On Mars as it is on Earth: Bioinspired technologies for sustainability on Earth are paving the way for a new era of space exploration

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ABSTRACT

This Perspective explores the synergy between bioinspired technologies for sustainability on Earth and their application in space exploration. We focus on the parallels between the paradigm shift toward sustainable development on our planet and establishing permanent human settlements on Mars and the Moon. Informed by Earth's ecological and technological progress, which emphasizes the critical need for efficiency and integration with the planet's metabolic processes, the discussion revolves around the challenges and opportunities in creating self-sustaining communities in space. Specifically, the focus is on the central role that bioinspired materials, particularly bioinspired chitinous materials, will play in developing sustainable manufacturing practices on Earth and in extraterrestrial environments. Considering the development of bioinspired chitinous manufacturing in the last decade, we argue that we are witnessing the birth of a new manufacturing paradigm embracing efficiency, resilience, and ecological cycles inspired by biological systems, which will be essential for sustainable living on Earth and advancing a new age of space exploration.

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FROM MASS PRODUCTION TO MARS PRODUCTION

A profound shift in space exploration initiatives has occurred in recent years, marked by a growing emphasis on establishing an ongoing human presence on celestial bodies, such as Mars and the Moon.[1] This is a pivotal episode in human exploration, marking a profound departure from traditional space endeavors, such as last century's brief lunar missions. It also aligns with the broader objective of making humanity a multi-planetary species, providing long-term platforms for scientific research and necessary stepping stones for future missions deeper into the cosmos. This represents the next chapter of humanity, wherein the "final frontier" is visited, inhabited, and explored in a manner that extends our presence beyond the confines of our home planet.

In this new stage of space exploration, the Moon, the closest celestial body and a "gateway"[2] beyond Earth, will be the site of the first grounded colony outside Earth. NASA's Artemis program and similar plans from Europe, China, and Russia aim to return astronauts to the Moon and establish permanent outposts on its surface by 2028.[3] Using lunar resources will be integral to enabling this prolonged presence by reducing the burden of transporting goods from Earth.[4] However, due to its relative closeness to Earth, a colony on the Moon does not need to be as independent from Earth as future colonies on other planets, hence providing an ideal testbed for developing the technologies and strategies required for human settlements on more distant worlds. The first of these distant settlements will be on Mars, a goal already in development and becoming increasingly feasible as NASA's perseverance rover and the upcoming Mars sample return mission help advance our understanding of the Martian environment and the potential of its resources to be implemented in self-sustainable production systems.[5] The goal is to make these settlements self-reliant and economically sustainable by producing efficient systems that reduce or eliminate the unfeasible transport of supplies from Earth, a task limited by narrow launch windows and the high logistics cost of interplanetary transportation.[6]

The self-reliant settlement on Mars would need to adapt to the planet's unique conditions. The Martian atmosphere, composed of

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0.13% oxygen and 95.32% carbon dioxide, has an oxygen concentration two orders of magnitude lower than that enabling human respiration. Yet, photosynthetic plants or solid oxide electrolysis could harness the abundant carbon dioxide to produce oxygen.[7] Similarly, the thin Martian atmosphere provides limited protection against radiation, restricting outdoor, above-ground exploration, suggesting that possible settlements would need to use the planet's extensive caves and lava tubes.[8] Water, an essential element for life, is absent from the dried-out ancient Martian rivers but so abundant under the soil as large pockets of ice that, if melted, could cover the entire planet with a 2 m deep layer of water.[9] Solar radiance has proven enough to power human exploration despite Mars being 1.5 times further from the Sun than Earth.[10]

Beyond the adaptation to planetary conditions, additional challenges distinct from traditional short-term missions remain. A persistent human presence necessitates the establishment of enduring, self-sustaining communities on these extraterrestrial bodies.[11,12] These communities would require using local resources to build the necessary infrastructure to support life over extended periods, if not indefinitely, including habitats, life-support systems, and sustainable sources of food, water, and energy[13–15] (Fig. 1). Modern societies have become heavily reliant on materials such as cement, metals, and polymers. These materials are not readily available on extraterrestrial bodies, are extremely energy-intensive to produce, and would face drastically different operating conditions, such as off-gassing, sublimation, low temperatures, and accelerated UV degradation. The food consumed and its sourcing methods would also need significant changes due to the limited artificial land created for biological life.[16]

Interestingly, as we gain an understanding of the formidable obstacles and complexity of the technologies necessary for establishing a sustainable and resilient system supporting human activities with the limited resources of Mars, the clearer their resonance with the needs and problems we are currently facing in our attempts to overcome the mounting ecological challenges on Earth.

Historically, human development has been grounded in the misguided belief in inexhaustible resources, leading to the current development model that disregards the natural ecological cycles

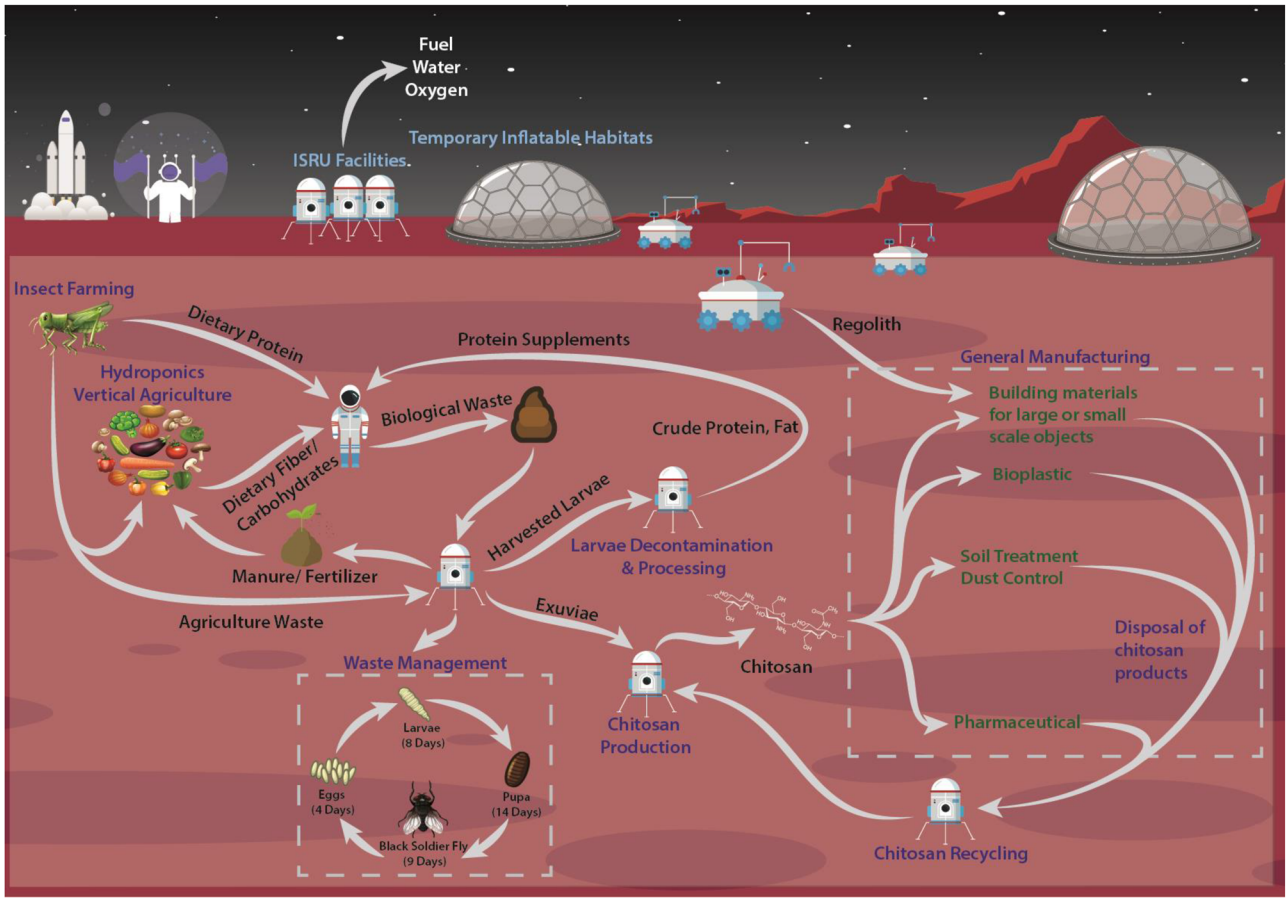


FIG. 1. A closed ecosystem on Mars. *In situ* resource utilization (ISRU) is a critical component for the colonization of Mars, utilizing resources found or manufactured on the planet to replace materials that would otherwise be brought from Earth. The development of ISRU must be linked to the creation of self-sustaining almost zero-waste circular systems that can operate independently of Earth. These systems must incorporate human activity, enhancing their efficiency and reducing the need for resupply missions.

