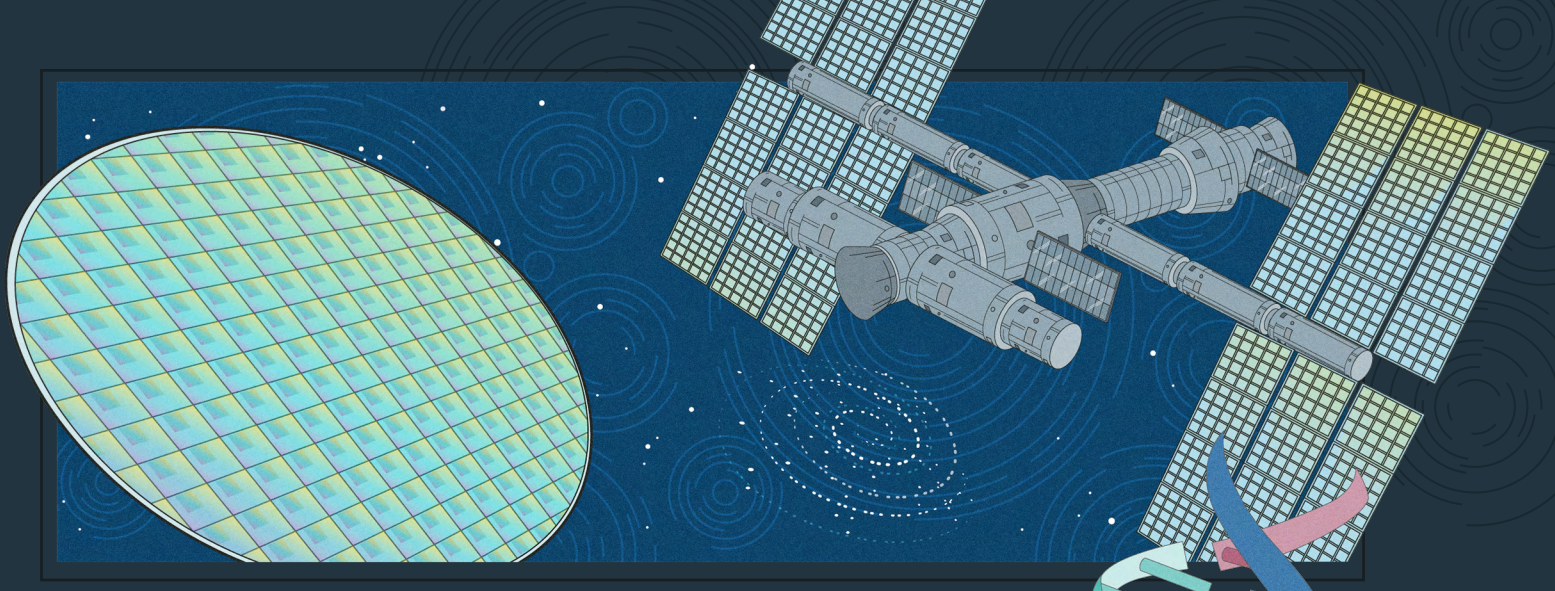

On the Horizon

Three Science and Technology Trends that Could Affect Society

Accessible Version

GAO

November 2024

GAO-25-107542

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Cover: Illustrated depiction of space-based manufacturing of semiconductors, gene editing, and biodegradable bioplastics.

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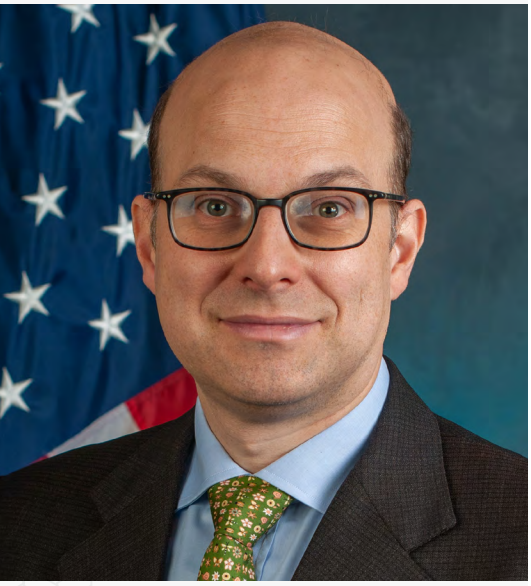
Sterling Thomas, PhD
GAO's Chief Scientist



Stephen Sanford
Managing Director,
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Foreword

Science and technology (S&T) are constantly evolving, and there is a need for analysis of emerging trends of the future to help prepare us for the benefits and disruptions that they may bring. To address this need, we developed this report focused on technologies which may develop significantly over the next 10 years. Our goal is to provide foresight into developing technologies that could have significant impacts on Americans. We are in an ideal position to inform Congress about science and technology to assist them in their role in oversight, but also in evaluating technology through our Technology Assessment reports.

For this report, we identified and monitored developments in science, technology, and engineering that may grow or subside over time as the United States continues to innovate. As there are many possible future trends, we did not take an exhaustive approach, but identified three significant technologies we think are demonstrating progression. Periodically, we plan to add to this body of work with new technologies that show signs of maturing and appear to be benefiting from improving market conditions.

Many methods exist to identify emerging technologies, but most are focused on the same goal—separating new S&T trends from the group of emerging technologies. Common methods that appear in popular literature leverage term frequency analysis to determine if a topic is trending up over time. This method can be valuable for technologies that are beginning to reach maturity but are less effective for technologies that are 10 years out.

Our method leverages the expertise of GAO scientists and engineers to identify new technologies that may have not gained popular attention but show significant acceleration in maturity. To guide our approach to horizon scanning and evaluating the technologies for this work, we followed the STEER framework. For each of the three technologies we address key elements derived from the **s**ocial impacts, **t**echnology drivers, **e**nvironment impacts, **e**conomic drivers, and the **r**egulatory landscape.

Source: GAO (icons). | GAO-25-107542

Each of these elements plays an important role in maturing a technology and creating market conditions that can bring an innovation to the American public. Innovations do not live in a vacuum so societal, environmental, regulatory, and other realities may also be useful to consider and evaluate for opportunities to accelerate innovation.

To conduct this work, we relied on a review of scientific literature from academic journals and position papers and held semi-structured interviews with five experts across the three identified technologies. The experts were selected based on the results of our literature review, previous GAO reports, and the expertise and judgment of GAO scientists and engineers. To help identify trends, we consulted with internal and external experts, including nonresident fellows with expertise in foresight from the Center for Strategic Foresight. We relied on our judgment and consideration of the collected information to describe key aspects of the technological trends, including identifying technological developments, market conditions, or economies of scale that could further accelerate the maturity of these new technologies, and considerations for policymakers, such as legislative bodies, government agencies, and other groups.

Gene Editing to Treat or Prevent Disease

Gene editing shows promise for treating or preventing disease as well as for potentially improving cognitive skills, increasing lifespan, and enhancing physical abilities. Since the development of the CRISPR gene editing tool in 2012, technology advances have led to new and improved gene editing tools.[1] These tools may accelerate progress in human gene editing. Policy decisions made in the near future may affect the way in which human gene editing to treat or prevent disease is regulated, covered by health insurance providers, and accepted by society.

A multichannel pipette is used to prepare samples on a microplate.

Source: luchschenF/stock.adobe.com. | GAO-25-107542

Overview

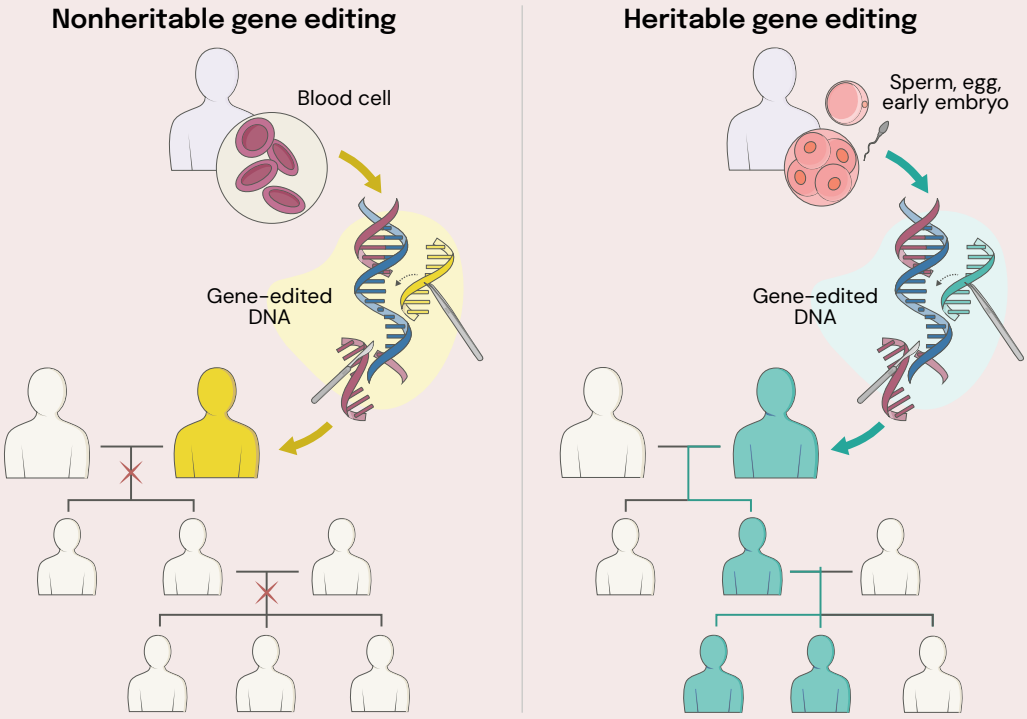
As of August 2024, gene editing to treat sickle cell anemia is the only gene editing therapy that has been approved for use in the United States.[2] There is also evidence that a researcher in China has edited genes in a manner that purportedly prevents HIV infection.[3] The sickle cell therapy involves editing the DNA of some of a patient's cells to correct a genetic mutation. Untreated, this mutation causes red blood cells to become sickle shaped. However, the current treatment does not allow the corrected gene to be passed to the patients' future offspring (i.e., nonheritable, see text box and fig. 1).

