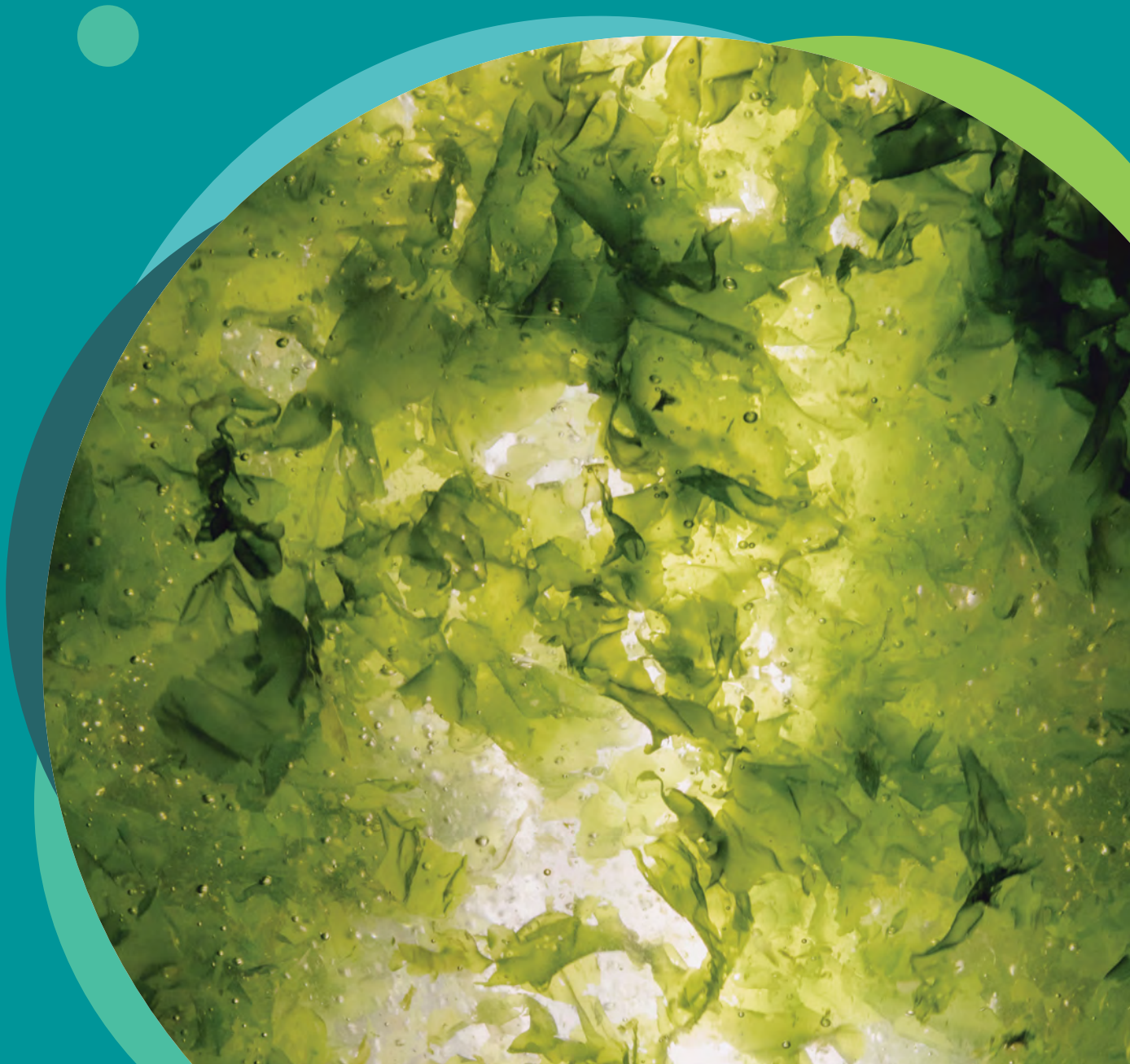
Deep Green Biotech Hub

UTS Deep Green Biotech Hub

# Unlocking the Growth and Innovation of the Australian Algae Industry:

## Insights from the 2023 Australian Algae Business Summit

2023 White Paper




Algae Business Summit Agenda
Event Details
Deep Green
Biotech Hub
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# Contents



# Sponsoring Organisations

## Marine Bioproducts Cooperative Research Centre

Marine Bioproducts CRC is Australia's largest R&D hub dedicated to producing new and sustainable products from our marine ocean. It is a not-for-profit Cooperative Research Centre (CRC) bringing together more than 70 partners from academia and industry.

We are driving Australia's transition to the 'third generation' of marine production (the first generation is fishing, and the second generation is aquaculture). We do this by funding research and the development of new products.

## Climate Change Cluster (C3), University of Technology Sydney

The Climate Change Cluster (C3) produces new insights into problems facing marine ecosystems by working at the intersection of the physical and life sciences. The research institute works to provide solutions to some of the most pressing challenges of our age. We're aligned with UN sustainable development goals and support the World Climate Statement, UN COP26 goals, and UN Decade of the Ocean.

## Deep Green Biotech Hub

The NSW Deep Green Biotech Hub (DGBH), hosted by UTS, connects NSW-based businesses and community members with cutting-edge algae biotechnologies and innovation support, so we can build a deep green future, together.

Our work is made possible by the NSW Government's Boosting Business Innovation Program.

## Acknowledgement of Country

UTS acknowledges the Gadigal people of the Eora Nation, upon whose ancestral lands our Broadway campus stands. We extend that respect to the traditional custodians of the lands and sea country on which we and our stakeholders and contributors live and work.

We would also like to pay respect to the Elders past and present, acknowledging them as the traditional custodians of knowledge for these lands.


## Acknowledgements

The authors would like to acknowledge the valuable expertise contributed to this research by representatives from industry and academia and the peer reviewers. This report was compiled by Lorenzo Paolieri, Kira Picknell, Emma Fineran, and Alex Thomson. Where relevant, adapted tables and graphs have been used with permission.




# About the Algae Business Summit

The Australian algae industry holds immense promise as a sustainable source of food, nutraceuticals, biomaterials, agricultural solutions, and more.

The Algae Business Summit (2023) brought together esteemed experts, researchers, and industry leaders for the first time to explore the opportunities and challenges in this burgeoning sector. This white paper aims to capture the key insights, recommendations, and findings from the Summit, providing a roadmap to unlock the growth and innovation potential of the Australian algae industry.

The Summit started with an insightful session focusing on the journey from supply to market, where case studies from across the Australian algae industry were presented. These presentations delved into the realm of novel food products, nutraceuticals, and agricultural applications, highlighting the transformative power of algae-based industry solutions. In addition, facilitated group discussions and workshops generated valuable insights into the opportunities and challenges faced by industry stakeholders (these are summarised in section 2 – **Stakeholder Consultation**).

Regulatory considerations and frameworks were the focus of the second session, emphasising the need for effective governance to support the growth of the Australian Algae Bioeconomy.

Key discussions concerned the regulatory landscape encompassing product development, market access, and compliance. Moreover, the session highlighted the importance of establishing a supportive business ecosystem to foster the industry's growth.

In the third session, the Summit participants embarked on developing a roadmap for the Australian algae industry. The session was led by Professor Catriona Macleod and resulted in recommendations aimed at unlocking the industry's growth and fostering innovation. These recommendations provide a strategic direction and actionable steps to propel the industry forward, ensuring sustainable development and widespread adoption.

The conference featured a keynote presentation by Alexandra Mosch, representative of the European Algae Biomass Association, to provide an international perspective. Her insights into the progression of the algae industry in Europe offered valuable lessons and trends that can be applied to the Australian context, facilitating the cross-pollination of ideas and experiences.

