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Microalgae: A Solution for Food Security and Multiplanetary Farming

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ABSTRACT

Human civilization is threatened by food insecurity and habitat loss owing to the cumulative effects of anthropogenic and natural factors. Thus, increasing food production while using fewer resources and exploring the potential of interstellar migration is essential. Particularly, microalgae can fulfil the biological, nutritional, and efficiency requirements of industrial food production on Earth and other potential planets. Herein, we discuss the industrial production of microalgae on Earth and in outer space, along with the technological advances that will help reshape the genetic and chemical properties of microalgae for better production, nutrition, and adaptation. We propose the concept of “multiplanetary farming” to address future requirements for agricultural development. This perspective review is intended to stimulate a broad debate and research on this paramount issue for the future of mankind.

1 | Introduction

According to the United Nations Food and Agriculture Organization, the global population will reach ~10 billion by 2050; thus, to meet the food requirements, crop production must increase by 50% (Gupta et al. 2020). However, the area of arable land on Earth has remained at ~1.5 billion hectares since 1990 and is expected to decline owing to increasing land-use conversion from arable land to urban areas to accommodate infrastructure expansion. Additionally, food production has been constrained by resource depletion, climate change, water scarcity, plant disease, pests, and ecological degradation (Barnosky et al. 2011; Cooley et al. 2021; Hasegawa et al. 2021; Mora et al. 2022). In the future, humans may need to establish new settlements on other planets if Earth can no longer provide the resources required to sustain the ever-growing population (Gibney 2018; Nangle et al. 2020). Continuous technological progress and planetary exploration have made this scenario increasingly feasible. However, regardless of the location, it is important to establish an efficient and sustainable system of mass food production with reduced natural resource requirements. Among the ~8.7 million species of living organisms on Earth, microalgae are one of the most promising candidates for addressing these pressing issues owing to their unique biological, nutritional, and functional characteristics, as well as their great production efficiency as a resource (Torres-Tiji et al. 2020). In our view, “multiplanetary farming” is a necessary supplement and inevitable trend for future agricultural development, and the primary task of this agricultural form is to screen for pioneer species. Therefore, we systematically compared chassis organisms such as animals, plants, heterotrophic microorganisms, and other sources (such as insects) and believe that microalgae have several advantages for increasing food production to meet the immediate needs of humans on Earth and the expected future requirements during interstellar migration. We further discuss how technical advances can be used to modify microalgal species to meet the requirements of mass production, nutrition, and adaptation. Additionally, we investigate the potential application of microalgae in multiplanetary farming and its future transformation direction. We hope our proposals stimulate extensive discussion and promote research in this critical area for the sustainable development of human civilization.

2 | Process of Agricultural Development

Over 4600 million years ago (Mya) when the Earth was formed, it was a barren landscape with numerous heat waves and a desert atmosphere filled with poisonous greenhouse gases (GHG). Cyanobacteria emerged ~2400 Mya (Figure 1A) and began absorbing CO_2 to produce organic matter, while concomitantly releasing O_2 as a by-product of photosynthesis, leading to the subsequent evolution of eukaryotes (Hohmann-Marriott and Blankenship 2011; Sánchez-Baracaldo et al. 2022). Eukaryotic algae belonging to the taxa Chlorophyta, Phaeophyceae, and Euglenophyta then consecutively emerged ~500 Mya (Gould et al. 2008), resulting in the continuous alteration of the Earth's ecosystem and promoting the evolution of lower, simpler, unicellular life forms into higher, more complex, multicellular organisms. Between 430 and 65 Mya, Earth experienced five mass extinctions, specifically during the Ordovician, Devonian, Permian, Triassic, and Cretaceous periods (Raup 1986). Microalgae not only survived these five mass extinctions but rejuvenated the barren Earth after each extinction with their strong adaptability and carbon neutrality, thus, contributing substantially to the evolution of humans (Antón et al. 2014).

The beginning of the Age of Discovery in the 15th century opened new sea routes and promoted the global exchange of crops and livestock. Maize, potatoes, sweet potatoes, tomatoes, cotton, and turkeys, all native to America, were introduced to Eurasia and Africa, while wheat, rice, canola, citrus fruits, onions, cattle, sheep, pigs, and other agricultural species from the eastern hemisphere were introduced to the Americas (Figure 1B). This global exchange of agricultural species facilitated the development of modern rural agriculture, which is characterized by improved seeds, fertile fields (arable land), mechanization (automation), and large-scale production under intensive crop management strategies aimed at maximizing output.