In 2018, a researcher in China announced the birth of twins with gene edits to confer resistance to HIV infection. Since this involved gene editing of early stage embryos, those edits would be expected to be passed down (i.e., heritable) to future offspring.

Researchers continue to test a variety of gene editing tools for other human diseases, including cystic fibrosis, high cholesterol, Alzheimer's, and various cancers but mainly in nonreproductive cells (i.e., nonheritable).[4] This is primarily due to U.S. restrictions on the use of federal funds for research where a human embryo is intentionally created or modified to include a heritable genetic modification as well as the inability to demonstrate long-term safety in treated individuals' offspring and future generations.[5]

Further, the U.S. Food and Drug Administration (FDA)-approved gene editing therapy for sickle cell disease costs $2.2 million per patient in large part due to the high costs of development, manufacturing, and clinical trials.[6] The perceived high cost may also be driven by the limited number of patients and comparing the trade-off between the cost of curing a genetic disease with a single treatment versus the costs incurred over a lifetime of managing illness.

Figure 1: Heritable vs Nonheritable Gene Editing



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Nonheritable versus heritable

Gene editing to treat or prevent disease involves changing a person's DNA. These changes can be made in nonreproductive cells (e.g., blood, muscle, and nerve cells); in reproductive cells (eggs, sperm); or in early stage embryos. Changes to nonreproductive cells cannot be passed to offspring (nonheritable) but changes to reproductive cells and early stage embryos can be passed to offspring (heritable).

Key Developments

Over the next 10 years, human gene editing to treat or prevent disease in the United States will be dependent, in part, on policy decisions, regulatory approval, classification as a therapy or enhancement (see text box), gene editing technology and manufacturing advancements, and societal acceptance. This could result in three general degrees of availability of human gene editing:

Therapy or enhancement?

Generally, a therapy takes people from an unhealthy "sick" state to a healthy or "less sick" state. An enhancement, on the other hand, pushes human abilities beyond normal "species-typical functioning" or confers a competitive advantage like gene doping in sports. While the distinction between therapy and enhancement is debatable, it could affect how gene editing is regulated, if it is covered by insurance, and if society accepts it, among other things.

01 Limited availability

Nonheritable gene editing therapies may remain limited to a relatively small number of diseases and continue to be expensive. Federal funding restrictions may continue to negatively impact the development of heritable gene editing therapies. Heritable gene editing and human embryo research may also continue to face ethical and moral concerns. For example, while eliminating disease in future generations may seem beneficial, it could also potentially lead to altering other non-disease traits which could be passed to future generations with unknown health risks.

02 Some availability

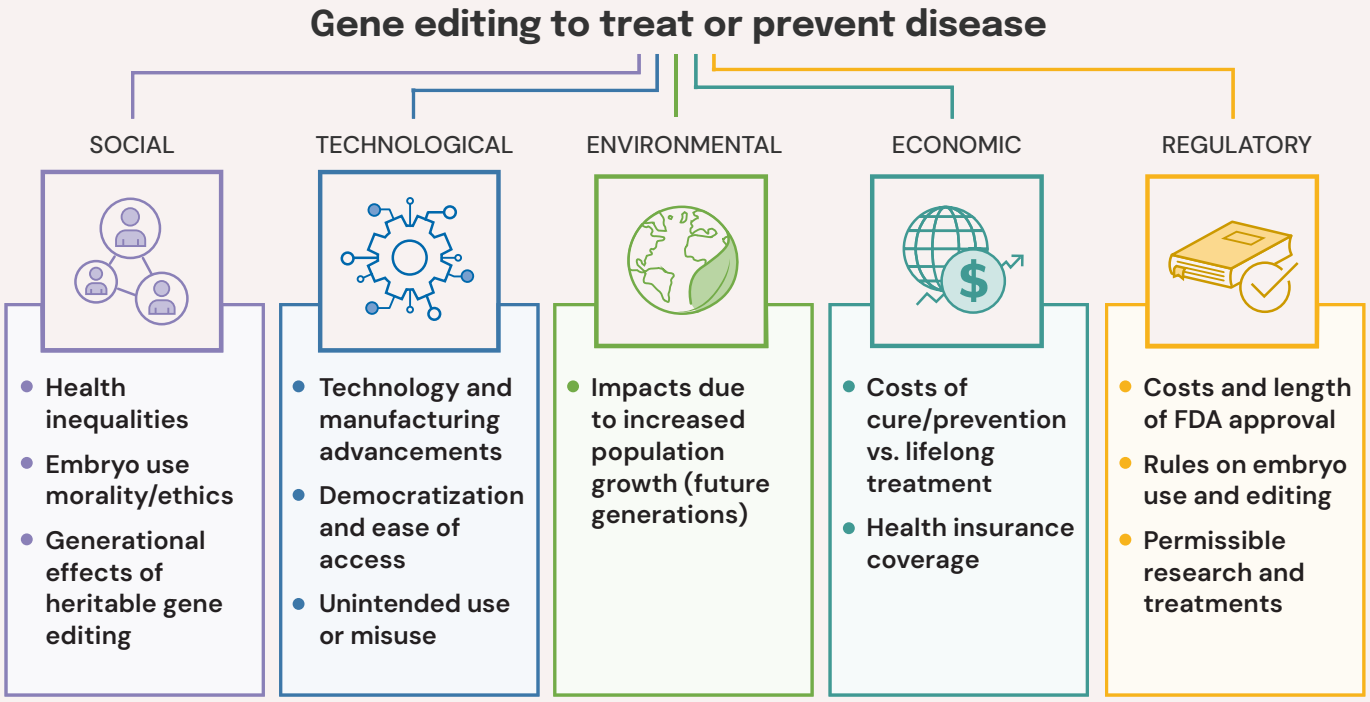
The number of available nonheritable gene editing therapies to treat or prevent disease may increase. As a result, costs may decrease as more therapies enter the market and development and manufacturing processes are improved. However, some companies may choose not to develop some therapies due to a limited number of patients and high development costs. Some insurance providers may choose to narrowly define gene editing therapies as enhancements that would not be covered (e.g., for nonfatal diseases or diseases for which other, less expensive treatments exist). For treatments not covered by insurance, costs could be managed through subscriptions and payment plans. If restrictions on the use of federal funds for heritable gene editing are relaxed, some limited heritable gene editing may be approved for serious, life-shortening diseases (e.g., cystic fibrosis, rapid aging progeria syndrome), but only if the potential risks associated with the therapy are clearly outweighed by the benefits of increased lifespans or by a dramatic improvement in the quality of life.

03 Wide availability

Both nonheritable and heritable gene editing may be widely considered medically necessary and morally and ethically beneficial or imperative for the health of individuals, public health, and society. Gene editing costs may decrease to the point that some insurance providers determine that covering one-time genetic cures is more economical for them than longer-term regimens of pharmaceutical-based treatments. Increased use of nonheritable gene editing therapies may be driven by social pressures and those who are willing to make health privacy trade-offs and take risks. Acceptance of heritable gene editing may be driven by disease advocacy groups, concerns over public health, and a desire to eliminate certain diseases for future generations.

Implications

We highlight implications of gene editing below and describe three selected implications in more detail.



Source: GAO (icons). | GAO-25-107542

The high costs of gene editing therapies are unlikely to significantly decrease soon according to one expert we spoke with and literature we reviewed. Companies may continue to justify the high cost by comparing the trade-off between the cost of curing a genetic disease with a single treatment versus the costs incurred over a lifetime of managing illness. Insurance companies and government health care programs may not initially cover these high costs. However, as more gene editing therapies reach the market, treatment costs could significantly fall, at which point insurance companies may cover them over existing treatments.[7] Lower treatment costs could also expand the availability to a wider breadth of individuals, including those with rare diseases.[8]

Rapid technology advancements in gene editing tools, delivery, and manufacturing, combined with decreasing costs, may lead to greater access. However, democratization and ease of access to gene editing tools may lead to do-it-yourself (DIY) gene therapy, gene doping in sports, and other misuse, in the absence of sufficient oversight.[9]

Regulation of human gene editing requires balancing costs and benefits. Regulations can help ensure that gene editing technologies are safe and effective before they are used in humans. However, according to one expert that we talked with, whether certain gene editing research is permissible under federal law is unclear. For example, there are no restrictions on privately funded heritable gene editing research. However, should a therapy result from this research, it is not clear if clinical trials could be conducted in the United States.