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of our planet and their limitations.[17] The consequences are evident in the depletion of primary resources and the accumulation of waste. While resource depletion can be understood as the consequence of overgrowing our planet's potential, waste is a clear indicator of the disregard for efficiency in our economy and production models.[18] As we develop on the shoulders of inefficient systems, waste production escalates proportionally, propelled by population growth, urbanization, and consumerism. In addition, until very recently, waste management strategies have exclusively focused on their integration into the linear production models that drive our economy, emphasizing waste disposal through landfilling and incineration, exacerbating the depletion of resources and contributing to environmental degradation.

However, a growing shift toward circular economy paradigms, expanding on the principles of reduce, reuse, and recycle, reflects an evolving perspective on waste.[19] The convergence of technological innovation, policy initiatives, and public awareness is shaping a new era in waste management, wherein waste is viewed not as a burden but as a potential resource. Despite this, the problem of waste generation is expected to worsen as the current path toward economic development increases the demand for resources and consumption. By 2050, global annual waste generation is projected to rise to 3.4×10^9 tons, a 70% increase from 2016. A significant contributor to this increasing waste is the group of polymers defining our current technological age and known generically as "plastic." Despite their numerous benefits, unlike the degradable components of waste, most plastics persist in the environment, a "curse" of their outstanding durability.[20] Therefore, the staggering 250×10^6 tons of plastic waste produced annually only accumulate, becoming an increasingly large disruptor of ecological cycles.[21]

Our inability to tackle the problem of waste, in general, and plastic waste, in particular, despite the growing awareness and work being done by society, businesses, and governments, cannot be entirely blamed on insufficient effort since there is limited potential in the current approach. Even in a hypothetical scenario wherein the most aggressive policies for waste reduction are enforced globally, they would only compensate for increasing urbanization and development, resulting in the same amount of plastic waste accumulating in the environment we have now (Fig. 2).[22]

The main limitation of the current approach is that it is based on the implicit assumption that our current manufacturing paradigm, strongly defined by plastic manufacturing, is the technological peak of humanity. Therefore, sustainability is approached as the need to compensate for this unavoidable manufacturing paradigm. As a result, the focus on policies and education is often resisted due to incompatibility with existing industrial or personal habits, while the increasingly complicated waste recovery processes cannot cope with production, requiring resources and infrastructure beyond the economically feasible.[18] Considering the current trend and state of the planet, the transformation into a sustainable society might seem to be an unreachable goal, just like becoming an interplanetary species.

Despite the challenging outlook, our history has been defined by rapid societal, economic, and technological leaps—similar to the one required now—arising from the continuous discovery and mastery of materials.[23] Harnessing stone, bronze, iron, and, recently, plastic resulted in an explosion of new technological possibilities and the transformation of human habits and organization. More importantly, these transitions to a new paradigm were fueled by novel

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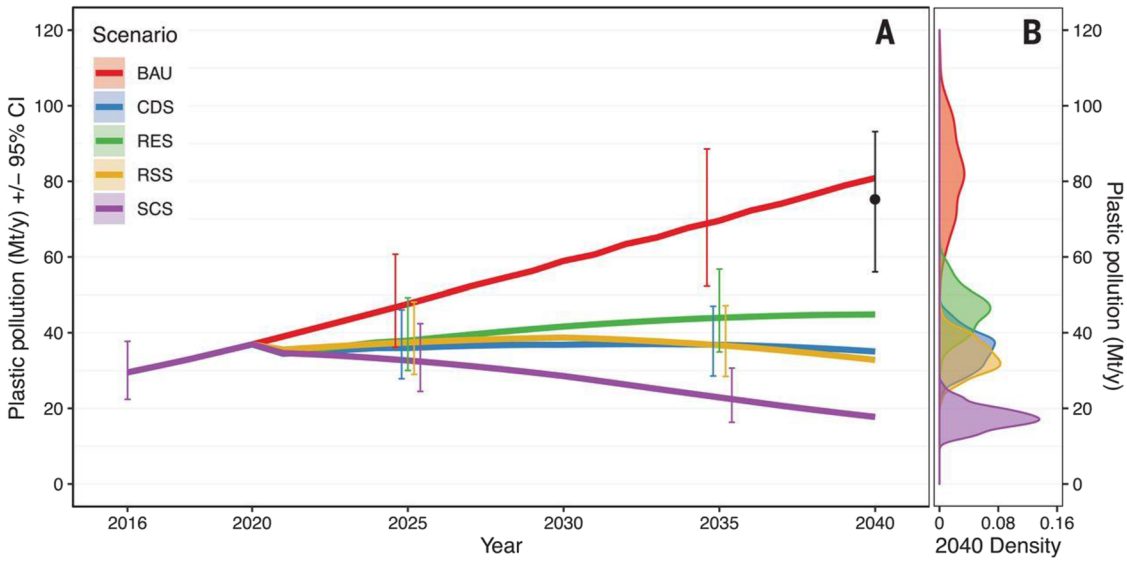


FIG. 2. Our waste problem. Time series of plastic pollution, measured in million metric tons per year (Mt/y; ±95% CI), entering aquatic and terrestrial ecosystems from 2016 to 2040. The scenarios depicted include Business as Usual (BAU), Collect and Dispose (CDS), Recycling (RES), Reduce and Substitute (RSS), and System Change (SCS). The pollution rates for all scenarios are identical between 2016 and 2020. While the theoretical scenario of implementing all feasible interventions could reduce plastic pollution by 78% relative to business as usual in 2040, that would still leave 710×10^6 metric tons of plastic waste in the environment. Image reproduced with permission from Lau *et al.*, Science **369**(6510), 1455–1461 (2020). Copyright 2020 AAAS.

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possibilities rather than a transformation or forced abandonment of existing practices.

Similarly, the future of sustainable manufacturing will not emerge as a mere modification of the paradigm created by plastics or from new materials developed to be integrated into the existing methodology and principles. The radical transformation required to achieve a sustainable society must emerge through the mastery of innovative materials, defining a fresh paradigm based on efficiency and integration with Earth's metabolism.[24,25] Predictably, materials that coordinate with biological systems are already functioning efficiently within them.

BIOINSPIRED CHITINOUS MANUFACTURING

The remarkable qualities exhibited by materials such as spider silk,[26] nacre (i.e., mother pearl),[27] mammalian bones,[28] and balsa wood[29] have long captivated the scientific community. These natural materials seamlessly integrating into Earth's ecological cycles possess exceptional mechanical properties, such as strength, toughness, and impact resistance, that often surpass those of their synthetic counterparts. These properties are even more extraordinary when we consider that these materials are made in extreme conditions of energy scarcity, and the choice of constituents is primarily driven by their prevalence rather than their inherent mechanical properties. This accomplishment is achieved through their hierarchical design, which spans from the molecular to the macroscopic levels,[30] an organizational principle that humanity has yet to replicate comprehensively (Fig. 3). We excel at fabricating materials and structures at specific scales, from the nanometric to the massive, but we struggle to synthesize materials with coordinated control across multiple length scales of organization. However, it is this simultaneous coordination at multiple length scales that natural systems have evolved the most and enabled them to produce materials of extraordinary structural properties with limited resources. Our inability to replicate this assembly of materials restricts the artificial use of biological materials to bulk composites that do not require the dissociation and reconstruction of their hierarchical organization for their use.