In 1903, the successful aircraft flight test by the Wright Brothers marked the advent of the Age of Aerospace (Suter 2003), which further accelerated global exchange and innovation of agricultural species, thereby promoting global urbanization (Figure 1C). According to the World Bank data (https://data.worldbank.org/), the global urbanization rate increased from 33.62% in 1960 to 56.16% in 2020. Horticultural crops, such as lettuce, tomatoes, and strawberries, were grown in park buildings, greenhouse facilities, balconies, and rooftops in major cities, while domesticated animals, such as chickens, pigs, and cattle were factory-farmed in urban suburbs and radial economic zones around cities. The use of vertical spaces in urban agricultural production reduces the need for rural cultivation conditions, such as arable land and the proper climate, region, and season; this further promotes the industrialization, annualization, and standardization of food production (Figure 1C; O'Sullivan et al. 2020).

The first artificial satellite was successfully launched in 1957 (Figure 1D), triggering the beginning of the Age of Spaceflight (Baker and Chandran 2018). Human civilization entered the era of interstellar travel with projects such as the Apollo Lunar Exploration Mission, the Chang'e Project, and the Mars immigration plan, in addition to the successful planting of crops on space stations and the generation of plant sprouts on the Moon (Castelvecchi and Tatalović; 2019; Gibney 2018; Nangle et al. 2020). Therefore, agriculture, along with humans, might soon move from Earth to the Moon, Mars, or other terrestrial planets (Figure 1D). Multiplanetary farming may involve screening a group of agricultural pioneer species and industrial and digital production technologies among existing agricultural systems on Earth and developing a set of food-production and life-support systems equally applicable to Earth, space stations, and bases on the Moon and Mars. This form of farming requires the pioneer species to adapt to the unique environmental conditions of these planets, such as gravity, climate, soil composition, and resource constraints and aims to utilize innovative agricultural techniques to achieve self-sufficiency.

However, several key challenges to multiplanetary farming must be addressed. First, the conditions on other planets are extremely harsh and not conducive to plant growth as we know it on Earth. For example, Mars has very low atmospheric pressure and virtually no oxygen. To support plant growth, controlled environments, such as greenhouses, vertical farming systems, hydroponics, and aeroponics, will be essential. Second, resources on other planets are limited. Therefore, agricultural production must utilize local resources (e.g., carbon dioxide and atmospheric moisture on Mars) via innovating biological and chemical cycles for plant growth and nutrient replenishment. Third, to ensure their survival and growth, the pioneer species must be selected or genetically modified to tolerate extreme environmental conditions such as low gravity, low temperatures, and high radiation. Fourth, for long-term sustainability in space, multiplanetary farming requires the creation of closed-loop ecosystems to recycle water, air, nutrients, and other resources to reduce dependence on a resupply from Earth. Most importantly, advances in technology are critical to efficiently grow crops in extraterrestrial environments, such as innovations in artificial lighting, smart temperature control systems, and automated farming equipment.

Multiplanetary farming would not only offer food and life support for humans who travel away from Earth for interplanetary tourism, exploration, and migration but could also provide solutions to issues currently faced by humans, such as climate change, the sharp reduction in arable land, the demographic threat, and food scarcity.