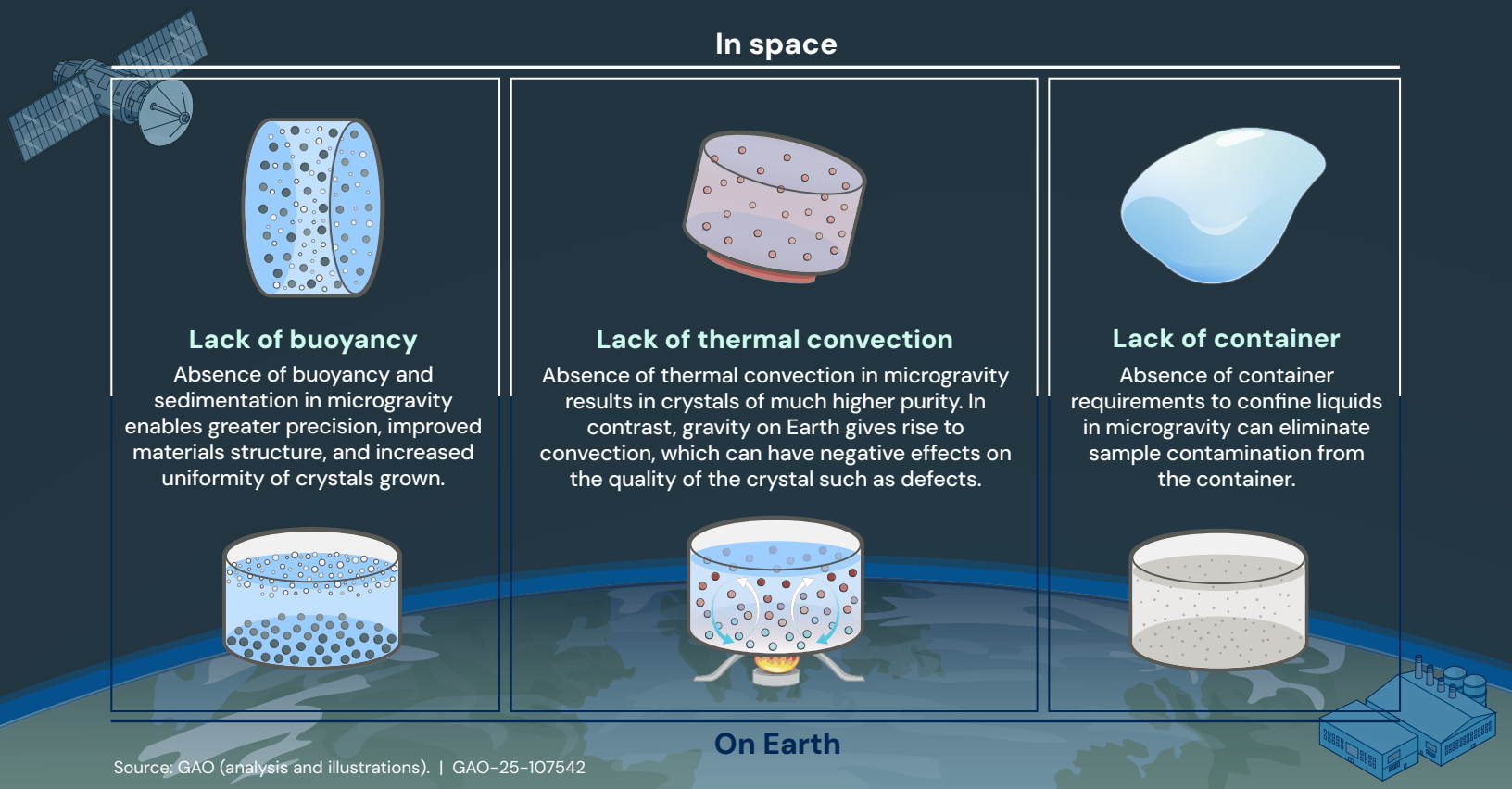
Potential Considerations for Policymakers

Policymakers may face gene editing decisions that affect health care, reproductive rights, public health, and health privacy. For example, to help ensure the United States maintains its technological competitive advantage and dissuade individuals from seeking treatments in other less regulated countries, policymakers may consider whether new policies and regulations are needed to streamline the regulatory approval process for nonheritable gene editing treatments. This could also include looking at pricing structures for current treatments and health insurance coverage, especially publicly funded programs like Medicare and Medicaid. Policymakers may also examine how the current federal funding restrictions affect current and future heritable gene editing research. Finally, it may be important for policymakers to be aware of the potential for misuse of the technology, such as in DIY gene therapy and gene doping in sports.

Space-based Manufacturing of Semiconductor Crystals

Decades after humans launched the first satellite, space activity has been dominated by research, exploration, and national security issues. But what was once described as the final frontier is now a new frontier – for commerce. In recent years, private entities have increased the commercialization of space as the commoditization of space hardware and reusability of launch vehicles have driven down the costs to manufacture and launch spacecraft. An emerging application of this commercialization is space-based manufacturing. Space has a microgravity environment with a natural vacuum and solar energy, all of which could improve certain manufacturing processes such as crystallization.[10] In microgravity, liquids and gases behave differently (see fig. 2), which can result in improved materials or crystalline structures. Space-based manufacturing takes advantage of one or more of these aspects of the space environment. There is ongoing research in manufacturing semiconductor materials, pharmaceuticals, fiber optics, and biologic tissue in space. This report focuses on the space-based manufacturing of semiconductor materials, which can take advantage of the space environment to improve their quality and reduce the occurrence of gravity-induced defects.

Figure 2: Example Advantages of the Microgravity Environment in Space for Crystal Growth

