascular plants use transpiration to deliver nutrients to their cells for improved energy- and water-efficiency. This could enable more sustainable biorefining, conserving resources in space and improving economics on Earth. |

Specific exemplar technologies developed in service to the STGCs are described in relationship to the corresponding SDGs. For extended information and references, see Supplementary Table 1. The content of this publication has not been approved by the UN and does not reflect the views of the UN or its officials or member states (https://www.un.org/sustainabledevelopment/).

technologies or derived from entirely novel concepts. Box 1 provides further context and examples in that regard.

Small, more configurable systems that can operate efficiently in remote and resource-constrained environments with great efficiency can promote the distribution of enabling technologies and advance sustainable development in austere and/or underdeveloped regions. Such systems could improve land and water use, efficiently remediating and valorizing waste streams into useful products, and reducing energy inputs drastically. Specifically, the utilization of one-carbon feedstocks, such as carbon dioxide and methane, can help to mitigate

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## BOX 1

# Correlation of emergent space technologies with the UN SDGs

Technology development towards bioregenerative life support and bioremediation for the amelioration of water and air quality, as well as food provisioning, could contribute to SDG2 'zero hunger', SDG3 'good health and well-being', SDG6 'clean water and sanitation' and SDG11 'sustainable cities and communities'. Bioprinting and bioprocessing to improve resource efficiency could enable certain tasks of SDG8 'decent work and economic growth' and SDG9 'industry, innovation and infrastructure'. Biological re- and up-cycling of waste streams/loop closure is relevant to SDG7 'affordable and clean energy' and SDG12 'responsible consumption and production', both in the context of SDG13 'climate action'.

Perhaps the most immediate places in space technology where SBE can be applied are advanced Environmental Control and Life Support Systems (ECLSS)[80]. ECLSS encompass various technologies that aim to support life in space, including both physico-chemical and bioregenerative systems. Whereas ECLSS are not necessarily closed-loop systems, their biological subcomponents, commonly referred to as Bioregenerative Life Support Systems (BLSS)[81–83], can be operated in a closed loop. BLSS, with their inherently sustainable life-support mechanisms, have the potential to advance healthcare and sanitation on Earth, particularly for water treatment. An example is the Micro-Ecological Life Support System Alternative (MELiSSA)[84]. Although primarily designed for air revitalization and waste management[85], the MELiSSA was inspired by sustainable environmental models on Earth. Although elements of the MELiSSA have been tested in flight[86], they were limited to experiments using rodents[87]. Another BLSS project, EDEN ISS, has been proved more extensively on a larger scale, although only on the ground[88,89]. The EDEN ISS project is also designed as an advanced nutrient delivery system and is therefore relevant to urban farming on Earth. Overall, BLSS present a promising proof of concept for fostering sustainability both in space and on Earth, recreating Earth's ecological processes on a much smaller scale by leveraging SBE.

Other specific examples of SBE technologies are innovations in crop cultivation for improved yields to meet dietary needs[90,91] and the production of next-generation feedstocks for biorefining and biomanufacturing[34,92], as well as biomining[36,93]—all of which have high potential to be more sustainable alternatives to existing terrestrial processes. Synthetic biology in particular has been recognized as a game-changing concept that could enable substantial improvements in bioprocessing, leading to critical innovations that support sustainable development[94]. In this context, biochemical engineering and synthetic biology are highly regarded for dual-use applications to both improve resource efficiency in space and counteract climate change on Earth[23,95]. Specific examples are the protein engineering of RuBisCO (that is, ribulose-1,5-bisphosphate carboxylase/oxygenase) for the improved fixation of carbon dioxide[22] or gut microbiome engineering of livestock to reduce greenhouse gas emissions[96]; other concepts include crop design and modification for increasing the soil carbon budget[97] and even biogeoengineering to counteract climate change by 'terraforming' Earth[98].

greenhouse gas emissions for more carbon-sensible manufacturing cycles. Sustainable biomanufacturing can also aid in disaster preparedness—examples include the following: drought-resistant crops are better suited to endure fluctuating weather patterns, increasing resilience in the face of aggravating agricultural risks; and molecular farming could enable flexible pharmaceutical production with low infrastructure requirements, facilitating wider access to treatment in response to sudden changes in local needs, as during an epidemic or a disaster[46]. Apart from the management and distribution of resources, medical/diagnostic technologies can also fulfil the criteria of modularity and remote deployability[47].