A decade ago, we formulated a hypothesis that became the cornerstone of our research: biological materials and their assembly mechanisms evolve in tandem.[31] To harness these materials for engineering applications without removing them from biological cycles, possessing the constituent ingredients is insufficient; we must replicate the assembly processes that have evolved over time. We turned to the insect cuticle as our model to prove this concept. Insect exoskeleton, the cuticle, serves as a protective shell that ranges from rigid wings to flexible joints. To reproduce it, we extracted fibroin

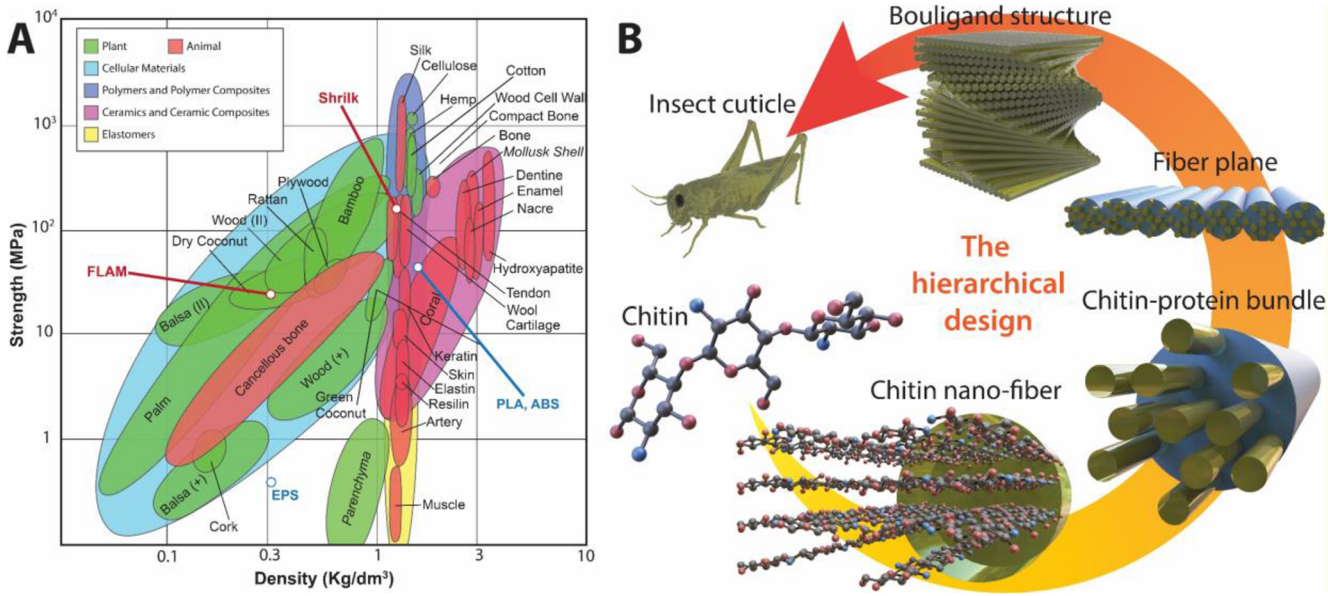


FIG. 3. Ashby plot of biological materials and hierarchical design. Biological materials have properties that range from the extreme impact resistance and toughness of bones and nacre to the combination of strength and lightness of balsa wood and the extreme strength of silk fibers (a). More importantly, these materials are made in extreme conditions of scarcity using only ubiquitous components that mostly have irrelevant mechanical properties on their own and in the absence of significant sources of energy enabling, for example, the temperatures necessary for changing the state of materials. Biological systems achieve these extraordinary properties in adverse conditions through the fine control of organization across many scales. The diagram on the right (b) represents some of the distinct levels of organization of hierarchical design, giving rise to the chitinous cuticle in insects. The chitinous polymers assemble in an antiparallel α-chitin crystal arrangement to create nano-fibrils. These nano-fibrils form bundles aggregated together with proteins with a composition similar to that of the fibroin in spider silk and different degrees of mineralization. The bundles are secreted parallel to each other in a 2D structure. This process is repeated, stacking a structure layer by layer, wherein each layer has a relative rotation of 10°–15° with respect to those above and below. However, small variations of this organization give rise to entirely different properties, enabling the production of various functionalities, such as the stiffness necessary in the wings to enable flight or the elasticity in the joint to enable jumping, with a single synthesis process and at minimum metabolic cost. The Ashby plot has been adapted from the work of J. G. Fernandez and D. E. Ingber, Adv. Funct. Mater. **23**(36), 4454–4466 (2013). Copyright 2013 Wiley-VCH GmbH.

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from silk and chitin from shrimp shells and combined them to create a material called "Shrilk" (shrimp + silk).

Shrilk represented a significant advance in the field of biomaterials. The unprecedented strength and toughness achieved with unmodified natural components were in the range of those of aluminum alloys but with half their density. More importantly, it demonstrated the replication of the synergies between structural biomolecules and their arrangement, giving rise to the outstanding mechanical properties of natural materials. When the chitosan and fibroin of Shrilk were blended, they yielded a material with predictable properties, showing strength greater than the weakest component but weaker than the strongest. Yet, the truly remarkable aspect of Shrilk is revealed when these components are artificially arranged in a manner akin to their natural configuration within the cuticle, a situation wherein their combined strength doubles compared to the strongest component in isolation. This unique property showed the potential of biomimetic engineering to utilize unmodified biological molecules, preserving their integration into Earth's ecological cycles in engineering applications. The key to this process is not the molecular structure itself but its association with the design and methodologies natively connected with it.

In pursuit of Shrilk, we strived not just to mimic nature but to understand and replicate the principles of hierarchical organization. We further developed this approach a few years later when we created a complete methodology for using chitinous polymers as plastic substitutes (Fig. 4). Interestingly, the material also retained its natural ability to produce topographies at the micro- and nanoscale, enabling tuning of the optical and wettability characteristics and providing secondary functionalities to products made of chitin. This ability of chitinous polymer, which is responsible in nature for