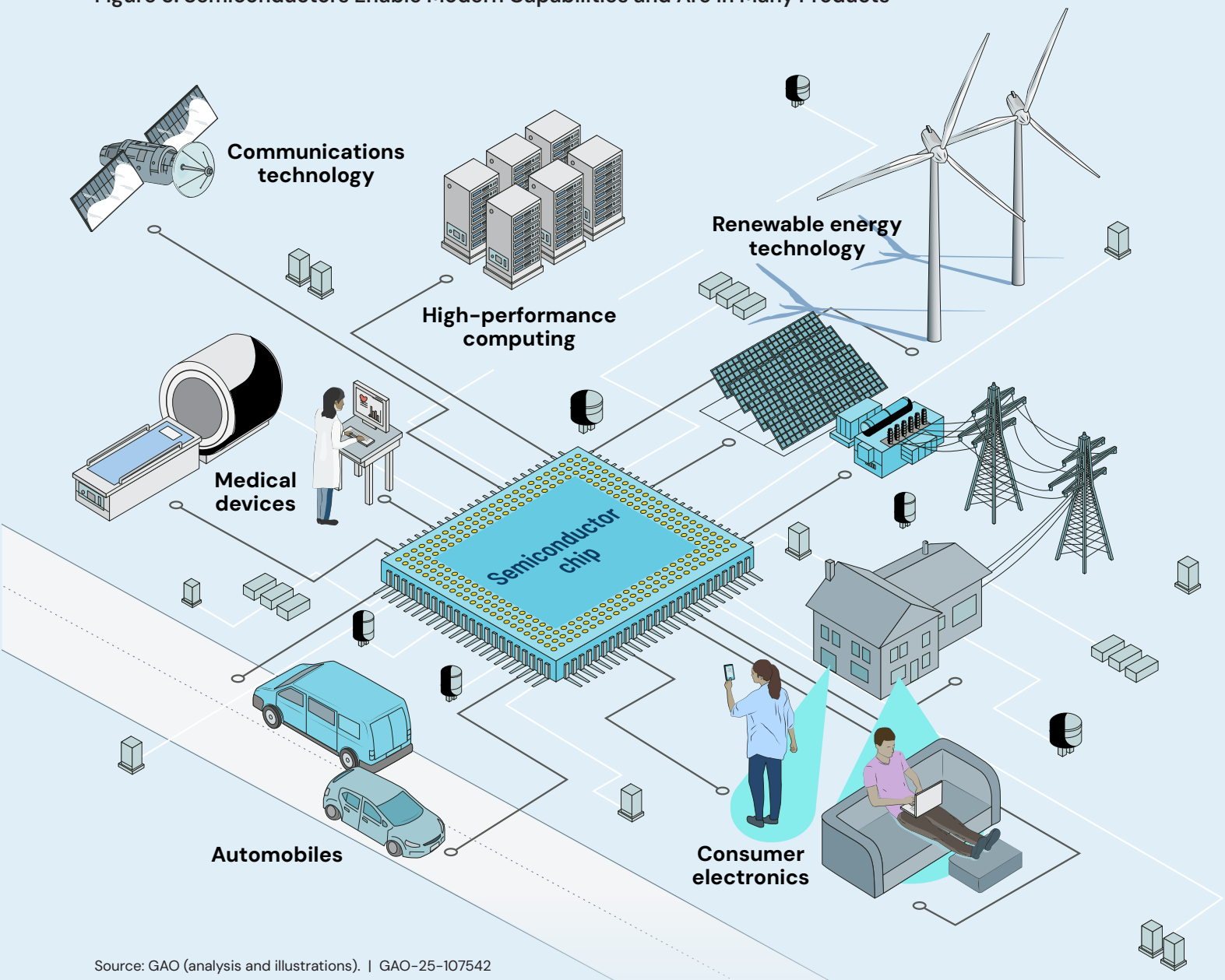


Source: GAO (analysis and illustrations). | GAO-25-107542

Overview

Semiconductors are crystalline materials that are vital for modern technologies.[11] They are used in many products such as computers, consumer electronics, communication equipment, medical devices, and automobiles (fig. 3). Demand for next-generation semiconductors made from materials such as gallium nitride, silicon carbide, and graphene are expected to rise due to advancements in technologies like artificial intelligence, electric vehicles, 6G communications, radar systems, renewable energy systems, and quantum computing.[12] Semiconductors manufactured in space could help meet some of these demands.

Figure 3: Semiconductors Enable Modern Capabilities and Are in Many Products

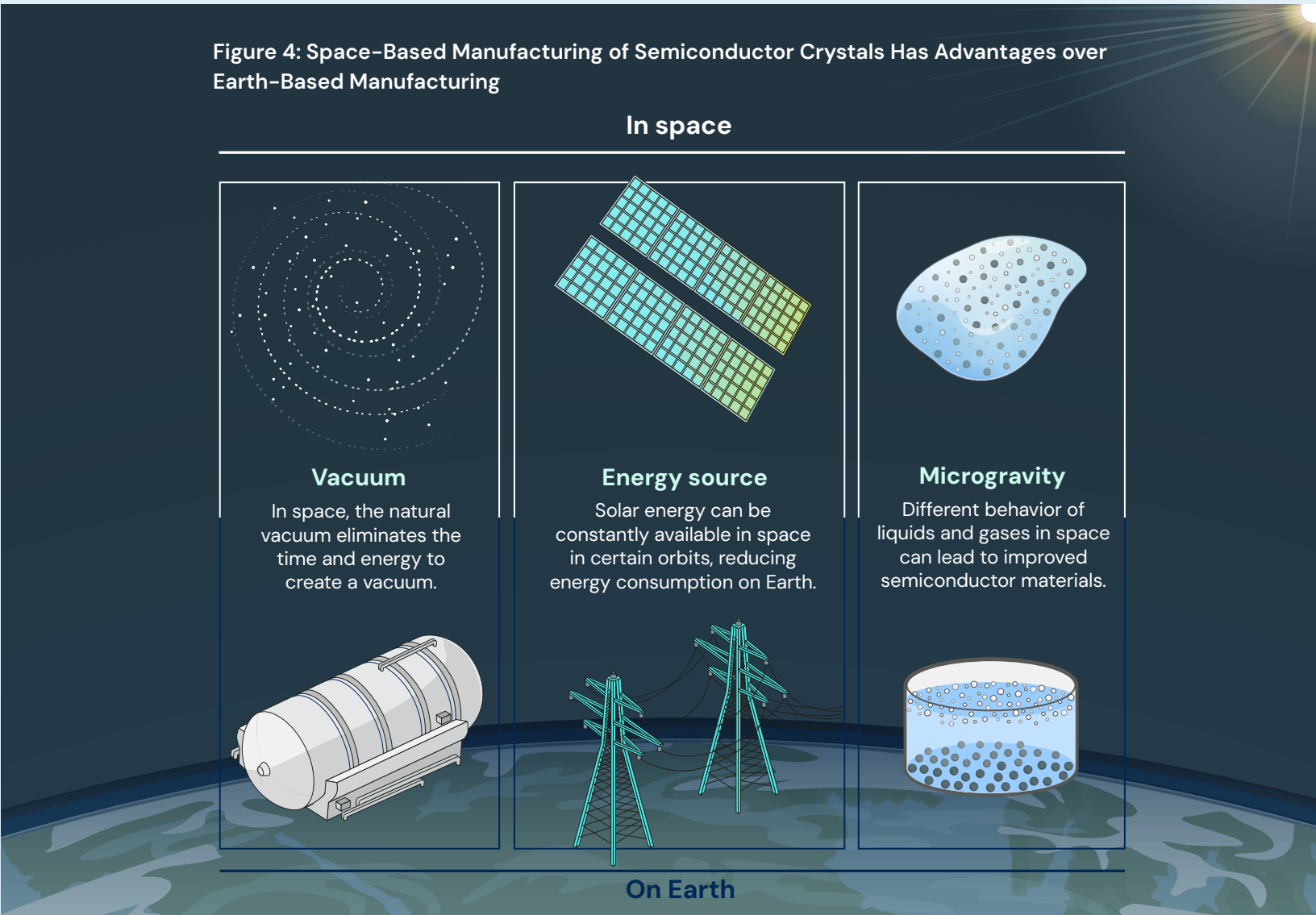


Source: GAO (analysis and illustrations). | GAO-25-107542

Key Developments

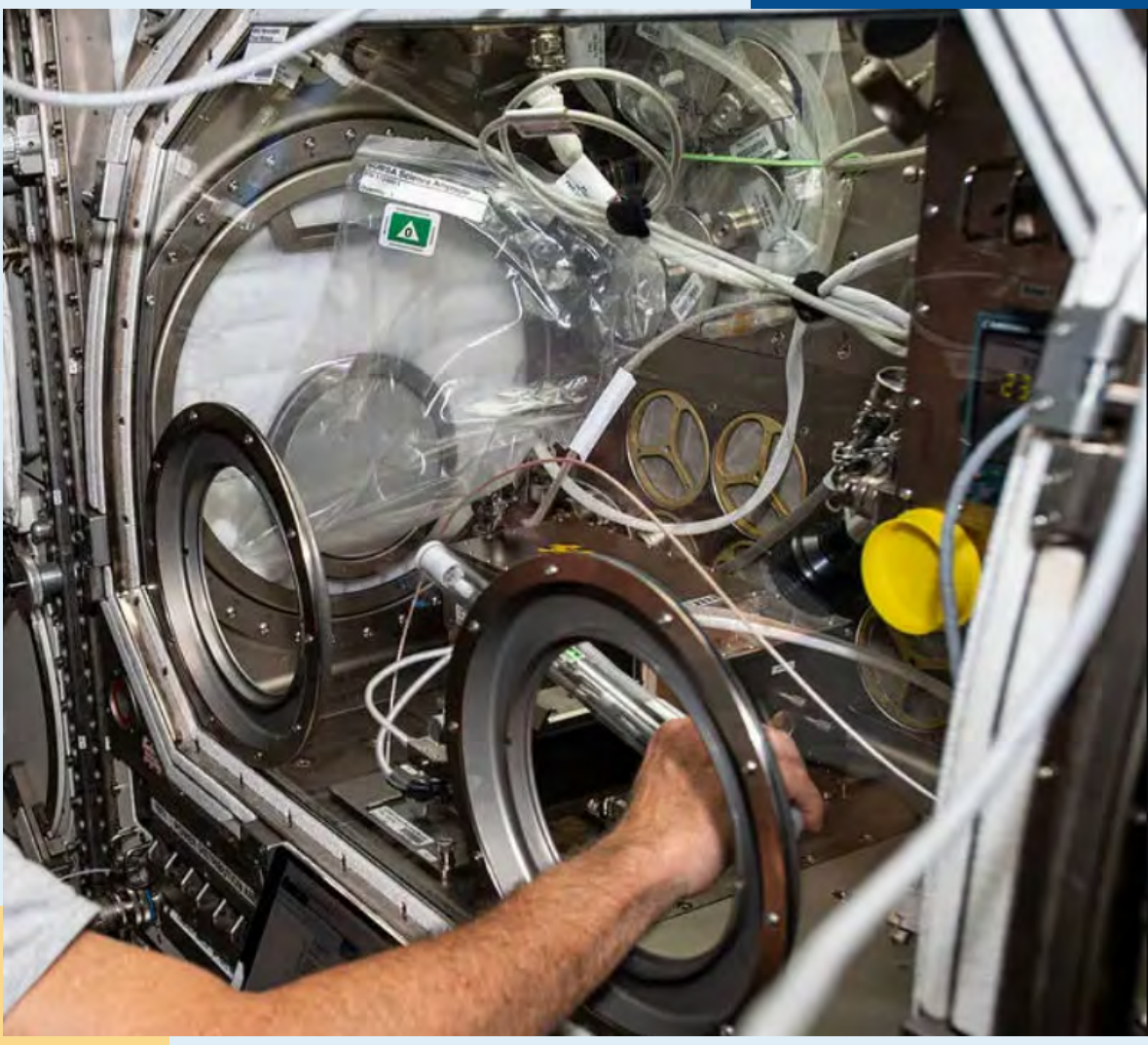
Manufacturing higher-quality semiconductor crystals in space rather than on Earth has certain advantages, according to experts. The manufacturing processes to create semiconductors on Earth are resource intensive. For example, these processes require creating a vacuum to remove potential contaminants and heating raw materials to a molten state, both of which are time or energy intensive. Furthermore, Earth-based methods often result in crystal defects that degrade device performance. In contrast, space provides a natural vacuum, reducing the need for time and energy to create one. Space-based environments also have fewer contaminants, allowing production of higher-quality semiconductors with fewer impurities. Additionally, microgravity causes liquids and gases to behave differently in space, which can lead to more uniform semiconductor crystals with fewer defects, enhancing the quality of semiconductors (fig. 4). Raw materials could be heated using solar energy available in space, and certain orbits offer constant solar exposure.