## The Venue

The Ariel Aerial UTS Function Centre exemplified sustainability and serves as a model for future events. Their eco-friendly practices included minimising waste by donating excess food to students in UTS housing and OzHarvest, contributing profits to funding UTS student activities, offering casual jobs to UTS and TAFE students, and converting excess food waste into clean soil-like material for renewable energy generation. Moreover, they upheld a plastic- free policy, opting for biodegradable disposables, and demonstrated a strong commitment to sustainable energy with 426 solar panels installed on their roof.

## Objectives of the Summit:

- Present key learnings from international markets.
- Identify Australia's unique global selling points.
- Consult stakeholders across business, research, and government on how they view key challenges and opportunities.
- Develop recommendations that have the potential to unlock the growth and innovation of the industry.

## Deliverables:

1. Snapshot of the state of the Australian algae industry in 2023 that identifies key strengths, weaknesses, opportunities, and threats.
2. A report documenting key challenges and opportunities identified by stakeholders and key recommendations for economic and policy levers to progress the Australian algae industry.
3. Activated network of algae industry stakeholders

## Outcomes:

1. Greater cross-jurisdictional and cross-sector collaboration and understanding amongst diverse algae industry stakeholders.
2. Growing an internationally competitive Australian algae sector that derives and contributes value to the global sector.
3. Informing the development of a roadmap for the regulatory and economic environment to encourage further investment and innovation.

The Summit consisted of a structured, facilitated workshop. Scribes captured the discussions and the results from each table were collated and summarised in a post-Summit report. This report seeks to present a fair summary of the industry-driven insights and recommendations presented by the collective Summit. The report will be disseminated to Federal and State policymakers, regulatory departments, algae businesses, and the private sector.

The primary objective of this white paper is to provide a guide for the readers about the status of the algae industry in Australia and overseas to help stakeholders understand issues and barriers in the scaling of this industry in Australia.

# Algae Business Summit Speakers

The detailed agenda for the Algae Business Summit can be accessed through this link: Link to Agenda

**Dr Alex Thomson**
Industry Engagement Manager, Climate Change Cluster (C3) UTS

**Professor Peter Ralph**
Executive Director C3, Professor of Marine Biology, Biosystems Founder: Deep Green Biotech Hub

**Professor Wei Zhang**
Research Director, Marine Bioproducts Cooperative Research Centre (MBCRC) and Flinders University

**Alexandra Mosch**
European Algae Biomass Association

**Nick Hazell**
Founder, v2food

**Colin McGregor**
Managing Director, Biogenesis

**Adrian Spencer**
Founder, Sampano

**Sam Bastounas**
CEO, PacificBio

**Nick Fletcher**
Manager Standards and Surveillance, Food Standards Australia New Zealand

**Ian Lyall**
Manager of Aquaculture, NSW Department of Primary Industries

**Phil Morle**
Partner, Main Sequence

**Prof Catriona Macleod**
Interim Executive Director – Institute for Marine and Antarctic Studies

# Algae Business Summit – Facilitator and Student Scribes

Gemma Gillette (C3, UTS)

Rachael Scott (C3, UTS)

Amber Brierley (C3, UTS)

Lilan Hoch (C3, UTS)

Sean Macdonald-Miller (C3, UTS)

Kira Picknell (C3, UTS)

Abeeha Khalil (C3, UTS)

Fateme Mirakhorli (C3, UTS)

Adele Mastroyannis (MBCRC/Flinders)

Dr Kath Fisher – ABS Facilitator

## Attendees and Contributors

- AGRENEW
- Algae Pharm
- Biogenesis
- Blue Futures – Translational Research Initiative (UOW)
- Bondi Bio
- Breckon Jones Consulting
- Calyx.Eco
- Climate Change Cluster (UTS)
- Committee for Sydney
- CSIRO
- Deep Green Biotech Hub
- Deloitte
- Department of Industry, Science and Resources
- Department of Planning and Environment NSW
- Diatomic Fuels
- DPI Fisheries
- The European Algae Biomass Association (EABA)
- Eyre Shellfish
- Flinders University
- Food Standards Australia New Zealand
- Green Blue Health Pty Ltd
- Grok Ventures
- Hancock and Grove Ocean Decade Australia
- Laing O'Rourke
- Main Sequence Ventures
- Office of the NSW Chief Scientist and Engineer
- Pacific Bio (Regen Aqua)
- Marine Bioproducts CRC (MBCRC)
- Monash University Malaysia
- Monash University/Algae Harvest
- Ocean Decade Australia
- Peakview Strategy
- People&Things
- Piping Hot
- Queensland Alliance for Agriculture and Food Innovation
- Refraction Media
- Sampano
- SCS
- Sea Forest
- Sea Health Products
- Sea$O_2$ Algae
- SeaPerfect Pty Ltd
- Southern Cross Shellfish
- Tasmanian Oyster Company
- ULUU
- The University of Newcastle
- v2food
- ValAsta
- Wide Bay Pacific
- Woods Group
- Young Henrys Brewing Company

# Purpose of this White Paper

This white paper encapsulates the proceedings of the inaugural Algae Business Summit (ABS), a collaborative effort between the Deep Green Biotech Hub, the Climate Change Cluster (C3) of the University of Technology Sydney, and the Marine Bioproducts Co-operative Research Centre (MBCRC). Held on Tuesday 30 May 2023 in Sydney, the Summit convened industry leaders, government representatives, and academics to address the imperative for progress within the Australian algae sector.

The Summit focused on identifying opportunities and challenges facing the Australian algae industry and leveraging insights gleaned from global markets to foster growth and innovation. Drawing from previous national and international assemblies, this event aimed to reignite the Australian algae sector by delving into pivotal industry development aspects and facilitating discussion that culminated the actionable recommendations.

Guided by the central question, **"How can we unlock the growth and innovation of the Australian algae industry?"**, the Summit pursued a comprehensive set of objectives, which are elucidated further in this document. By uniting industry, government, and academic stakeholders, the Algae Business Summit fostered an atmosphere of collaboration, knowledge-sharing, and collective troubleshooting.

By harnessing the momentum generated at the summit and incorporating the wealth of insights garnered, the Australian algae industry is poised to surmount barriers and flourish within the dynamic global landscape. **This white paper serves as a consolidation of the knowledge and expertise exchanged during the summit,** distilling these valuable insights and recommendations into a cohesive framework.

There is a footrace globally to commercialise the benefits of algae from its diverse applicability and the environmental potential to mitigate climate change. Australia is well positioned geographically and has advanced research underway to capitalise and compete globally. **Algae** may serve as a continuous and reliable source of natural products with the ability to be grown on non-arable land because they can be cultivated in bioreactors on a large scale and be controlled so that they contain no herbicides or pesticides [1].

Catering to a diverse audience ranging from stakeholders to policymakers, researchers, and entrepreneurs involved in the Australian algae sector, this white paper serves as an indispensable resource. As we navigate the transformative potential of the algae industry, this document paves a path toward a robust and sustainable future, inviting all interested parties to embark on this journey of exploration and progress.

## How to read the White Paper

This White Paper aims to provide context to the global algae market and ecosystem, while positioning the burgeoning Australian ecosystem in the broader global context (see "Background to the Global Algae Ecosystem"). It also provides additional background information on algae as a product, and the required mechanics of the industry (see "Algae Value Chain").

The areas above provided the basis for discussion during the stakeholder consultation at the Algae Business Summit (see "Stakeholder Consultation"). The breadth of participant discussion and feedback generated data, including key challenges and opportunities for the growth of the Australian ecosystem that are considered critical to achieving a sustainable algae industry in Australia. Further discussions generated recommendations for road-mapping the future of the Australian algae ecosystem.

