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Review article

Breathing life into Mars: Terraforming and the pivotal role of algae in atmospheric genesis

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ABSTRACT

The Martian environment, characterized by extreme aridity, frigid temperatures, and a lack of atmospheric oxygen, presents a formidable challenge for potential terraforming endeavors. This review article synthesizes current research on utilizing algae as biocatalysts in the proposed terraforming of Mars, assessing their capacity to facilitate Martian atmospheric conditions through photosynthetic bioengineering. We analyze the physiological and genetic traits of extremophile algae that equip them for survival in extreme habitats on Earth, which serve as analogs for Martian surface conditions. The potential for these organisms to mediate atmospheric change on Mars is evaluated, specifically their role in biogenic oxygen production and carbon dioxide sequestration. We discuss strategies for enhancing algal strains' resilience and metabolic efficiency, including genetic modification and the development of bioreactors for controlled growth in extraterrestrial environments. The integration of algal systems with existing mechanical and chemical terraforming proposals is also examined, proposing a synergistic approach for establishing a nascent Martian biosphere. Ethical and ecological considerations concerning introducing terrestrial life to extra-planetary bodies are critically appraised. This appraisal includes an examination of potential ecological feedback loops and inherent risks associated with biological terraforming. Biological terraforming is the theoretical process of deliberately altering a planet's atmosphere, temperature, and ecosystem to render it suitable for Earth-like life. The feasibility of a phased introduction of life, starting with microbial taxa and progressing to multicellular organisms, fosters a supportive atmosphere on Mars. By extending the frontier of biotechnological innovation into space, this work contributes to the foundational understanding necessary for one of humanity's most audacious goals—the terraforming of another planet.

1. Introduction

Terraforming, the theoretical process of deliberately modifying a planet's atmosphere, temperature, and ecology to make it habitable for Earth-like life, has become paramount in space exploration and planetary science (Genta, 2021). With humanity standing at the crossroads of climate change, declining sustainability, and the over-exploitation of Earth's finite resources, the vision of establishing a secondary habitat on another celestial body is not just a matter of scientific curiosity but also a potential contingency for our species long-term survival (Çelekli and Zariç, 2023a; Awan, 2013). In the discourse on terraforming Mars, it is imperative to acknowledge the foundational contributions that have shaped our understanding of this audacious endeavor. Carl Sagan's seminal article, "Planetary Engineering on Mars," published in Icarus in 1973, is a landmark in the field (Sagan, 1973). Sagan's visionary perspective laid the groundwork for contemporary discussions on planetary transformation, proposing the possibility of altering Mars' atmosphere to make it habitable for Earth's life. His-pioneering ideas, which included using darkening agents to absorb solar radiation and trigger atmospheric warming, have inspired subsequent generations of scientists and engineers to explore the feasibility of terraforming Mars. This historical context enriches our current exploration of algae's potential role in this grand undertaking, bridging early speculative theories and today's empirical research efforts. Harsh realities of climate change and the rapid depletion cause problems serious problems, profound problems which realities of climate change and the rapid depletion of the Earth's natural resources cause serious problems such as human migrations (Çelekli et al., 2023a). Mars, the fourth planet from the Sun, has long been the focus of these terraforming discussions due to its proximity and certain similarities to Earth (Graham, 2004). However,

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the current Martian atmospheric conditions present formidable challenges (Petrosyan et al., 2011). Mainly comprising carbon dioxide, with traces of argon and nitrogen, and lacking a significant magnetic field, the Martian atmosphere is thin and incapable of supporting terrestrial life as we know it. Furthermore, its surface pressure is less than 1% of Earth's, making liquid water—a crucial element for life—currently unsustainable on its surface (Petrosyan et al., 2011).

In light of the consequences stemming from anthropogenic climate change, including the significant degradation of bioclimatic comfort on Earth, the exploration of and potential control over the atmospheric conditions of another planet, notably Mars, could provide valuable insights into the myriad challenges confronting us (Çelekli et al., 2023b). Suppose we can conceive methods to induce an atmospheric metamorphosis on Mars. Might we also derive strategies to rectify the atmospheric degradation we have instigated on our home planet? While appearing as a solution to resource scarcity and overpopulation, the stark reality of Earth's changing climate and diminishing resources further underscores the urgency to explore terraforming (Beech, 2021; Çelekli and Zariç, 2023b).

Given these pressing concerns and the potential benefits that terraforming Mars might hold, this review will delve deeply into the prospective role of algae in this grand endeavor, juxtaposing our need for survival with the lessons nature offers through these resilient microorganisms.

2. Understanding algae: Earth's photosynthetic powerhouses

Algae, encompassing a diverse group of photosynthetic organisms, are fundamental players in Earth's ecological tapestry. Their basic biology is intricate: while they share a common photosynthetic trait, they span many forms, from microscopic phytoplankton to macroscopic kelps. Unlike higher plants, algae do not possess true stems, roots, or leaves, yet their cellular structures are adept at harnessing sunlight, facilitating their primary role as photosynthetic dynamos (Van Den Hoek et al., 1995).

Algae assume a critical function that transcends their aquatic ubiquity within the intricate web of Earth's biosphere. These organisms are lauded for their formidable oxygenic capabilities, often likened to the terrestrial biosphere's pulmonary system (Bradbury, 1991). Microscopic phytoplankton, which populate the planet's marine environments, contribute significantly to the biospheric oxygen turnover, engendering more than half of the global atmospheric oxygen—a testament to their photosynthetic vigor. This process of oxygenic photosynthesis is not the linchpin of biogenic vitality that underpins Earth's habitability (Knoll, 1992).

Algae, through the process of photosynthesis, absorb CO_2 from the atmosphere, using it alongside sunlight and water to produce oxygen and glucose; this biochemical process not only purifies the atmosphere by reducing CO_2 levels but also contributes to the sequestration of carbon, a critical factor in mitigating global climate change (Sayre, 2010). Concomitant with oxygen production is the process of carbon fixation. Through photosynthetic activity, algae orchestrate the conversion of carbon dioxide—a potent greenhouse effluent—into organic matrices, sequestering carbon and mitigating its pervasiveness in the atmosphere, as shown in Fig. 1 (Stirbet et al., 2020). This symbiotic relationship between oxygen generation and carbon sequestration elevates the status of algae to that of indispensable stewards of the atmospheric regime (Sarwer et al., 2022). As sentinel species in the fight against anthropogenic climate perturbation, algae play an instrumental role in regulating atmospheric constituents and stand at the forefront of ecological strategies to address the difficulties of escalating atmospheric CO_2 levels (Stirbet et al., 2020).

Photosystems II and I (PSII and PSI): PSII: Depict the water/plastoquinone (PQ) photo-oxidoreductase function, including the manganese-calcium complex [Mn_4O_5Ca], the tyrosine-161 (YZ) on the D1 protein, pheophytin (Pheo), plastoquinones QA and QB, and the non-haem iron with bicarbonate (HCO_3^-). PSI: Show it functioning as a plastocyanin (PC)/ferredoxin (Fd) photo-oxidoreductase with its electron donors and acceptors (A0, A1, Fe-S centers). Cytochrome b6/f Complex: Include cytochrome f, the Rieske iron–sulfur protein, and cytochromes b6 that participate in PQH2 and PQ oxidation and reduction at the Qp- and Qn-sites (also known as Qo- and Qi-sides). ATP Synthase: Show the production of ATP from ADP and phosphate (Pi) using the proton motive force (pmf), which consists of the proton concentration difference (ΔpH) and the electric potential (ΔΨ) across the thylakoid membrane. Electron Transport (ET) Pathways: Show the linear flow from water to NADP+. Illustrate alternative electron flows like cyclic electron flow (CEF) around PSI, water-water cycle (WWC), chlororespiration, and the malate valve. Include the various players in these pathways, such as Fd-NADP+-reductase (FNR), proton gradient regulator (PGR5), NADPH dehydrogenase (NDH), plastid terminal oxidase (PTOX), and malate dehydrogenase (MDH). Light Harvesting Complexes (LHCI and LHCII): Depict pigments absorbing light and transferring energy to the reaction centers P700 (in PSI) and P680 (in PSII). Calvin-Benson Cycle: Not in detail, but indicates the role of ATP and NADPH in light-dependent reactions in fixing CO_2 to make sugars. Chemical Labels and Annotations: Label all complexes (PSII, PSI, Cyt b6/f, ATP synthase) and include their subcomponents. Annotate with arrows to show the direction of electron flow (Stirbet et al., 2020).