Figure 4: Space-Based Manufacturing of Semiconductor Crystals Has Advantages over Earth-Based Manufacturing



Source: GAO (analysis and illustrations). | GAO-25-107542

Over the past decades, studies on semiconductor crystals grown in space have demonstrated significant improvement in one or more material properties such as more uniform and improved crystal structure, reduced defects, increased electrical conduction, and increased optical transparency compared to crystals made on Earth.[13] However, space-based environments pose challenges to semiconductor manufacturing that do not apply to Earth-based manufacturing. For example, space-based manufacturing requires developing and launching specialized facilities and transporting materials. While launch costs have decreased significantly over the past several decades, they are still a major cost contributor. Therefore, products manufactured in space must be good enough to capture a sizable market or meet important national or public needs such that there is long-term commercial viability. Large capital investments would be required to establish space-based, automated semiconductor manufacturing infrastructure. For example, a silicon crystal production facility on Earth can cost up to $5 billion, a cost that may be greater in space.[14] Additionally, it is not fully clear what risks or challenges the space environment poses, such as space radiation that could potentially damage semiconductors.

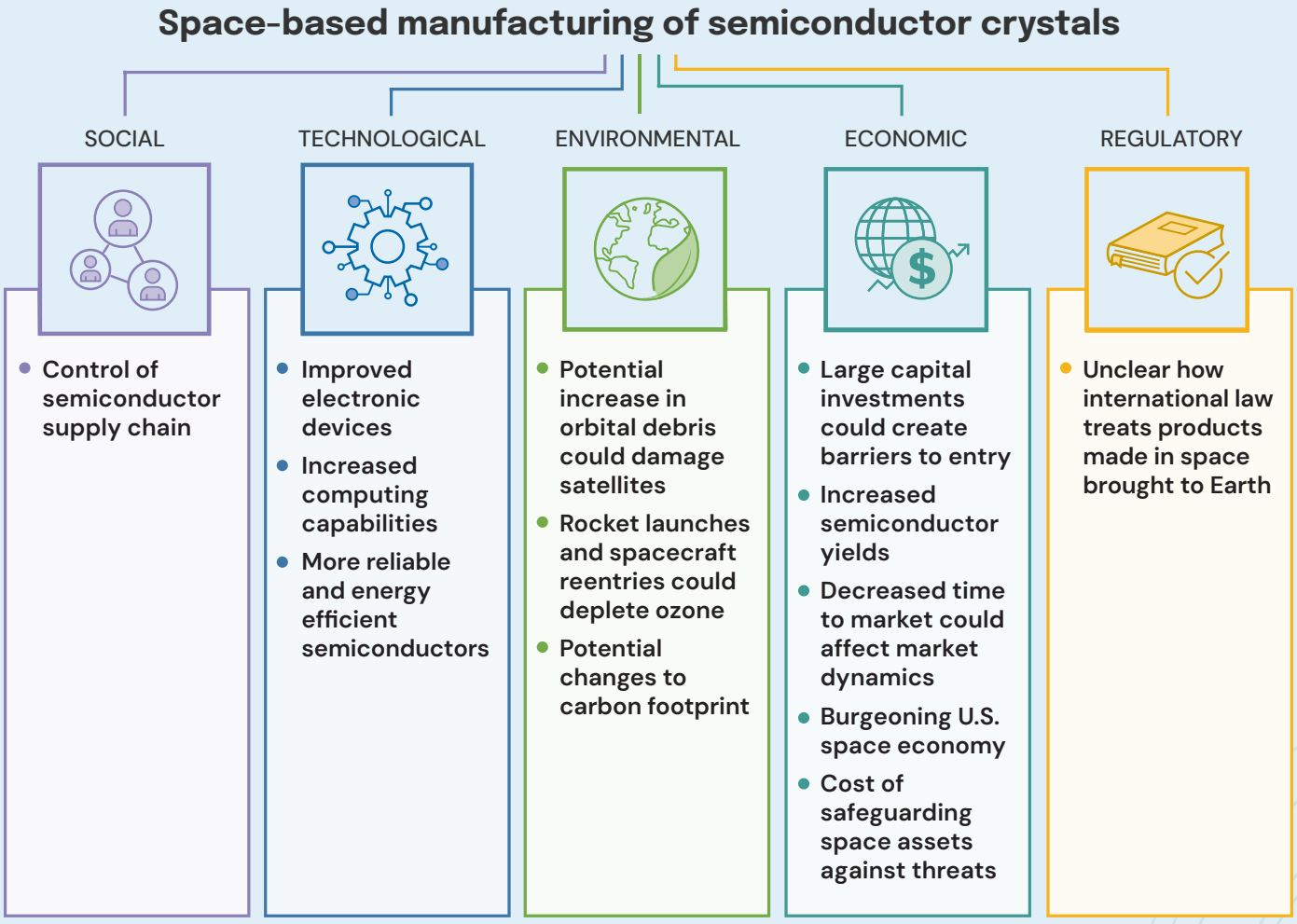


A NASA astronaut works on samples inside the Microgravity Science Glovebox for the Solidification Using a Baffle in Sealed Ampoules (SUBSA) experiment. SUBSA crystallizes melts in microgravity to learn more about the process of semiconductor crystal growth to benefit Earth and space industries.

Source: NASA, https://www.nasa.gov/image-article/astronaut-shane-kimbrough-works-microgravity-science-glovebox/. | GAO-25-107542

Implications

We highlight the implications of space-based manufacturing of semiconductor crystals below and describe five selected implications in more detail.



Source: GAO (icons). | GAO-25-107542

Supply chain resilience

U.S. manufacturers depend on non-domestic sources of high-purity crystalline silicon, of which Asia currently controls over 70 percent of the market. The microgravity environment of space presents opportunities to develop next-generation semiconductor materials, potentially reducing U.S. dependence on specific aspects of foreign supply chains, such as crystal growth.[15] However, a significant portion of their semiconductor supply chains could still rely on foreign entities for raw materials like certain minerals, metals, and high-purity gases used in semiconductor processing.

Advanced electronics

Compared to semiconductors made on Earth, the potentially higher purity and lower defect density of semiconductors

grown in space could significantly enhance the energy efficiency and performance of electronic devices. Additionally, researching semiconductor crystal growth in space may lead to new discoveries on crystallization processes, accelerating the development of next-generation materials such as gallium nitride and graphene with enhanced properties and larger crystal sizes compared to those grown on Earth. These materials are essential for advancing emerging technologies in telecommunications, transportation, cloud services, energy generation and storage, and extended reality.[16] Thus, advancements enabled by this new approach of space-based research and manufacturing of semiconductors have the potential to yield more powerful computers, faster communication systems, and improved consumer electronics, thereby driving economic growth and technological progress.

Economic competitiveness

Establishing a robust space-based semiconductor manufacturing industry could strengthen the U.S. economy by creating high-tech jobs and fostering innovation. Manufacturing semiconductors in space could offer competitive advantages, including higher product yields, fewer defects, and faster turnaround times which could reduce time-to-market, according to an expert we interviewed in this trend area.[17] This may benefit the semiconductor sector, where companies may prioritize quicker time-to-market to gain a competitive edge over cost-effective but slower Earth-based routes. According to insights from an expert we interviewed, most executives prioritize reducing time-to-market, as missing deadlines can result in substantial revenue losses. However, the benefits of in-space semiconductor manufacturing may be limited to a few commercial entities capable of making large infrastructure investments. The competitiveness of space-based manufacturing could also depend on the level of investment from government and other interested parties.

Costs of safeguarding space assets

Spacecraft that manufacture semiconductor crystals in space could become targets for destruction or disruption by malicious or careless actors because semiconductor crystals are important to the economy and national security. Spacecraft could be designed to be more resilient and protected from negative actions such as physical or kinetic attacks, radiofrequency jamming, and cybersecurity threats, but this would likely increase their costs. Additionally, space-based manufacturing systems, particularly autonomous robotic platforms, must be reliable and robust enough to endure the harsh conditions of space, including extreme temperatures, radiation, and atomic oxygen exposure, as in-space repairs may be infeasible.[18] As space exploration and commercial ventures increase, the role of defense operations in safeguarding U.S. assets and interests, both in space and on Earth, is likely to expand and cost more.