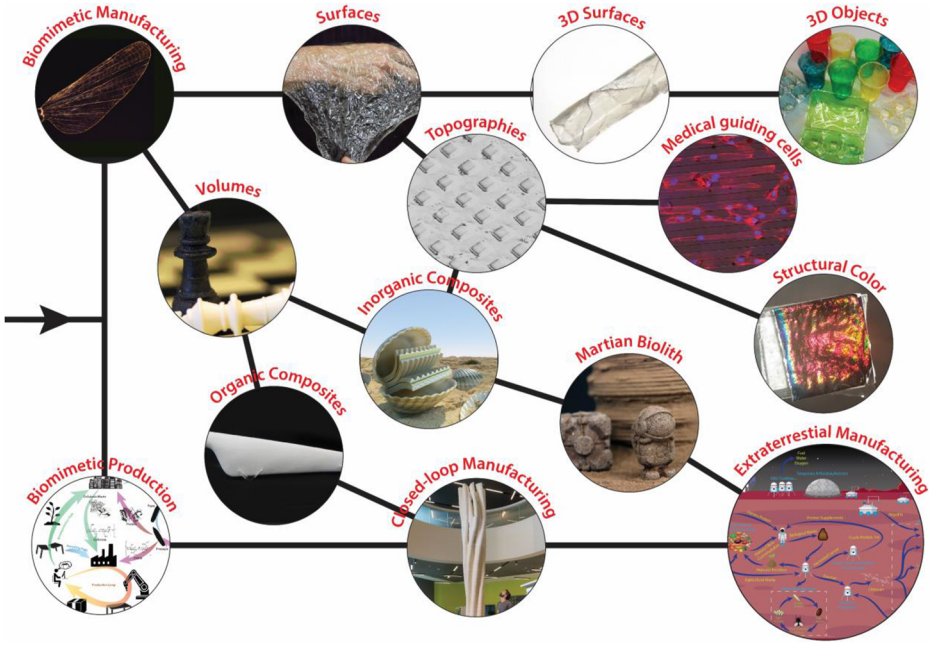


FIG. 4. The development of bioinspired chitinous manufacturing. While chitinous polymers were first described more than two centuries ago and their ability to be dispersed and vitrified in organic solvents was known for several decades, it has not been until very recently that attempts were made to reproduce their native mechanical properties by **biomimetic manufacturing** associating them with their natural designs.[33] This enabled the reproduction of the synergies between the components of the insect cuticle for the first time and the production of strong materials and large **surfaces**.[31] Additionally, chitinous polymers have been demonstrated to form **3D surfaces** artificially,[34] which were first reported for their use in medical applications but extended to the production of **3D objects** in general manufacturing.[35] Chitinous polymers retain their ability to form complex **topographies** at the microscales[36] and nanoscales[37] after their isolation from their natural source, a property animals use to explore surface functionalities, such as those of the arthropod cuticle. Because of the material's biocompatibility, this ability to form topographies is used to drive the behavior of cells in **medical devices**[34] and, in a more general context, to reproduce the **structural color** of arthropods (e.g., butterfly wings) in product manufacturing.[38] In natural systems, chitin tends to form the thin outermost structural layer of an organism. To explore the formation of thicker structures, achieve novel mechanical properties, and lower the metabolic cost, chitinous polymer often associates with other components to form structures with large **volumes**.[35] Using the ability of the material to form topographies, the nanoscale features contributing to nacre's extraordinary toughness can be reproduced artificially and combined with external mineralization to create complex **inorganic composites** with novel mechanical properties.[39] Similarly, the combination with cellulose enables the reproduction of an oomycete wall in **organic composites** called fungal-like adhesive materials,[40] which have enabled the generalization of bioprinting with unmodified natural molecules at an unprecedented scale. In parallel to the development of biomimetic manufacturing, the development of **biomimetic production** of the necessary materials for such technologies enabled their combination to create closed-loop manufacturing systems as a part of the surrounding ecological cycles, including those in urban environments.[41] When the same principles of ecological integration are combined with the production of chitinous inorganic composites, it enables the development of **closed-loop manufacturing** in the absence of large biomass sources and, in particular, using the inorganic regolith on Mars' surface to make the so-called **Martian biolith**.[42] Despite the completely different availability of resources, similar to the case on Earth, **extraterrestrial manufacturing** should be integrated as part of the ecological cycles supporting human life.

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striking effects, such as the color of butterfly and moth wings, enabled the artificial production of objects with different mechanical properties and surface functionalities using a single material.[32]

The selection of chitin for bioinspired product manufacturing was not arbitrary. Shrilk has been used in dozens of medical applications,[43] such as contact lenses,[44] bandages,[45] and tissue engineering scaffolds,[46] in which biocompatibility takes priority over the cost and scale of the material. However, the general applicability of Shrilk at a large scale was hampered by a design focused on demonstrating for the first time the reproduction of the synergies of a biological composite by artificially matching its design and composition. The cost, complexity, production limitations, and environmental impact of fibroin extraction (requiring lithium bromide for its dissociation) made Shrilk a material that, by design, was limited to niche applications. In contrast to fibroin, chitin is the second most abundant polymer on Earth, surpassed only by cellulose. Despite the significant difference in the scales of their industrial use, chitin shares many chemical and functional characteristics with cellulose, and it is produced in large amounts in every ecosystem, making it a suitable candidate to replace plastics in large-scale applications.

However, unlike plastics, chitin does not exhibit a melting point, and therefore, it cannot be used in most mass manufacturing processes developed for thermoplastics. On the other hand, when compared with cellulose, the most prevalent material for manufacturing structural components, the processing of chitin is much easier when it is produced with a high degree of deacetylation (i.e., chitosan), such as that synthesized by fungi or extracted from crustaceans, as it can be dispersed in a weak organic acid,[47,48] such as low non-toxic concentrations of acetic and formic acids. In contrast, cellulose requires solvents, such as *N*-methylmorpholine-*N*-oxide (NMMO) or dimethyl sulfoxide (DMSO), that are usually flammable, corrosive, carcinogenic, or mutagenic to disrupt the strong intermolecular bonds. Therefore, cellulose products are limited in their use because of the controlled environment and waste processing required for their production and the potential for the solvents to remain in the final product, leaching out over time.

Despite chitin's environmental advantages and the fact that it is the recurrent functional solution in nature in many of its most outstanding structures, such as the exoskeletons of arthropods and the cell walls of fungi, the chemical composition and high nitrogen content of chitin and chitosan are the basis of their leading industrial uses, such as in fertilizers and pesticides in agricultural applications or as food and cosmetics additives. In 2013, we demonstrated that chitosan, if precipitated in a hydrated crystal conformation similar to that in natural systems, can form the structural part of complex forms and products.[35] The premise of that work diverged from the usual approach to bioplastics followed up to that point, in which the objective was to preserve extant manufacturing principles and strategies based on thermoplastics and modify the biomaterial chemistry to conform to those principles, a process in which the material loses its initial integration in ecological systems and requires specialized facilities and recovery strategies for reintegration into nature. In stark contrast, the principles of chitosan manufacturing were based on keeping the molecule in its natural form and, therefore, seamlessly integrated into Earth's ecological cycles and used a bioinspired manufacturing strategy based on reproducing the biological principles of natural chitinous structures.

Chitin is found in many organisms' external skin and cuticles and, when regenerated artificially, retains its tendency to produce films and three-dimensional surfaces.[34,49] This natural ability of chitosan to form surfaces contrasts with the difficulty in producing 3D objects, as the process of water exchange necessary to precipitate the polymer becomes increasingly difficult with a lesser specific surface area for evaporation, while bulk material volume increases. With this limitation in mind, we embarked on the generalization of the production of chitinous objects by developing materials that, while preserving the principles of bioinspired manufacturing (i.e., no modification of the molecule and its association with its native methodologies and designs), were suitable to form bulk 3D objects. The result of that development was fungal-like adhesive materials (FLAMs), which are composed of a blend of chitin and cellulose, two natural polymers found in the cell walls of fungi and plants, respectively, but that rarely appear together with the notable exception of water molds' walls (i.e., oomycetes).[40,50] The process of producing FLAMs involves introducing small amounts of chitin between cellulose fibers, replicating the structure found in the walls of oomycetes, resulting in a strong, lightweight, and inexpensive material that can be molded or processed using woodworking techniques. To avoid the drawbacks of using cellulose at a dissociation level beyond the micrometric fibers (i.e., use of strong organic solvents), FLAM employed cellulose fibers obtained just by mechanical means, avoiding chemical processes harmful to health and the environment required for their further dissociation to the molecular level.

One of the main limitations of working with chitinous polymers and their composites is the lack of advanced techniques centered on using biopolymers for large-scale manufacturing due to the almost unique focus on product manufacturing with thermoplastics in the last century. FLAMs were developed in parallel with production tools created from scratch within the paradigm of bioinspired manufacturing, ranging from new modeling tools based on machine learning that are specifically designed to model structures formed through water exchange[51,52] to production tools based on robotics adapting in real time to the variability of biological materials.[53–55] Notably, the development of FLAMs preserved the central premise of our work with chitinous polymers, avoiding the adaptation of the materials to the principles of synthetic materials and adapting the manufacturing to the principles of biology,[56] thereby preserving their seamless integration into ecological cycles, be it in nature or purposefully recreated.

TOWARD EFFICIENCY: ECOLOGICALLY INTEGRATED MANUFACTURING ON AND BEYOND EARTH

Artificial manufacturing, in general, and the paradigm of plastic manufacturing, in particular, are firmly based on unlimited resources and energy principles, relying on high pressure and temperature to construct intricate structures with materials produced specifically for the task through globalized supply chains. In stark contrast, biological systems are developed in a paradigm of scarcity, in terms of both energy and resources, developing systems wherein their resilience is based on their manufacturing efficiency and ubiquitous components. This development driven by an evolutive pressure toward efficiency is often called "the survival of the cheapest."[57] Biological systems do not have access to sources of energy enabling

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high temperatures, such as those required to melt plastics or metals, and cannot afford to develop systems and organisms that exist depending on the availability of rare components with unique characteristics. Natural systems utilize ubiquitous components of negligible mechanical significance and low-energy processes, primarily driven by water exchange and pH changes, to self-assemble structures with extraordinary mechanical characteristics based on abundant components.