The detailed depiction of the photosynthetic apparatus and electron transport (ET) pathways in plants and algae, as illustrated in Fig. 1, underscores the complex biological machinery that underpins algae's

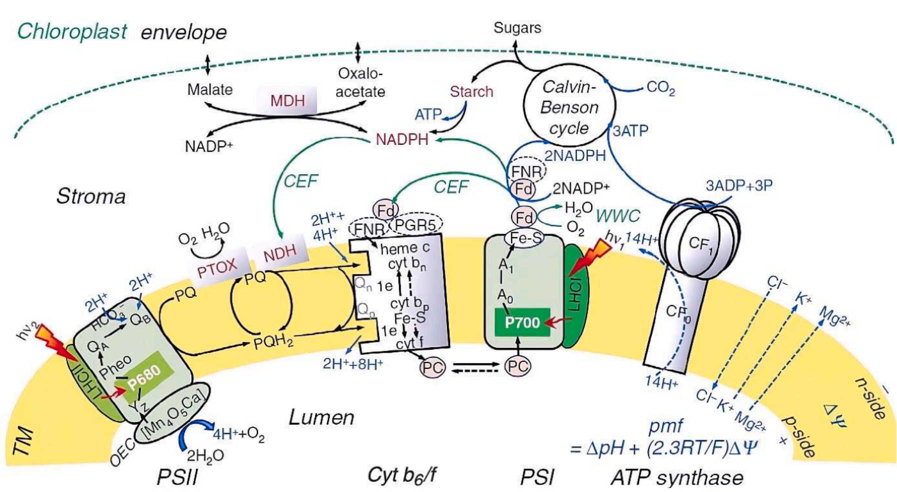

Fig. 1. Diagram of the photosynthetic apparatus and electron transport (ET) pathways in plants and algae (Stirbet et al., 2020).

potential for atmospheric transformation on Mars. The efficiency of photosystems II and I (PSII and PSI), coupled with the cytochrome b6/f complex and alternative electron flows, exemplifies the adaptability of algal photosynthesis. These mechanisms are crucial for optimizing photosynthetic efficiency under the Martian conditions of reduced light and altered atmospheric composition. Through genetic modifications aimed at enhancing these specific pathways, we can potentially increase the productivity of algae in producing oxygen and sequestering carbon dioxide, making them invaluable assets in the terraforming of Mars.

Furthermore, algae's versatility extends into biotechnology (Fabris et al., 2020). Their ability to produce valuable bio-compounds and remove harmful dyes, spanning a spectrum from biofuels to pharmaceuticals, underscores their ecological significance and potential as solutions to contemporary society's pressing challenges (Çelekli and Zariç, 2024; Richmond and Vonshak, 1991; Zariç et al., 2022). Furthermore, their application in the production of functional foods, which are crucial for sustainability due to their health benefits and minimal environmental impact, highlights the versatility of algae as a critical resource in advancing global food security and environmental health (Çelekli and Zariç, 2023c; Wells et al., 2017). Table 1 indicates critical algal species and their distinctive features (Blouin et al., 2011; Bowler et al., 2008; Ciferri, 1983; Goodenough, 2023; Rupérez et al., 2002). In understanding the role algae might play in the atmospheric genesis of Mars, it is imperative to first appreciate their foundational role on Earth, both in shaping our atmosphere and in offering innovative biotechnological solutions.

3. Mars atmosphere: Challenges and opportunities

Mars, often called the 'Red Planet' due to its iron oxide-rich surface, presents a starkly different atmospheric profile than Earth (Jiang et al., 2022). Delving into the intricacies of its atmosphere unveils both the challenges that need to be surmounted and the opportunities that can be harnessed for potential terraforming endeavors (Levchenko et al., 2021). The Martian environment presents several formidable challenges that are critical to consider in the context of terraforming efforts. Among these, Mars's low water activity (aw) stands out, with values below 0.5 in most regions, except in designated 'Special Regions' where transient liquid water may occur (Olsson-Francis et al., 2023). This factor significantly limits the viability of terrestrial life forms, including algae, which typically require higher water activity for metabolic processes (Grant et al., 2004). The Martian climate is characterized by low temperatures and substantial diurnal temperature variations, which could impose thermal stress on terrestrial organisms. Strong oxidants on the Martian surface, such as perchlorates, further complicate the survival of potential bioengineered or naturally resilient algal strains (Verseux et al., 2016). These oxidants can disrupt cellular structures and metabolic functions, posing a significant barrier to colonization efforts. The hostile Martian climate, marked by strong winds and pervasive dust storms, could also impact the deployment and maintenance of algal cultivation systems (Hender, 2010). Such environmental factors necessitate the development of robust containment and life support systems to shield algal cultures from physical damage and ensure their growth and productivity. While ultraviolet (UV) radiation's detrimental effects on terrestrial life forms are acknowledged, the impact of cosmic rays represents an additional layer of environmental stress. These high-energy particles can cause direct damage to DNA and cellular components, leading to increased mutation rates or cellular death (Atri and Melott, 2014). Although some extremophile algae on Earth exhibit remarkable UV resilience, the quantitative data on their resistance to cosmic radiation is sparse (Baldanta et al., 2023; Zorzano et al., 2023). This gap underscores the need for further research into the genetic and physiological adaptations that could enable algae to withstand the combined effects of UV and cosmic radiations on Mars.

Table 1
Critical algal species and their distinctive features.

Algal species	Class	Distinctive features
Chlamydomonas reinhardtii	Chlorophyta	Model organism in research, biflagellate, freshwater habitats
Phaeodactylum tricornutum	Bacillariophyceae	Silica-based cell walls, critical contributors to marine primary production
Arthrospira platensis	Cyanobacteria	High protein content, used as a dietary supplement, spiral structure
Fucus vesiculosus	Phaeophyta	Coastal marine habitats, bladder-like structures for buoyancy
Porphyra spp.	Rhodophyta	Edible, used to produce nori for sushi, intertidal marine environments

3.1. Current composition and structure of the Martian atmosphere

The Martian atmosphere has a starkly different composition atmosphere, starkly different composition atmosphere, starkly different composition from Earth's, dominated by carbon dioxide, which constitutes approximately 95.3% of the atmospheric gases (Forget et al., 2007). The remaining components include argon at about 1.9%, nitrogen at roughly 2.7%, and trace amounts of oxygen and water vapor. It is important to note that the presence of methane in the Martian atmosphere is currently a subject of scientific debate. While some studies suggest intermittent releases of methane, which could imply active geological or even biological processes, others have not detected significant concentrations, leaving its existence and origins unresolved in Martian research. (Forget et al., 2007). This composition contributes to a surface pressure of less than 1% of Earth's average sea level pressure. The lack of the Martian atmosphere leads to substantial diurnal temperature oscillations, with variations that exceed those on Earth by a considerable margin. Moreover, Mars lacks a powerful magnetosphere, a deficiency that renders the planet susceptible to augmented levels of solar and cosmic radiation, presenting significant challenges to the potential for extant life and future human habitation (Jakosky and Phillips, 2001).

3.2. Theoretical changes needed to support terrestrial life

A series of profound atmospheric alterations are requisite to render Mars hospitable for terrestrial organisms. Firstly, the atmospheric pressure must be significantly elevated to support liquid water on the surface – a cornerstone for sustaining known life forms. This necessitates introducing and accumulating greenhouse gases to induce a warming effect, thereby thickening the atmosphere (Fairén et al., 2010). Concurrently, reducing the overwhelming dominance of carbon dioxide while increasing oxygen levels is crucial. Achieving an atmospheric balance where carbon dioxide is lowered to non-toxic levels while oxygen is raised to a range that can sustain aerobic organisms is paramount. Additionally, considerations related to shielding the planet from harmful radiation must be addressed through atmospheric augmentation or alternative protective measures (Westall et al., 2015).

In this context, the challenges presented by the Martian atmosphere are undeniably daunting. However, they also offer a unique canvas for scientific innovation, pushing the boundaries of what is conceivable in planetary transformation. As we delve into potential solutions, such as leveraging the capabilities of algae, it becomes evident that these atmospheric challenges may also herald unprecedented opportunities for biotechnological and ecological advancements (Verseux et al., 2016).

4. The potential of algae in Martian terraforming

The ambition to harness algae as instrumental agents in Martian terraforming emerges from their proven adaptability on Earth and inherent biological functions. Delving into their potential applications in a Martian context offers intriguing insights (Starr and Muscatello, 2020).

One way to overcome Earth's dependency is to gather and process the resources already available on Mars. This approach is called In-Situ Resource Utilization (Fig. 2) (Mapstone et al., 2022).

The transition from localized algal bioreactors to a planet-encompassing biosphere involves several key considerations. Firstly, the scalability of algal cultivation systems must be addressed, considering the vast differences in environmental and spatial conditions across Mars (Solé et al., 2015). Strategies could include the development of a network of interconnected bioreactors or establishing algal farms in regions with the most favorable conditions. Furthermore, the ecological impact of expanding algal habitats on a planetary scale must be carefully evaluated (Conde-Pueyo et al., 2020). This involves assessing the potential for algal oxygen production to alter Mars' atmospheric composition and the implications for subsequent stages of terraforming, such as the introduction of higher plants or even animals. A phased approach, beginning with small-scale experiments and gradually expanding to larger areas, could allow for continuous monitoring and adjustment of terraforming strategies. This iterative process would provide valuable insights into the challenges of planetary-scale algal cultivation, including resource management, environmental integration, and the maintenance of genetic diversity among algal populations. The extrapolation of microhabitat success to a Martian-wide terraforming effort underscores the necessity for innovative engineering solutions, ecological foresight, and a robust framework for planetary stewardship. This endeavor requires advancements in biotechnology and ecological engineering and a comprehensive understanding of Martian geology and climatology to identify potential sites for large-scale algal cultivation (Neukart, 2024).