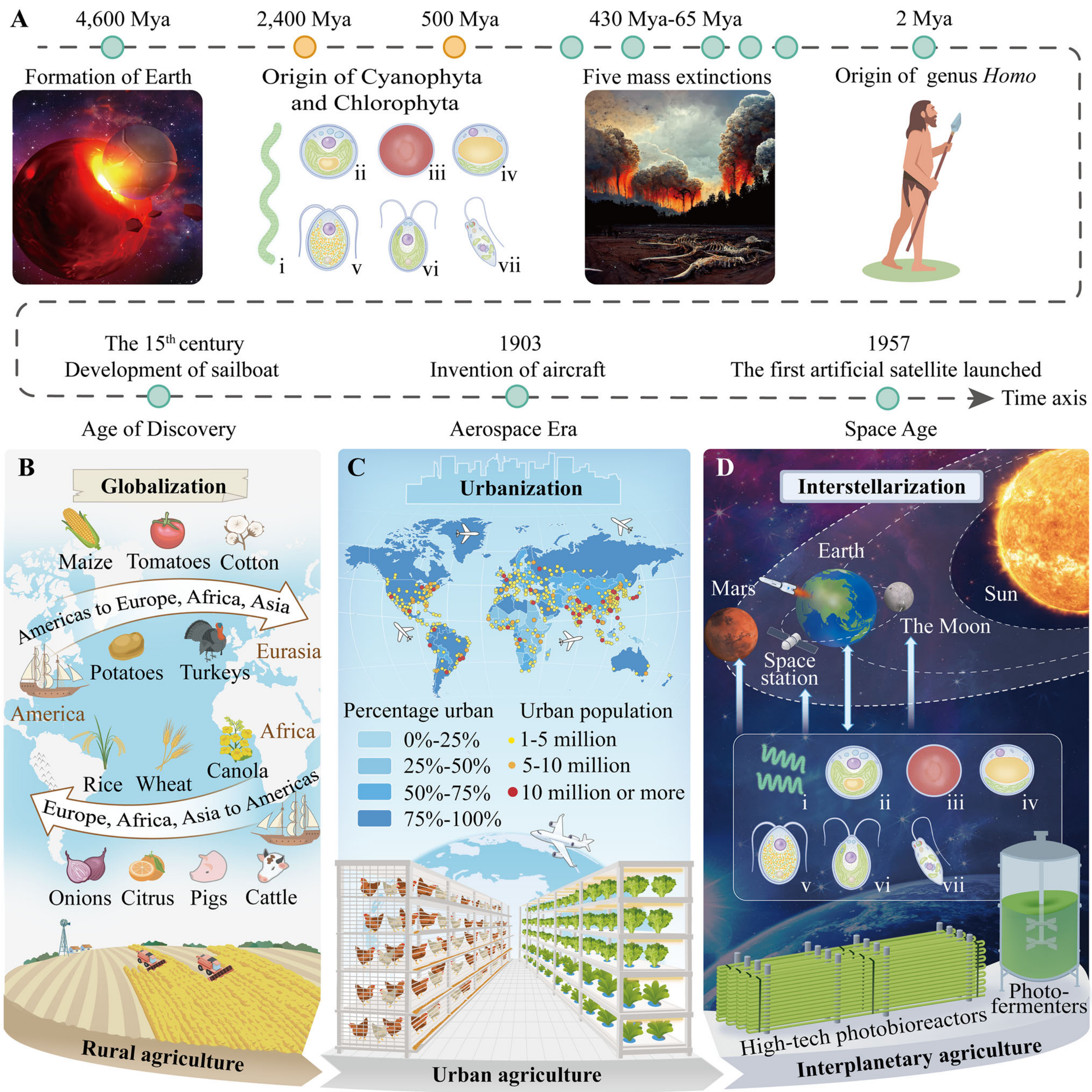

FIGURE 1 | Historical background of agricultural development and the application of microalgae in interplanetary agriculture. (A) History of edible microalgae and humans. Microalgae are the earliest photosynthetic life forms on Earth and have survived five mass-extinction events. They rejuvenated the Earth after each extinction with their strong adaptability and carbon neutrality, contributing substantially to the evolution of humans. (i–vii) show several microalgal species that have been used in commercial food preparations: *Limnospira maxima* and *L. platensis* (Spirulina), *Auxenochlorella pyrenoidosa*, *Haematococcus lacustris*, *Microchloropsis gaditana (Nannochloropsis gaditana)*, *Dunaliella salina*, *Chlamydomonas reinhardtii*, and *Euglena gracilis*. (B) Beginning of the late 15th century. The Age of Discovery promoted the globalization of agricultural species and development of rural agriculture. (C) The Aerospace Era. The successful aircraft flight test in 1903 by the Wright Brothers further accelerated the urbanization of human civilization and urban agriculture development. (D) The Space Age. The first artificial satellite was successfully launched in 1957, which advanced human civilization and the development of interplanetary agriculture. Mya, million years ago. Illustrations are not drawn to scale.

3 | Selection of Pioneer Species for Multiplanetary Farming

The screening of species as potential food sources on Earth and in space exploration missions is a crucial step to ensure the continued growth of future human populations. Currently, food for human consumption is mainly derived from domesticated plants and animals. However, there are numerous downsides to our continued reliance on traditional food sources. Livestock such as cows and pigs require large amounts of natural resources such as water and land; they generate GHG emissions and are energy-inefficient, making them an unsustainable option for feeding the growing population on Earth (Springmann et al. 2018). In addition, livestock operations occupy approximately one-third of the agricultural land on Earth, consuming a quarter of all freshwater and releasing ~14.5% of total GHG emissions (Cardador et al. 2022). The energy conversion efficiency of livestock is ~10% of that of plants, and the meat yield is only ~50% of their body mass. Additionally, domesticated animals pose health risks to humans in the form of contagious diseases such as avian influenza and severe acute respiratory syndrome (such as COVID-19), and the production of harmful by-products from the consumption of animal-based foods, including saturated fatty acids, cholesterol, and hormones (Godfray et al. 2018; Van Boeckel et al. 2019). In addition, outer space constitutes an extreme environment characterized by cosmic radiation, microgravity, and weak magnetic fields that are not suitable for domesticated animals (Afshinnekoo et al. 2020; Garrett-Bakelman et al. 2019). Therefore, a synergistic combination of measures will be required within all planetary boundaries simultaneously.