The principles of manufacturing observed in natural systems provide a roadmap for developing a sustainable society, emphasizing the importance of employing readily available resources and low-energy processes, mirroring the cyclical nature of ecosystems and moving away from linear extractive methods. However, the journey toward sustainability is not merely about creating circular systems in isolation but about fostering systems that are globally integrated and considerate of the surrounding ecology.[58,59]

While circular production systems, where waste is eliminated and resources are continuously used and reused, are aligned with the principles of natural systems, they largely remain as measures isolated from their environment. A paradigmatic example is our plastic recycling concept, in which locally created circular systems in the technosphere are materially inert to the environment and, therefore, isolated from the surrounding biosphere. These systems require very specific local conditions and, when globalized, face the issue of waste management and collection that must scale up in parallel with production. As mentioned previously, this process is unfeasible even with aggressive policy changes.[22]

The true lesson from natural systems is not solely their basis in a local circularity but an extreme efficiency resulting from the competition for the energy and resources embedded in every object and the incorporation into systems across scales that together add up to a dynamically balanced equilibrium. We must adapt to the rules that have shaped the complexity we observe around us and create circular systems in our technosphere that are naturally integrated and synergistic with a surrounding local ecology.[60,61] This approach naturally minimizes environmental impact, reduces dependence on finite resources, and creates sustainable value by working with nature rather than separating from or acting against it. It is a fundamental shift that will foster systemic change from isolation to integration, extraction to regeneration, and waste to value.

This path for enabling the development of a sustainable society on Earth is the same that should enable the colonization of other planets, adding to the growing set of evidence that a new paradigm of manufacturing based on biological systems and their principles is both imminent and necessary not only to ensure our survival and well-being but also to develop as a scientific and technological society. The current manufacturing paradigm limits our ability to translate existing manufacturing models to space exploration.[56,62] Without additional complications in scenarios outside Earth, the inefficiency and lack of resilience of relying on complex logistical networks are becoming more evident as the global dependence on scarce and locally concentrated elements faces the consequences of pandemics, geopolitical tensions, and the blockage of crucial transit points (e.g., the Panama and Suez Canals). This inefficiency in the path a molecule follows to become a product not only hinders our sustainable development on Earth but also further advances into more sophisticated tasks, such as the extremely complicated process of supplying a Martian settlement.

Our results highlight how the bioinspired approach,[63] based on integration into existing ecologies, low-energy systems, and ubiquitous renewable materials, marks a new era of technology enabling achievements unreachable within the current manufacturing paradigm. These achievements, however, require the development of a paradigm around the material rather than adapting it to current practices, enabling an exploration of its full potential unbounded by the restrictions imposed by previous methodologies. In the case of ubiquitous natural materials in general and chitin specifically, their incorporation into current models of global supply chains demonstrated limited environmental benefits due to the impacts of transport.[64] However, this incorporation is unnecessarily borrowed from the current manufacturing approach, as large amounts of chitinous materials exist and can be produced locally anywhere, either as a by-product of existing industrial operations,[65,66] such as shrimp, crab, and insect protein productions, or through bioconversion techniques, including food waste processing.[41,67,68]

To demonstrate the potential of chitinous manufacturing when aligned with its associated supply and production chains, we showed that it can be incorporated into the ecosystem of a fully urban context (i.e., without primary industry) as part of its waste management system. FLAM was produced with chitin using black soldier flies (*Hermetia illucens*) as bioconverters to valorize food leftovers in Singapore. At the same time, discarded paper and carton were used as cellulose sources. The same experiment was also replicated in Italy, confirming that the production and characteristics of chitinous polymers for manufacturing are independent of climate or chitin source.[41] Discarding the preconceived system of globalized supply chains and associating biomaterials with their inherent regional nature enabled the minimization of transportation emissions and improved resilience based on decentralized sourcing (Fig. 5). This achievement was only possible due to the ubiquitous nature of the molecule and its seamless integration into a multitude of ecological cycles.

Similar to Earth's case, we applied the principles of bioinspired chitinous materials and manufacturing, initially developed for production within circular regional economies in urban environments,[41] to develop a composite with low manufacturing requirements, ecological integration, and versatile utility in a Martian environment.[42] However, as Mars is not characterized by abundant organic materials, Martian manufacturing strategies must capitalize on the inorganic components readily available in the regolith (i.e., loose mineral dust) of the planet's surface.[69,70] In this regard, the manufacturing methods used on Earth for inorganic materials are based on technologies developed for its bountiful paradigm and commonly characterized by processes involving elevated temperature and pressure,[69,71] polymers with complex and dedicated biosynthesis,[72] limited reclamation,[11] and niche use (i.e., lacking versatility).[73] Since any resource obtained on Mars comes at an opportunity cost, the sustainable production of these materials must be contextualized within a Martian ecosystem.[16,74]

To help achieve this objective, nature presents successful strategies of life adapting to harsh environments. In biological organisms, rigid structures are formed by integrating inorganic filler procured

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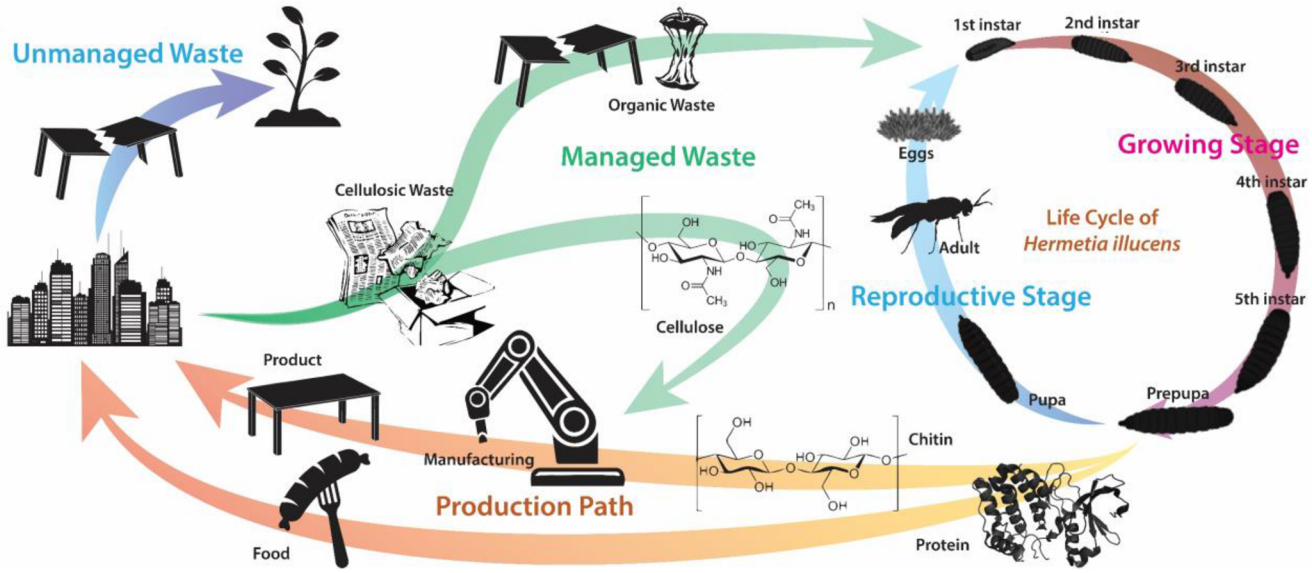


FIG. 5. Urban chitinous circular manufacturing. It illustrates a circular manufacturing system utilizing chitin-producing organisms found across various biological kingdoms for bioconversion. These organisms, including heterotrophs, such as fungi, arthropods, and annelids, are bioconverters of organic waste. Mollusks and even some vertebrates have also been found to produce chitin in small quantities. The black soldier fly (BSF, *Hermetia illucens*) is highlighted for its global popularity due to its efficient conversion of diverse organic materials into biomass, including urban and agricultural waste. Within 14 days from egg hatching to the prepupal stage, a BSF processes waste weighing 20 times its weight, reaching an average weight of 220 mg per individual. Chitin constitutes 6%–9% of its dry weight. This rapid bioconversion of a wide variety of organic materials into protein and chitin with consistent properties allows for its integration into tight circular production systems that combine nutrient and material manufacturing. The diagram presents a simplified version of the system demonstrated in Ref. [41], where two different waste streams from two different urban regions worldwide are utilized to develop a comprehensive circular and biologically integrated system for general manufacturing and food production.

from the environment at a low energy cost (e.g., calcium carbonate) and incorporated into an organic matrix (e.g., chitin) produced at a relatively high metabolic cost.[75,76] Chitin is a paradigmatic example of an organic matrix often found in mineralized composites; nacre, the shells of mollusks, is an instance of extraordinarily tough material made with mechanically irrelevant inorganic components. The same principle of aggregating inorganic minerals within a chitinous organic matrix was used to produce a "Martian biolith" involving Martian regolith simulant, ubiquitous biomolecules in a bio-based circular life-support system and water-based solvents that are easily integrated into any ecological cycle and avoid the need for complex polymer synthesis, shipment of specialized equipment, or dedicated feedstock (Fig. 6). The material is produced and used with minimal energy requirements, retaining the versatility of its biological counterparts and enabling the rapid manufacturing of objects ranging from tools to rigid shelters.