4.1. How algae could thrive in extreme conditions

Algal taxa demonstrate a remarkable spectrum of extreme tolerance, thriving in many of Earth's most inhospitable biotopes. Extremophiles variants among these photosynthetic organisms can be found prospering in the frigid aqueous realms of polar latitudes, the hypersaline environs of saline basins, and even within the thermally and chemically volatile ecosystems of acidic geothermal springs (Seckbach and Oren, 2006). Their versatility stems from an array of adaptive mechanisms. To ensure the effective monitoring of Mars' evolving ecosystems, it is imperative to devise monitoring methodologies akin to those employed in terrestrial ecological studies (Çelekli and Zariç, 2023d) . This approach will enable the systematic observation of biodiversity alterations and landscape transformations, thereby furnishing essential data for the formulation of adaptive terraforming strategies. For instance, certain algae possess specialized pigments, like carotenoids, that allow them to photosynthesize efficiently under limited light conditions and offer protection against UV radiation (Larkum, 2020). This trait could be particularly beneficial on Mars, where the thinner atmosphere permits a higher penetration of solar radiation. Some algal species have also evolved mechanisms to endure freezing conditions, creating cryoprotective compounds that prevent cellular damage (Boroda et al., 2014). Such adaptabilities make these organisms' prime candidates for potential introduction into Martian environments.

In the realm of Martian terraforming, the adaptability of algal strains to the hostile Martian environment—characterized by extreme UV radiation, low temperatures, and minimal water activity—is paramount. Research has progressively unveiled a cohort of extremophilic organisms, notably certain algae, and cyanobacteria, endowed with natural and, through biotechnological interventions, enhanced resilience to these stressors. The extremophilic cyanobacterium *Chroococcidiopsis*, for instance, exhibits remarkable UV resistance and can withstand desiccation and extreme thermal fluctuations, making it a prime candidate for Martian bioengineering efforts (Baldanta et al., 2023). Similarly, *Dunaliella salina* demonstrates an exceptional capacity to survive in high salinity conditions by accumulating glycerol, thus maintaining osmotic balance (Kaçka and Dönmez, 2008). This trait signifies its potential adaptability to Mars' arid terrain. Advancements in genetic engineering have further expanded the frontier of possibilities, enabling the augmentation of stress-related gene expressions in model species like *Chlamydomonas reinhardtii* (Newkirk et al., 2021). Such modifications enhance their tolerance to Martian environmental stressors, including UV radiation and low water activity, thus providing a robust foundation for their utility in terraforming Mars (McKay, 2018). The deployment of algae-based regenerative life support systems (RLSS) on Mars presents a compelling approach to oxygen production and CO_2 sequestration (Holmer, 2020). However, transitioning from localized systems to a planetary-wide application necessitates a detailed examination of scalability. Assuming an RLSS can support a defined area of algal cultivation, producing a quantifiable amount of oxygen and sequestering CO_2 annually, extrapolation models suggest that the implementation of thousands, potentially tens of thousands, of these systems could be required to effect a measurable atmospheric transformation on Mars. This estimation, however, hinges on continued advancements in RLSS technology and a deeper understanding of Mars' environmental dynamics. A phased expansion strategy, underscored by continuous assessment and technological adaptation, is imperative for ensuring the effectiveness and sustainability of RLSS deployments. Integrating robotic and artificial intelligence technologies could significantly enhance

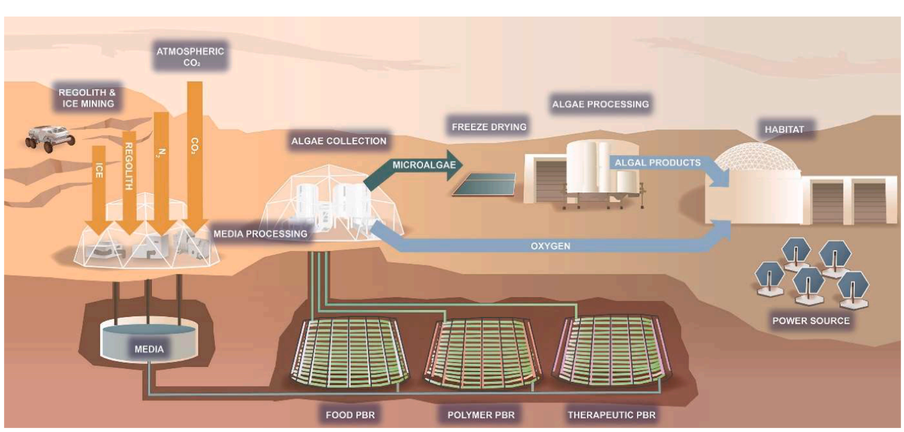

Fig. 2. The concept of an extraterrestrial habitat on Mars showcases the integration of atmospheric CO_2 and water extracted from ice and nutrients derived from the Martian soil to cultivate microalgae (Mapstone et al., 2022). The cultivation occurs within subterranean photobioreactors (PBRs), which rely on artificial illumination provided by light banks. These lights are energized by solar panels deployed on the Martian surface. The oxygen generated via photosynthesis by the microalgae contributes to life support systems, and the harvested algal biomass is processed into edible products, biopolymers, and pharmaceutical compounds (Mapstone et al., 2022).

the scalability and automation of these systems, aligning with broader efforts toward Martian colonization. Despite the speculative nature of precise numerical estimations at this juncture, the overarching analysis highlights the critical role of developing efficient, scalable RLSS in the broader context of Martian terraforming. Future research endeavors must focus on refining these estimates through empirical data from pilot projects and simulations, thereby informing a comprehensive strategy for atmospheric engineering on a planetary scale (De Micco et al., 2023).

4.2. Potential algae-driven processes to produce oxygen and sequester carbon dioxide on Mars

Algae's photosynthetic machinery enables them to play a dual role crucial for atmospheric transformation. Primary producers consume carbon dioxide during photosynthesis, converting it into organic biomass and releasing oxygen as a byproduct. This capability can be harnessed in a Martian context to gradually reduce the prevailing carbon dioxide levels while augmenting atmospheric oxygen (Janssen et al., 2014). By establishing stable algal populations, a sustained oxygen release could be achieved. Based on current models and understanding of ecological dynamics, this process could contribute to building an atmosphere conducive to more complex life forms over several decades to a few centuries. It is essential to note that the exact timeline can vary significantly based on the scale of deployment, environmental conditions on Mars, and the efficiency of genetically engineered algal strains (Häder, 2020). Moreover, when subjected to stressful conditions, certain algal strains can produce carbonate rocks, further aiding in long-term carbon sequestration (Verseux et al., 2016). It is worth noting that realizing such a transformative role for algae on Mars would necessitate significant initial interventions. Ensuring their survival and proliferation in Martian conditions might require genetic modifications, creating controlled habitats, or a combination. However, the potential rewards make these endeavors compelling in terms of forging an atmosphere that resonates with life (Starr and Muscatello, 2020). With their evolutionary honed capabilities and biotechnological potential, algae emerge as frontrunners to breathe life into the Martian atmosphere, underscoring the symbiotic relationship between advanced scientific techniques and nature's adaptive solutions (Latif et al., 2021).

5. Case studies: Extremophile algae on earth

The adaptability of algae is perhaps best exemplified by extremophiles, species that have evolved to thrive under conditions inhospitable to most forms of life (Table 2) (Seckbach et al., 2007). By understanding the specific mechanisms and traits that enable these algae to survive and flourish under extreme conditions on Earth, we can better appreciate their potential for adaptation to Martian environments.

Table 2
Extremophile algae on Earth and their potential Mars adaptations.