**Industry Vision:** The vision for the Australian Algae Industry is to foster growth, innovation, and international competitiveness, leveraging its unique selling points to contribute value to the global bioeconomy.

# Executive Summary

The Algae Business Summit 2023 marked a pivotal moment for the Australian algae industry, convening experts, researchers, and industry leaders to explore the vast potential of algae as a sustainable source across various sectors.

This white paper encapsulates the key insights and recommendations from the Summit, providing a strategic roadmap for unlocking growth and innovation in the Australian algae industry.

The Summit covered essential aspects, beginning with a focus on supply-to-market journeys through insightful case studies. Stakeholder consultations in workshops unveiled challenges and opportunities. Regulatory considerations took centre stage in the second session, stressing effective governance to support the industry's growth. The third session, led by Professor Catriona Macleod, crafted a roadmap with actionable recommendations for sustainable development and widespread adoption.

A keynote from Alexandra Mosch, European Algae Biomass Association, offered an international perspective, enhancing cross-pollination of ideas. Summit objectives included presenting international insights, identifying Australia's unique strengths, consulting stakeholders, and formulating recommendations.

Deliverables encompass a snapshot of the industry, a report on challenges and opportunities with policy recommendations, and an activated network of stakeholders. Anticipated outcomes involve enhanced collaboration, a globally competitive sector with boosted resourcing, and the groundwork for regulatory and economic frameworks.

This white paper, derived from structured workshops, seeks to inform policymakers, regulatory bodies, businesses, and the private sector. It aims to guide stakeholders in understanding the status of the algae industry, addressing issues, and overcoming barriers to informed decision-making.

The literature review provides a comprehensive primer, emphasising the pivotal role of algae in addressing global needs. Reasons for focusing on Australia include its environmental suitability, biodiversity, and potential for economic growth. The timing is opportune as global trends and renewed interest in algae present a promising solution to challenges in food, nutrition, energy, and climate change.

While the global seaweed market is thriving, Australia's domestic industry faces constraints such as approvals and infrastructure. Nevertheless, the potential for clean and green seaweed-derived products presents an opportunity for Australia to enter and lead the market.

In the microalgae sector, Australia is poised to become a significant player, leveraging its biodiversity. Despite variations in regulations globally, positive signals from the EU and the US indicate a growing focus on sustainable practices.

Australia's regulatory landscape involves complexities in bioprospecting legislation, requiring navigation through different state policies. A comprehensive understanding is crucial as changes are anticipated in response to the sector's growth.

In conclusion, the white paper serves as a compass for stakeholders, navigating the current state of the Australian algae industry and charting a course toward sustainable development, innovation, and global competitiveness.

# Snapshot of Findings from Stakeholder Consultation

## Session 1: Challenges in Algae Markets

**Challenges:** Policy and regulation improvement (18%) and funding complexities (15%) were identified as the primary obstacles to upscaling algae markets.

**Solutions:** Respondents emphasised the need for consistent regulations (38%) and addressing the lack of trained personnel (22%).

## Session 2: Regulatory Frameworks

**Interpretation/Access/Application:** 27% highlighted the need for a shared vision and coordinated funding initiatives to improve regulatory frameworks.

**Gaps:** Lack of a government roadmap (21%) and misallocation of funding were identified as key gaps.

**Additional Regulation:** Recommendations included coordinated regulations (24%) and more incentives for market access (22%).

## Session 3: Roadmap and Recommendations

**Future Priorities:** Participants identified developing a leadership roadmap (29%) and streamlining regulations (17%) as top priorities for the algae sector.

## Key Issues Raised:

1. **Workforce Training:** Improvement in training for algae workers, especially in regional areas, is essential.
2. **Provenance of Australian Produce:** Inconsistencies in the "Made in Australia" label process need to be addressed.
3. **Algae's Image Problem:** Public perception needs improvement to attract investment and emphasise algae's sustainable aspects.
4. **Regulatory Challenges:** Inconsistent regulations across states and the need for a state-based information officer were highlighted.
5. **Biorefinery and Piloting Facilities:** There is a need for improved access to downstream processing facilities for startups and universities.

Centralised services like biorefinery/pilot facilities are essential for scaling and diversifying product offerings. Streamlining regulatory requirements and providing guidance on connecting with circular economy initiatives and carbon credits is crucial for industry growth.

The Stakeholder Consultation identified critical challenges and opportunities for the Australian algae industry. Addressing workforce training, and regulatory inconsistencies, and enhancing public perception are pivotal for unlocking growth and innovation in this promising sector. Recommendations include centralised services, streamlined regulations, and a strategic roadmap for industry development.

# Background to the Global Algae Industry

The following section is a literature-based primer for a reader new to the algae field. It provides foundational insights into algae markets, encompassing both seaweed and microalgae, while also pinpointing potential avenues for innovation, expansion, and Australia's strategic positioning within the burgeoning global algae bioeconomy.

# 1 Why Algae Bioeconomy?

Algae have been part of human and animal diets for thousands of years. There are an estimated 300,000 micro and macro algae species globally, with new species being discovered every year. Only very few are intensively cultivated at present and are mainly used as food and feed, with some used as a source of products (Fig. 1) such as pharma- and nutraceuticals, biofertilisers, biostimulants, biofuel, and for bioremediation [2]. Key drivers are leading to the opportunity for algae to address global needs.

Algae have a vital role to play in marine coastal ecosystem preservation and restoration by developing marine aquaculture and permaculture. Algae need water, sunlight/energy, and nutrients to grow, but no terrestrial land, and if managed appropriately can provide an array of ecosystem services [3].

Our rapidly growing global population requires further innovation to address the practical limitations and serious environmental concerns associated with current industrial and agricultural practices. Microalgae are emerging as a next-generation resource with the potential to address these urgent industrial and agricultural demands [4].

International initiatives acknowledge the important role of microalgae as a source of alternative protein for a sustainable food system, global food security, and the establishment of an algae **bioeconomy**. Enhanced EU production and use of algae will help ensure sustainable food and farming systems, economic circularity, and bio-based products [3].

According to EU report data 2019, the value of the EU bioeconomy is worth **657bn EUR** [5]. The shift to a sustainable, low-carbon, circular bioeconomy represents a business opportunity worth **USD $7.7 trillion** by 2030 [4].

*Most of the data collected is EU data, therefore to support the industry we need better domestic and APAC region data collection.

### Macroalgae (Seaweed) and Microalgae definition

**Microalgae** are microscopic uni-cellular organisms, representing around 80% of the globe's total algae species.

**Macroalgae** are larger, multi-cellular organisms, some of which are defined as seaweeds.

Most algae are photosynthetic, and can be found in freshwater systems including rivers, dams, and lakes, and saltwater systems including coastal and estuarine systems. Algae are commonly classed as red, brown, or green, and produce about 50% of the oxygen we breathe.

### Bioeconomy definition

The bioeconomy aims to drive both circularity and sustainable development. It is the generation of value-added products, such as feed, food, bio-based products, and bioenergy from renewable biological resources [3]. In the algae context, it is the incorporation and utilization of algae (biomass, extracts, or otherwise) in the generation of products and services.

# 2 Why Australia?

Australia has the resources, and skills to build an economically sustainable domestic algae industry, and scale to include significant export to help meet the increasing global algae demand. These opportunities also play a crucial role in aligning with UN Sustainable Development Goals (SDGs) [7].

