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Exploring Algal Germplasm Diversity: Strategies for Conservation and Sustainable Utilization

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Abstract The conservation and sustainable use of algal germplasm diversity are crucial for maintaining ecological balance and supporting the aquaculture industry. This study explores the current status of algal germplasm, conservation strategies, and sustainable utilization, highlighting the extensive genetic diversity within algal species and their key roles in ecosystems. Essential conservation strategies, such as in situ and ex situ preservation, including advanced cryopreservation techniques, are vital for protecting this diversity. The study also discusses innovative biotechnological applications of algae, including the production of biofuels, pharmaceuticals, nutritional supplements, and environmental management. It emphasizes that integrating conservation and utilization strategies is critical for balancing ecological sustainability and economic feasibility. This study aims to contribute to the development of integrated strategies that balance the conservation of algal biodiversity with its economic and environmental benefits.

Keywords *Algal germplasm*; Cryopreservation; Sustainable utilization; Biodiversity; Genetic diversity; Environmental management

1 Introduction

Algal germplasm diversity encompasses a wide range of genetic material from various algal species, playing a critical role in the resilience and adaptability of these organisms. Algae, which include microalgae and macroalgae, are essential components of aquatic ecosystems and have significant applications in biotechnology, agriculture, and biofuels. The genetic diversity found within algal populations is a valuable resource for developing new strains with desirable traits, such as increased biomass production, resistance to environmental stressors, and enhanced nutrient profiles. Understanding and preserving this diversity is crucial for both ecological stability and biotechnological advancement (Wade et al., 2020).

Algal germplasm refers to the genetic material that determines the hereditary makeup of algal species. This genetic diversity is the result of millions of years of evolution, adaptation, and natural selection. It is reflected in the vast array of morphological, physiological, and biochemical traits found among different algal species. Algae are highly adaptable organisms, capable of thriving in a variety of environments, from freshwater to marine ecosystems, and even in extreme conditions such as hot springs and polar regions (Mock, 2023). This adaptability is largely due to their genetic diversity, which allows them to respond to changing environmental conditions and stresses (Khan et al., 2020). The evolutionary history of algae, marked by primary and secondary endosymbiotic events, has led to the emergence of various lineages, each with unique characteristics and adaptations (Petersen et al., 2021; Mock, 2023).

The conservation of algal germplasm is of paramount importance for several reasons. It ensures the continued availability of genetic resources that can be used for research and development in various industries. For instance, specific algal strains are being explored for their potential in biofuel production, bioremediation, and as sources of high-value compounds like omega-3 fatty acids and antioxidants (Priyanka et al., 2021). Preserving algal diversity helps maintain ecosystem health and stability, as algae play crucial roles in primary production, nutrient cycling, and as habitats for aquatic organisms (Fabris et al., 2020).

The sustainable utilization of algal resources can lead to the development of a bioeconomy that addresses current industrial and agricultural challenges while minimizing environmental impact (Fabris et al., 2020; Nowruzi et al., 2022), Strategies for sustainable utilization include the development of algal culture collections, cryopreservation techniques, and biotechnological approaches to enhance desirable traits (Yang et al., 2021). By integrating conservation and utilization efforts, we can ensure that algal resources remain available for future generations while meeting current industrial and environmental needs (Cheng et al., 2019).

This study comprehensively outlines the current state of algae germplasm diversity, emphasizing its significance and the need for effective conservation strategies. It analyzes the range and distribution of algal genetic diversity, evaluates the current conservation methods and their effectiveness, explores sustainable practices for maximizing the potential of algal germplasm without harming natural populations, and identifies gaps in current research to propose future directions for the conservation and sustainable use of algal germplasm. This study aims to contribute to the development of integrated strategies that balance the conservation of algal biodiversity with its economic and environmental benefits.

2 Current Status of Algal Germplasm Diversity

2.1 Overview of algal species diversity

Algae represent one of the most diverse groups of photosynthetic organisms, ranging from microscopic phytoplankton to large seaweeds such as kelps. The diversity within algal species is reflected in their morphology, physiology, and genetic makeup. Recent advancements in molecular taxonomy have significantly reshaped our understanding of algal diversity. The use of DNA sequence analysis has led to the discovery of numerous cryptic species and has provided a more accurate understanding of algal species boundaries (Leliaert, 2021). For instance, the red algal genus *Pyropia*, which includes commercially important species, has revealed high cryptic diversity through DNA barcoding techniques (Koh and Kim, 2018).

Algal diversity is not just limited to species level but extends to functional diversity within ecosystems. Algae occupy various ecological niches and exhibit a wide range of functional traits that allow them to adapt to different environmental conditions. This functional diversity is crucial for ecosystem resilience and productivity (Mock, 2023).