Algal species	Earth habitat	Special adaptations	Potential mars adaptability
Chlamydomonas nivalis (Remias et al., 2005)	Alpine snowfields	UV radiation resistance, cold tolerance	Survival under Mars' thin atmosphere and UV exposure
Dunaliella salina (Ramos et al., 2011)	Hyper-saline lakes	High salt tolerance	Adaptation to potential saline water sources on Mars
Cyanidium caldarium (Doemel and Brock, 1971)	Acidic hot springs	Acid and heat tolerance	Potential resilience to acidic Martian soils
Pseudopleurochloris antarctica (Andreoli et al., 1999)	Antarctic ice sheets	Extreme cold tolerance, low light adaptation	Survival in Mars' polar regions with limited light
Desmococcus olivaceus (Hu et al., 2002)	Arctic soils	Desiccation and cold resistance	Withstanding Mars' dry and cold conditions

Chlamydomonas nivalis - Often referred to as 'snow algae,' this species predominantly thrives in freezing conditions, painting snowfields and glaciers with a characteristic pinkish-red hue. Their survival is attributed to specialized pigments, which protect them from UV radiation but also assist in capturing limited sunlight efficiently. The ability of these algae to thrive in cold and UV-intensive environments might be of particular interest for Martian applications (Goodenough, 2023). *Dunaliella salina* - Native to hypersaline environments like salt ponds, this green alga can survive and flourish under high salt concentrations. Their resilience under osmotic stress and ability to produce valuable carotenoids offer potential strategies for survival in environments with fluctuating water availability or salinity (Ramos et al., 2011). *Cyanidioschyzon merolae* - Found in highly acidic hot springs, this red alga can endure pH levels as low as 0.2. Their cellular mechanisms, evolved to handle extreme acidity, might offer insights into potential adaptabilities for extraterrestrial habitats with acidic conditions (Kuroiwa et al., 2018). *Pleurochrysis carterae* - Known to form calcium carbonate (coccolith) plates around their cells, these marine algae play a role in long-term carbon sequestration through limestone formation; such a carbon-capturing mechanism could be integral to offsetting high carbon dioxide levels on Mars (Moheimani and Borowitzka, 2006). The aforementioned extremophilic algae exhibit specific survival strategies that could be particularly relevant to Martian terraforming. Research indicates that certain extremophilic algae, such as *Chlamydomonas nivalis*, can survive UV radiation levels up to 500 $\mu W/cm^2$, closely approximating Martian surface conditions during peak sunlight hours. This UV resistance could prove vital for survival on Mars, where atmospheric protection is estimated to be less than 1% of Earth's, explicitly requiring a minimum UV shielding of 0.1 mm of polycarbonate to simulate comparable protection. Similarly, *Dunaliella salina*'s osmoregulatory capabilities enable it to thrive in environments with up to 35% salinity levels, which could be particularly relevant for adapting to Mars' potential briny water sources. The lifespan of these algae under simulated Martian conditions has been observed to extend up to several months, contingent upon adequate nutrient supply and environmental control on Mars (Ramos et al., 2011; Remias et al., 2005).

While the direct transplantation of these species to Martian environments remains speculative, their study provides a conceptual framework. These extremophiles could pave the way for more ambitious ecological interventions on Mars through biotechnological manipulations or by providing specially designed habitats that mimic their Earthly niches.

In conclusion, Earth's extremophilic algae serve as natural case studies, exemplifying adaptability and resilience. Their profound potential for Martian adaptation underscores the importance of intertwining our understanding of Earth's biology with our aspirations for extraterrestrial colonization.

6. Strategies for introducing algae to mars

To realize the dream of leveraging algae for Martian terraforming, a systematic approach is essential in selecting suitable algal strains and the strategies used for their introduction and sustenance on the Red Planet.

6.1. Methods of transport and initial introduction

Algal strains could be cryogenically preserved for the journey to Mars, ensuring their viability during prolonged space travel (Day, 2007). Upon arrival, they would be revived in controlled environments before being introduced to designated habitats. Algae can be transported in bioreactors that maintain optimum growth conditions throughout the journey. These bioreactors could be designed to recycle waste products, ensuring an autonomous system (Show et al., 2019). Certain algae produce spores, dormant structures capable of withstanding adverse conditions (Moss and Fryxell, 1984). These spores could be transported to Mars, where they would be stimulated to germinate under appropriate conditions.

6.2. Ensuring long-term survival and growth

Advances in synthetic biology could allow for the genetic modification of algal strains, tailoring them to endure the Martian environment better (Hlavova et al., 2015). Traits like radiation resistance, tolerance to reduced pressure, and enhanced photosynthetic efficiency under limited light conditions could be introduced or augmented. The initial stages of algal introduction might necessitate controlled environments akin to greenhouses, where temperature, light, moisture, and nutrient levels can be modulated (Schwarz et al., 2014). These biomes would serve as nurseries, allowing algal populations to grow and acclimate before being introduced to broader regions. Developing regenerative life support systems is essential to ensure the long-term sustenance of algae on Mars. These systems would recycle waste products, converting them into valuable nutrients for algal growth, thus establishing a closed-loop cycle (Mapstone et al., 2022; Nelson et al., 2010). The abundant carbon dioxide in the Martian atmosphere and potential subsurface water reserves can be utilized (Malin et al., 2001; Pellenbarg et al., 2003). Algal growth systems could be devised to extract these resources, reducing the need for continuous resource supplementation from Earth. Introducing algae with complementary microorganisms could enhance their chances of survival (Häder, 2020). For instance, nitrogen-fixing bacteria could provide essential nutrients, while specific fungi might form mutualistic associations, similar to terrestrial lichen (Aschenbrenner et al., 2016).

While ambitious, the journey of introducing algae to Mars epitomizes the convergence of diverse scientific disciplines, from astrobiology to biotechnology. Each strategy must be underpinned by meticulous planning and robust scientific data, ensuring our biotic ambassadors can thrive in a once-barren world.

7. Ecological implications and feedback loops

7.1. How the growth of algae could influence other aspects of the Martian environment

As primary producers, algae's photosynthetic activity would contribute to the gradual increase in atmospheric oxygen levels and the reduction of carbon dioxide. Over time, this could lead to a thicker atmosphere, which may help regulate temperature and protect against solar radiation (Graham, 2004; Latif et al., 2021). The decay of algal biomass would introduce organic matter into the Martian regolith. This organic influx could aid in developing rudimentary soil structures, enhancing water retention and nutrient cycling, potentially paving the way for more complex plant introductions in the future. As the atmosphere thickens and greenhouse gases accumulate, Mars might experience rising surface temperatures. Algal-driven carbon sequestration and oxygen production could amplify this greenhouse effect, aiding in the eventual water stability on the surface. As algae proliferate, the increased oxygen release and carbon dioxide uptake could enhance the greenhouse effect, warming the planet. A warmer world might, in turn, support more extensive algal growth, creating a feedback loop that could accelerate terraforming (Latif et al., 2021). Certain algal species, mainly snow algae with pigmentation, could influence the albedo (reflectivity) of the Martian surface. A change in albedo could further impact temperature regulation, either amplifying or mitigating warming effects, depending on the characteristics of the algal cover (Cook et al., 2017).

7.2. Consideration of unintended consequences

Like any introduced species, the risk of uncontrolled algal blooms presents a significant concern. Such blooms could lead to rapid oxygen production or other ecological imbalances, potentially surpassing our capacity to manage the terraforming process efficiently (Hallegraeff, 2004). Moreover, the introduction of algae on Mars, while based on current evidence suggests Mars is barren, raises the prospect of competition for resources with any dormant or extremophilic life forms that might be discovered, possibly posing a threat to native Martian life (Farmer, 1996). Additionally, the production of a range of secondary metabolites by algae, with their potential unforeseen impacts on Martian soil chemistry, atmospheric composition, and the introduction of subsequent organisms, adds layers of complexity to the terraforming endeavor (Verseux et al., 2016). The ambitious goal of altering Mars' atmosphere to create a habitable environment also prompts concerns about unintended climatic shifts, drawing a parallel to Earth's climatic evolution driven by human activities such as industrialization, deforestation, and the proliferation of green there issues (Filippelli, 2022). These activities have led to rapid climate change, characterized by global warming, altered weather patterns, and increased extreme weather events (Ummenhofer and Meehl, 2017). This historical precedent from Earth underscores the imperative for a measured and ecologically responsible approach to terraforming Mars, emphasizing comprehensive environmental impact assessments and sustainable practices (Graham, 2004). The intertwined ecological implications and lessons from Earth's environmental challenges highlight the importance of a phased, adaptive approach to Mars terraforming. Such an approach must be receptive to environmental feedback and prepared for this monumental endeavor's challenges and opportunities. By drawing on Earth's experiences, we can avoid replicating past ecological mistakes, ensuring that our efforts to transform Mars into a new home for humanity proceed ethically, sustainably, and scientifically (Markley, 2019).

8. Comparative analysis: Other organisms and methods

8.1. How algae compares to other proposed organisms or methods for terraforming

Often considered the Earth's earliest oxygen producers, cyanobacteria have been proposed as primary candidates due to their photosynthetic abilities, nitrogen-fixing capabilities, and resilience (Conde-Pueyo et al., 2020). While similar to algae in many respects, certain cyanobacteria might be better suited to extreme conditions, such as high radiation or low nutrient availability (Genta, 2021). Their ability to form symbiotic relationships (especially lichens, which are mutualistic associations between fungi and algae or cyanobacteria) could offer advantages regarding nutrient cycling and soil formation (Honegger, 1991). Complex communities of microorganisms, working in tandem, can perform a broad range of metabolic activities, potentially accelerating various terraforming processes. These consortia might be custom-designed for specific tasks like soil formation, nitrogen fixation, or methane production (Honegger, 1991). Beyond biological entities, there are proposals to use large-scale machinery to release subsurface CO_2 or even to deploy gigantic mirrors to reflect sunlight onto Mars' poles, sublimating CO_2 and thickening the atmosphere (McKay, 1997). While potentially faster than biological methods, these approaches have considerable technological and logistical challenges.