Although domesticated crop plants are more efficient food sources than domesticated animals, they pose challenges to food security. Crops are the main source of energy for humans and may be good candidates as a food source for interstellar travel. Plants use solar energy to trigger the chemical reactions that convert inorganic compounds (water and CO_2) into food, fiber, medicine, and O_2 (Heyduk et al. 2019). However, the domesticated plants currently used to produce grains, fibers, fats, vegetables, fruits, or medicines have long growth cycles and strong seasonality. In addition, many of these plants are not suitable for genetic transformation or subsequent improvement for industrial production. Crop production requires large amounts of arable land, freshwater, and conducive environments, as well as large amounts of fossil energy to produce fertilizers and pesticides and operate machinery (Tzachor et al. 2021). Thus, in terms of population growth, climate change, and interstellar migration, these factors pose strong challenges to the ongoing reliance on domesticated plants as reliable food sources.

In contrast to traditional food sources, industrialized microorganisms can grow fast; their genetics are easily manipulated, and they are highly productive. Therefore, they have the potential to serve as an alternative energy resource for humans and mitigate food insecurity (Jahn et al. 2023; Llorente et al. 2022). However, the current commercial production of microorganisms has considerable limitations. For example, large-scale bacterial production can be contaminated with endotoxins owing to a lack of stability and post-translational modifications, while yeast industrial production is prone to incorrect protein folding (Xu et al. 2020). Moreover, numerous microorganisms can only grow heterotrophically and, therefore, cannot fully utilize photosynthesis to convert solar energy, water, and CO_2 into food and O_2 (Tzachor et al. 2021). Concomitantly, the ability to recycle wastewater and other human emissions such as CO_2 and generate O_2 is particularly important for interstellar migration.

Compared with animals, plants, heterotrophic microorganisms, and other sources (such as insects) recently proposed by the United Nations, microalgae have several advantages for increasing food production to meet the immediate needs of humans on Earth and expected future requirements during interstellar migration (Su et al. 2023).

4 | Advantages of Microalgae

4.1 | Low Resource Usage

Microalgae are small and structurally simple; thus, they are readily grown and reproduced, conveniently transported, and can be directly eaten. In addition, several notable characteristics favor the industrial production of microalgae. First, microalgae consume less freshwater than animals and plants. For example, while it takes ~900, ~3300, ~5000, and ~15,500 L of water to produce 1 kg of potatoes, eggs, cheese, and beef, respectively (Mekonnen et al. 2019), it only takes ~10 L of water to produce 1 kg of algae flour. Second, microalgae can use a wide range of materials as energy sources. They not only sequester CO_2, NO_x, and SO_x from industrial and agricultural waste, vehicle exhaust fumes, and volcanic eruptions but can also absorb nutrients from domestic sewage, industrial wastewater, and other residues, thereby effectively reducing GHG and environmental pollution (Figure 2A; Gondi et al. 2022; Ma et al. 2022). For example, for every kilogram of beef produced, ~36.4 kg of CO_2 is released into the atmosphere, which could be used to produce ~15 kg of dry microalgae using a photobioreactor (Hepburn et al. 2019). *Microchloropsis gaditana* (also known as *Nannochloropsis gaditana*; Eustigmatophyceae), *Dunaliella salina* (Chlorophyta), and *Limnospira* spp. (formerly *Arthrospira*, commercial name *Spirulina*; Cyanobacteria) use seawater to convert dissolved inorganic carbon species such as HCO_3^-, CO_3^{2-}, CO_2, and H_2CO_3 into organic matter (Figure 2A; Zhu et al. 2022), thereby suppressing carbon emissions from the ocean to the atmosphere. Along with sequestering CO_2, microalgae can also serve as a source of O_2. Finally, microalgae produce high-value-added products of economic importance, as they can be used as human food, fiber, animal feed, and fertilizer, and can be further processed to produce biofuels.

4.2 | High Energy Efficiency and Edibility

The current number of microalgal species on Earth is estimated to be between 200,000 and 8,000,000. Some of these species, including *Limnospira maxima* and *L. platensis*, *Auxenochlorella pyrenoidosa* (formerly *Chlorella pyrenoidosa*; Chlorophyta), *Haematococcus lacustris* (formerly *H. pluvialis*; Chlorophyta), *N. gaditana*, *D. salina*, *Chlamydomonas reinhardtii* (Chlorophyta), and *Euglena gracilis* (Euglenophyta), have already been used in commercial food preparations (Figures 1 and 2(i–vii); Diaz et al. 2022). One of the key differences between microalgae and domestic crop plants is that microalgae can be consumed in their entirety, thereby reducing waste. They do not have roots, stems, or leaf differentiation and multicellular gametophytes. Further, the roots, stems, and leaves of many crop plants are not edible and result in a low yield to total biomass ratio (i.e., harvest index). For example, the harvest index of some of the main agricultural crops, such as rice or soybean, is approximately 0.4 (J. Chen et al. 2021). These wasted portions typically form GHG as they biodegrade (Bailey-Serres et al. 2019). Furthermore, producing food from livestock in the form of meat, eggs, or milk, is energy-inefficient owing to the “10% rule,” which states that only 10% of energy is transferred from one trophic level to the next (i.e., from plants to livestock to humans). For these reasons, microalgae have higher energy efficiency as a food source than crops and livestock.