2.2 Geographic distribution of algal species

The geographic distribution of algal species is influenced by a variety of factors, including temperature, light availability, and water chemistry. Algae exist in diverse habitats, ranging from freshwater ecosystems to marine environments, and can even survive in extreme conditions such as glaciers (Figure 1).

For example, a comprehensive study on the freshwater red algal diversity in Africa revealed significant geographic variation, with some species being endemic to specific regions (Szinte et al., 2020). Similarly, the brown algal genus *Padina* shows high species diversity in tropical and subtropical waters of the western Pacific, with phylogenetic analyses revealing distinct clades corresponding to specific geographic regions (Win et al., 2020). The distribution of algae is also dynamic, with some species expanding their range due to changing climatic conditions and other environmental factors (Borgato et al., 2022).

2.3 Threats to algal diversity

Algal diversity faces numerous threats from anthropogenic activities and environmental changes. One of the significant threats is habitat destruction, particularly in coastal areas where urbanization, pollution, and overfishing are prevalent. For instance, the algal reefs in Taoyuan County, Taiwan, are under threat from industrial activities, which affect the diversity and phylogenetic relationships of non-geniculate coralline algae (Liu et al., 2018).

Climate change is another critical factor impacting algal diversity. Rising sea temperatures and ocean acidification alter the distribution and physiological functioning of algal species. Additionally, harmful algal blooms (HABs), often exacerbated by nutrient pollution, can drastically reduce biodiversity by creating hypoxic conditions and releasing toxins that affect marine life (Chai et al., 2019).

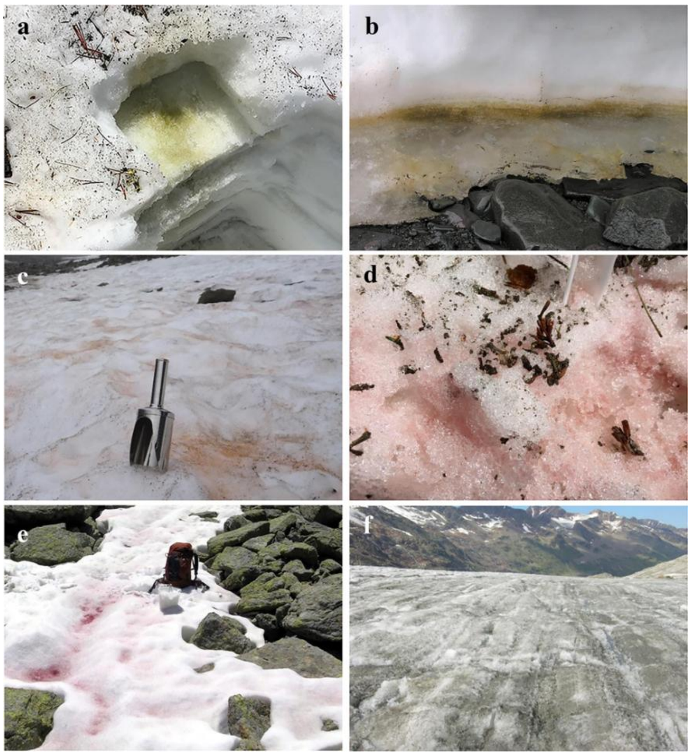


Figure 1 Field images of snow and glacial algae (Adopted from Hoham and Remias, 2020)
Image caption: (a) Green snow, *Chloromonas brevispina* (Chlorophyta, Chlamydomonadales), Carson Mountains, NV, June 2016. (b) Golden-brown snow, *Hydrurus* sp. (Chrysophyceae), King George Island, Antarctica, January 2009. (c) Orange snow, *Sanguina aurantia* (Chlorophyta, Chlamydomonadales), Svalbard (Norway), July 2018. (d) Pink snow, *Chlainomonas kolii* (Chlorophyta, Chlamydomonadales), Donner Pass, CA, June 2016. (e) Red snow, *Sanguina nivaloides* (Chlorophyta, Chlamydomonadales), European Alps, Austria, July 2008. (f) Grey-colored glacier, *Mesotaenium berggrenii* (Streptophyta, Zygnematales), Gurgler Glacier, Austria, August 2017 (Adopted from Hoham and Remias, 2020)

Furthermore, invasive species pose a significant threat to native algal populations. The introduction of non-native algal species can lead to competitive displacement of local species, altering ecosystem dynamics and reducing overall biodiversity (Wade and Sherwood, 2018).

In conclusion, the current status of algal germplasm diversity highlights the extensive genetic and functional diversity within algal species, their wide geographic distribution, and the significant threats they face. Efforts to conserve algal diversity must consider these factors to ensure the sustainable utilization of these vital genetic resources.