Environmentally, Australia is also well positioned to both grow and source ("bioprospect") microalgae with environmental conditions suitable for outdoor algal cultivation, such as access to abundant light (sunshine), large areas of non-arable land and coastal ecosystems inhabited with various seaweed species [8]. Australian waters host around 15% of the world's recorded brown and red seaweed species, making it the global seaweed diversity hotspots.

**More efforts are required to achieve the vision of an algal bioeconomy, which is a key part of addressing the climate crisis and offers numerous opportunities Australia's future, as outlined below:**

- Reduction of greenhouse gases (GHG) through decarbonisation.
- Diversifying income streams through innovation.
- Ensuring food and energy security.
- Cost-effective methods for remediating toxic pollutants.
- Integrating new and sustainable business models or technologies across industries, such as agtech, biotech, and cleantech.
- Promoting regional economic development and investment (including job creation, skills development, and exports).
- Playing an essential role in transforming existing industries into a circular bioeconomy model.
- Developing and strengthening sovereign supply chains.

### Algae may be cultivated via four mature technologies

**1. Seaweed farming:**

Seaweed – or kelp – farming includes growing and harvesting seaweed. In some instances, collection from naturally occurring beds or from beach wrack is practiced, while in other cases farming includes management of the entire life cycle.

**2. Open-air Ponds:**

Raceway-type ponds and lakes are open to the elements. The open raceway pond system has a very simple structure, usually consisting of a raceway and paddle wheel [6]. Microalgae are inoculated and cultivated in the raceway, and the paddle wheel promotes the circulation of culture media or wastewater in the raceway. The closed raceway can be constructed by using low-cost materials

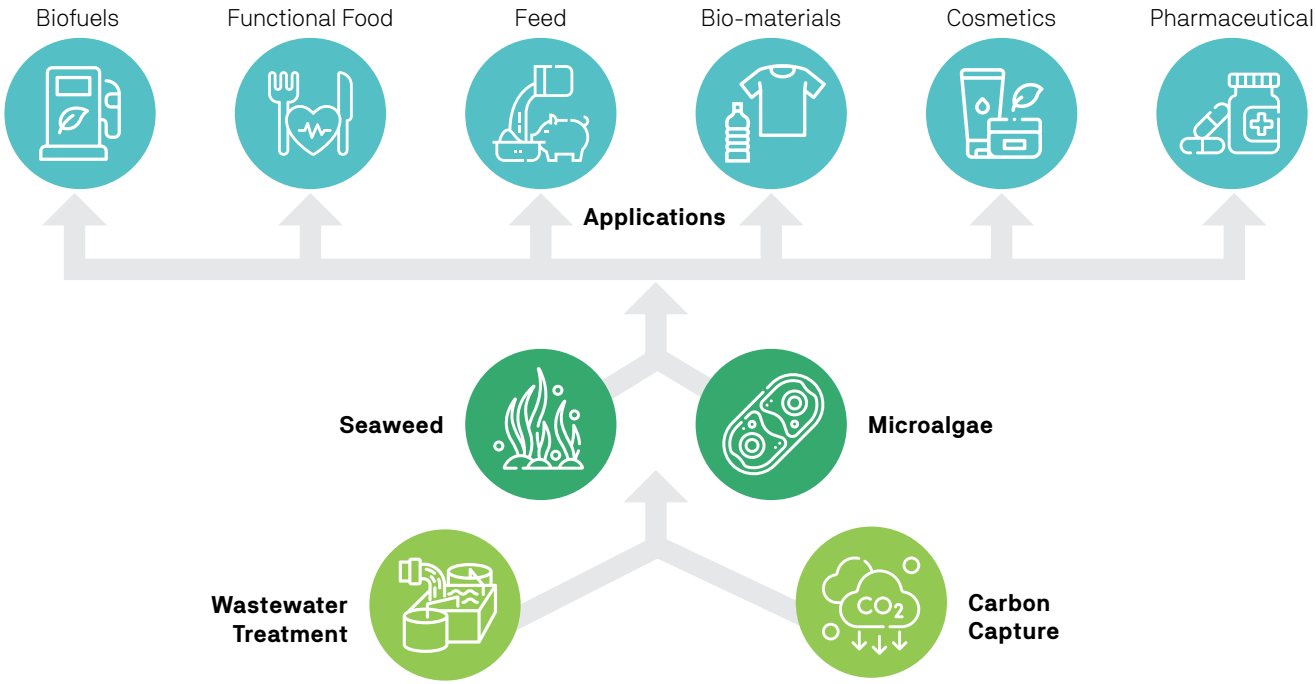
**3. Photo bioreactors (PBR):**

A PBR is a bioreactor which incorporates a light source and it is used to cultivate photosynthesising microalgae under controlled growth conditions. It is mainly used with the aim of production of, high-value products and efficient carbon sequestration.

**4. Heterotrophic bioreactors:**

Heterotrophic cultivation overcomes the light supply predicament of photoautotrophy, and in the present scenario it can be easily adapted for commercial scale production of microalgal biomass.

Figure 1: Applications for the Algae Bioeconomy. Source: Authors' own elaboration.




With significant past investment into algae-based biofuels there is an abundance of knowledge and infrastructure readily available for retrofitting and repurposing to assist algae farming and cultivation to address many of industry's needs, including carbon capture and utilisation and production of nutraceuticals for human health uses. More recently there has been considerable global consultation and review aiming to understand and identify the opportunities , particularly economic, associated with algae. This report further analyses these opportunities and how they can be actualised. With several activities already underway, it is designed to help inform the next series of investments and recommendations amongst various stakeholder groups (e.g. industry, government, and research) so that the industry can continue to scale in a coordinated manner.

### Microalgae and Macroalgae are incredibly diverse

Microalgae and Macroalgae are incredibly diverse and varied in both evolutionary and ecological terms [9], with tens of thousands of species exhibiting a wide range of forms and functions. Building upon the research of many scientists, it is now the task of forward-thinking businesses, regulators, and investors to promote the widespread adoption of these innovative technologies. As we shift towards a circular economy that minimises waste and environmental impact, it is abundantly clear that algae will play a growing role in various aspects of our lives [10].

# 3 Why Now?

While investment and support for the development of the global algae industry has varied over the past decade, currently (2024), many new innovations and areas of interest have led to a renewed focus on algae, particularly in addressing new and emerging global issues.

Both **microalgae** and **seaweed (macroalgae)** industries already exist at a sizable scale (macroalgae accounting for 50% of global marine aquaculture production) and value at least $8 billion. The ongoing emergence of new startups reflects a revived global interest, notably in regions like the EU and Australia. Algae stands out as an innovative foundation for these ventures, offering numerous advantages and holding significant promise as a solution to pressing global issues in food, nutrition, energy, and climate change.

Australia has world-leading research facilities, and researchers, therefore is investing in R&D to support its emerging marine bioproducts industry. One such initiative is the **Marine Bioproducts Cooperative Research Centre** (MB-CRC), a collaboration of research partners, state governments, third-party participants, and industry partners including, among others, algae farming startups such as Qponics, Sea Forest, and Venus Shell Systems, which are tasked with turbocharging the industry [12].