Environmental considerations

Space-based semiconductor manufacturing has environmental considerations such as emissions and orbital debris. By using the constant source of solar energy available in certain orbits around Earth instead of the Earth-based mixture of energy sources, space-based semiconductor manufacturing could reduce emissions on Earth.[19] Additionally, emissions from the manufacturing process itself are vented into space. However, those benefits may be offset by emissions from increased rocket launches and spacecraft reentries to transport materials and products. These emissions pollute the air and could affect atmospheric temperatures and deplete ozone.[20] More spacecraft, including those for space-based manufacturing facilities in orbit, could increase the risks of creating orbital debris that could damage other satellites and create additional debris.[21]

Potential Considerations for Policymakers

National and international regulations and governance for space-based manufacturing, including for semiconductors, may not be clear or stable, which could create uncertainty for investment, development, and intellectual property protection. Policymakers may consider whether a comprehensive authorization or licensing framework may be needed to enable and regulate space-based manufacturing activities. Such a framework could include operating licenses conditioned on standards or regulations regarding collisions, orbital debris, emissions, export controls, and intellectual property protection, some of which already exist.[22] A global framework could define the roles and responsibilities of participating countries to potentially foster a more collaborative and secure environment for future space-based semiconductor manufacturing. However, it may be difficult to achieve a robust and effective global framework agreeable to countries with varying levels of space capabilities and different and competing interests.

The United States relies on foreign sources for silicon semiconductor materials since Asia dominates that market. To potentially mitigate or avoid similar reliance on foreign suppliers for next-generation semiconductor materials—which are essential for technologies such as wireless communications, high-performance computing, weapons systems, and medical devices—policymakers may consider whether initiatives for domestic research, development, and manufacturing are needed. In particular, policymakers could consider whether investing in the in-space manufacturing of high-quality, next-generation semiconductor crystals is needed to create an increasingly domestic supply chain and reduce dependence on foreign suppliers for certain aspects of the supply chain.

While there is an increasing commercialization of space, there are also concerns about the viability of space-based semiconductor manufacturing. Policymakers may consider whether demonstrating the manufacturing technology, establishing shared infrastructure such as space factories and transport vehicles, and setting policies are needed to reduce technical and financial risks to levels acceptable to commercial industry.

Biodegradable Bioplastics

Biodegradable bioplastics are plastics made from biological origin materials that decompose in the environment more rapidly than conventional plastics. According to one association affiliated with the bioplastics industry, global bioplastic production in 2023 was 2.18 million tons—or roughly 0.5 percent of all plastic produced annually. Capacity of biodegradable bioplastic is expected to increase to 4.6 million tons in 2028.[23] Bioplastics can have properties similar to conventional plastics; some are already used for packaging, consumer goods, and textiles. Biodegradable bioplastics are proposed as alternatives to some conventional plastics due to their comparable mechanical properties and their ability to decompose more rapidly in the environment. Applications for biodegradable bioplastics can include single use plastics, sterile plastic packaging, grocery bags, or trash bags. Bioplastics can be used for other products, such as clothing or plastic bottles, but recyclability in these contexts should be prioritized over biodegradability due to longer term use.

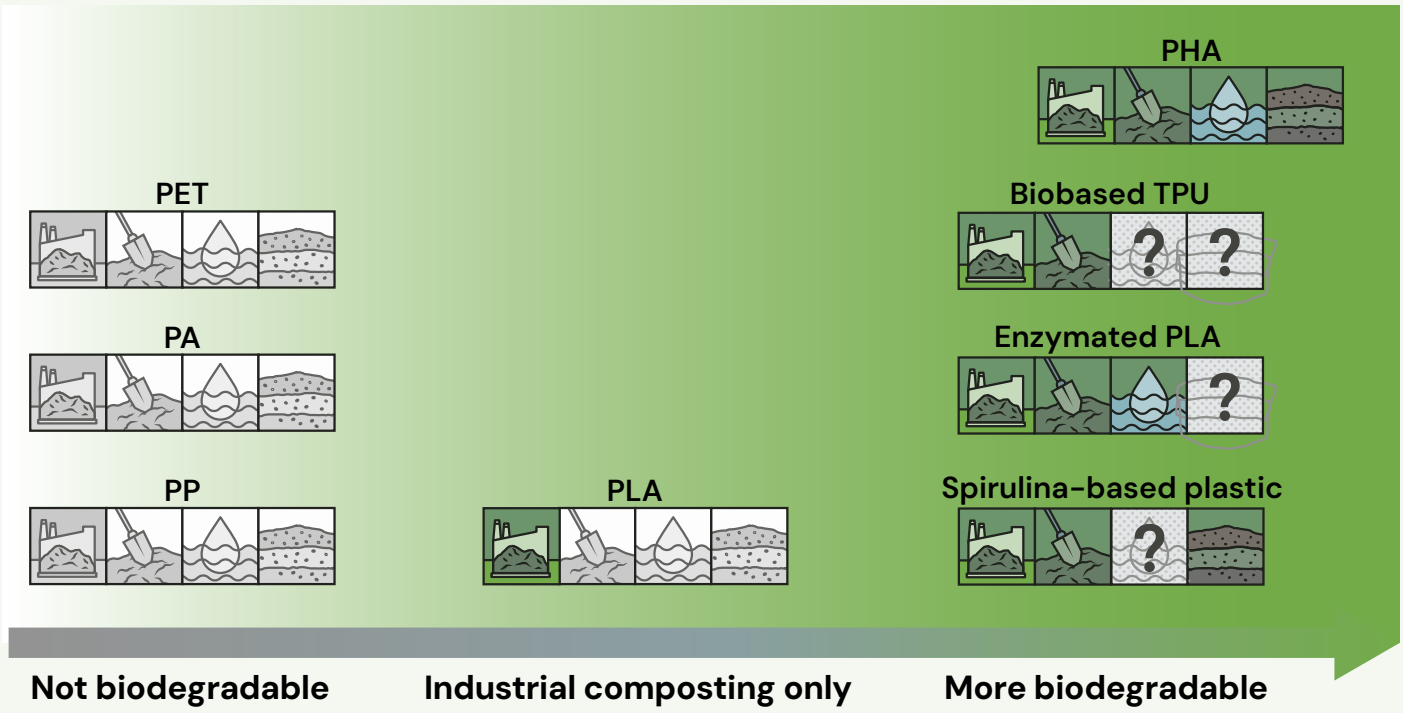
Microplastics on a person's finger.
Source: Pcess609/stock.adobe.com. | GAO-25-107542

Overview

Humans have often looked to nature for inspiration to solve problems or for renewable material sources. One modern problem is plastic and microplastic pollution, which has continuously increased over the past 50 years. Most plastics used today are fossil-fuel based (e.g., polyethylene terephthalate [PET] and polypropylene [PP]) and lead to tiny plastic particles or *microplastics* that accumulate in the environment, including in drinking water, food, and even in the bodies of humans and animals. For example, recent studies have found low levels of microplastics in heart tissue from cardiac surgery patients and in the stomach tissue of some coastal birds.[24] Microplastics form when the natural environment is unable to fully biodegrade plastic products (i.e., the process of microbes breaking down a plastic product into water, carbon dioxide (CO_2), and biomass). It remains an open question on what the long-term health and environmental effects of microplastic pollution may be.

To reduce plastic and microplastic pollution, scientists are turning to nature and developing biodegradable bioplastics as one part of a portfolio of approaches. Two of the most common biodegradable bioplastics on the market are polylactic acid (PLA) and polyhydroxyalkanoates (PHA). PLA is produced through bacterial fermentation using renewable carbon sources, such as corn starch and sugarcane, and is currently used in 3D printing and packaging, for example. PHAs are a class of bioplastics primarily synthesized from bacteria using plant sugars, such as glucose or fructose from corn or sugarcane, but can also be made from methane. PHAs are used for a variety of products, including food packaging. Although certain bioplastics, like PHA, are biodegradable, others, like PLA, are only biodegradable under industrial composting conditions that are not found in nature and can be challenging for some people to access. Furthermore, some bioplastics, such as biobased PET or polyamide (PA), are not biodegradable at all (see fig. 5). Other challenges faced by current bioplastics include higher production costs and a reliance on food sources (e.g., sugarcane, corn, etc.).

Figure 5: Spectrum of Biodegradability of Selected Plastics



Source: GAO (analysis and icons). | GAO-25-107542

Key Developments

Emerging biodegradable bioplastics may solve some of the problems encountered by current bioplastics. To address challenges in biodegradability, research has focused on modifying or creating new bioplastics to be home compostable. Additionally, there have been some innovations in algae-based bioplastics that may reduce production costs and address challenges for food source reliance.