3 Strategies for Conservation of Algal Germplasm

3.1 In situ conservation

In situ conservation involves protecting and maintaining algal species in their natural habitats. This strategy is essential for preserving the ecological integrity and natural evolutionary processes of algal populations. Marine protected areas (MPAs) and other conservation zones are established to safeguard critical habitats and biodiversity hotspots from anthropogenic pressures. These protected zones are crucial for maintaining the genetic diversity of algal species, as they allow populations to evolve naturally and adapt to changing environmental conditions. Effective in situ conservation requires continuous monitoring and management to mitigate threats such as pollution, overfishing, and climate change (Priyanka et al., 2021).

3.2 Ex situ conservation

Ex situ conservation involves the preservation of algal germplasm outside their natural habitats. This strategy includes methods such as algal culture collections, seed banks, and botanical gardens. Ex situ conservation allows for the safe storage of genetic material, which can be used for research, breeding programs, and restoration projects, and provides a backup in case of catastrophic events that may wipe out natural populations. Macroalgal germplasm banking, for instance, is increasingly recognized for its potential in conservation and industry applications. These banks store genetic material from various algal species, ensuring that it remains available for future use in mariculture, biotechnology, and ecological restoration (Wade et al., 2020). Techniques such as slow growth cultures and the use of pollen and DNA banks are commonly employed in ex situ conservation (Priyanka et al., 2021), The development of germplasm repositories, which include frozen samples and genetic assessment systems, is also a key strategy for the conservation of endangered aquatic species (Liu et al., 2019).

3.3 Cryopreservation techniques

Cryopreservation is a critical method for the long-term storage of algal germplasm. This technique involves freezing algal cells, spores, or tissues at extremely low temperatures (typically in liquid nitrogen at -196°C), effectively halting all biological activity and preserving the genetic material indefinitely. Cryopreservation is particularly valuable for preserving the genetic diversity of species that are difficult to maintain in culture collections. Cryopreservation has been proven to maintain the viability of algae samples for decades. Effectively preserving the viability and genetic integrity of various algal species, cryopreservation serves as a valuable tool for long-term conservation. Various cryopreservation protocols, such as controlled-rate cooling and vitrification, have been developed to optimize the survival rates of post-thaw samples. For instance, the cryopreservation of Saccharina latissima gametophytes using controlled-rate cooling methods combined with dimethyl sulfoxide has been reported to yield high viability (Visch et al., 2019), The use of cryotubes and straws for packaging germplasm samples is also common practice in cryopreservation studies (Yang et al., 2021).

Visch et al. (2019) explored the effectiveness of cryopreserving male and female gametophytes of the brown alga (*Saccharina latissima*) using different cryoprotectants and cooling methods (Figure 2), The study compared the impacts of various cooling rates and cryoprotectant combinations on gametophyte viability, finding that controlled-rate cooling with 10% dimethyl sulfoxide (DMSO) achieved the highest survival rates. Additionally, the study evaluated the trait performance and sporophyte development after revival, indicating that the cryopreserved gametophytes successfully developed into sporophytes. This confirms that cryopreservation is an effective method of preservation, providing technical support for the future development of biotechnology in brown algae. This technique is crucial for maintaining genetic diversity, supporting breeding programs, and managing wild populations, especially in scenarios where climate change could lead to the loss of potential genetic resources.

3.4 Legal and policy frameworks

The conservation of algal germplasm is supported by various legal and policy frameworks that aim to protect biodiversity and promote sustainable use of genetic resources. International agreements, such as the Convention on Biological Diversity (CBD), provide guidelines and commitments for the conservation of biological diversity, including algal species. National policies and regulations further reinforce these commitments by establishing protected areas, regulating access to genetic resources, and promoting conservation research. Effective implementation of these frameworks requires collaboration among governments, research institutions, and local communities to ensure that conservation strategies are both scientifically sound and socially equitable (Priyanka et al., 2021).

The conservation of algal germplasm encompasses a range of strategies, from in situ and ex situ conservation to advanced cryopreservation techniques and robust legal frameworks. These combined efforts are essential for safeguarding algal biodiversity and ensuring the sustainable utilization of these critical genetic resources.

4 Sustainable Utilization of Algal Germplasm

4.1 Biotechnological applications

Algal germplasm holds significant promise for various biotechnological applications due to its rich genetic diversity and high adaptability to different environmental conditions. One of the most notable applications is in the production of biofuels, microalgae and cyanobacteria have been identified as promising candidates for next-generation biofuels due to their high lipid content and rapid growth rates. Advances in metabolic and genetic engineering have further enhanced their biofuel production capabilities, making them a sustainable alternative to fossil fuels (Khan and Fu, 2020, Algae can be cultivated to produce biomass that is rich in lipids, which can be converted into biodiesel through transesterification. Research has shown that using a mixotrophic cultivation strategy enables algae to treat organic and inorganic wastes while producing biomass for biofuel feedstock, thereby improving the sustainability of biofuel production (Patel et al., 2020). Algae-based biorefineries that integrate multiple production processes, such as anaerobic digestion and hydrothermal liquefaction, can enhance the overall energy yield and economic viability of biofuel production (Allen et al., 2018).