**Figure 2: High-growth (seaweed) companies per region (cumulative). Graph adapted from Hermans [11].**

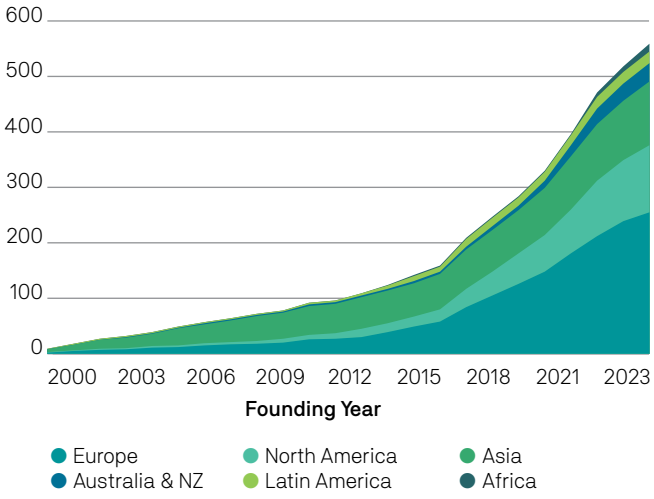



**Figure 3: Seaweed (macroalgae) market. Graph adapted from Hatch Services Innovation [14]**

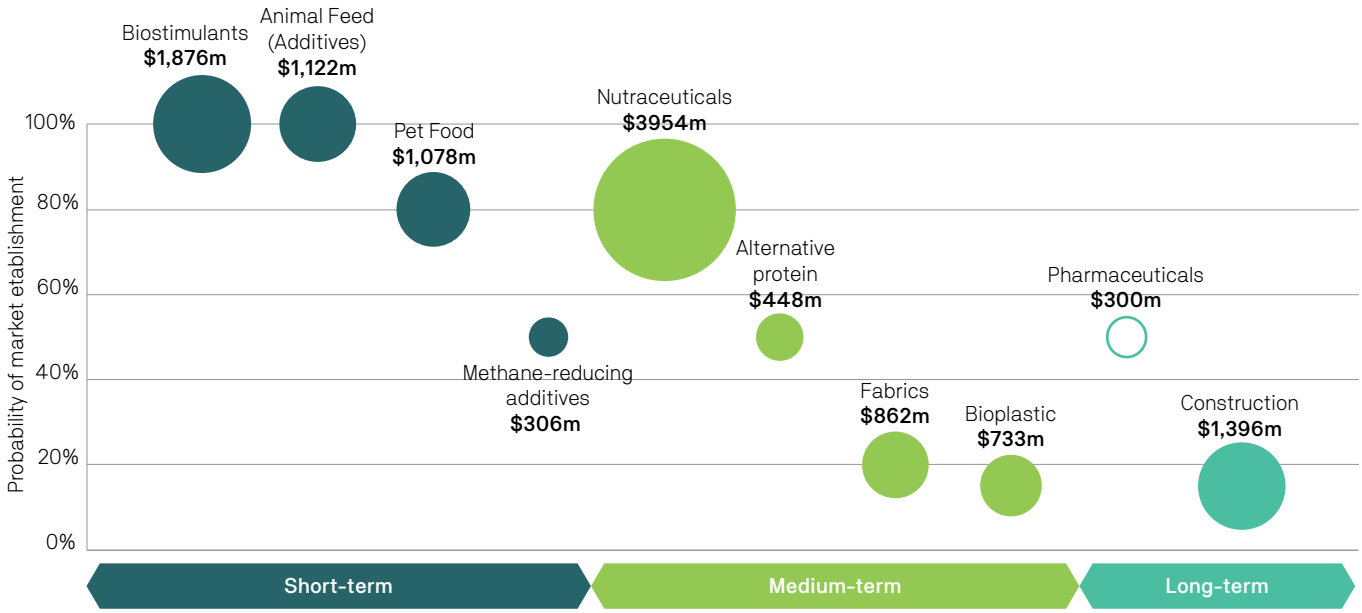
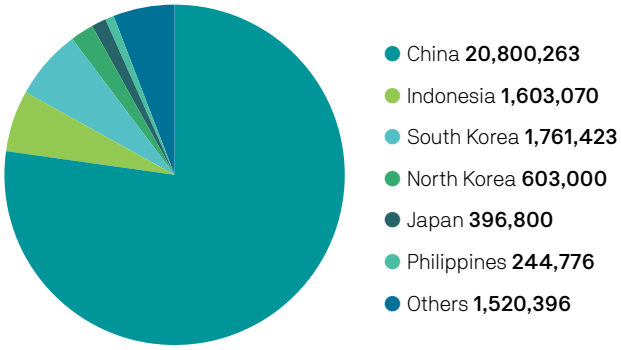


**Figure 4: Seaweed production [MT] by country. Graph adapted from Hermans [11].**




A recent report commissioned by the World Bank Group analysed new and emerging global seaweed markets, with the potential application of seaweed by time horizon and predicted market size ($) by 2030 [14] (Fig. 3). While several markets have seen significant expansions in their markets, the Australian market is comparatively small (Fig. 2). Recent investments into seaweed businesses (Fig. 2) largely comprised of downstream companies processing seaweeds into products and vertically integrated growers/processors [11]. While Europe leads the way in seaweed startup formation, a rising number of startups in Asia likely reflects businesses operating outside seaweed food and extracts. Startups focussed exclusively on cultivation are the least popular business model, both for investors and entrepreneurs [11].

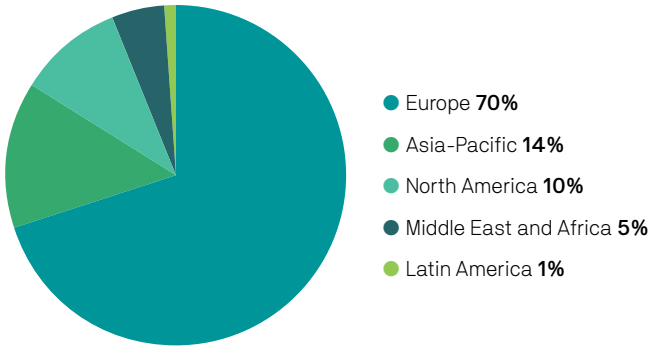
The Australian domestic seaweed industry has an approximate value of **$3 million per year**. It is predicted this figure will grow significantly due to the strong demand for algae locally and internationally. Growth of the algal industry value will be subject to the rate of expansion of the Australian supply chain. Hence, increased participation in the algal industry requires several factors, such as investment in infrastructure and up scaling research. Approvals have also been identified as an emerging constraint as state governments are still refining approval workflows that enable growers to commercialise novel strains in Australia. As a result of suboptimal application processing time it can take 2-3 years to commercial production [8].

Looking at the global scenario, while the potential applications of seaweeds are diverse, the high cost of cultivated seaweeds in Europe and the US means that only food and cosmetics/nutraceuticals are currently viable markets for seaweed farmers.

According to *Phyconomy* [11], over the last few years the top-producing seaweed countries have seen a declining trend in production (Fig. 4). Diversifying of markets, investing in research and development to safeguard traditional strains from climate impacts, and investing in automation are likely needed to see trends return to growth. Therein lies a clear opportunity for Australia to enter the market for both innovative R&D and export, including demanding clean and green seaweed-derived products, scientific substantiation and globally recognised TGA approval.

## Microalgae Market

**Figure 5: Global sales of Spirulina microalgae-based products with an estimation of USD 2 billion by 2026. Graph adapted from Show [15].**




To date, there are more than 75,000 identified microalgae species, however, less than ten are intensively cultivated for commercial purposes worldwide (e.g. *Spirulina, Chlorella* spp, *Dunaliella salina, Nannochloropsis* spp, and *Haematococcus* spp).

In recent years, microalgae production has gained traction in China, with the country recently taking over from Japan as the major worldwide producer of *Chlorella*, a microalgae species commonly used in food products. While *Chlorella* production (in volume) is only about a quarter of that of Spirulina production, it offers a significantly higher price per ton than that of Spirulina [16]. China is also the largest global producer of Spirulina (by ton) (Fig. 4), produced typically for human and aquaculture feeds, a factor contributing to China becoming China one of the major global microalgae producers of the past 15 years.