The energetically expensive chitosan can be readily recovered from biolith-based tools and other chitosan-based bioplastics in a closed artificial Martian ecosystem (Fig. 1). The most direct approach would involve introducing pure chitosan and organic and inorganic chitinous composites into the standard bioconversion strategy for all organic materials, where they would be metabolized and transformed into a standardized mix of organic materials, including chitin, while the inorganic materials will remain.[41] Alternatively, some chitinous constructs could be resuspended in a weak acid solution (achievable by fermentation) and separated from the insoluble phase.[35] This last route would be more efficient in yield but would require an additional processing path and tools. The recycled chitosan solution could then be reconcentrated and reused, as the molecule is not chemically transformed in the manufacturing or recovery processes.

These results represent an entirely new approach to Mars colonization, departing from the current path of adapting manufacturing technologies already developed for Earth's paradigm. We address the development of composites based on large volumes, low metabolic and energy costs, and simple chemistry. The low concentration of acetic acid (1% v/v) used to disperse chitosan was selected to align with the anaerobic limit. At this concentration, it is a common by-product of fermentation processes and can be utilized in its native form, eliminating the need for additional chemical or physical processing. Water can be obtained by heating subsurface ice or extracting it from the large deposits concentrated at the equator of Mars.[9] The process of deacetylating chitin to chitosan is not required if the polymer is extracted from fungi, as it is already biosynthesized in its deacetylated form. Alternatively, if the polymer is extracted from arthropods, the most efficient and easy-to-integrate process in a biology-based production system would involve its enzymatic deacetylation.[41] The resulting material provides a unique versatility in manufacturing options from tools to buildings and hand shaping to 3D printing. The results demonstrate that developing closed-loop zero-waste solutions to tackle unsustainable development on Earth may also be the key to our development as an interplanetary species.

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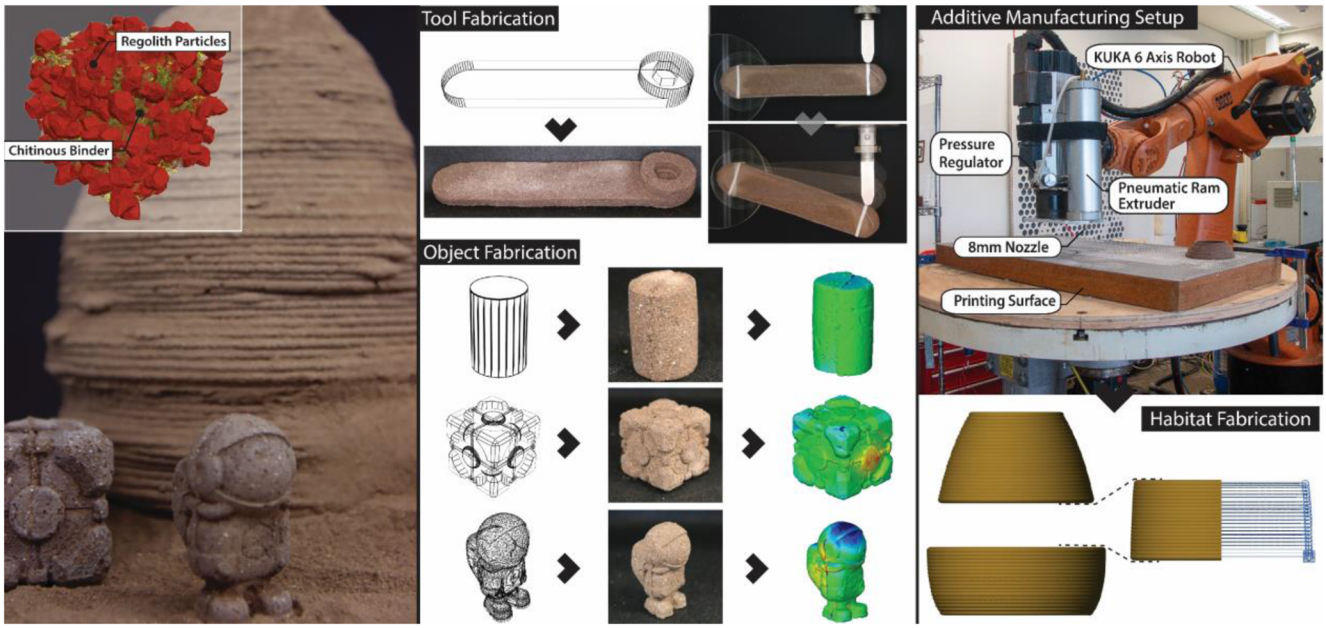


FIG. 6. Martian biolith. The image, adapted from the work of Shiwei *et al.*, PLoS One **15**(9), e0238606 (2020). Copyright 2020 Author(s) under Creative Common Attribution License, shows the creation of chitinous composites using Martian regolith as the inorganic component and chitosan, which is produced as part of a circular system based on the bioconversion of waste and nutrient production, as the organic binder. These composites have been proven suitable for integration into various manufacturing systems, ranging from casting to additive manufacturing, for producing objects, including small tools and buildings. They have also demonstrated their capability to repair structures of the same or different materials. The versatility of a material to perform multiple tasks is crucial in both natural and artificial systems, as minimizing the number of different synthesis routes enables resource-intensive and more resilient production systems.

Because of the ubiquitous production of chitin in every ecological cycle, bioinspired chitinous manufacturing on Mars will likely become a prominent technology in the later stages of multiple Mars missions, in conjunction with the incremental incorporation of biotechnology[11] and biomanufacturing.[77] A potential—and probably unavoidable—source of chitin is the cuticle of heterotrophs, such as insects and fungi, which are used for both the production of proteins[16,78] and organic waste valorization.[74,79] However, it could also be purposely produced with micro-organisms.[80] The advent of alternative food production systems, synthetic biology, fermentation biotechnology, and bioprinting is likely to have a synergistic effect. Any potential manufacturing approach would need to resonate and seamlessly integrate with such biological processes without competing, a unique characteristic of the bioinspired chitinous manufacturing.

THE FUTURE: THE BIOMATERIAL AGE

Today, the idea of sustainable materials makes most people think of objects that look primitive or unfinished or a return to traditional manufacturing methods and lifestyles. In most cases, this portrayal of sustainability and integration with nature perpetuates one of the most widespread misunderstandings of real sustainability: it is not about past engineering and living patterns but about what lies ahead and the steps toward technological efficiency that will require mastery of the true potential of materials and engineering well beyond what we can currently achieve.

Many of our problems as a society are due to the use of systems conceived in a paradigm of inefficiency, a product of assuming unlimited resources, and the result of this inefficiency is large quantities of by-products. In the case of our current manufacturing system, the main by-product is our waste, in the form of either pollutants or solid waste. Migrating to sustainable models thus requires a paradigm shift based on maximizing the system's efficiency. However, this efficiency is unreachable with current materials and the associated production models, preventing our sustainable development and progress to the next stages of humanity. Our transformation into an interplanetary species, which will start with establishing a permanent outpost on Earth's Moon first and Mars later, is a paradigmatic example of an achievement unreachable with the current inefficient paradigm.

The principles of bioinspired manufacturing, which are focused on self-sustainable general manufacturing developed in the last decade, have been demonstrated to be critical in the path to establishing the first human settlement in an extraplanetary environment. The research and developments in chitinous materials and manufacturing have demonstrated the potential to revolutionize our manufacturing processes, simultaneously providing a multidisciplinary roadmap of unprecedented scale for the next stages of space exploration. This approach pursues sustainability not by tweaking the existing manufacturing paradigm through policy changes, adapting current materials for better biodegradability, or developing recovery strategies to mitigate environmental impact. Instead, it is based on integrating manufacturing processes with ecological cycles.[25] The use of chitin is, therefore, not arbitrary. As the second

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most abundant polymer on Earth, chitin offers an ample and renewable resource for manufacturing processes.[81,82] More importantly, it is produced by a wide array of organisms, many of which contribute to the decomposition of organic waste. This positions chitin not only as a readily available resource in every ecosystem but also as a key component in bioconversion and waste management systems centered on a circular economy, in which waste is transformed into valuable resources.