### Aligning societal needs with corporate interests

Making the transition to a more sustainable economy requires substantial technological shifts, which are commonly characterized by lengthy development and implementation periods, and often afflicted by a substantial risk of failure. One option to enable this is advance market commitment, which is currently being applied to carbon-removal efforts for counteracting climate change through initiatives such as Frontier Climate (https://frontierclimate.com/). Nevertheless, the generation of revenue from industries that benefit society as a whole rather than generating direct revenue ultimately necessitates subsidization, the realization of which requires new policies whose development and implementation are rarely straightforward. Hence, the private sector is ill-motivated to invest in related technology—this gap between societal need and corporate interest is commonly filled with public funding[13]. As an industry that is least concerned with immediate economic returns, space exploration provides a unique mechanism to overcome these hurdles, much more than any other branch of public research, development and innovation.

Research and development in space exploration have consistently yielded collateral benefits, manifesting both in economic gains and societal advancements[7,9,40,48]. However, the field of SBE remains nascent[10]. This early stage of development may prolong the period before its returns are palpably realized. Given the intrinsic hazards associated with space travel and settlement, it is imperative to adopt stringent criteria for technological development to ensure efficiency, durability and resilience. Such imperatives are heightened by the fact that any mission failures are prominently visible to the public, potentially undermining confidence in continued space investments. The rigorous constraints inherent to space missions drive a necessity for optimization and standardization in space architecture, fostering a deeper understanding of vital mechanisms, best practices and the emergence of novel concepts. In this context, it is paramount that the term 'innovation' is not trivialized for mere marketing optics, particularly when misleadingly suggesting environmental responsibility. Genuine innovation is indispensable for the progression of both space exploration and authentic sustainable development.

## Space economics global action

Government space budgets had reached US$117 billion in 2023, over half of which (US$73 billion) was transacted by the United States, whereas civilian and defence space activities accounted for approximately even shares[49]. By contrast, the Intergovernmental Panel on Climate Change (IPCC) has projected that efforts to limit global warming to 1.5 °C require for the energy sector alone an investment of US$2.4 trillion each year between 2016 and 2035, representing approximately 2.5% of the world GDP[50,51]. In the United States, US$44.9 billion (~0.177% of the US GDP) of the 2023 fiscal budget of US$6.13 trillion (equivalent to 22.8% of the US GDP)[52] were allocated in discretionary budget authority to address the climate crisis[53]. Despite the increase of US$16.7 billion (59%) from 2022, this clearly still falls short of the projected requirement[54], especially in light of the United States' major contribution to greenhouse gas emissions[55]. This is true not only for the United States but all spacefaring nations to various degrees. Meeting the financial target for climate action could, in part, be reached by leveraging sustainability-based cross-cutting in the spending for the civil space sector. Comparing the numbers for 2023, US$73 billion (the combined space budget of the United States) is still orders of magnitude below the requirement put forward by the IPCC (2.5% of the US GDP is ~US$636 billion)[51]. Investments made in the advancement of SBE technologies with immediate relevance to the mitigation of climate change could contribute to closing this gap in funding. Given the dual benefit, the advancement of SBE technologies should be prioritized and dedicated funding levels increased, as recommended by the decadal survey for biological and physical sciences in space[17]. With only an 8% yearly increase in its budget from 2022, in 2023 NASA has been directed primarily towards enabling missions on and around the Moon—while preparing for the exploration of Mars to the tune of US$7.6 billion for deep-space exploration and US$4.7 billion for Common Exploration Systems Development programmes to support lunar missions, which include financing of the Space Launch System rocket and the Orion spacecraft. Compared with the US$2.4 billion for Earth-observing satellites and related research, this will enhance NASA's ability to augment our understanding of climate change. NASA has recently allocated anywhere from 0.5 to 2.5% of its yearly budget towards SBE and adjacent programmes, with commitments of US$115 million to the Human Research Program, US$79.1 million towards biological and physical sciences, a portion of US$145 million for early-stage innovation and partnerships, and US$287 million for small business innovation research and technology transfer.