**The price range for algal based products varies greatly between products**

Price per kg can range between $150 for algal oil to $12,000 for astaxanthin (carotenoid) [12]. By 2031 it is expected the global microalgae market (including all products and applications) will reach $4.2 billion, hence expanding at a compound annual growth rate of ~6% [12].

While the production of microalgae for food and animal feeds leads the way in China, the microalgae industry in Japan focuses more on the use of microalgae for biofuel, working alongside the European Union (EU) [17]. The market size of microalgal biofuel in Japan is worth an estimated 128 billion yen (USD 1170 million) and there are continual investments in the research and development programs of algal science where priorities are in microalgal biofuel and expanding towards other microalgal markets such as foods, chemicals, and supplements [18].

The microalgae industry in Europe has yet to reach the scale of Asian markets such as Japan or China [19]. In the EU algae aquaculture is still considered within early stages as production only accounted for ~1.14% of global biomass produced between 2006-2015 [20]. The leaders in European algae production are primarily based in Norway, Ireland, France, Iceland, and the Russian Federation. However, there is a strong focus in Denmark on the research and development of algae-based products, including research projects such as "MacroFuels", where research breakthroughs in biofuel production are sought after for improving the efficiency of the region's climate [21].

As the world's population continues to grow, microalgae are gaining prominence as a sustainable source of high-quality protein and omega-3's, reducing the reliance on ocean fish as the main source of omega-3 oils [12].

Australia is the world leading producer of algae derived beta-carotene. However, cultivation companies are also expanding efforts to leverage the extensive biological diversity of algae present within Australia. Companies are utilising extraction methods to gain high value oils, carbohydrates and proteins from microalgae biomass, therefore offering opportunities to diversify the algae market within Australia.

## Regulations

Regulations governing the growth and usage of both macroalgae and microalgae vary across the globe. Emerging issues such as the utilization of genetically modified organisms are often contentious, and in some instances, lead to bottlenecks at industry scale. For example, genetically modified algae that have high growth rates to meet market demands have a limited uptake in many countries. This deters outdoor cultivation and drives up production costs, making algae applications less accessible. Actions addressing the Nagoya protocol and consumer perception behavioural studies need to be improved progressively to promote market uptake.

## Global

Positive signals have come from the EU's Algae initiative that proposed 23 actions to kickstart the algae sector in Europe. This collaborative endeavour involves identifying the most suitable locations for **seaweed** cultivation while also incorporating the practice of seaweed farming and multiple uses of the sea into the broader framework of maritime spatial planning. This concerted action emphasises the commitment to sustainable resource utilization, economic growth, and the integration of innovative practices within Europe's maritime zones.

In the United States, should the SEAfood Act be approved by Congress (as of December 2022), it will establish regulations for aquaculture activities in offshore federal waters. First the first time since 1983, the National Aquaculture Development Plan is being updated by the US Federal Government in Washington. Updates will incorporate three new strategic initiatives focusing on Science, Regulatory Efficiency, and Economic Development, laying the groundwork for a comprehensive expansion of domestic aquaculture practices.

The bills would support comprehensive, transparent research initiatives and practical on-site projects that are essential for integrating offshore aquaculture into a holistic ocean management approach. Through the cultivation of a sustainable aquaculture sector and bolstering wild capture fisheries, w marine ecosystems and coastal communities would be safeguarded while fostering a robust local seafood economy that satisfies the increasing needs of consumers [22].

Legislators have introduced several key acts aimed at advancing American aquaculture [13]:

- **The Advancing the Quality and Understanding of American Aquaculture (AQUAA) Act**, which proposes national standards for offshore aquaculture and streamlining development.
- **The Sustaining Healthy Ecosystems, Livelihoods, and Local Seafood (SHELLS) Act**, which aims to establish a new office of aquaculture within the U.S. Department of Aquaculture.
- **The Supporting Equity for Aquaculture and Seafood (SEAS) Act**, which seeks to ensure equitable treatment for aquaculture producers within USDA programs.
- **The Coastal Seaweed Farm Act**, which would investigate the benefits of seaweed farming and offer grants for indigenous communities.

## Australia

Due to there being no single commercial licenser for macroalgae cultivation in Australia, algae must be bioprospected. Bioprospecting involves sourcing algae from its natural habitat, approval is then required prior to its commercial use. An alternative to bioprospecting is obtaining a culture from an existing grower who has acquired the required licenses for use. [8].

Compliance regarding the rights for commercial exploitation of genetic resources, is complex. For instance, bioprospecting legislations and commercialisation pathways vary between the Australian Government and the state and territory governments. Some of the complexities involve integrating with international policies, such as the *Nagoya Protocol on Access to Genetic Resources and the Fair and Equitable Sharing of Benefits Arising from their Utilization* [23].

In early 2023 a report from AgriFutures was published to provide a comprehensive understanding of the various governance and policy structures for marine seaweed aquaculture and to document the state of seaweed aquaculture in Australia (Table 1). As interest in this sector gains traction, there are likely to be significant changes in the Australian federal state and territory regulations that govern this space. Ongoing consultations with growers and users will be needed to ensure the industry growth requirements can be met, and learnings from the growth of overseas markets are integrated.

**Table 1. State-based comparison of governance for seaweed aquaculture development in Australia. Table adapted from Kelly and Macleod [24].**

| | Queensland | New South Wales | Victoria | Tasmania | South Australia | Western Australia | Northern Territory |
|---|---|---|---|---|---|---|---|
| Specific seaweed sector strategy/policy? | No | No[1] | No | No | Yes | Yes | No |
| Provision for seaweed aquaculture in existing legislation? | Yes | Yes | No[2] | Yes | Yes | Yes | Yes |
| One-stop shop for all aquaculture approvals? | No | No | Yes | Yes[3] | Yes[3] – proclamation of the ARMA[4] will fully embed this | No | |
| Designated zones for seaweed aquaculture in formal marine spatial planning? | Some – Great Sandy Regional Marine Aquaculture Plan | No | No | Yes | Yes | No | No |
| Commercial seaweed aquaculture approved/ allocated? | No | Yes | No | Yes | Yes | Yes | No |
| Provision for pilot/trial/ research licence? | Yes – development application still required | No – full state significant development process applies | Yes | Yes | Yes | Yes | Yes |
| Research/trials conducted or in progress | Yes – two smallscale pilots underway in different regions | No – application(s) are under consideration | Yes – some smallscale pilots on sites within aquaculture reserves | Yes | Yes | Yes | Yes |

1 Aquaculture strategy mentions seaweed.

2 Review of seaweed aquaculture governance arrangements in progress at time of publishing.

3 Application and assessment process managed by a single agency. Separate permit from Fisheries for collection of broodstock/seedstock.

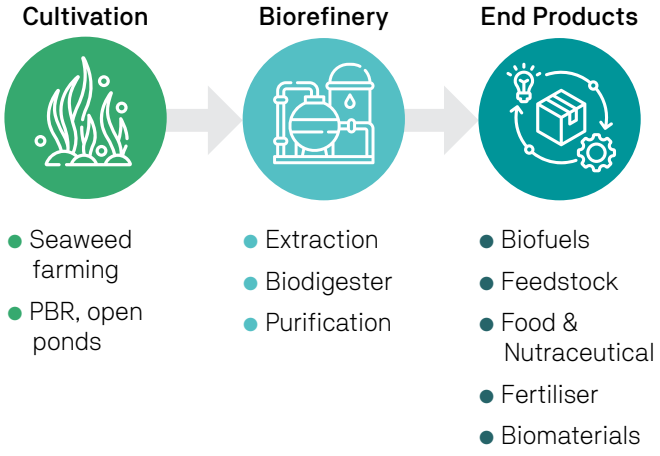
4 Aquatic Resources Management Act 2016.