The essence of this new paradigm lies in integrating materials discovery and mastery as part of an ecological process, adopting the principles of efficiency and resilience of biological systems. This approach is not about imposing restrictions or regressions of societal behaviors but about leveraging advancements in technology and materials science, mirroring historical transformations in technology and society, where major changes were not forced but emerged naturally due to embracing new methods and understanding existing materials. Therefore, humanity's future hinges on our ability to understand and control materials with seamless integration into ecological cycles. This integration of materials sciences into the broader concept of materials ecology is the key to unlocking a sustainable future driven by innovation and efficiency, rather than restriction and compensation.

The race to the Moon landing was a significant step for space exploration and a by-product of geopolitical rivalry that led to a surge in technological advancements, propelling humanity forward in numerous fields. The opposite is occurring now; the collective quest for solutions in many fields to our planet's global environmental issues could lead to a paradigm shift toward efficient and biologically integrated materials, inadvertently paving the way for human habitation on other planets.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Javier G. Fernandez: Conceptualization (equal); Funding acquisition (lead); Visualization (lead); Writing – original draft (lead); Writing – review & editing (equal). **Shiwei Ng**: Conceptualization (equal); Writing – original draft (supporting); Writing – review & editing (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

REFERENCES

[1] K. Laurini, J. C. Piedboeuf, B. Schade, K. Matsumoto, F. Spiero, and A. Lorenzoni, "The Global Exploration Roadmap," in *62nd International Astronautical Congress (2011)* (International Astronautical Federation, 2012).

[2] NASA, "Gateway" (2023); available from https://www.nasa.gov/mission/gateway/

[3] V. Angelopoulos, *The ARTEMIS Mission* (The ARTEMIS Mission, 2014), pp. 3–25.

[4] D. M. Bushnell and R. W. Moses, "Frontier in-situ resource utilization for enabling sustained human presence on Mars," in Report No. NF176L-20756 (NASA, 2016).

[5] R. Mattingly and L. May, "Mars sample return as a campaign," in 2011 Aerospace Conference, 2011.

[6] J. E. Palaia *et al.*, "Economics of energy on Mars," in *Mars: Prospective Energy and Material Resources*, edited by V. Badescu (Springer, Berlin, Heidelberg, 2009), pp. 369–400.

[7] M. Hecht *et al.*, "Mars oxygen ISRU experiment (MOXIE)," Space Sci. Rev. **217**(1), 9 (2021).

[8] J. Zhang *et al.*, "From the top of Martian Olympus to deep craters and beneath: Mars radiation environment under different atmospheric and regolith depths," J. Geophys. Res.: Planets **127**(3), e2021JE007157, https://doi.org/10.1029/2021je007157 (2022).

[9] T. R. Watters *et al.*, "Evidence of ice-rich layered deposits in the Medusae Fossae formation of Mars," Geophys. Res. Lett. **51**(2), e2023GL105490, https://doi.org/10.1029/2023gl105490 (2024).

[10] G. Landis *et al.*, "Mars solar power," in 2nd International Energy Conversion Engineering Conference, 2004.

[11] S. N. Nangle *et al.*, "The case for biotech on Mars," Nat. Biotechnol. **38**(4), 401–407 (2020).

[12] M. Nelson *et al.*, "Closed ecological systems, space life support, and biospherics," in *Environmental Biotechnology. Handbook of Environmental Engineering* vol 10. (Humana Press, Totowa, NJ, 2010).

[13] H. Läkka *et al.*, "Fungal based biocomposite for habitat structures on the Moon and Mars," in *69th International Astronautical Congress (IAC)* (International Astronautical Federation, Bremen, Germany, 2018).

[14] I. Levchenko *et al.*, "Mars colonization: Beyond getting there," Global Challenges **3**(1), 1800062 (2019).

[15] C. Verseux *et al.*, "Sustainable life support on Mars – the potential roles of cyanobacteria," Int. J. Astrobiol. **15**, 65–92 (2016).

[16] K. M. Cannon and D. T. Britt, "Feeding one million people on Mars," New Space **7**(4), 245–254 (2019).

[17] C. D. Ives *et al.*, "Reconnecting with nature for sustainability," Sustainability Sci. **13**(5), 1389–1397 (2018).

[18] S. Kaza *et al.*, *What a Waste 2.0: A Global Snapshot of Solid Waste Management to 2050* (World Bank Publications, 2018).

[19] J. Sachs *et al.*, The Sustainable Development Goals Report 2019, edited by L. Jensen (Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN)), United Nation, New York, 2019.

[20] "The future of plastic," Nat. Commun. 9(1), 2157 (2018).

[21] OECD, *Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options* (OECD Publishing, Paris, 2022).

[22] W. W. Y. Lau *et al.*, "Evaluating scenarios toward zero plastic pollution," Science **369**(6510), 1455–1461 (2020).

[23] S. L. Sass, *The Substance of Civilization: Materials and Human History from the Stone Age to the Age of Silicon* (Arcade Publishing, 1998).

[24] R. Miehe *et al.*, "The biological transformation of industrial manufacturing – Technologies, status and scenarios for a sustainable future of the German manufacturing industry," J. Manuf. Syst. **54**, 50–61 (2020).

[25] J. G. Fernandez and S. Dritsas, "The biomaterial age: The transition toward a more sustainable society will be determined by advances in controlling biological processes," Matter **2**(6), 1352–1355 (2020).

[26] J. A. Kluge *et al.*, "Spider silks and their applications," Trends Biotechnol. **26**(5), 244–251 (2008).

[27] A. Jackson, J. F. Vincent, and R. Turner, "The mechanical design of nacre," Proc. R. Soc. London, Ser. B **234**(1277), 415–440 (1988).

[28] E. A. Zimmermann and R. O. Ritchie, "Bone as a structural material," Adv. Healthcare Mater. **4**(9), 1287–1304 (2015).

[29] K. Easterling *et al.*, "On the mechanics of balsa and other woods," Proc. R. Soc. London, Ser. A **383**(1784), 31–41 (1982).

[30] P. Fratzl and R. Weinkamer, "Nature's hierarchical materials," Prog. Mater. Sci. **52**(8), 1263–1334 (2007).

[31] J. G. Fernandez and D. E. Ingber, "Unexpected strength and toughness in chitosan-fibroin laminates inspired by insect cuticle," Adv. Mater. **24**(4), 480–484 (2011).