Algae-based bioplastics

Algae's versatility may help produce home compostable bioplastics with lower costs and lower emissions. Algae create sugars from CO_2 through photosynthesis—acting as a carbon sink—and grow rapidly in a variety of aquatic environments. Sugars produced from algae could serve as a lower cost, non-food source for the production of PHA.[25] Furthermore, algae's versatility may allow for it to be grown near facilities where they can be transformed into bioplastics, thus reducing transportation emission and costs. Algae can also be used to produce unique types of biodegradable bioplastics. In 2023, researchers developed a bioplastic using spirulina, a microalgal species that is widely commercially available.[26] The method developed in this study uses a heated compression molding process where heat and pressure are applied to transform spirulina powder—made from dried whole spirulina cells—into a rigid bioplastic. The production process does not use any binders or additives or require any extraction or chemical modification processes. The spirulina-based bioplastic has very similar properties compared to other commodity plastics, including PLA, and has a similar degradation profile to that of a banana peel in soil (see fig. 6). While there may be many future benefits to algae-based bioplastics, there are also several considerations, such as water usage for cultivation and downstream processing costs that may affect the scalability of algae-based bioplastic production.

Figure 6: Artistic Rendering Comparing Degradation of Spirulina Bioplastic to a Banana Peel in Soil

Source: Iyer, H. et al., "Fabricating strong and stiff bioplastics from whole spirulina cells," *Advanced Functional Materials*, 2023, 33, 2302067 (analysis); GAO (illustration). | GAO-25-107542

Self-biodegradable PLA

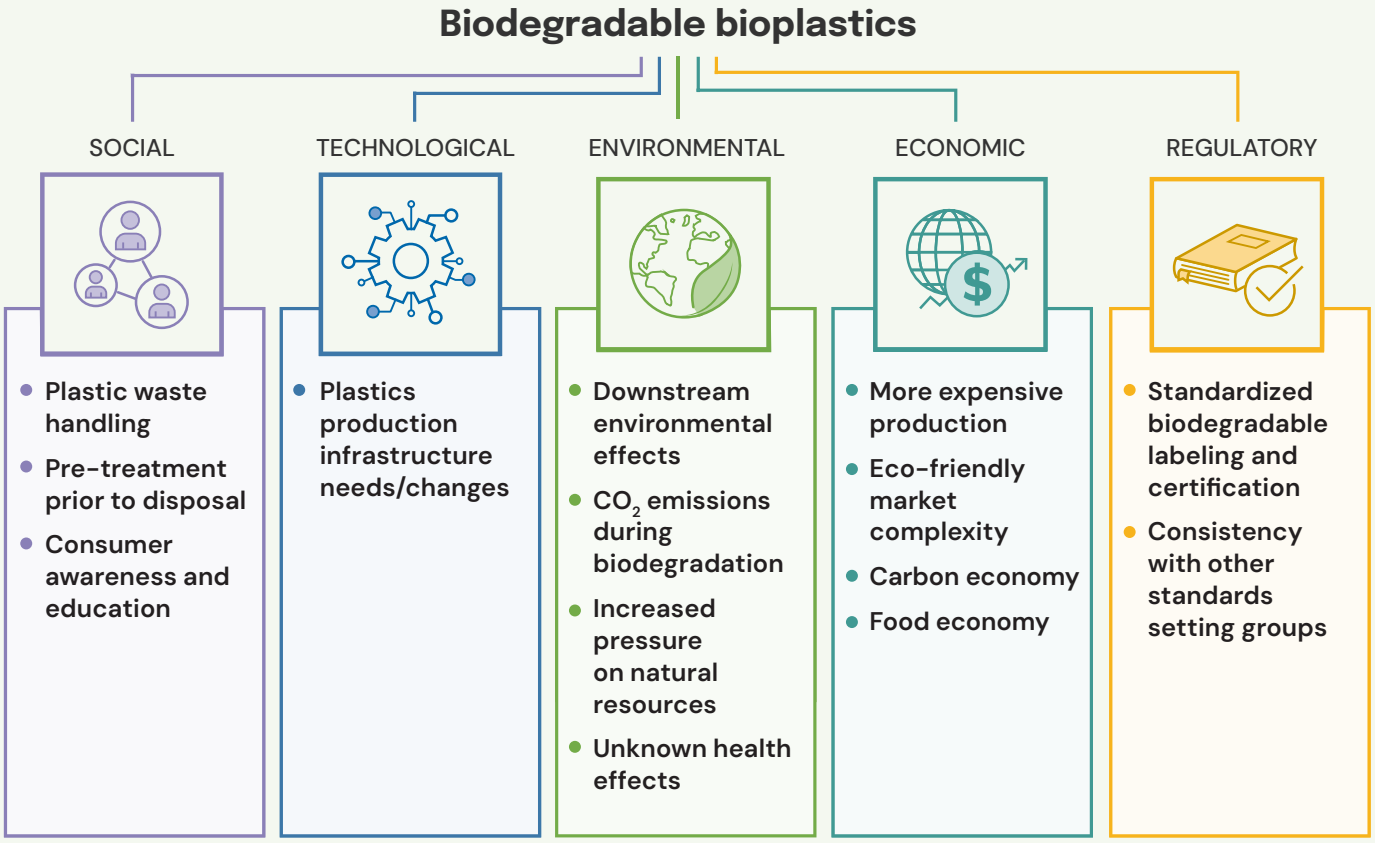
In 2024, researchers reported successfully creating a modified version of PLA that is capable of self-biodegrading in home compost conditions within 6 months.[27] The researchers genetically engineered an enzyme—a specialized protein—to break the chemical bonds that are specifically found in PLA. The enzyme was first incorporated into a separate biodegradable plastic and then blended with PLA to create what the researchers call "enzymated PLA." Bioplastic films made from enzymated PLA fully degraded within 6 months in home composting conditions in contrast to normal PLA which is only compostable in industrial conditions as discussed above. Enzymated PLA also does not need any external microbes to biodegrade since the biodegradation mechanism is inside the plastic, possibly increasing the range of environments that PLA can biodegrade in. Finally, the researchers also showed that, even though the bioplastic is capable of self-degradation, it was shelf-stable in storage for over 18 months.

Home compostable biobased polyurethane

In 2024, researchers reported successfully home composting microplastics generated from a biobased thermoplastic polyurethane (TPU)—a flexible, meltable plastic that can be used for cellphone cases or waterproof fabric coatings, among other things—in a little over 6 months.[28] Results showed that 97 percent of bioplastic-generated microplastics biodegraded after 200 days of composting due to certain bacteria present in the compost. In contrast, microplastic particles generated from a non-biodegradable thermoplastic did not significantly biodegrade after 200 days. These researchers also created a phone case using their TPU bioplastic and found that, while it showed some evidence of biodegradation with composting, the phone case had not completely degraded even a year later. Thus, it may be important to shred or mechanically preprocess a biodegradable bioplastic before composting to enhance the rate of biodegradation.

Implications

We highlight implications of biodegradable bioplastics below and describe three selected implications in more detail.



Source: GAO (icons). | GAO-25-107542

Downstream environmental effects and CO_2 emissions during biodegradation

Having "bio" as a prefix does not necessarily mean that a product is universally better for the environment. Even with biodegradable bioplastics, there are tradeoffs that need to be considered. For example, biodegradable bioplastics and resulting microplastics often break down into biomass and CO_2 more quickly than conventional plastics. One benefit is that microplastics may not linger in the environment if the biodegradable bioplastic has been appropriately disposed of. One downside is that CO_2 release or acid byproducts from bioplastics undergoing biodegradation in the ocean may increase ocean acidification. When considering the utility and implementation of biodegradable bioplastics, it is important to consider life cycle implications, their timescales, and ensuring that any resulting byproducts are biocompatible—compatible with and not toxic to living systems.

Eco-friendly market complexity

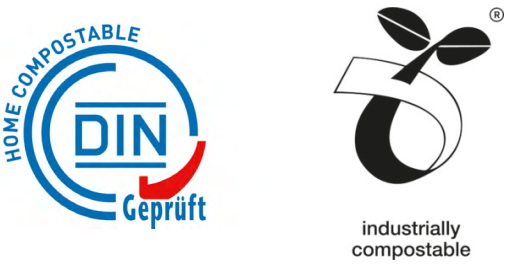
There are many products marketed as more environmentally friendly alternatives to conventional, fossil-fuel based plastics which can create a complex and confusing market for a consumer to navigate and make choices in. For example, there may be certain sectors in which it might make more sense for a consumer to acquire a plastic-free alternative (e.g., glass containers instead of plastic), certain sectors where it might make more sense for a recycled plastic alternative (e.g., bottles made from recycled plastic), and certain sectors for a biodegradable bioplastic alternative (e.g., single use plastics). Each of these alternatives to fossil-fuel based plastics come with their own set of benefits and challenges, and there may be substantial burden on consumers to stay adequately informed as to which purchase may be the best in certain instances.

Potential Considerations for Policymakers

Potential considerations for policymakers as new biodegradable bioplastics are developed and enter the market include clarity on biodegradability and consumer education. Policymakers may consider whether greater clarity regarding proper disposal of products marketed or labeled as "biodegradable" or "compostable" may help ensure that biodegradable bioplastics, including those newly developed, are disposed of as intended. For example, some products marketed as biodegradable may degrade in home compost or may only degrade under industrial composting conditions. This could create confusion for consumers who may want to properly dispose of biodegradable bioplastic waste but may not be able to accurately determine the appropriate conditions to dispose of that bioplastic or access those conditions.