# Algae Value Chain

Drawing value from the production of algae requires several processes, and often increasing levels of technological requirements. This is particularly true for products developed using extracts from algae. Understanding how to drive value from various parts of the algae value chain and the full range of products that can be generated is critical in understanding how to fully leverage the potential of the algae industry, and take advantage of rapid innovation.

**Algae "value chains" refer to trains of activities that are required:**

- to produce algae biomass ("cultivation")
- to process this algae biomass into extracts, components, or ingredients ("biorefinery"), and
- to formulate the extracts or components into algae-based products [25] ("end products").




**The algae biomass production chain involves the following sequential components at farm or site level:**

1. Selection of suitable algae species to cultivate.
2. Small scale cultivation, maintenance of culture.
3. Up-scaling cultivation: large scale algae biomass production.
4. Algae harvesting: at minimum requires partial dewatering to occur at farm/on site.
5. Recycling of the medium: Reuse for future cultures.
6. Other considerations: input sources (i.e. carbon dioxide and water), medium composition, discharges, climate control (i.e. light and temperature).

**There are two competing technologies currently used for commercial algae production [26]:**

- **Open raceway ponds:** open system, environment is more challenging to control, higher risk of contamination, relatively capital efficient.
- **Closed photobioreactors:** contain water inside a complex piping system. Environment is more controllable, reducing contamination risks by other biological organisms, however capital intensive.

**The following are key consideration within the algae supply chain:**

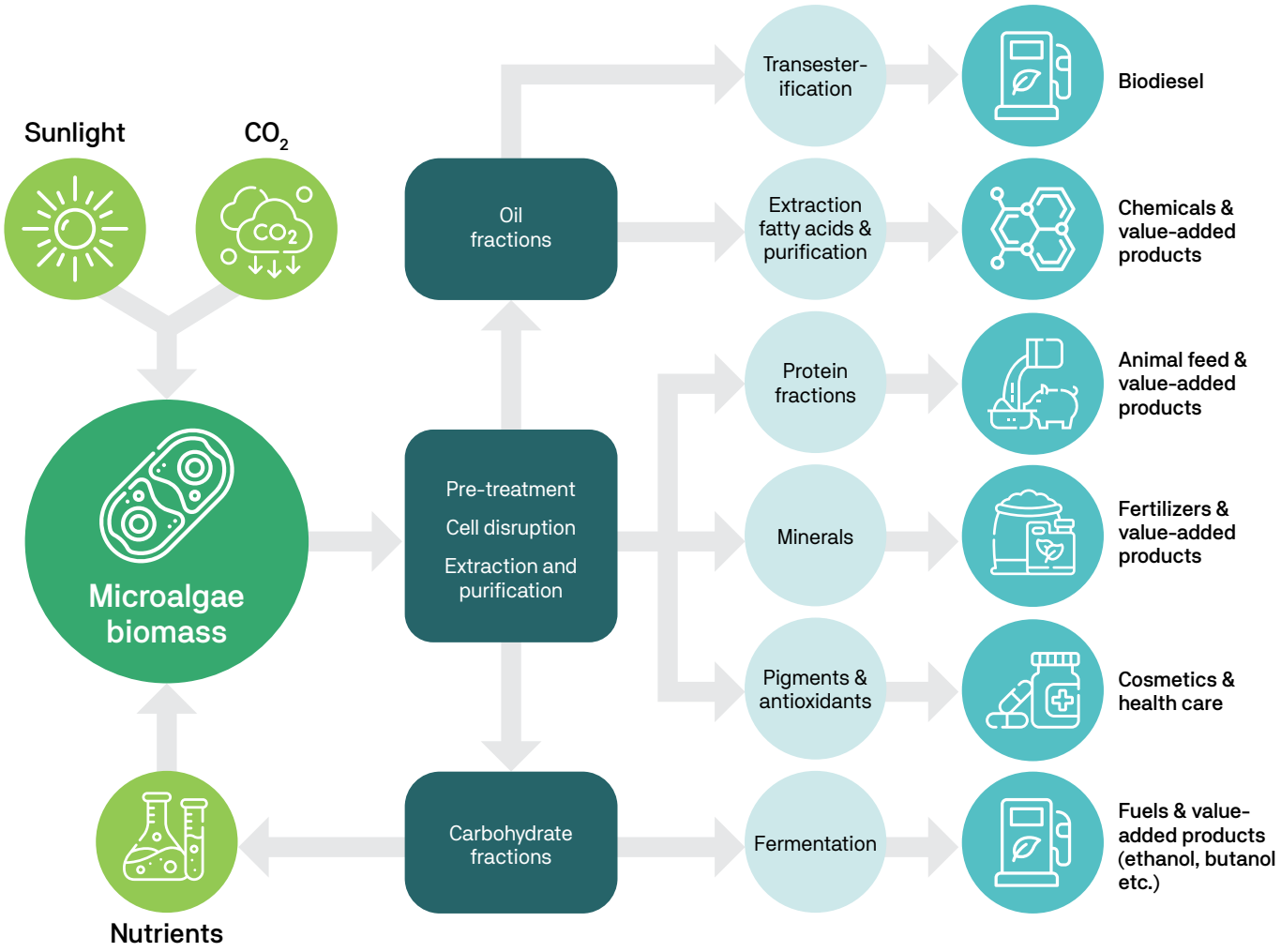
1. Logistic related to storage and transport of wet algae biomass.
2. Energy and cost expenditure associated with dewater and drying of wet biomass.
3. Potential (cascading) fractionation of algae biomass and tailoring of ingredients.
4. Other aspects: packaging, storage of ingredients, shelf life etc.

**Downstream** considerations for use of algae-based ingredients in marketable products:

1. Selection/tailoring of suitable ingredients to the application (i.e. nutraceuticals);
2. Designing and testing product formulations;
3. Selling of the products to the end-users;
4. Other aspects: consumer awareness and acceptance, marketing, legal aspects, etc.

A consideration that is vital for improving the successful cultivation of microalgae is the selection of a suitable strain. Algae strains have varying growth rates, temperature, light and carbon tolerances. It is important these factors are considered when selecting strains for cultivation in different geographical locations and climates [8]. Commercial viability is also dependent on expenses related to, operational, energy, harvesting, labour, and product delivery costs.

Figure 6: Microalgae Biorefinery Process. Diagram adapted from Sivaramakrishnan [27].




## Biorefinery of Algae

Biorefining is a sustainable way of processing biomass into a spectrum of marketable products using clean and green technologies in each processing step [28] (Fig. 6).

Irrespective of the method used to produce biomass, the most effective downstream processing occurs within an integrated biorefinery. This approach facilitates the extraction of the highest number of products and co-products while minimising residual waste. By doing so, it guarantees the greatest return on investment for downstream processing. Algae, especially microalgae have the ability to tolerate and utilise atmospheric and industrial carbon dioxide, hence sequestering carbon emissions and minimising the production of harmful greenhouse gasses [29].

Nowadays, algae biorefineries could be potentially fully automated with internet of things (IoT) technologies to reduce operational costs. Biorefineries can be located at regional hubs to service surrounding producers The downstream processing of biorefinery of microalgae biomass consists of extraction and purification of the value-added products.

## Extraction

Microalgae biomass can be categorised into three main fractions: oil, protein, and carbohydrates. These fractions represent the primary metabolites of microalgae. Additionally, microalgae contain secondary metabolites such as minerals and vitamins, which are extracted due to their nutraceutical properties [27]. Figure 6 above focuses on possible product streams to obtain numerous products from a single energy flow.