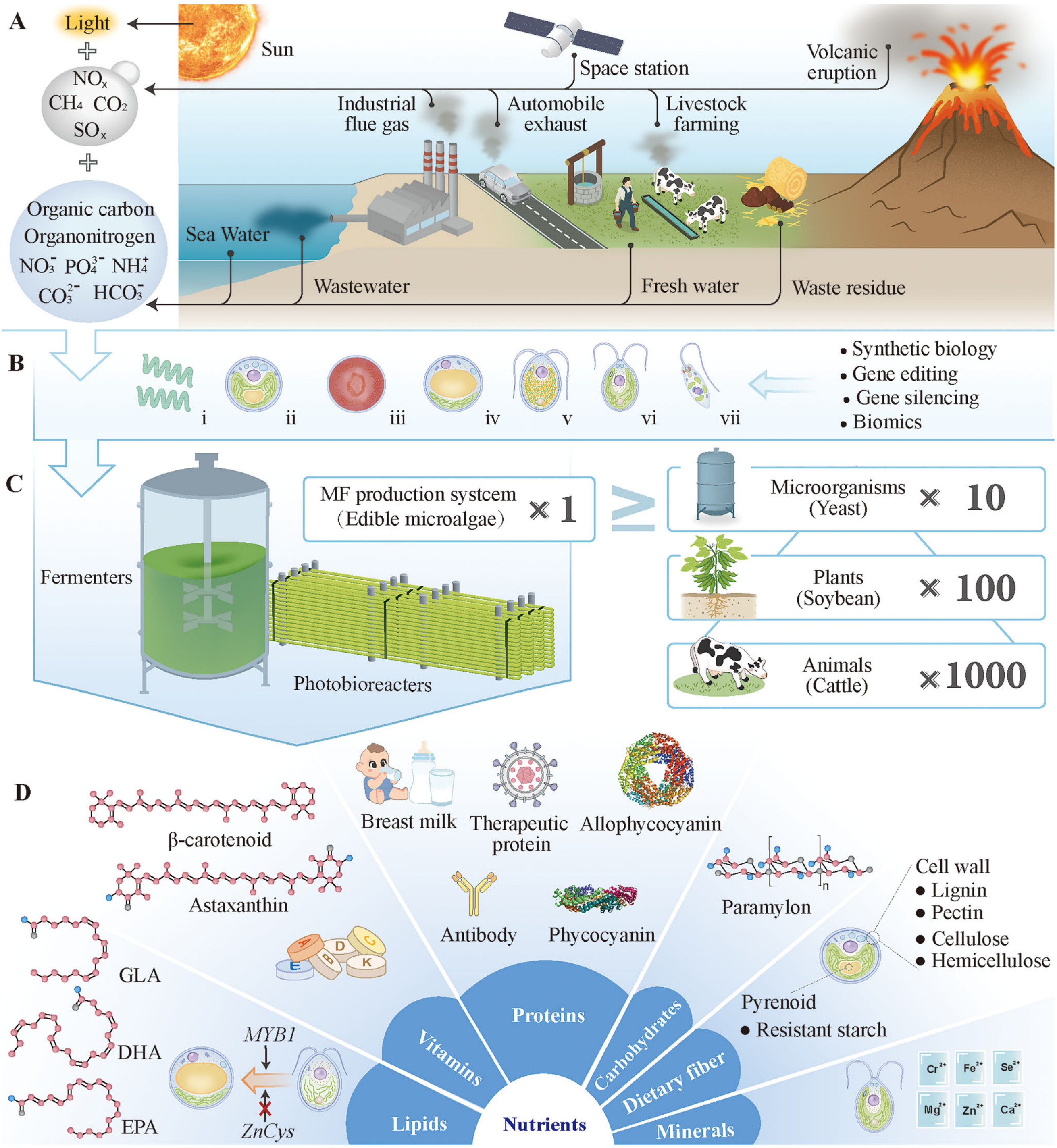

FIGURE 2 | Edible microalgae can meet the nutritional requirements of the human body. (A) Energy sources for microalgae production systems. Microalgae use light, CO_2, NO_x, and SO_x as energy sources to convert inorganic matter into organic matter. Microalgae can also directly use organic and inorganic matter dissolved in wastewater, waste residue, and seawater as energy sources. (B) Biotechnological modification of edible microalgae; (i–vii) indicate several microalgal species that have been used in commercial food preparations: *L. maxima* and *L. platensis* (Spirulina), *A. pyrenoidosa*, *H. lacustris*, *M. gaditana (N. gaditana)*, *D. salina*, *C. reinhardtii*, and *E. gracilis*. (C) Comparison of a microalgal production system with an industrial microorganism (yeast), plant (soybean), and animal (cattle); the microalgae system uses high-tech photobioreactors and photo-fermenters for industrial production. The microbial (yeast) system is used for heterotrophic fermentation. The domesticated crop plant (soybean) system adopts a rural agricultural production mode. The domesticated animal (cattle) system adopts an urban agricultural production mode. (D) Edible microalgae can produce nutrients required by the human body. DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid; GLA, γ-linolenic acid; MF, multiplanetary farming; NOx, nitrogen oxides; SOx, sulfides; *ZnCys*, *Zn(II)$_2$Cys$_6$*. Illustrations are not drawn to scale.