8.2. Synergistic approaches using multiple organisms or techniques

A phased approach where algae or cyanobacteria are first introduced to kickstart atmospheric generation, followed by more complex organisms like mosses or lichens, could optimize the terraforming process, ensuring each phase builds upon the previous one (Table 3) (Graham, 2004; Verseux et al., 2016). Simultaneous introduction of complementary organisms, such as algae and nitrogen-fixing bacteria, might ensure better nutrient cycling, enhanced growth rates, and more robust ecosystems (Llamas et al., 2023). Combining biological, mechanical, or

Table 3
Comparative analysis of algae with other organisms and terraforming methods.

Method/Organism	Primary mechanism	Advantages	Limitations	Compatibility with algae
Algae	Photosynthesis, carbon sequestration	Efficient oxygen production, adaptable to extreme conditions	Requires specific nutrients, potential for overgrowth	
Cyanobacteria	Photosynthesis, nitrogen fixation	Can fix nitrogen, hardy in extreme conditions	Slower oxygen production compared to algae	Synergistic: can complement nutrient cycles
Lichens	Mutual symbiosis (fungi & algae/cyanobacteria)	Durable, can break down rock into soil	Slower growth, limited scalability	Compatible; lichens can contain algal components
Mechanical CO_2 Scrubbers	Physicochemical capture of CO_2	Direct carbon capture can operate continuously	High energy demand maintenance is required	Can work alongside algae to enhance CO_2 removal
Solar Mirrors	Increase solar radiation on Mars' surface	Can raise surface temperatures	Requires significant infrastructure, potential for uneven heating	Can improve conditions for algal growth

chemical techniques might offer accelerated results. For example, after using machinery to thicken the atmosphere initially, algae could be introduced to maintain and enhance the new atmospheric conditions (Zubrin and Mckay, 1997).

Quantitative assessments derived from terrestrial closed ecological system experiments provide a basis for estimating the impact of algae on Martian atmospheric engineering. For instance, the BIOS-3 Siberian experiments, which integrated *Chlorella* algae for air regeneration, demonstrated the capability of algae to maintain human breathable atmospheres in closed environments over continuous cycles (Salisbury et al., 1997). Drawing parallels to Mars, leveraging data from the Mars Atmosphere and Volatile Evolution (MAVEN) mission, which revealed Mars' atmospheric escape rates, allows for modeling gas accumulation rates in the context of algal oxygen production (Filippelli, 2022). Given MAVEN's findings and assuming an algal photosynthetic efficiency similar to terrestrial rates of approximately 5–10 gs of oxygen per square meter per day, preliminary calculations suggest that a 1% increase in Mars' atmospheric oxygen could indeed require between 100 and 200 years with extensive, global deployment of algae-based systems. This assumes the cultivation of algae over approximately 1% of Mars' surface area, an ambitious yet theoretically feasible target with current bioengineering capabilities. Further, extrapolating from Earth's current global oxygen production rates—approximately 100 teragrams (1 teragram = 1 million metric tons) annually from phytoplankton alone (Matthews, 2023) —to the scale necessary for Mars underscores the monumental scale of the endeavor. Mars' surface area, at 144.8 million square kilometers, presents a vast canvas for algal cultivation. Assuming a conservative photosynthetic efficiency and the need to counteract atmospheric escape, the path to a minimally breathable atmosphere hinges on bioengineering advances and the development of supportive technologies for large-scale cultivation and environmental management (Kumar et al., 2020; Long et al., 2022).

Creating contained biomes where multiple organisms coexist, each playing a specific role (e.g., algae producing oxygen, fungi breaking down rocks, and mosses stabilizing the soil), could serve as prototypes for more expansive Martian ecosystems (Silverstone et al., 2003).

In conclusion, while algae offer distinct advantages for Martian terraforming, their potential might be realized most effectively when used with other organisms or techniques (Verseux et al., 2016). A holistic approach, integrating the strengths of multiple methods, could pave the way for a more rapid and sustainable transformation of the Red Planet.

9. Potential challenges and solutions in the path forward

The myriad of unknown factors presents a challenge, from potential subsurface water reservoirs to unanticipated soil chemistries (Silverstone et al., 2003). Robust robotic missions can aid in detailed reconnaissance, gathering precise data to inform biological introductions. The sustainability of introduced algae, especially under fluctuating conditions and potential resource limitations, is a concern (Verseux et al., 2016). Developing adaptive, self-regulating algal systems, possibly incorporating AI-driven feedback mechanisms, can optimize growth and metabolic outputs in real-time. Ensuring that algal introductions do not tip the environmental balance unfavorably, leading to unintended consequences like runaway greenhouse effects or toxic byproduct accumulation (Ausubel, 2012). Close monitoring through sensors and satellite observations, combined with the ability to introduce regulatory or counterbalancing organisms, and could maintain desired ecological trajectories. Altering an entire planet, with its potential implications for any native life forms or future human inhabitants, raises profound ethical questions. Engaging a broad spectrum of stakeholders, from scientists to ethicists, in deliberative dialogues can guide the formation of responsible and inclusive terraforming policies. Establishing regulatory or counterbalancing bodies is essential in response to terraforming Mars's complexities and potential ecological impacts. An example of such an entity could be an 'Interplanetary Environmental Protection Agency' (IEPA), modeled after Earth's various national environmental agencies, such as the United States Environmental Protection Agency (US EPA) or the European Environment Agency (EEA). The IEPA's mandate would include developing and enforcing terraforming guidelines, monitoring environmental changes on Mars, and ensuring that terraforming activities do not compromise the Martian environment or any potential indigenous life forms (Board and National Academies of Sciences and Medicine, 2017). Additionally, a 'Mars Terraforming Advisory Council' (MTAC), comprising astrobiology, planetary science, environmental ethics, and space law experts, could serve as a counterbalancing body. The MTAC would provide oversight, review terraforming strategies for ecological and ethical compliance, and recommend adjustments to mitigate adverse outcomes (French, 2013). This council could work with international space agencies and scientific communities, such as the International Astronomical Union (IAU) and the Committee on Space Research (COSPAR), to ensure a coordinated and responsible approach to Mars terraforming (Zorzano et al., 2023). These bodies would regulate terraforming efforts and facilitate international collaboration, share research and data, and engage the public in understanding and supporting responsible extraterrestrial environmental management. The ethical considerations of terraforming Mars are multifaceted and complex, warranting a thorough and nuanced exploration. Central to these ethical debates is the principle of planetary protection, which seeks to prevent biological contamination of celestial bodies, preserve their native states for scientific study, and respect any potential indigenous life forms (Szocik, 2021). Terraforming, which inherently alters the Martian environment, raises significant ethical questions about humanity's right to modify another planet (Sparrow, 1999). Moreover, the potential discovery of dormant or extremophilic Martian life forms introduces the ethical dilemma of prioritizing Earth-originating life over native Martian ecosystems. This concern aligns with the broader ethical principle of astrobiological conservation, advocating protecting extraterrestrial life and environments as part of our cosmic heritage. Another critical ethical issue involves the equitable access to and distribution of Martian resources. As terraforming efforts progress, ensuring that the benefits and opportunities presented by a habitable Mars are shared equitably among all nations and peoples becomes a paramount concern. This issue touches on broader themes of space colonization, sovereignty, and the potential for new forms of colonialism or resource monopolization. Lastly, the long-term sustainability of terraforming initiatives raises ethical questions about our obligations to future generations (Szocik, 2021). This includes ensuring that terraforming efforts do not inadvertently create an inhospitable environment on Mars or deplete resources to the detriment of Martian inhabitants and Earth's population. Addressing these ethical issues requires a collaborative international approach involving scientists, engineers, ethicists, philosophers, policymakers, and the global public. Establishing comprehensive ethical frameworks and international agreements will be crucial in guiding the responsible terraforming of Mars, ensuring that such endeavors are conducted with respect for scientific integrity, planetary protection, and the equitable sharing of extraterrestrial opportunities (McKay, 2018).

The roadmap to harnessing algae for Martian terraforming is an evolving tapestry of scientific innovation, exploration, and ethical contemplation (Häder, 2020). As we stand on the cusp of potentially transforming another world, the intertwining of rigorous research and visionary foresight will be paramount. The lessons learned, challenges overcome, and successes achieved on this path not only shape the destiny of Mars but also reflect on our capacity as stewards of life in the broader cosmos.