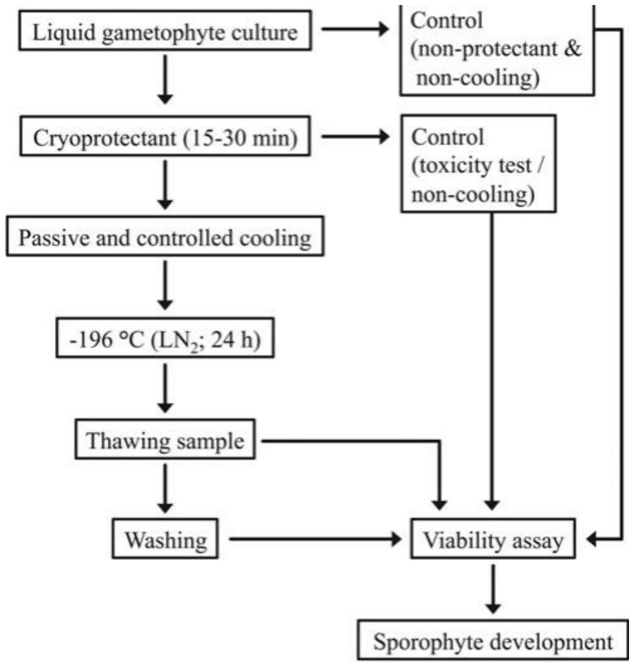


Figure 2 Procedure for the cryopreservation of S. latissima gametophytes and the viability assay (Adopted from Visch et al., 2019)

4.2 Pharmaceutical and nutraceutical uses

Algal germplasm is also being explored for its potential in the pharmaceutical and nutraceutical industries. Algae are a rich source of bioactive compounds, including antioxidants, polyunsaturated fatty acids, and pigments, which have various health benefits. For instance, algal extracts have been found to possess antimicrobial, antiviral, and anti-inflammatory properties, making them valuable in the development of new drugs and health supplements (Fabris et al., 2020). Moreover, microalgae like *Chlorella* and *Spirulina* are commonly used in dietary supplements due to their high nutritional content, including proteins, vitamins, and minerals. The utilization of algae in these sectors not only provides health benefits but also offers a sustainable alternative to synthetic additives and supplements (Zabochnicka et al., 2022).

4.3 Agricultural and environmental applications

The agricultural and environmental applications of algal germplasm are vast and diverse. Algae can be used as biofertilizers to enhance soil fertility and promote plant growth. The co-cultivation of microalgae with plant growth-promoting bacteria, such as Methylobacterium, has been shown to significantly increase algal biomass production, which can be leveraged for sustainable agriculture (Krug et al., 2020), Studies have shown that algal biochar and microalgal extracts can significantly improve crop yields and soil health by providing essential nutrients and stimulating plant growth (Mona et al., 2021). For example, the application of microalgal extracts as biostimulants has been demonstrated to increase the growth rate and yield of tomato plants (Supraja et al., 2020). Additionally, algae play a crucial role in bioremediation, where they are used to treat wastewater and capture carbon dioxide. Algal-based systems can efficiently remove nutrients and pollutants from wastewater while simultaneously producing biomass that can be used for bioenergy or other value-added products (Choudhary et al., 2020).

The sustainable utilization of algal germplasm spans various sectors, including biotechnology, pharmaceuticals, nutraceuticals, agriculture, and environmental management. By leveraging the unique properties and diverse applications of algae, it is possible to develop innovative solutions that contribute to sustainability and address global challenges.

5 Case Studies in Conservation and Utilization

5.1 Successful conservation programs

One of the notable conservation programs for algal germplasm is the establishment of germplasm cryopreservation techniques, particularly for macroalgae. A review by Yang et al. (2021) highlights the development and implementation of cryopreservation protocols for various macroalgal species (Table 1). These techniques include programmable controlled cooling and vitrification, which have been shown to effectively preserve the genetic material of algae at ultra-low temperatures, ensuring long-term viability and genetic stability. This approach is crucial for both aquaculture breeding programs and the conservation of natural biodiversity.

Yang et al. (2021) systematically reviewed research since 1964, summarizing the cryopreservation methods for 33 species of seaweeds and the factors affecting survival rates after thawing. The study indicates that commonly preserved materials include haploid or diploid algal bodies, spores, and gametes, with dimethyl sulfoxide (DMSO) being the primary cryoprotectant used. The two main cooling methods highlighted are programmable controlled-rate cooling and vitrification. The research emphasizes optimizing various steps in the preservation process, such as the selection of cryoprotectants, packaging, cooling rates, and thawing methods, to enhance survival rates post-thaw.