Because of this confusion, some states have begun to implement limitations on the use of "biodegradable" on plastic products and the Federal Trade Commission (FTC) has guidelines that certain label claims of "compostable" should be qualified. Policymakers could consider whether it would be helpful to create additional standards or other methods to minimize consumer confusion. For example, some independent standardization and certification organizations, including at least one in the United States, have developed individualized labels that clarify the conditions that a product is biodegradable in. These labels provide quick ways of determining if a product is degradable in conditions such as industrial compost, home compost, soil, or marine environments (see fig. 7).

Figure 7: Selected Certification Marks for Compostable Materials



Source: DIN Certco; European Bioplastics. | GAO-25-107542

Because consumer decisions play a key role in furthering the viability of new biodegradable bioplastics in the market, consumer education and awareness of biodegradable bioplastics may also be important. Consumers may see a "biodegradable" or "bioplastic" label and assume that it means the product will naturally decompose in a trash bag, when, in fact, it may need to be pre-treated and composted. Other consumers may purchase a biodegradable bioplastic and instinctively place the bioplastic waste in a recycling bin which may cause contamination in plastic recycling facilities if it is not an easily recycled material. As biodegradable bioplastics enter larger parts of the market, policymakers may consider how educating consumers may impact proper bioplastic waste handling and prevent the "green paradox." The green paradox describes the risk of some consumers purchasing more of an eco-friendly solution than they need, thereby potentially negating some of its eco-friendly effect. In the case of biodegradable bioplastics, this may mean that consumers exclusively purchasing single use biodegradable bioplastics for the prevention of environmental microplastics, instead of purchasing reusable goods, may lead to increased CO_2 emissions. If the production of CO_2 from a large number of biodegrading bioplastics is faster than what nature can capture, there may be net CO_2 emissions from biodegradable bioplastics as a result.

Plastic drinking straws, one possible application for biodegradable bioplastics.

Source: Vanchuree/stock.adobe.com. | GAO-25-107542

Endnotes

[1]GAO previously reported on CRISPR gene editing. See GAO-20-478SP *CRISPR Gene Editing*. New tools include prime editing which only cuts one of the two DNA strands while CRISPR cuts both DNA strands at the place they make an edit. By only cutting one strand, prime editing avoids generating unwanted mutations that happen during repair of the CRISPR cuts in both DNA strands. This makes prime editing more precise and flexible than CRISPR.

[2]*FDA Approves First Gene Therapies to Treat Patients with Sickle Cell Disease*. U.S. Food and Drug Administration News Release. December 8, 2023. See https://www.fda.gov/news-events/press-announcements/fda-approves-first-gene-therapies-treat-patients-sickle-cell-disease.

[3]The First Chinese Edited Babies: A Leap of Faith in Science. 2019. JBRA Assisted Reproduction 2019;23(3):197-199. Some researchers speculate that the modification may have been a human enhancement to create better memory and higher IQ. The results of this work seem to indicate one twin may not be resistant to HIV infection, but the other twin may be resistant (see https://www.science.org/content/article/did-crispr-help-or-harm-first-ever-gene-edited-babies).

[4]Clinical trials are underway for gene editing therapies to treat a variety of cancers and other diseases, including high cholesterol and diabetes. Further, preclinical gene editing research continues to treat cystic fibrosis, Alzheimer's, and other diseases.

[5]Annual appropriations acts have included restrictions on the use of federal funding for heritable gene editing. See e.g., Consolidated Appropriations Act 2024 Pub. L. No. 118-42, 138 Stat. 25, 110 (2024).

[6]Vertex Pharmaceuticals set the price of Casgevy® at $2.2 million. Costs for other gene therapy treatments that do not involve gene editing range from $373,000 to $3.5 million (see Witkowsky, L., M. Norstad, A. R. Glynn, and M. Kliegman. "Towards affordable CRISPR genomic therapies: a task force convened by the Innovative Genomics Institute." *Gene Therapy*, vol. 30 (2023): 747-752).

[7]One expert we spoke with indicated the costs for future gene editing therapies could decrease to less than $100,000.

[8]A rare disease is a disease or condition that affects less than 200,000 people in the United States. See Orphan Drug Act, P.L. 97-414, 96 Stat. 2049 (1983) as amended, (codified at 21 U.S.C. § 360ee).

[9]State or non-state entities such as violent extremist organizations and transnational criminal organizations could potentially use gene editing to enhance the performance of military personnel or develop new types of biological weapons using genetic engineering. See GAO's report entitled *National Security: Long-Range Emerging Threats Facing the United States As Identified by Federal Agencies* (GAO-19-204SP). The World Anti-Doping Agency (WADA) defines gene doping in sports as "The non-therapeutic use of cells, genes, genetic elements, or of the modulation of gene expression, having the capacity to enhance athletic performance."

[10]Microgravity is the condition in which people or objects appear to be weightless because they are in free fall. The effects of microgravity can be seen when astronauts and objects float in space.

[11]Semiconductors, sometimes referred to as integrated circuits or microchips, are made from pure elements, typically silicon or germanium, or compounds such as gallium arsenide. The production of semiconductor crystals is the initial step in the complex manufacturing of semiconductor devices within a microchip. In this report, when we describe semiconductor manufacturing, we are only describing the growing of semiconductor crystalline materials.

[12]6G is the sixth generation of wireless mobile network standards, expected to operate on higher radio frequencies than 5G, delivering data rates up to 20 times faster, with significantly lower latency—the time it takes for information to travel from its source to its destination—at microsecond timescales, according to one estimate. GAO has several publications on artificial intelligence and quantum computing technologies. GAO, "Artificial Intelligence," (Washington, D.C.), accessed September 5, 2024, https://www.gao.gov/artificial-intelligence; and Quantum Computing and Communications: Status and Prospects, GAO-22-104422 (Washington, D.C.: Oct. 19, 2021).

[13]Hannah Wright et al., "An Analysis of Publicly Available Microgravity Crystallization Data: Emergent Themes Across Crystal Types," *Crystal Growth & Design*, vol. 22, no. 12 (2022): 6849–6851.

[14]Jessica Frick et al., "Semiconductor Manufacturing in Low-Earth Orbit for Terrestrial Use," November 2023.

[15]Jessica Frick et al., "Semiconductor Manufacturing in Low-Earth Orbit for Terrestrial Use."

[16]Extended reality—which includes augmented, mixed, and virtual reality, combines the real and digital worlds to create new kinds of interactivity and perception. GAO, *Science & Tech Spotlight: Extended Reality Technologies*, GAO-22-105541 (Washington, D.C.: Jan. 26, 2022).

Endnotes (continued)

[17]Manufacturing semiconductor chips in space could significantly reduce production time compared to Earth-based methods, where a product might travel 25,000 miles before completion. In contrast, manufacturing in an orbiting facility would allow 50 round trips to and from the facility in the same amount of time required by Earth-based manufacturing, speeding up chip delivery. Jessica Frick et al., "Semiconductor Manufacturing in Low-Earth Orbit for Terrestrial Use," November 2023.

[18]Carlo Menon et al., "Biomimetics and robotics for space applications: challenges and emerging technologies," 2007 IEEE International Conference on Robotics and Automation - Workshop on Biomimetic Robotics.

[19]Earth-based semiconductor production contributes to air pollution and greenhouse gas emissions. In contrast, manufacturing in space could reduce these environmental impacts. Additionally, utilizing solar energy in space could further decrease reliance on fossil fuels for energy generation. Jessica Frick et al., "Semiconductor Manufacturing in Low-Earth Orbit for Terrestrial Use," November 2023.

[20]GAO, *Large Constellations of Satellites: Mitigating Environmental and Other Effects*, GAO-22-105166 (Washington, D.C.: Sept. 29, 2022).

[21]GAO-22-105166.

[22]The Federal Aviation Administration (FAA) and the Federal Communications Commission (FCC) have proposed or adopted rules regarding orbital debris. For example, to limit the growth of orbital debris, the FAA proposed that upper stages of commercial launch vehicles and other components resulting from launch or reentry be removed from orbit within 25 years after launch, either through atmospheric disposal or maneuvering to an acceptable disposal orbit. See 88 Fed. Reg. 65835 (September 26, 2023). Similarly, to minimize the risk of collisions that would create debris, the FCC adopted a rule requiring operators planning to dispose of a space station in low-Earth orbit through uncontrolled atmospheric reentry to do so within 5 years of mission completion. See 47 C.F.R. 25.114(vii)(D)(1).

[23]European Bioplastics, *Bioplastics Market Development Update*, 2023.

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[27]Guicherd, M. et al., "An engineered enzyme embedded into PLA to make self-biodegradable plastic," *Nature*, 2024.

[28]Allemann, M. N. et al., "Rapid biodegradation of microplastics generated from bio-based thermoplastic polyurethane," *Scientific Reports*, 2024, 14, 6036.

Image sources

Unless specified, all other graphics in this report were created by GAO.

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