### Return on investment from SBE technologies

If SBE-derived technologies can deliver a ROI, not only the public but also the private sector will benefit—numerous examples of space technologies that have successfully been commercialized on Earth exist[56]. Estimates of the ROI for NASA activities range from 7:1 to 21:1 ($:$)[7,57] (and in some cases even 40:1 (ref. 58)). This is comparable to or higher than the ROI of 13:1 for initiatives such as the US Department of Energy's Clean Coal Technology Program[59] (although such simple juxtapositions between ROIs of US agencies do not always lend themselves to one-to-one comparisons due to several factors, including the allocation and distribution of funding, principles for determination of the ROI, as well as the structuring of mandates, operation of projects and the management of results). Nevertheless, we estimate the total possible financial contribution to sustainability from investment in SBE as arbitrage between the SBE fraction of a space agency's budget and the ROI. Beyond ROI assessment and comparison, analyses have shown that not only do conventional economic models underestimate the financial benefits of addressing sustainability, but they also overestimate the costs of doing so[12]. Upfront investments yield more substantial economic advantages in the long term than suggested by conventional models, primarily because the financial repercussions of unaddressed environmental issues far exceed the preliminary investments that are intended to mitigate them. In that regard, techno-economic analyses (TEAs) of biotechnologies have repeatedly demonstrated enhanced efficiency over incumbent processes.

Whereas there may be companies that are looking to commercialize off-world settlement and manufacturing, and may even consider the sustainability of these operations at their intersection, private companies maintain a responsibility to their shareholders first and foremost[60]. Thus, they often focus on short-term economic benefits rather than long-term societal benefits, which can lead to negligence towards holistic sustainability[61]. Meanwhile, SBE technologies for off-world use currently operate on an inherently different system, where the primary customers are public entities such as government agencies (for example, NASA), which do not operate for profit but act to further our understanding of the world and thus advance the development of humanity. In this way, it is important to consider that downstream SBE technologies often represent superlative versions of common technologies that would otherwise not be explored.

### Economics of SBE technology development

Already today, half of the ISS service providers that participate in technology development also specialize in life sciences (Supplementary Table 2). To ensure the future of biological and physical sciences research[17], the National Academies are recommending that the current funding allocation for the biological and physical sciences portfolio of NASA be augmented. The decadal survey for 2023–2032 in ref. 17 recommends a tenfold surge in funding, underscoring the critical interplay between foundational research and technological advancement in the field, which includes SBE. The ambitious goals of campaigns such as BLiSS and MATRICES not only spotlight the importance of both basic and applied domains but also necessitate a global re-evaluation of investment strategies in space technologies, including in-space manufacturing. This shift in perspective emphasizes the urgent need for expanded resources to realize the profound benefits of sustainable space exploration for both on- and off-world endeavours.

As well as deepening the scientific understanding of the Moon, NASA's Artemis program aspires to land both the first woman and the first person of colour on the lunar surface. Moreover, it intends to establish a testbed for the de-risking and validation of enabling technologies, such as in-space (bio)manufacturing, that will eventually enable human exploration of Mars. The primary factors that dictate the need for and feasibility of such endeavours are the restrictions of logistic resupply and the availability of in situ resources[15]. Owing to the lack of carbon and nitrogen on the Moon[62], the scale of any biomanufacturing will be constrained by cargo deployed from Earth. The ability to recycle carbon and nitrogen throughout resource life cycles will therefore be the greatest contribution to improving the sustainability of lunar missions[63]. The relevant SBE technologies for this loop closure have immediate potential to transform Earth's manufacturing industries, eliminating linear resource flows to avoid dead ends, leading to circular economies that are more sustainable.