Table 1 Research progress in cryopreservation of different seaweed species (Adapted from Yang et al., 2021)

Species 种类	Cryoprotectant 冷冻保护剂	Cooling method 冷却方法	Post-thaw viability 解冻后存活率
Ulva pertusa	DMSO, Glycerol, Sucrose 二甲基亚砜，甘油，蔗糖	Controlled-rate cooling 可编程控制降温	50%
Ulva intestinalis	Glycerol, NaCl, Ethylene glycol 甘油，氯化钠，乙二醇	Controlled-rate cooling 可编程控制降温	60%
Neopyropia tenera	DMSO, Diglycerol 二甲基亚砜，二甘油	Vitrification 玻璃化法	80%
Saccharina japonica	DMSO, Glycerol 二甲基亚砜，甘油	Controlled-rate cooling 可编程控制降温	70%
Gracilaria corticata	DMSO 二甲基亚砜	Controlled-rate cooling 可编程控制降温	65%
Hypnea musciformis	Glycerol 甘油	Vitrification 玻璃化法	55%
Ulva prolifera	Glycerol 甘油	Controlled-rate cooling 可编程控制降温	90%
Ectocarpus fasciculatus	Glycerol 甘油	Controlled-rate cooling 可编程控制降温	75%

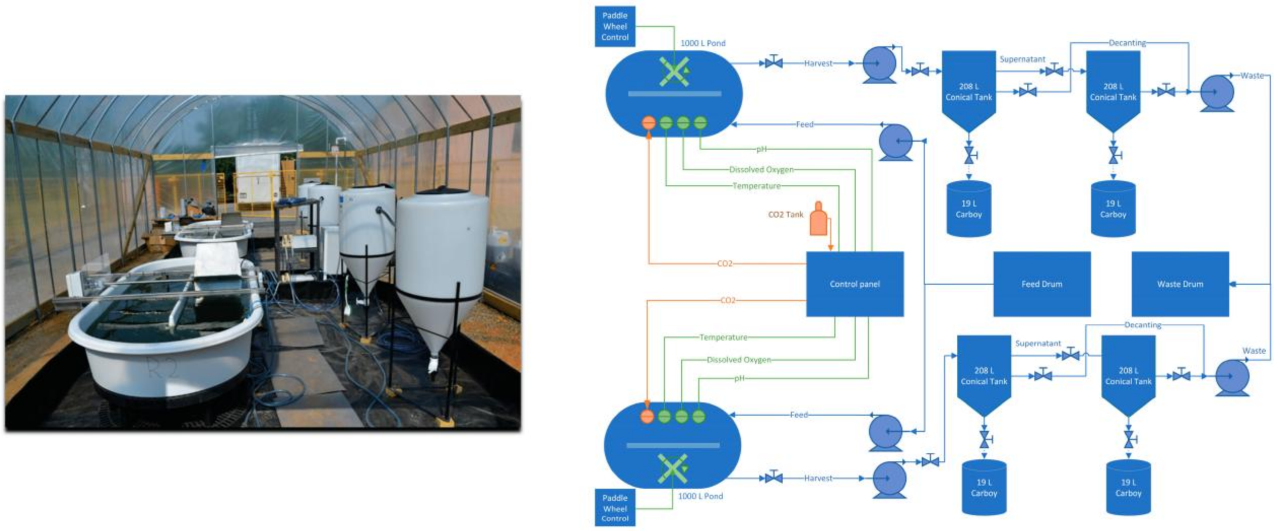
Table 1 summarizes the research progress in the cryopreservation of different seaweed species, covering studies from 1960 to the present. The table lists the seaweed species studied, the cryoprotectants used, the cooling methods, and the survival rates after thawing. The subjects include green, brown, and red algae, with the primary cryoprotectants used being dimethyl sulfoxide (DMSO), glycerol, and sucrose. Cooling methods include programmable controlled-rate cooling and vitrification. The survival rates presented in the table vary depending on the species and the methods used, demonstrating significant differences in freeze tolerance and survival rates among different species under the same cryoprotectant and cooling rate conditions.

Another successful initiative is the macroalgal germplasm banking program, which focuses on ex situ conservation of marine algae. This program aims to preserve the genetic diversity of macroalgal species by establishing seed banks and culture collections. The initiative not only supports biodiversity conservation but also facilitates research and industrial applications, including mariculture and biotechnological developments. The coordinated efforts in germline preservation of marine algal species via germplasm banking underscore the importance of maintaining genetic resources for future use (Wade et al., 2020).

5.2 Innovations in algal biotechnology

Innovative approaches in algal biotechnology have significantly advanced the sustainable utilization of algal germplasm. One such innovation is the use of industrial wastewater for cultivating microalgae, as demonstrated by a pilot-scale study conducted at an industrial munition facility. The study employed open raceway ponds to cultivate a resilient consortium of green microalgae and cyanobacteria using wastewater, resulting in high biomass productivity and bioenergy potential. This approach not only valorizes industrial waste streams but also enhances the sustainability of algal biofuel production (Abraham et al., 2023).