10. Conclusion

Mars presents itself as a tantalizing enigma, a celestial body that has, for generations, ignited our collective imagination with prospects of life and habitation. Amidst this backdrop, algae have emerged as organisms of terrestrial significance and potential agents of planetary transformation. This discourse synthesizes our current understanding of algal biology and ecology, drawing attention to their historic role in sculpting Earth's atmospheric composition and their potential application in terraforming efforts on Mars. In elucidating the attributes of algae, we recognize their photosynthetic efficiency, capacity for carbon fixation, and adaptability to extreme terrestrial biotopes—traits that underscore their suitability for off-world ecological engineering. This review critically evaluates algae alongside alternative terraforming agents, advocating for a holistic strategy that marries biological systems with technological innovations. The quest to re-engineer the Martian atmosphere encompasses technological hurdles and ethical considerations. Introducing biota to a desolate planet instigates a cascade of potential ecological transformations and necessitates deeply contemplating our stewardship over extraterrestrial environments. The research community is thus poised at a pivotal intersection of discovery and creation, charged with decrypting the complexities of the Martian milieu. Through continuous inquiry and empirical rigor, we progressively elucidate the feasibility of such an enterprise. It is crucial that this endeavor, predicated on the latent power of algae, be grounded in a framework of scientific integrity, international collaboration, and visionary prudence. To envisage a thriving, oxygen-rich Mars is to engage with a vision steeped in both challenge and potential—an idea that indeed, indeed, the microalga of humans herald a new epoch in the annals of human achievement, symbolizing our relentless quest to expand beyond the confines of our home planet. As humanity peers into the cosmic vastness, armed with ingenuity and the lessons of terrestrial life, the dream of a transformed Mars reflects our pursuit of knowledge and indomitable resolve to extend life's tapestry into the cosmos. In summary, the potential of algae as pivotal agents in terraforming Mars is grounded in their remarkable photosynthetic efficiency, unparalleled carbon fixation capability, and inherent resilience to extreme envsignify algae's evolutionary triumph on Earth and triumph on Earth but also their prospective utility in extraterrestrial ecosystem engineering. By leveraging algae's biological mechanisms, we can envision a systematic approach to terraforming that integrates the natural potential of these organisms with cutting-edge technologies. The collective endeavor to render Mars habitable will undoubtedly hinge on our ability to harness these qualities, transforming the red desolation into a verdant expanse capable of supporting life. Thus, algae do not merely represent a tool for planetary transformation but embody the symbiosis of Earth's life-sustaining principles with our extraplanetary aspirations, offering a blueprint for the sustainable habitation of Mars and beyond.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Andreoli, C., Moro, I., La Rocca, N., Rigoni, F., Valle, L.D., Bargelloni, L., 1999. *Pseudopleurochloris antarctica* gen. et sp. nov., a new coccoid xanthophycean from pack-ice of wood bay (ross sea, antarctica): ultrastructure, pigments and 18s rrna gene sequence. Eur. J. Phycol. 34, 149–159. https://doi.org/10.1080/09670269910001736202.

Aschenbrenner, I.A., Cernava, T., Berg, G., Grube, M., 2016. Understanding microbial multi-species symbioses. Front. Microbiol. 7, 180. https://doi.org/10.3389/fmicb.2016.00180.

Atri, D., Melott, A.L., 2014. Cosmic rays and terrestrial life: a brief review. Astropart. Phys. 53, 186–190. https://doi.org/10.1016/j.astropartphys.2013.03.001.

Ausubel, K., 2012. Dreaming the Future: Reimiagining Civilization in the Age of Nature. Chelsea Green Publishing.

Baldanta, S., Arnal, R., Blanco-Rivero, A., Guevara, G., Navarro Llorens, J.M., 2023. First characterization of cultivable extremophile *Chroococcidiopsis* isolates from a solar panel. Front. Microbiol. 14, 982422 https://doi.org/10.3389/fmicb.2023.982422.

Beech, M., 2021. Terraforming mars: a cabinet of curiosities. Terraform. Mars 417–465. https://doi.org/10.1002/9781119761990.ch18.

Blouin, N.A., Brodie, J.A., Grossman, A.C., Xu, P., Brawley, S.H., 2011. Porphyra: a marine crop shaped by stress. Trends Plant Sci. 16, 29–37. https://doi.org/10.1016/j.tplants.2010.10.004.

Board, S.S., National Academies of Sciences and Medicine, E., 2017. The Goals, Rationales, and Definition of Planetary Protection: Interim Report. National Academies Press.

Boroda, A.V., Aizdaicher, N.A., Odintsova, N.A., 2014. The influence of ultra-low temperatures on marine microalgal cells. J. Appl. Phycol. 26, 387–397. https://doi.org/10.1007/s10811-013-0093-5.

Bowler, C., Allen, A.E., Badger, J.H., Grimwood, J., Jabbari, K., Kuo, A., Maheswari, U., Martens, C., Maumus, F., Otillar, R.P., Rayko, E., Salamov, A., Vandepoele, K., Beszteri, B., Gruber, A., Heijde, M., Katinka, M., Mock, T., Valentin, K., Verret, F., Berges, J.A., Brownlee, C., Cadoret, J.P., Chiovitti, A., Choi, C.J., Coesel, S., De Martino, A., Detter, J.C., Durkin, C., Falciatore, A., Fournet, J., Haruta, M., Huysman, M.J.J., Jenkins, B.D., Jiroutova, K., Jorgensen, R.E., Joubert, Y., Kaplan, A., Kröger, N., Kroth, P.G., La Roche, J., Lindquist, E., Lommer, M., Martin-Jézéquel, V., Lopez, P.J., Lucas, S., Mangogna, M., McGinnis, K., Medl, Montsant, A., Secq, Le, M.P.O., Napoli, C., Obornik, M., Parker, M.S., Petit, J.L., Porcel, B.M., Poulsen, N., Robison, M., Rychlewski, L., Rynearson, T.A., Schmutz, J., Shapiro, H., Siaut, M., Stanley, M., Sussman, M.R., Taylor, A.R., Vardi, A., Von Dassow, P., Vyverman, W., Willis, A., Wyrwicz, L.S., Rokhsar, D.S., Weissenbach, J., Armbrust, E.V., Green, B.R., Van De Peer, Y., Grigoriev, I.V., 2008. The Phaeodactylum genome reveals the evolutionary history of diatom genomes. Nature 456, 239–244. https://doi.org/10.1038/nature07410.

Bradbury, I.K., 1991. The Biosphere. Springer Science & Business Media. https://doi.org/10.2307/622470. The biosphere.

Çelekli, A., Yaygır, S., Zariç, Ö.E., 2023a. A review of climate change-induced migration. Acta Biologica Turcica 36, 1–3. https://doi.org/10.5281/zenodo.8190755.

Çelekli, A., Yeşildağ, İ., Yaygır, S., Zariç, Ö.E., 2023b. Effects of urbanization on bioclimatic comfort conditions. Acta Biologica Turcica 36, 1–9, 2-.

Çelekli, A., Zariç, Ö.E., 2024. Plasma-enhanced Microalgal cultivation: a sustainable approach for biofuel and biomass production. Emerging Applications of Plasma Science in Allied Technologies. IGI Global, pp. 243–263.

Çelekli, A., Zariç, Ö.E., 2023a. From emissions to environmental impact: understanding the carbon footprint. Int. J. Environ. Geoinform. 10, 146–156. https://doi.org/10.30897/ijegeo.1383311.

Çelekli, A., Zariç, Ö.E., 2023b. Hydrobiology and ecology in the context of climate change: the future of aquatic ecosystems. In: 6th International Eurasian Conference on Biological and Chemical Sciences, pp. 539–545. https://doi.org/10.5281/zenodo.10021473.

Çelekli, A., Zariç, Ö.E., 2023c. Assessing the environmental impact of functional foods. In: 6th International Eurasian Conference on Biological and Chemical Sciences, p. 103. https://doi.org/10.5281/zenodo.10021465.