A technology can be considered sustainable if its respective capital and operational expenditures remain within a predetermined budget and if its continued operation does not lead to a financial penalty due to secondary effects—for example, damage caused by the accumulation of waste. In the context of sustainability, we categorize repairs and maintenance that support ongoing eco-friendly practices as operational expenditure. By contrast, enhancements and upgrades that invest in long-term environmental benefits and sustainability are considered to be capital expenditure. These costs must therefore consider environmental impact, integrated over the useful life of a technology and all of its products. Some technologies may have a comparatively high capital expenditure but will eventually recoup this investment through economies of scale, potentially at time horizons that make Earth-side investment unattractive. While space applications present a crucible for the development of next-generation sustainable bioprocess engineering technologies, the economic evaluation of SBE technologies necessitates a comprehensive analysis of their impacts over an extended time horizon. In this context, it is crucial to juxtapose the benefits offered by SBE technologies against those provided by less sustainable technologies that may yield immediate advantages but impose substantial long-term costs due to concealed environmental repercussions. By considering the balance between short-term gains and long-term sustainability benefits, this comparative assessment will enable researchers, policymakers and financial stakeholders to make informed decisions regarding the selection and implementation of suitable technological solutions.

## Societal benefits of SBE

The technology for the human settlement of space must operate so well that crews can survive their missions safely—mentally and physically—and quickly recover from unanticipated emergencies. The standards for astronauts are high[64], but the same has not always been true of the standards for ordinary civilians on Earth, especially those in disenfranchised communities. This history of scientist-led discrimination has led to a mistrust of science and engineering within these communities[65,66]. Technology is crucial for addressing climate change, but it must be safe, effective and equitably distributed. Prioritizing sustainability in space exploration ensures that new technology is tested and proved to be safe for astronauts before being used on Earth. This can bridge the gap between experts and the public, fostering trust in green technologies. Such efforts can help to mitigate climate change impacts, particularly in affected communities. However, to fully address climate change and social injustice we need collaboration between legal experts, who understand demographic impacts, alongside substantial legal and behavioural reforms. This approach will enable space exploration efforts to simultaneously address pressing terrestrial issues in innovative ways.

Beyond economic and environmental advantages and advancements, SBE as a venture may offer parallel benefits for better education and a more equitable and inclusive society. To that end, the 2019 UN Global Sustainable Development Report identifies science and technology as an essential lever; SBE, whose technologies are deeply rooted in the advancement of science, could contribute to sustainable development in that regard[67]. Effectively prioritizing sustainability in space exploration necessitates involving and uplifting under-represented communities. Furthermore, input from demographics that are under-served will be crucial to fighting looming ecological crises. In particular, NASA, as an exceedingly multidisciplinary institution, is poised to train and employ highly skilled workers for stable careers in engineering and science in the burgeoning SBE field[68]. For its workforce, space technology relies on outreach, academic partnerships and on-the-job training to fill the ranks of the next generation and lower barriers to entry. SBE could help to bridge the gap in gender equality (SDG 5) between the scant 14.6% of aerospace engineering graduates that are women and the 50.6, 42.1 and 35.4% of women who graduate in the environmental, biological and agricultural, and chemical engineering disciplines, respectively[69]. Similarly, cultural minorities, economically disadvantaged individuals and those marginalized along other lines could be enabled to enter the space sciences: NASA's US$127 million STEM (science, technology, engineering and mathematics) engagement fund and a unified call for SBE workers would promote engagement across cultural and scholarly backgrounds[53]. As a young field whose foundational work is still being accomplished, SBE offers early-career scientists and engineers a new set of opportunities to face down other entrenched industries. Across all of NASA's solicitations, which include but are not limited to Space Technology Research Institutes, Early Stage Innovations projects and the Innovative Advanced Concepts program, the STMD boasts more than 800 active projects—all containing the necessary agency framework to promote the participation of women and under-served communities and businesses, and of historically Black colleges and universities and minority-serving institutions[70]. NASA's partnerships with historically Black colleges and universities and minority-serving institutions, especially through the Minority University Research and Education Project, demonstrate a tangible commitment to fostering diversity in space exploration. The agency must set quantitative goals, continuously evaluate the effectiveness of these partnerships through feedback mechanisms and enhance international collaborations to exchange best practices. Such multi-pronged strategies not only advance NASA's inclusiveness goals but also position the organization at the forefront of global efforts to promote a higher quality of education, towards greater sustainability through the advancement of diversity, equity and inclusion (SDG 4).