Abraham et al. (2023) discussed the feasibility of using industrial wastewater for cultivating microalgae to produce bioenergy. The study was conducted at an industrial ammunition facility using two 1000-liter open raceway ponds, with operational parameters such as temperature, pH, light intensity, and dissolved oxygen monitored through an online system (Figure 3), The experimental results demonstrated that the algal inoculum evolved into a weather-resistant consortium containing green microalgae and cyanobacteria. Under optimized experimental conditions, the average surface biomass productivity in summer reached 23.9±0.9 g/m²·d, with a bio-methane potential (BMP) of 350 scc/gVS, and an oil content of 22 wt.%. Additionally, techno-economic analysis and life cycle assessment indicated that algae cultivation using wastewater is economically and environmentally feasible, contributing to the advancement of a circular bioeconomy model. The study showed that adjusting cultivation conditions and harvesting frequency can significantly enhance biomass productivity and bioenergy output, demonstrating the potential and prospects for the resource utilization of industrial wastewater.



(a) (b)

Figure 3 illustrates the experimental layout and system diagram for cultivating microalgae using industrial wastewater within a greenhouse at an industrial ammunition facility (Adapted from Abraham et al., 2023)

Image caption: (a) A real-life photo of microalgae cultivation, showing two 1000-liter open raceway ponds situated inside the greenhouse. (b) A schematic diagram of the system layout, detailing the experimental equipment and processes. The system includes online monitoring devices for real-time recording of temperature, pH, light intensity, and dissolved oxygen changes. The photosynthesis within the ponds effectively utilizes natural light from the greenhouse environment, with regular additions of carbon dioxide and nutrients to maintain suitable cultivation conditions (Adapted from Abraham et al., 2023)

Another significant innovation is the integration of algal and bacterial biotechnology for environmental management and biofuel production. Algal-bacterial consortia have been shown to enhance carbon capture and wastewater bioremediation while simultaneously producing valuable biofuels. This synergistic interaction between algae and bacteria optimizes nutrient cycling and improves the efficiency of biorefinery processes, contributing to a more sustainable bioeconomy (Yong et al., 2020).

5.3 Integrated approaches for sustainable utilization

Integrated approaches that combine various technologies and processes have proven effective for the sustainable utilization of algal germplasm. One case study involves the use of algal biofilm photobioreactors for the treatment of hog manure wastewater. This system not only efficiently purifies the wastewater but also produces high-quality algal biomass that can be used for biofuel production. The integration of wastewater treatment and bioenergy generation exemplifies a circular bioeconomy approach, where waste is converted into valuable resources (Wu et al., 2019).

Additionally, the use of flue gas and wastewater for algal cultivation demonstrates another integrated approach. By utilizing carbon dioxide from industrial emissions and nutrients from wastewater, this method supports the dual goals of reducing greenhouse gas emissions and treating wastewater while producing algal biomass for biofuel. This integration addresses environmental challenges and promotes sustainable industrial practices (Kothari et al., 2019).

6 Technological Advances and Future Trends

6.1 Advances in genomic and genetic techniques

Recent advancements in genomic and genetic techniques have revolutionized our understanding and utilization of algal germplasm. The sequencing of over 100 algal genomes has significantly expanded the available genetic data, providing insights into the functional capabilities and evolutionary history of algae. High-throughput sequencing technologies, coupled with bioinformatics tools, have facilitated the identification of genes involved in various metabolic pathways, enhancing our ability to genetically manipulate algae for desired traits (Blaby-Haas and Merchant, 2019). Additionally, synthetic biology approaches, such as the creation of designer algal mitochondrial genomes, have enabled precise modifications to enhance biofuel production and other biotechnological applications (Cochrane et al., 2020).

6.2 Emerging technologies for conservation

Emerging technologies are playing a crucial role in the conservation of algal germplasm. Cryopreservation techniques, particularly those involving programmable controlled cooling and vitrification, have been optimized to preserve the genetic material of various algal species. These advancements ensure the long-term viability and genetic stability of algae, which is vital for both conservation and industrial applications (Yang et al., 2021). Moreover, genomic technologies are being applied to support in situ conservation efforts. Genomic tools enable the identification of novel alleles and adaptive traits, guiding the establishment of genetic reserves and monitoring genetic diversity changes due to environmental factors (Wambugu and Henry, 2022).

6.3 Future directions in algal research

The future of algal research is poised to benefit from a combination of advanced genomic techniques, synthetic biology, and emerging conservation technologies. One promising direction is the integration of systems biology and CRISPR/Cas genome editing to optimize metabolic pathways for enhanced biofuel production. This approach allows for precise genetic modifications, leading to increased lipid synthesis and overall biomass productivity (Banerjee et al., 2018). Additionally, the development of algal-based biosensors for environmental monitoring represents a significant advancement. These biosensors can provide real-time data on environmental conditions, contributing to more effective conservation strategies (Antonacci and Scognamiglio, 2019).