Çelekli, A., Zariç, Ö.E., 2023d. Utilization of Herbaria in Ecological studies: Biodiversity and Landscape Monitoring. d. Herbarium Turcicum. https://doi.org/10.26650/HT.2023.1345916. Advance Online Publication.
Ciferri, O., 1983. *Spirulina*, the edible microorganism. Microbiol. Rev. 47, 551–578. https://doi.org/10.1128/mmbr.47.4.551-578.1983.
Conde-Pueyo, N., Vidiella, B., Sardanyés, J., Berdugo, M., Maestre, F.T., Lorenzo, V.de, Solé, R., 2020. Synthetic biology for terraformation lessons from mars, earth, and the microbiome. Life 10, 14. https://doi.org/10.3390/life10020014.
Cook, J.M., Hodson, A.J., Gardner, A.S., Flanner, M., Tedstone, A.J., Williamson, C., Irvine-Fynn, T.D.L., Nilsson, J., Bryant, R., Tranter, M., 2017. Quantifying bioalbedo: a new physically based model and discussion of empirical methods for characterising biological influence on ice and snow albedo. Cryosphere 11, 2611–2632. https://doi.org/10.5194/tc-11-2611-2017.
Day, J.G., 2007. Cryopreservation of microalgae and cyanobacteria. Methods Mol. Biol. 368, 141–151. https://doi.org/10.1007/978-1-59745-362-2_10.
De Micco, V., Amitrano, C., Mastroleo, F., Aronne, G., Battistelli, A., Carnero-Diaz, E., De Pascale, S., Detrell, G., Dussap, C.G., Ganigué, R., Jakobsen, Ø.M., Poulet, L., Van Houdt, R., Verseux, C., Vlaeminck, S.E., Willaert, R., Leys, N., 2023. Plant and microbial science and technology as cornerstones to Bioregenerative life support systems in space. npj Micrograv. 9, 69. https://doi.org/10.1038/s41526-023-00317-9.
Doemel, W.N., Brock, T.D., 1971. The physiological ecology of Cyanidium caldarium. J. Gen. Microbiol. 67, 17–32. https://doi.org/10.1099/00221287-67-1-17.
Fabris, M., Abbriano, R.M., Pernice, M., Sutherland, D.L., Commault, A.S., Hall, C.C., Labeeuw, L., McCauley, J.I., Kuzhiuparambil, U., Ray, P., Kahlke, T., Ralph, P.J., 2020. Emerging technologies in algal biotechnology: toward the establishment of a sustainable, algae-based bioeconomy. Front. Plant Sci. 11, 279. https://doi.org/10.3389/fpls.2020.00279.
Fairén, A.G., Davila, A.F., Lim, D., Bramall, N., Bonaccorsi, R., Zavaleta, J., Uceda, E.R., Stoker, C., Wierzchos, J., Dohm, J.M., Amils, R., Andersen, D., McKay, C.P., 2010. Astrobiology through the ages of Mars: the study of terrestrial analogues to understand the habitability of Mars. Astrobiology 10, 821–843. https://doi.org/10.1089/ast.2009.0440.
Farmer, J.D., 1996. Hydrothermal systems on Mars: an assessment of present evidence. CIBA Foundation Symposia. Wiley Online Library, pp. 273–299. https://doi.org/10.1002/9780470514986.ch15.
Filippelli, G.M., 2022. Climate Change and Life: The Complex Co-evolution of Climate and Life on Earth, and Beyond. Elsevier.
Forget, F., Spiga, A., Dolla, B., Vinatier, S., Melchiorri, R., Drossart, P., Gendrin, A., Bibring, J.P., Langevin, Y., Gondet, B., 2007. Remote sensing of surface pressure on Mars with the Mars Express/OMEGA spectrometer: 1. Retrieval method. J. Geophys. Res.: Planets 112. https://doi.org/10.1029/2006JE002871.
French, R.H., 2013. Environmental Philosophy and the Ethics of Terraforming Mars: Adding the Voices of Environmental Justice and Ecofeminism to the Ongoing Debate. University of North Texas.
Genta, G., 2021. Terraforming and colonizing mars. Terraform. Mars 3–22. https://doi.org/10.1002/9781119761990.ch1.
Awan, A.G., 2013. Relationship between environment and sustainable economic development: a theoretical approach to environmental problems. Int. J. Asian Soc. Sci. 3, 741–761.
Goodenough, U., 2023. The *Chlamydomonas* Sourcebook, Volume 1: Introduction to *Chlamydomonas* and Its Laboratory Use. Academic press. https://doi.org/10.1016/C2019-0-02739-2. The Chlamydomonas Sourcebook: Volume 1: Introduction to Chlamydomonas and Its Laboratory Use.
Graham, J.M., 2004. The biological terraforming of Mars: planetary ecosynthesis as ecological succession on a global scale. Astrobiology 4, 168–195. https://doi.org/10.1089/153110704323175133.
Grant, W.D., Danson, M.J., Scott, D.J., Halling, P.J., Engberts, J.B.F.N., Ho, M.W., Berendsen, H.J.C., 2004. Life at low water activity. Philos. Trans. R. Soc. B: Biol. Sci. 359, 1249–1267. https://doi.org/10.1098/rstb.2004.1502.
Häder, D., 2020. On the Way to Mars—Flagellated Algae in Bioregenerative Life Support Systems Under Microgravity Conditions. Front. Plant Sci. 10, 1621. https://doi.org/10.3389/fpls.2019.01621.
Hallegraeff, G.M., 2004. Harmful algal blooms: a global overview. Manual on Harmful Mar. Microalgae 33, 25–50.
Hender, M., 2010. Colonization: A Permanent Habitat for the Colonization of Mars (Doctoral dissertation). School of Mechanical Engineering. University of Adelaide.
Hlavova, M., Turoczy, Z., Bisova, K., 2015. Improving microalgae for biotechnology - from genetics to synthetic biology. Biotechnol. Adv. 33, 1194–1203. https://doi.org/10.1016/j.biotechadv.2015.01.009.
Holmer, C., 2020. Bio-Regenerative Life Support Systems Functional Stability and Limitations, a Theoretical Modeling Approach, Doctoral dissertation. The University of North Dakota.
Honegger, R., 1991. Functional aspects of the lichen symbiosis. Annual Rev. Plant Physiol. Plant Mol. Biol. 42, 553–578. https://doi.org/10.1146/annurev.pp.42.060191.003005.
Hu, C., Liu, Y., Song, L., Zhang, D., 2002. Effect of desert soil algae on the stabilization of fine sands. J. Appl. Phycol. 14, 281–292. https://doi.org/10.1023/A:1021128530086.
Jakosky, B.M., Phillips, R.J., 2001. Mars' volatile and climate history. Nature 412, 237–244. https://doi.org/10.1038/35084184.
Janssen, P.J.D., Lambreva, M.D., Plumeré, N., Bartolucci, C., Antonacci, A., Buonasera, K., Frese, R.N., Scognamiglio, V., Rea, G., 2014. Photosynthesis at the forefront of a sustainable life. Front. Chem. 2, 1–22. https://doi.org/10.3389/fchem.2014.00036.
Jiang, Z., Liu, Q., Roberts, A.P., Dekkers, M.J., Barrón, V., Torrent, J., Li, S., 2022. The magnetic and color reflectance properties of hematite: from earth to mars. Rev. Geophys. 60, e2020RG000698 https://doi.org/10.1029/2020RG000698.
Kaçka, A., Dönmez, G., 2008. Isolation of Dunaliella spp. from a hypersaline lake and their ability to accumulate glycerol. Bioresour. Technol. 99, 8348–8352. https://doi.org/10.1016/j.biortech.2008.02.042.
Knoll, A.H., 1992. The early evolution of life. Sci. Earth 256, 436–457.
Kumar, G., Shekh, A., Jakhu, S., Sharma, Y., Kapoor, R., Sharma, T.R., 2020. Bioengineering of microalgae: recent advances, perspectives, and regulatory challenges for industrial application. Front. Bioeng. Biotechnol.
Kuroiwa, T., Miyagishima, S., Matsunaga, S., Sato, N., Nozaki, H., Tanaka, K., Misumi, O., 2018. Cyanidioschyzon merolae: A new Model Eukaryote for Cell and Organelle Biology, Cyanidioschyzon merolae: A New Model Eukaryote for Cell and Organelle Biology. Springer. https://doi.org/10.1007/978-981-10-6101-1.
Larkum, A.W.D., 2020. Light-harvesting in cyanobacteria and eukaryotic algae: an overview. Photosynthesis Algae: Biochem. Physiol. Mech. 207–260. https://doi.org/10.1007/978-3-030-33397-3_10.
Latif, K., Ray, J.G., Planchon, O., 2021. Algae on mars: a summary of the evidence. J. Astrobiol. Algae Mars 22 7, 22–28. JournalofAstrobiology.com Journal of Astrobiology.
Levchenko, I., Xu, S., Mazouffre, S., Keidar, M., Bazaka, K., 2021. Mars colonization: beyond getting there. Terraform. Mars 73–98. https://doi.org/10.1002/9781119761990.ch5.
Llamas, A., Leon-Miranda, E., Tejada-Jimenez, M., 2023. Microalgal and nitrogen-fixing bacterial consortia: from interaction to biotechnological potential. Plants 12, 2476. https://doi.org/10.3390/plants12132476.
Long, B., Fischer, B., Zeng, Y., Amerigian, Z., Li, Q., Bryant, H., Li, M., Dai, S.Y., Yuan, J. S., 2022. Machine learning-informed and synthetic biology-enabled semi-continuous algal cultivation to unleash renewable fuel productivity. Nat. Commun. 13, 541. https://doi.org/10.1038/s41467-021-27665-y.
Malin, M.C., Caplinger, M.A., Davis, S.D., 2001. Observational evidence for an active surface reservoir of solid carbon dioxide on Mars. Science 294, 2146–2148. https://doi.org/10.1126/science.1066416.
Mapstone, L.J., Leite, M.N., Purton, S., Crawford, I.A., Dartnell, L., 2022. Cyanobacteria and microalgae in supporting human habitation on Mars. Biotechnol. Adv. 59, 107946 https://doi.org/10.1016/j.biotechadv.2022.107946.
Markley, R., 2019. Terraforming and Eco-Economics in the Mars Trilogy. Kim Stanley Robinson. https://doi.org/10.5622/illinois/9780252042751.003.0004.
Matthews, M.L., 2023. Engineering photosynthesis, nature's carbon capture machine. PLoS Biol. 21, e3002183 https://doi.org/10.1371/journal.pbio.3002183.
McKay, C.P., 2018. The search on mars for a second genesis of life in the solar system and the need for biologically reversible exploration. Biol. Theory 13, 103–110. https://doi.org/10.1007/s13752-017-0284-4.
McKay, D.P., 1997. Terraforming: engineering planetary environments. Martyn J. Fogg. Icarus 130, 552. https://doi.org/10.1006/icar.1997.5849.
Moheimani, N.R., Borowitzka, M.A., 2006. The long-term culture of the coccolithophore Pleurochrysis carterae (Haptophyta) in outdoor raceway ponds. J. Appl. Phycol. 18, 703–712. https://doi.org/10.1007/s10811-006-9075-1.
Moss, B., Fryxell, G.A., 1984. Survival strategies of the algae. J. Ecol.. CUP Arch. https://doi.org/10.2307/2259561.
Nelson, M., Pechurkin, N.S., Allen, J.P., Somova, L.A., Gitelson, J.I., 2010. Closed ecological systems, space life support and Biospherics. Environ. Biotechnol. 517–565. https://doi.org/10.1007/978-1-60327-140-0_11.
Neukart, F., 2024. Towards sustainable horizons: a comprehensive blueprint for mars colonization. Heliyon e26180. https://doi.org/10.1016/j.heliyon.2024.e26180.
Newkirk, G.M., de Allende, P., Jinkerson, R.E., Giraldo, J.P., 2021. Nanotechnology approaches for chloroplast biotechnology advancements. Front. Plant Sci. 12, 691295 https://doi.org/10.3389/fpls.2021.691295.
Olsson-Francis, K., Doran, P.T., Ilyin, V., Raulin, F., Rettberg, P., Kminek, G., Mier, M.P. Z., Coustenis, A., Hedman, N., Shehhi, O.Al, Ammannito, E., Bernardini, J., Fujimoto, M., Grasset, O., Groen, F., Hayes, A., Gallagher, S., Kumar, K., .P.., Mustin, C., Nakamura, A., Seasly, E., Suzuki, Y., Peng, J., Prieto-Ballesteros, O., Sinibaldi, S., Xu, K., Zaitsev, M., 2023. The COSPAR Planetary Protection Policy for robotic missions to Mars: a review of current scientific knowledge and future perspectives. Life Sci. Space Res. 36, 27–35. https://doi.org/10.1016/j.lssr.2022.12.001.
Pellenbarg, R.E., Max, M.D., Clifford, S.M., 2003. Methane and carbon dioxide hydrates on Mars: potential origins, distribution, detection, and implications for future in situ resource utilization. J. Geophys. Res.: Planets 108. https://doi.org/10.1029/2002je001901.
Petrosyan, A., Galperin, B., Larsen, S.E., Lewis, S.R., Määttänen, A., Read, P.L., Renno, N., Rogberg, L.P.H.T., Savijrvi, H., Siili, T., Spiga, A., Toigo, A., Vázquez, L., 2011. The Martian atmospheric boundary layer. Rev. Geophys. 49 https://doi.org/10.1029/2010RG000351.
Ramos, A.A., Polle, J., Tran, D., Cushman, J.C., Jin, E.-S., Varela, J.C., 2011. The unicellular green alga Dunaliella salina Teod. as a model for abiotic stress tolerance: genetic advances and future perspectives. Algae 26, 3–20. https://doi.org/10.4490/algae.2011.26.1.003.
Remias, D., Lütz-Meindl, U., Lütz, C., 2005. Photosynthesis, pigments and ultrastructure of the alpine snow alga Chlamydomonas nivalis. Eur. J. Phycol. 40, 259–268. https://doi.org/10.1080/09670260500202148.
Richmond, A., Vonshak, A., 1991. Algal biotechnology. Bioresour. Technol. 38, 83–252. https://doi.org/10.1016/b978-0-12-815870-8.00003-6.
Rupérez, P., Ahrazem, O., Leal, J.A., 2002. Potential antioxidant capacity of sulfated polysaccharides from the edible marine brown seaweed Fucus vesiculosus. J. Agric. Food Chem. 50, 840–845. https://doi.org/10.1021/jf010908o.