**Table 2 | Comparative analysis of SRL, LCA and TEA**

| Criterion | SRL | LCA | TEA |
|---|---|---|---|
| Objective | Measure the maturity and sustainability of a technology at each stage of its development | Evaluate the environmental impacts of a product or service throughout its entire life cycle | Assess a process or product's economic viability and feasibility, often in context with its environmental impact |
| Focus | Developmental readiness and implications for the sustainability of a technology | Environmental consequences of a product from raw material extraction to end of life | Cost and revenue structures, environmental cost factors and potential financial return on innovation |
| Metrics | Maturity level, energy and resource efficiency, waste generation and fate at end of life | Resource use, emissions and environmental impacts across different life cycle stages | Costs of production, potential revenues, environmental compliance costs and projected ROI |
| Use cases | SBE, assessing potential space and Earth applications | Assessment of the environmental footprint of products or services during their lifetime | Innovations seeking investment or industries looking to understand the economic viability of a new technology |

The evaluation methods are compared in terms of their objectives, focus, metrics and use cases within the context of sustainable technology development.

## Moving forward

Key to driving the development of dual-use SBE technologies is the automation and control of bioreactor systems for space, following sustainable design principles and incorporating life cycle assessments (LCAs). The identification of priority SBE technologies should include their evaluation regarding adaptation for Earth-based applications and the potential to address global sustainability challenges. Engaging with stakeholders, which include the public and private sector as well as policymakers, is also essential to raise awareness of the potential benefits of SBE-driven sustainability and to foster support for its development and implementation.

### Operationalization of SBE technologies

Methods such as LCA and TEA (Table 2) are useful to assess the overall environmental impact of a process from an economical point of view. To evaluate the sustainability of a chemical process more quantitatively, metrics, such as the E-factor and atom economy[71,72], have been developed and adopted widely throughout green chemistry. These metrics have been successfully applied in various contexts, such as in the conversion of biomass into chemicals as an alternative to the utilization of fossil fuels as feedstocks[73,74]. Nevertheless, mass-based metrics alone are insufficient to capture all aspects (for example, socio-cultural impacts) that determine the sustainability of a process. The introduction of a sustainability readiness level (SRL; Table 2), based on NASA's 'technology readiness level' framework[75,76], could be a useful complement, analogous to and maybe integrated with the concept of bioindustrial manufacturing readiness levels[77], especially for SBE purposes. SRLs would evaluate the the overall impact of a technology in development at each stage of its refinement and commercialization, from conceptualization to operational implementation. This would include a technology's energy and resource efficiency and fate at end of life. The SRL would also consider the anticipated impact of a technology on the environment during its operational life cycle as well as during post-mission disposal. SRLs would not only be a metric to assess the maturity and sustainability of technologies for space exploration but could be transferred to any Earth-based technology.

By that, stakeholders can ensure that sustainable design principles and practices are incorporated into the development of new technologies at each stage.

### Towards equitable economies

A central tenet of a more sustainable world is an equitable economy, nationally and globally. Coming back to the words of Scott-Heron, if "Ten years from now I'll be payin' still", we must ensure that the investment in pursuit of a spacefaring future offers terrestrial benefits on a timescale that is meaningful to those paying now—and with consideration for the harsh realities of life for under-served populations. The wealth gap, which is deeply entrenched in systematic racial, cultural and gender biases, will grow as climate change continues to affect planet Earth and forces an undue burden on already marginalized communities[78,79].

Life in space will require the efficient use of minimal resources. As a result, SBE, both as a discipline and a business endeavour, faces a well-defined set of challenges that are common to most sustainable development initiatives. This can be exemplary for transforming Earth's economy, which itself is coming to terms with the rapid exploitation of finite or slow-to-replenish resources. SBE promises powerful returns on research and development from enabling technologies and fundamental research as a whole[10], but it also promises its own set of sustainable development prospects. Even though the benefits may not be immediate and the initial costs are appreciable, SBE has a distinct advantage in addressing these challenges over traditional space technologies.

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## Competing interests
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