01 March 2024 00:15:32

© Author(s) 2024

[32]B. Rukmanikrishnan, K. J. Tracy, and J. G. Fernandez, "Secondary reorientation and hygroscopic forces in chitinous biopolymers and their use for passive and biochemical actuation," Adv. Mater. Technol. **8**(18), 2300639 (2023).
[33]J. G. Fernandez and D. E. Ingber, "Bioinspired chitinous material solutions for environmental sustainability and medicine," Adv. Funct. Mater. **23**(36), 4454–4466 (2013).
[34]J. G. Fernandez, C. A. Mills, and J. Samitier, "Complex microstructured 3D surfaces using chitosan biopolymer," Small **5**(5), 614–620 (2009).
[35]J. G. Fernandez and D. E. Ingber, "Manufacturing of large-scale functional objects using biodegradable chitosan bioplastic," Macromol. Mater. Eng. **299**(8), 932–938 (2014).
[36]J. G. Fernandez *et al.*, "Micro- and nanostructuring of freestanding, biodegradable, thin sheets of chitosan via soft lithography," J. Biomed. Mater. Res., Part A **85A**(1), 242–247 (2008).
[37]J. G. Fernandez *et al.*, "Forced soft lithography (FSL): Production of micro- and nanostructures in thin freestanding sheets of chitosan biopolymer," Adv. Mater. **19**(21), 3696–3701 (2007).
[38]H. K. Raut *et al.*, "The height of chitinous ridges alone produces the entire structural color palette," Adv. Mater. Interfaces **9**(35), 2201419 (2022).
[39]H. K. Raut *et al.*, "Tough and strong: Cross-lamella design imparts multifunctionality to biomimetic nacre," ACS Nano **14**(8), 9771–9779 (2020).
[40]N. D. Sanandiya *et al.*, "Large-scale additive manufacturing with bioinspired cellulosic materials," Sci. Rep. **8**(1), 8642 (2018).
[41]N. D. Sanandiya *et al.*, "Circular manufacturing of chitinous bio-composites via bioconversion of urban refuse," Sci. Rep. **10**(1), 4632 (2020).
[42]N. Shiwei, S. Dritsas, and J. G. Fernandez, "Martian biolith: A bioinspired regolith composite for closed-loop extraterrestrial manufacturing," PLoS One **15**(9), e0238606 (2020).
[43]A. Tuwalska, S. Grabska-Zielińska, and A. Sionkowska, "Chitosan/silk fibroin materials for biomedical applications-A review," Polymers **14**(7), 1343 (2022).
[44]R. Jeencham *et al.*, "Novel daily disposable therapeutic contact lenses based on chitosan and regenerated silk fibroin for the ophthalmic delivery of diclofenac sodium," Drug Delivery **27**(1), 782–790 (2020).
[45]S. Guang *et al.*, "Chitosan/silk fibroin composite scaffolds for wound dressing," J. Appl. Polym. Sci. **132**(35), 42503 (2015).
[46]N. Bhardwaj and S. C. Kundu, "Chondrogenic differentiation of rat MSCs on porous scaffolds of silk fibroin/chitosan blends," Biomaterials **33**(10), 2848–2857 (2012).
[47]E. R. Hayes, D. Davies, and V. Munroe, *Organic Acid Solvent Systems for Chitosan* (Department of Chemistry, Acadia University, Wolfville, NS, 1978), pp. 103–106.
[48]S. Mima *et al.*, "Highly deacetylated chitosan and its properties," J. Appl. Polym. Sci. **28**(6), 1909–1917 (1983).
[49]J. G. Fernandez, J. Samitier, and C. A. Mills, "Simultaneous biochemical and topographical patterning on curved surfaces using biocompatible sacrificial molds," J. Biomed. Mater. Res., Part A **98A**(2), 229–234 (2011).
[50]S. Dritsas *et al.*, "Cellulosic biocomposites for sustainable manufacturing," in *Fabricate 2020* (UCL Press, 2020), pp. 74–81.
[51]S. Dritsas *et al.*, "Shrinkage prediction and correction in material extrusion of cellulose-chitin biopolymers using neural network regression," Virtual Phys. Prototyping **18**(1), e2225039 (2023).
[52]J. L. Hoo, S. Dritsas, and J. G. Fernandez, "Improving the geometric accuracy in large-scale additive manufacturing of fungus-like adhesive materials," Mater. Today: Proc. **70**, 603–610 (2022).
[53]Y. Vijay *et al.*, "Control of process settings for large-scale additive manufacturing with sustainable natural composites," J. Mech. Des. **141**(8), 081701 (2019).
[54]S. Dritsas *et al.*, "Digital fabrication with natural composites," Constr. Rob. **2**(1–4), 41–51 (2018).
[55]J. Xu *et al.*, "Hand-eye calibration for 2D laser profile scanners using straight edges of common objects," Robot. Comput.-Integr. Manuf. **73**, 102221 (2022).
[56]G. Byrne *et al.*, "Biologicalisation: Biological transformation in manufacturing," CIRP J. Manuf. Sci. Technol. **21**, 1–32 (2018).
[57]J. F. V. Vincent, "Survival of the cheapest," Mater. Today **5**(12), 28–41 (2002).
[58]Y. Geng, J. Sarkis, and R. Bleischwitz, "How to globalize the circular economy," Nature **565**, 153–155 (2019).
[59]A. A. Menezes *et al.*, "Towards synthetic biological approaches to resource utilization on space missions," J. R. Soc., Interface **12**, 20140715 (2015).
[60]M. V. M. Sarto *et al.*, "Deep soil carbon stock, origin, and root interaction in a tropical integrated crop–livestock system," Agrofor. Syst. **94**(5), 1865–1877 (2020).
[61]E. M. Bennett and P. Balvanera, "The future of production systems in a globalized world," Front. Ecol. Environ. **5**(4), 191–198 (2007).
[62]C. Herrmann *et al.*, "Biological transformation of manufacturing as a pathway towards environmental sustainability: Calling for systemic thinking," CIRP J. Manuf. Sci. Technol. **34**, 157–170 (2020).
[63]J. Aizenberg and P. Fratzl, "New materials through bioinspiration and nanoscience," Adv. Funct. Mater. **23**(36), 4398–4399 (2013).
[64]S. Ng, B. Song, and J. G. Fernandez, "Environmental attributes of fungal-like adhesive materials and future directions for bioinspired manufacturing," J. Cleaner Prod. **282**, 125335 (2021).
[65]H. Amiri *et al.*, "Chitin and chitosan derived from crustacean waste valorization streams can support food systems and the UN Sustainable Development Goals," Nat, Food **3**(10), 822–828 (2022).
[66]L. W. Bessa *et al.*, "Food safety of consuming black soldier fly (*Hermetia illucens*) larvae: Microbial, heavy metal and cross-reactive allergen risks," Foods **10**, 1934 (2021).
[67]M. M. Abo Elsoud and E. M. El Kady, "Current trends in fungal biosynthesis of chitin and chitosan," Bull. Natl. Res. Cent. **43**(1), 59 (2019).
[68]I. J. Banks, W. T. Gibson, and M. M. Cameron, "Growth rates of black soldier fly larvae fed on fresh human faeces and their implication for improving sanitation," Trop. Med. Int. Health **19**, 14–22 (2014).
[69]B. J. Chow *et al.*, "Direct formation of structural components using a Martian soil simulant," Sci. Rep. **7**(1), 1151 (2017).
[70]R. Mueller *et al.*, "Additive construction using basalt regolith fines," in *Earth and Space 2014* (ASCE, 2015), pp. 394–403.
[71]L. Wan, R. Wendner, and G. Cusatis, "A novel material for in situ construction on Mars: Experiments and numerical simulations," Constr. Build. Mater. **120**, 222–231 (2016).
[72]L. J. Rothschild, "Synthetic biology meets bioprinting: Enabling technologies for humans on Mars (and Earth)," Biochem. Soc. Trans. **44**(4), 1158–1164 (2016).
[73]A. E. Jakus *et al.*, "Robust and elastic Lunar and Martian structures from 3D-printed regolith inks," Sci. Rep. **7**(1), 044931 (2017).
[74]D. L. J. Rothschild *et al.*, "Myco-architecture off planet: Growing surface structures at destination," in Report No. HQ-E-DAA-TN66707 (NASA, 2019).
[75]B. S. Welinder, "The crustacean cuticle—I. Studies on the composition of the cuticle," Comp. Biochem. Physiol., Part A: Physiol. **47**, 779–787 (1974).
[76]D. A. Wharton and T. Jenkins, "Structure and chemistry of the egg-shell of a nematode (*Trichuris Suis*)," Tissue Cell **10**, 427–440 (1978).
[77]A. J. Berliner *et al.*, "Towards a biomanufactory on Mars," Front. Astron. Space Sci. **8**, 711550 (2021).
[78]R. Kok and A. van Huis, "Insect food in space," J. Insects Food Feed **7**(1), 1–4 (2021).
[79]I. Rai *et al.*, "Biowaste recycling strategies for regenerative life support system: An overview," Sustainable Energy Technol. Assess. **53**, 102525 (2022).
[80]L. A. Anderson, M. A. Islam, and K. L. J. Prather, "Synthetic biology strategies for improving microbial synthesis of 'green' biopolymers," J. Biol. Chem. **293**(14), 5053–5061 (2018).
[81]J. P. Martínez, M. P. Falomir, and D. Gozalbo, "Chitin: A structural biopolysaccharide with multiple applications," in *Encyclopedia of Life Sciences* (John Wiley & Sons, Ltd., 2014).
[82]N. Morin-Crini *et al.*, "Applications of chitosan in food, pharmaceuticals, medicine, cosmetics, agriculture, textiles, pulp and paper, biotechnology, and environmental chemistry," Environ. Chem. Lett. **17**(4), 1667–1692 (2019).

01 March 2024 00:15:32

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