Sagan, C., 1973. Planetary engineering on Mars. Icarus 20, 513–514. https://doi.org/10.1016/0019-1035(73)90026-2.

Salisbury, F.B., Gitelson, J.I., Lisovsky, G.M., 1997. Bios-3: siberian experiments in bioregenerative life support. Bioscience 47, 575–585. https://doi.org/10.2307/1313164.

Sarwer, A., Hamed, S.M., Osman, A.I., Jamil, F., Al-Muhtaseb, A.H., Alhajeri, N.S., Rooney, D.W., 2022. Algal biomass valorization for biofuel production and carbon sequestration: a review. Environ. Chem. Lett. 20, 2797–2851. https://doi.org/10.1007/s10311-022-01458-1.

Sayre, R., 2010. Microalgae: the potential for carbon capture. Bioscience 60, 722–727. https://doi.org/10.1525/bio.2010.60.9.9.

Schwarz, D., Thompson, A.J., Kläring, H.P., 2014. Guidelines to use tomato in experiments with a controlled environment. Front. Plant Sci. 5, 625.

Seckbach, J., Chapman, D.J., Garbary, D., Oren, A., Reisser, W., 2007. Algae and Cyanobacteria Under Environmental Extremes. Springer. https://doi.org/10.1007/978-1-4020-6112-7_42.

Seckbach, J., Oren, A., 2006. Introduction to the extremophiles. Origins. Springer, pp. 371–396. https://doi.org/10.1007/1-4020-2522-x_23.

Show, K.Y., Yan, Y., Lee, D.J., 2019. Bioreactor and bioprocess design for biohydrogen production. In: Biomass, Biofuels, Biochemicals: Biohydrogen, Second Edition, 102, pp. 391–411. https://doi.org/10.1016/B978-0-444-64203-5.00016-2.

Silverstone, S., Nelson, M., Alling, A., Allen, J., 2003. Development and research program for a soil-based bioregenerative agriculture system to feed a four person crew at a Mars base. Adv. Space Res. 31, 69–75. https://doi.org/10.1016/S0273-1177(02)00661-0.

Solé, R.V., Montañez, R., Duran-Nebreda, S., 2015. Synthetic circuit designs for earth terraformation. Biol. Direct 10, 1–10. https://doi.org/10.1186/s13062-015-0064-7.

Sparrow, R., 1999. The ethics of terraforming. Environ. Ethic. 21, 227–245. https://doi.org/10.5840/enviroethics199921315.

Starr, S.O., Muscatello, A.C., 2020. Mars in situ resource utilization: a review. Planet. Space Sci. 182, 104824 https://doi.org/10.1016/j.pss.2019.104824.

Stirbet, A., Lazár, D., Guo, Y., Govindjee, G., 2020. Photosynthesis: basics, history and modelling. Ann. Bot. 126, 511–537. https://doi.org/10.1093/aob/mcz171.

Szocik, K., 2021. Ethical, political and legal challenges relating to colonizing and terraforming mars. Terraform. Mars 123–134. https://doi.org/10.1002/9781119761990.ch8.

Ummenhofer, C.C., Meehl, G.A., 2017. Extreme weather and climate events with ecological relevance: a review. Philos. Trans. R. Soc. B: Biol. Sci. 372, 20160135 https://doi.org/10.1098/rstb.2016.0135.

Van Den Hoek, C., Mann, D.G., Jahns, H.M., 1995. Algae: an Introduction to phycology, Search. Cambridge university press.

Verseux, C., Baqué, M., Lehto, K., De Vera, J.P.P., Rothschild, L.J., Billi, D., 2016. Sustainable life support on Mars - The potential roles of cyanobacteria. Int. J. Astrobiol. 15, 65–92. https://doi.org/10.1017/S147355041500021X.

Wells, M.L., Potin, P., Craigie, J.S., Raven, J.A., Merchant, S.S., Helliwell, K.E., Smith, A. G., Camire, M.E., Brawley, S.H., 2017. Algae as nutritional and functional food sources: revisiting our understanding. J. Appl. Phycol. 29, 949–982. https://doi.org/10.1007/s10811-016-0974-5.

Westall, F., Foucher, F., Bost, N., Bertrand, M., Loizeau, D., Vago, J.L., Kminek, G., Gaboyer, F., Campbell, K.A., Bréhéret, J.G., Gautret, P., Cockell, C.S., 2015. Biosignatures on mars: what, where, and how? Implications for the search for martian life. Astrobiology 15, 998–1029. https://doi.org/10.1089/ast.2015.1374.

Zariç, Ö.E., Yeşildağ, İ., Yaygır, S., Çelekli, A., 2022. Removal of harmful dyes using some algae. In: 3rd International Congress on Plant Biology, 173. https://doi.org/10.5281/zenodo.8190776.

Zorzano, M.P., Olsson-Francis, K., Doran, P.T., Rettberg, P., Coustenis, A., Ilyin, V., Raulin, F., Shehhi, O.Al, Groen, F., Grasset, O., Nakamura, A., Ballesteros, O.P., Sinibaldi, S., Suzuki, Y., Kumar, P., Kminek, G., Hedman, N., Fujimoto, M., Zaitsev, M., Hayes, A., Peng, J., Ammannito, E., Mustin, C., Xu, K., 2023. The COSPAR planetary protection requirements for space missions to Venus, Life Sciences in Space Research. Copernicus Meetings. https://doi.org/10.1016/j.lssr.2023.02.001.

Zubrin, R.M., Mckay, C.P., 1997. Technological requirements for terraforming mars. JBIS - J. Brit. Interplanet. Soc. 83–92. https://doi.org/10.2514/6.1993-2005.