4.3 | High Production Efficiency

In the past, the identification and utilization of microalgae required microscopes, centrifuges, fermenters, photobioreactors, and other advanced industrial equipment. However, with current advances in biological knowledge and industrial technology, an efficient, eco-friendly, and safe food production system can be built to expand the use of microalgae.

The cell density of industrial microalgae heterotrophic fermentation can reach 100–200 g/L. In contrast with yeast and other microorganisms (e.g., *Escherichia coli* and *Bacillus subtilis*), microalgae can utilize both organic and inorganic nutrients, grow in various substrates, including seawater and wastewater, and perform photosynthesis. The production efficiency of microalgae is approximately 10-, 100-, and 1000-fold greater than that of yeast, crops, and livestock, respectively (Moura et al. 2022; Rubio et al. 2020; Tzachor et al. 2021). This increased efficiency is attributed to numerous factors, including constant production potential, reduced demand for resources such as water and land, and lower requirements for industrial inputs such as pesticides, fertilizers, agricultural machinery, and labor. In addition, issues associated with crop production and animal husbandry, such as GHG emissions, environmental damage, and human health risks from animal pathogens are practically nonexistent when microalgae are used (Figure 2C; Moura et al. 2022; Rubio et al. 2020; Tzachor et al. 2021). The flexibility and versatility of microalgae make them ideal candidates for industrial production.

4.4 | Rich and Comprehensive Nutritional Profile

Microalgae are rich in diverse nutrients; they are also an excellent source of vitamins A, B, C, D, E, and K and minerals such as iron, zinc, and selenium (Puri et al. 2022). Most microalgae contain non-starch polysaccharides (i.e., lignin, pectin, cellulose, and hemicellulose) in the cell walls and resistant starches in the pyrenoid—particularly, *Euglena* contains β-1,3-glucan paramylon. All of these can serve as forms of healthy dietary fiber (Figure 2D; Barros de Medeiros et al. 2022).

Limnospira spp. are highly enriched in protein (60%–70% of their dry weight) and may contain some high-quality proteins such as phycocyanin and allophycocyanin, which are not found in animals or plants (Figure 2D). In addition, they contain considerable concentrations of omega-3 essential fatty acids, including docosahexaenoic acid, eicosapentaenoic acid (EPA), and γ-linolenic acid (Costa et al. 2019). Similarly, *A. pyrenoidosa* has a high protein content (~60%), contains most of the essential amino acids, and has abundant bioactive compounds. Meanwhile, *Microchloropsis*/*Nannochloropsis* is a promising algal genus owing to its high lipid content (~68%), which mainly consists of polyunsaturated fatty acids (Georgianna and Mayfield 2012). *Dunaliella salina* has been used for the commercial production of β-carotene, which accounts for 10% of its biomass (dry weight) (Lamers et al. 2008), and *H. lacustris* is the richest known natural source of astaxanthin, which is a red pigment that belongs to the carotenoids and is known as a "super antioxidant" (Li et al. 2020). Thus, microalgae show the potential to sufficiently meet human nutritional needs for macronutrients, vitamins, minerals, and dietary fiber (Figure 2D).

4.5 | Wide and Rapid Adaptation

Microalgae are the earliest photosynthetic life forms on Earth, and their persistence in extreme environments during past mass extinction events demonstrates their high stress tolerance, strong resistance, and adaptability (Figure 1A; Benton 1995), making them a highly sustainable option in the context of climate change and the development of multiplanetary farming. Currently, microalgae can grow in extreme environments such as polar regions, plateaus, deserts, and oceans (Treves et al. 2020). They can also thrive under both light and dark conditions owing to their ability to be cultivated under photo-autotrophic, heterotrophic, or mixotrophic schemes. In the absence of light, microalgae use dissolved organic compounds as their energy and carbon sources, assimilating them through osmosis, whereas in the presence of light, they use light and CO_2 as energy and carbon sources for photosynthesis, respectively (Godrijan et al. 2022). Microalgae mainly inhabit aquatic environments, where their physiological characteristics allow them to reproduce in the state of balance between buoyancy and gravity. Due to the similarity between the conditions of approximate neutral buoyancy in the water environment and the microgravity environment in outer space, microalgae have the potential to adapt to low gravity conditions. Microalgae have shown good adaptability to microgravity conditions, such as those within the International Space Station, and to the weak gravity environments on the surface of celestial bodies such as the Moon (about 1/6 of Earth's gravity) and Mars (about 1/3 of Earth's gravity; Hader 2019).