Furthermore, the application of artificial intelligence (AI) and the Internet of Things (IoT) in algal biotechnology is expected to enhance the efficiency and scalability of algal cultivation systems. These technologies can automate and optimize growth conditions, leading to higher yields and reduced operational costs (Fabris et al., 2020). Overall, the integration of cutting-edge technologies and interdisciplinary approaches will be key to unlocking the full potential of algal germplasm for sustainable development.

7 Policy and Regulatory Considerations

7.1 International agreements and conventions

International agreements and conventions play a critical role in the conservation and sustainable utilization of algal germplasm. The Convention on Biological Diversity (CBD) is one of the most significant frameworks, providing guidelines for the conservation of biological diversity, sustainable use of its components, and fair and equitable sharing of benefits arising from genetic resources. The CBD encourages countries to develop national strategies and action plans for biodiversity conservation, which include algal species (Priyanka et al., 2021). Similarly, the Nagoya Protocol on Access and Benefit-sharing (ABS) under the CBD regulates access to genetic resources and the fair sharing of benefits derived from their use, ensuring that the exploitation of algal germplasm contributes to conservation and sustainable development.

7.2 National policies and regulations

National policies and regulations are essential for implementing international agreements and ensuring the conservation of algal germplasm within countries. For instance, the United States has the National Marine Sanctuaries Act, which helps protect significant marine environments, including those with diverse algal populations. In the European Union, the Habitats Directive aims to promote the maintenance of biodiversity by requiring member states to designate Special Areas of Conservation (SACs) to protect various species and habitats, including marine algae (Yang et al., 2021).

Countries like Japan and China have also established specific regulations to control the exploitation and conservation of their marine resources. These regulations often include measures such as the establishment of marine protected areas (MPAs), restrictions on harvesting, and support for research on algal biodiversity and conservation techniques (Wade et al., 2020). Furthermore, national policies should encourage research and development in algal biotechnology, which can lead to the sustainable exploitation of algal resources for various applications, including biofuels, bioplastics, and pharmaceuticals (Yong et al., 2020; Mock, 2023).

7.3 Recommendations for policy development

To enhance the conservation and sustainable utilization of algal germplasm, several recommendations for policy development can be made:

1) Strengthening Legal Frameworks: National legal frameworks should be strengthened to regulate the collection, use, and trade of algal germplasm. This includes ensuring compliance with international agreements such as the CBD and Nagoya Protocol and implementing strict monitoring and enforcement mechanisms to prevent illegal exploitation (Priyanka et al., 2021).

2) Strengthening International Collaboration: Countries should collaborate on international platforms to share knowledge, resources, and technologies for algal germplasm conservation. This includes participating in global initiatives and adhering to international agreements such as the CBD and the Nagoya Protocol (Priyanka et al., 2021; Yang et al., 2021).

3) Establishing National Germplasm Repositories: Governments should invest in the establishment and maintenance of national germplasm repositories that follow standardized protocols for the collection, storage, and documentation of algal germplasm. These repositories should be equipped with advanced cryopreservation technologies to ensure the long-term viability of stored germplasm (Liu et al., 2019; Yang et al., 2021).

4) Promoting Research and Development: Policies should support research and development in algal biotechnology to explore the potential applications of algal resources. This includes funding for genomic studies,

biotechnological innovations, and the development of sustainable algal-based products (Yong et al., 2020; Khan et al., 2020; Mock, 2023).

5) Ensuring Fair and Equitable Benefit Sharing: National regulations should align with the principles of the Nagoya Protocol to ensure that benefits arising from the utilization of algal genetic resources are shared fairly and equitably with the countries and communities that provide these resources (Priyanka et al., 2021).

6) Raising Public Awareness: Public awareness campaigns should be conducted to educate stakeholders, including policymakers, researchers, and the general public, about the importance of algal germplasm conservation and sustainable utilization. This can help garner support for conservation initiatives and promote the responsible use of algal resources (Yong et al., 2020; Priyanka et al., 2021).

Robust policy and regulatory frameworks are crucial for the effective conservation and sustainable utilization of algal germplasm. By integrating conservation strategies, promoting research, strengthening legal frameworks, engaging stakeholders, and fostering international collaboration, we can ensure the long-term preservation and responsible use of these valuable genetic resources.

8 Challenges and Opportunities

8.1 Conservation challenges

The conservation of algal germplasm faces several significant challenges. One major issue is the difficulty in maintaining and preserving the genetic diversity of algae in both in situ and ex situ conditions. In situ conservation efforts are often hampered by environmental changes, pollution, and habitat destruction, which can lead to the loss of natural populations. Additionally, the establishment and maintenance of marine protected areas (MPAs) are often met with logistical and financial constraints, making it challenging to effectively protect algal diversity in their natural habitats (Wade et al., 2020).