4.6 | Convenient Genetic Enhancement

Most microalgae are haploid and reproduce asexually (Hirooka et al. 2022), making them excellent systems for easy genetic modification to meet the diverse requirements for future food security. Furthermore, they will permanently retain the modified properties in their genome. Additionally, genomic data on microalgae have accumulated over the past decades, and technologies to engineer traits such as protein properties, and methods for their large-scale production, are constantly being improved. For example, as a model species for elucidating fundamental cellular processes, 62,389 mutants have been generated from the *C. reinhardtii* genome, providing an enormous amount of material for the improvement and synthesis of its traits (Fauser et al. 2022; Li et al. 2019). In particular, Fauser et al. (2022) constructed a genome-wide microalgal mutant library, providing sufficient materials for the early discovery of gene function in synthetic biology. The *Microchloropsis*/*Nannochloropsis* Design and Synthesis (NanDeSyn) database (http://nandesyn.single-cell.cn) also provides excellent materials and tools for the molecular breeding of *Microchloropsis*/*Nannochloropsis* (Gong et al. 2020). With microalgae gaining increasing attention, novel technologies such as synthetic biology (Naduthodi et al. 2021) are being used to generate new microalgae varieties (Arora and Philippidis 2021) with higher productivity, improved quality, and more diverse nutritional functions.

5 | Industrial Production of Microalgae

5.1 | Capacity to Increase Food Security on Earth

Microalgae offer a unique opportunity to increase sustainable food production on Earth. They can be produced industrially indoors, in a controlled environment, or outdoors under natural conditions. Indoor systems can produce microalgae year-round with little impact from biotic and abiotic stressors, including pollution and disease. The use of vertical spaces in urban agricultural production reduces the need for arable land and mitigates the influence of climate, region, and season, further supporting the industrialization and standardization of food production (Figure 1C; O'Sullivan et al. 2020). However, these production systems are often expensive and entirely dependent on artificially supplied resources, including mineral elements and lighting. In addition, indoor production generally has lower yields due to factors such as lower cell density and photosynthetic efficiency. These drawbacks can be surpassed with new production methods such as the combination of photobioreactor and fermentation technology to establish "high-tech photobioreactors" or "photofermenters" (Figures 1D and 2D). Photobioreactors have many advantages, including reduced risk of contamination and the ability to grow microalgae at optimum conditions without environmental influences (Zhu et al. 2022). Fermentation tank technology reduces production costs by increasing cell density and resource efficiency. A fermentation tank also uses sensors to monitor CO_2 levels, O_2 content, cell density, temperature, and pH in real time and incorporates artificial intelligence to optimize growth conditions (G. Q. Chen and Jiang 2018). These high-tech methods could significantly improve future industrial production of microalgae.

Advances in biology, particularly in molecular genetics and biochemistry, and biotechnology (e.g., synthetic biology, gene editing, gene silencing, and genomics) can also improve the indoor production of microalgae greatly by altering key traits related to their resource efficiency and cellular growth capacity (Figure 2B,D; Muñoz et al. 2021). For example, cellular density in *N. oceanica* (Eustigmatophyceae) was greatly enhanced by the integration of a hemoglobin gene from *Vitreoscilla* (bacteria), leading to a 7.4%–18.5% increase in biomass and up to a 21.0% increase in the EPA content (Ding et al. 2021; Zhao et al. 2021). Additionally, transferring *CrMYB1* into *C. reinhardtii* resulted in a 66% reduction in triglyceride content, as the conserved *MYB1* gene in green algae is a positive regulator of triglyceride accumulation (Shi et al. 2022). Furthermore, decreasing the expression of a single transcriptional oil accumulation regulator, *Zn(II)*$_2$*Cys*$_6$ (*ZnCys*), doubled oil production in *M. gaditana* without affecting its growth, thereby providing an important solution for the commercialization of microalgal-derived biofuels (Ajjawi et al. 2017).

However, in an outdoor system, most of the resources required for microalgae production can be sourced from nature and production does not require special facilities, which greatly reduces the production cost. Microalgae can be grown in park buildings, on balconies and rooftops in cities, and can be factory-farmed in suburban and rural areas. Furthermore, many of the deserts, offshore islands, and reefs found on Earth, which are not suitable for crop production or human survival, could very well be used for microalgae farming. For example, the total area of all deserts on Earth is currently ~31.4 million km^2 and continues to expand. Moreover, ~71% of the Earth's surface is covered by water, including oceans, lakes, and rivers. These barren lands and waters provide ample space for outdoor microalgal production. The ecosystems of these areas are often harsh, and traits associated with ecological adaptations are particularly important in cultivation. For example, outdoor production on plateaus requires adaptation to high ultraviolet radiation exposure and low-oxygen environments, while water-use efficiency and tolerance to extreme temperatures are major concerns for outdoor microalgal production in desert environments. However, advances in biology and biotechnology will play a major role in adaptive breeding to produce microalgae that can thrive under such conditions.