Ex situ conservation methods, such as germplasm banking and cryopreservation, also face technical difficulties. Developing effective cryopreservation protocols for various algal species is complex due to the unique physiological and biochemical characteristics of algae. Moreover, the lack of standardized methods for cryopreservation and the limited availability of cryopreserved algal strains in germplasm banks pose additional hurdles (Yang et al., 2021). Furthermore, there is a need for coordinated international efforts to integrate and manage algal germplasm repositories effectively.

8.2 Utilization challenges

The utilization of algal germplasm for biotechnological and industrial applications also presents several challenges. One of the primary obstacles is the high operational and capital costs associated with large-scale algal cultivation and biomass processing. The economic feasibility of producing algal biofuels and other bioproducts remains a significant challenge, primarily due to the costs related to harvesting, dewatering, and downstream processing (Rao et al., 2021).

Another challenge is the technical complexity of integrating algal cultivation systems with industrial processes, such as wastewater treatment and carbon capture. Achieving optimal growth conditions and maintaining stable algal cultures in open ponds or photobioreactors are difficult due to the variability in environmental conditions and the risk of contamination by other microorganisms (Pathak et al., 2018). Additionally, the regulatory frameworks for the use of genetically modified algae and the potential environmental impacts of large-scale algal operations need to be carefully considered and managed (Shokravi et al., 2021).

8.3 Opportunities for collaboration and innovation

Despite these challenges, there are significant opportunities for collaboration and innovation in the conservation and utilization of algal germplasm. Collaborative efforts between academic institutions, industry, and government agencies can drive research and development in algal biotechnology. For instance, integrating algal cultivation with wastewater treatment plants offers a dual benefit of environmental remediation and biomass production, providing a sustainable solution to waste management and energy production (Kothari et al., 2019).

Innovative technologies, such as the use of artificial intelligence (AI) and machine learning, can optimize algal cultivation systems by automating monitoring and control processes, thereby enhancing productivity and reducing operational costs (Fabris et al., 2020). Moreover, advancements in genetic engineering and synthetic biology hold promise for developing algal strains with enhanced traits, such as higher lipid content for biofuel production or increased resilience to environmental stresses (Blaby-Haas and Merchant, 2019).

Global cooperation and knowledge sharing are crucial for addressing the conservation and utilization challenges of algal germplasm. International initiatives and networks can facilitate the exchange of best practices, technical expertise, and germplasm resources, promoting a unified approach to algal conservation and sustainable utilization. By leveraging these opportunities, we can harness the full potential of algal germplasm for environmental, economic, and societal benefits.

9 Concluding Remarks

This systematic review has highlighted the critical importance of algal germplasm diversity and the strategies required for its conservation and sustainable utilization. The findings underscore the vast genetic diversity within algal species, their crucial roles in ecosystems, and the significant applications they hold for biotechnology, pharmaceuticals, agriculture, and environmental management. Conservation strategies such as in situ and ex situ conservation, including cryopreservation, are essential for maintaining this diversity. Innovative technologies in algal biotechnology, such as the use of biofilms and photobioreactors, demonstrate the potential for sustainable production and environmental remediation .

The integrated approach to the conservation and utilization of algal germplasm is vital for ensuring both ecological sustainability and economic viability. By combining conservation methods with biotechnological advancements, it is possible to create a synergistic system where algal resources are protected while also being utilized efficiently. The development of germplasm banks, cryopreservation techniques, and biotechnological innovations such as biofilm reactors and genetic modifications are key components of this integrated strategy. These efforts not only preserve the genetic diversity of algae but also enhance their application potential in various industries .

Future research and policy development should focus on several key areas to enhance the conservation and sustainable utilization of algal germplasm. First, there is a need for more comprehensive and coordinated international efforts to establish and manage germplasm repositories. This includes standardizing cryopreservation protocols and ensuring the accessibility and exchange of genetic material globally. Second, advancements in genomic and synthetic biology techniques should be leveraged to develop algal strains with enhanced traits for biofuel production, environmental remediation, and other applications .

Additionally, policies should encourage the integration of algal cultivation with industrial processes, such as wastewater treatment and carbon capture, to create sustainable and economically viable production systems. This approach not only addresses environmental issues but also enhances the commercial potential of algal products. Finally, fostering collaborations between academia, industry, and government agencies will be crucial for driving innovation and implementing effective conservation strategies .

The conservation and sustainable utilization of algal germplasm require a multifaceted approach that integrates advanced technologies, comprehensive policies, and collaborative efforts. By addressing the challenges and leveraging the opportunities presented in this review, we can ensure the long-term preservation and beneficial use of algal resources for future generations.

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Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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