5.2 | Potential in Multiplanetary Farming

With the continuous growth of the global population, interstellar migration could be a possibility for the sustainable development of human civilization, and advances in space technology and exploration such as the Apollo Lunar Exploration Mission, Chang'e Project, and Mars immigration plan have increased the feasibility of interstellar migration (Castelvecchi and Tatalović 2019; Lapôtre et al. 2020). However, this undertaking will require humans to establish sustainable food production and life support systems suitable for multiplanetary farming (Figure 1D). To achieve this, a group of agricultural pioneer species and industrial and digital production technologies among the existing agricultural systems on Earth must be screened and selected.

Microalgae show potential as pioneering species for multiplanetary farming, with the capacity to play multifaceted roles in interstellar migration, including nutrient provision, drug production, and ecological establishment (Aronowsky 2018; Mapstone et al. 2022; Vinayak 2022). The indoor system proposed above could potentially be used for microalgae production on other planets, although additional genetic and genome modifications would be essential to meet the limitations of production resources and the diverse demands of human nutrition. Newly inhabited locations are expected to have extremely limited production resources, where they will have to rely on long-distance transport from Earth, particularly during the early stages of migration. Microalgal production on other planets will require considerably higher resource efficiency than that on Earth and should have the ability to efficiently recycle waste such as water and CO_2. In this case, the photobioreactor fermentation production system can be powered by photovoltaics while the microalgae use solar energy to absorb the CO_2 exhaled by astronauts, recycle a small amount of water, and produce O_2 and food. Each astronaut consumes ~0.9 kg of O_2 per day and emits ~1 kg of CO_2 (Scott et al. 2020). Using CO_2 as a raw material for microalgae photosynthesis, 0.55 kg of algae-based biomass could be synthesized per kilogram of CO_2, meeting the nutritional and energy requirements of the astronaut. Moreover, this process would release ~0.74 kg of O_2, thereby supplementing other O_2-producing methods.

In contrast with the abundant nutritional resources on Earth, where diverse crops and animals can be farmed, the food choices of early inhabitants of other planets may be limited. Microalgae must be genetically engineered to produce food with different nutritional functions, complement other candidate crops such as potatoes (Liu et al. 2021), and produce chemicals for medicinal purposes. This has gradually become more feasible with the recent development of synthetic biology. Indeed, various nutritional and medicinal substances have been produced from microalgae in laboratories, including oral vaccines, antibodies, breast milk proteins, ovalbumin, hemoglobin, protein therapeutics, bioactive peptides, and other protein-related substances (Figure 2D; Jester et al. 2022; Lafarga et al. 2021).

Multiplanetary farming, along with interstellar migrators, will eventually move from an indoor space station to outdoor environments. Microalgae can rapidly and extensively adapt to harsh environments and serve as pioneer species that facilitate the establishment of a conducive ecosystem for agriculture beyond Earth. Their adaptation may be further improved by combining synthetic biology and experimental evolution in space laboratories that mimic the environmental conditions of space (e.g., cosmic radiation).

6 | Future Perspectives

Human society is facing unprecedented challenges associated with population growth, climate change, and resource depletion, which have led to the current food insecurity and ecological degradation. Microalgae, with their unique biological traits and evolutionary history, could be industrialized to meet these challenges by increasing the food supply on Earth and fulfilling multifaceted nutritional, medicinal, and ecological roles during interstellar migration, which may become inevitable with the continuous growth of the human population. Although continuous innovation in, and integration of biology, information, industry, and space exploration provide scientific and technological support for the realization of this vision, significant challenges persist. Multiplanetary farming requires advances in mass transportation. Despite their nutritional advantages, microalgae have problems with palatability and texture, with a flavor that is reported to be earthy and mildly sulfuric. This limitation could be countered by genetically modifying microalgae to contain more palatable compounds. Another disadvantage of *A. pyrenoidosa*, *H. lacustris*, and *D. salina* for consumption is their cellulose cell wall, which requires cooking to release its full nutritional range; however, this is also true for the majority of crops. Although the shift to alternative protein sources has increased, the low public acceptance of algae as a new healthy food remains a significant challenge. Combating this challenge depends on implementing marketing strategies to inform the public of the health benefits these organisms can provide, as well as using breeding and genetic modifications to increase yield and improve the flavor of algae. We hope our proposals stimulate extensive discussion and promote research in this critical area for the sustainable development of human civilization.

Author Contributions

Xiulan Xie: funding acquisition, project administration, visualization, writing–original draft, review, and editing. **Jiasui Zhan**: writing–review and editing. **Maozhi Ren**: funding acquisition, project administration, writing–review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

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

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