Macroalgae (seaweeds) consists of carbohydrate polymers such as alginate, agar, and carrageenan, which can be extracted and purified to obtain hydrocolloids [30, 31]. While agar and carrageenan can be extracted using hot water, their rheological properties are relatively weak. Therefore, an alkaline treatment is often conducted to enhance their performance [32]. Seaweed extracts have also shown promise as liquid biostimulants, demonstrating the ability to enhance plant resilience against salinity and drought stress. Beyond its bio-stimulatory effects, extracts are now being employed in the eco-friendly biosynthesis of metal nanoparticles, aiding in efficient waste reduction [33].

Additionally, residual waste or by-products can be recycled as nutrients within the culture medium or utilised for power generation typically in the form of combined heat and power (CHP) within the bio-refinery.

## Purification

Purification involved the separation of compounds of interest from those of lower interest. Following extracting algae biomolecules are usually mixed with either solvent or combined in a single phase to remove impurities that may diminish the biomass value or introduce toxicity. Consequently, depending on the anticipated use of the product, separation techniques may be necessary for purifying the extracted compounds. Such methods encompass electrophoresis, membrane separation, and ultracentrifugation.

## Technological Advancements

In recent years, there have been significant leaps in innovations and applied research and development in areas such as algae genetic engineering, bioreactors, and algae-to-product conversion processes. For example:

- Bioreactors: Diversification of tubular reactors, flat panels, and changes in designs
- Genetic engineering has taken a huge leap forward, with scientists continuously working on finding new strains of algae for specific, either through random mutagenesis, or emerging methods, including algae phenomics.
- There are concentrated efforts in southeast Queensland to develop new technologies for the intensive cultivation of Nannochloropsis spp. [12].
- Danish researchers are aiming to use residual waste (i.e. nutrients and carbon dioxide) generated from land-based seafood farming to cultivate sea lettuce, with the intent of supply it for human consumption due to its nutritional value (i.e. high protein, and fibre content) [34].
- Standardization of equipment and automation to upscale seaweed production [35].

## Algae Applications

In terms of their applicability in local and world markets, algal biomass (microalgae and macroalgae) is a source of energy (biofuels), fertiliser, pollution control, stabilization, nutrition, high-value molecules, and different bioactive metabolites to be explored for new drugs. For each of them, challenges and opportunities are represented in the Summary of Key Challenges and Investment Priorities table (page 24).

## Biofuels

Currently, the cost of cultivating seaweed is far greater than the cost associated with existing fossil fuel inputs. It is generally accepted that as long as fossil fuels exist, the cultivation of seaweeds for bioethanol as the main product is unlikely to be economically feasible [36, 37]. A major contributing factor to the poor economic viability of algae for biofuels is the lack of infrastructure that supports mass cultivation, which is required to enable bio-fuel scale magnitude of production. Microalgae grown in salt-water and arid areas of Australia offer a considerable opportunity for advanced biofuel production, due to the availability of input resources (i.e. light and seawater) and land; however, it also represents a considerable challenge due to infrastructure and technology requirements.

To improve the feasibility of algal based biofuels, several highly innovative technologies have been explored at various scales. Two technologies have achieved commercial status to some degree, for example lignocellulosic ethanol and CTO (Crude Tall Oil)-biofuel technologies are considered within the early stages of being commercial, whilst hydrotreating of vegetable oils (HVO, or HEFA) is considered fully commercial.

So far the main process for obtaining biofuel from algae is cultivation of biomass with a focus on lipid accumulation, extracting the oil and valorising co-products, then converting the algae oil into biodiesel through either esterification or Hydrotreated Esthers and Fatty Acids (HEFA). The HEFA method represents the production of very high-quality biofuels, which is close to being suitable for either road of aviation transport [38].

## Feeds

The aquaculture industry is well established, having used algae for the production of “aquafeed” for decades [39]. The high productivity of microalgae in addition to a balanced nutritional profile makes it an ideal aquafeed. Microalgae can be either fed directly as a live deed or indirectly as an algal meal. Algal meal typically consists of the residual biomass that is left over after lipid extraction [40].

In the recent decade there has been increasing consumer demand for more sustainable food products. This has resulted in an increase in demand of fishmeal alternatives such as algal meal, soybean meal, cottonseed meal, insect meal, and legumes [41, 42].

## Food and Nutraceutical

The nutritional composition of microalgae allows for the incorporation of ingredients and products derived from microalgal biomass into numerous food and feed markets. For instance, microalgae is known to contain high concentration of proteins making it a sustainable alternative source to meet increasing global demands for alternate and new sources of protein [43]. Additionally, microalgal derived proteins are a promising alternative feedstock for use in sustainability focused agriculture production systems.

Microalgae also contain compounds that can be greatly beneficial for human and animal health. Due to the presence of bioactive secondary metabolites, microalgae have the potential to ameliorate disease symptoms or causes, such as inflammation [44]. Additionally, microalgae typically contain healthy fats in the form of omega-3’s. Omega-3 fatty acids are polyunsaturated fatty acids, which have been shown to provide several vital health functions for eukaryotic organisms [45].

Macroalgae also contain bioactive compounds in the form of polysaccharides, pigments, fatty acids, polyphenols, and peptides, which have been proven to possess various beneficial properties for human health and functioning. Some of the suggestive functions of these compounds include antioxidative, antibacterial,anticancer, antidiabetic, antitumor, antiviral, anti-inflammatory, and anticoagulant [46].

## Biofertiliser

Algae possess potential to be utilised in a multitude of industries, for example within agriculture as biofertilisers and soil conditioning agents to enhance soil fertility and plant productivity [47, 48]. Bio-fertilization is a sustainable agricultural practice that uses bio-fertilisers to upsurge the nutrient content of the soil, resulting in higher productivity [49].

## Biomaterials

Algae is a sustainable biomaterial that can make almost anything, including plastics, paints, carpets, and cosmetics. Alternatives to petrochemical-based plastic sources are in high demand, as they make plastic production sustainable while mitigating the issue of plastic pollution. Algae have the potential to be an economically viable feedstock for bioplastics production [50]. Microalgae are an excellent alternative for producing green materials such as microalgae polymers, co-blends, and combinations of biomass or microalgae biomolecules with other polymeric materials. Microalgae-based biopolymers have better mechanical properties than petroleum-based polymers and can be modified by adding plasticisers, additives, and bulking agents to improve their durability, strength, and flexibility [51] [52].

Finally, algae also find space for applications in the construction industry, such as the use of algae on the façades of buildings as a source of energy and also as a means of providing shade to buildings [53].

## Wastewater Treatment

Algae have recently emerged as a potentially cost-effective method to remediatetoxic pollutantsthrough the mechanism of biosorption, bioaccumulation, and intracellular degradation.

Microalgae have the ability to absorb nitrogen, phosphorus, and carbon in natural water systems. Algae can improve wastewater treatment by producing oxygen that allows aerobic bacteria to break down organic contaminants in the water and take up excess nitrogen and phosphorus in the process. It is also a sustainable and affordable alternative to current wastewater treatment practices [54].

In Australia, scientists at James Cook University, developed RegenAqua™, a bioremediation solution that uses native green macroalgae to naturally remove nitrogen and phosphorus from water [55]. The technology supports organizations to achieve discharge license compliance and can effectively return restored marine and freshwater to the environment.

# Summary of Key Challenges and Investment Priorities

Scaling and unlocking the full potential of the Australian algae ecosystem is faced with many challenges. Key investment priorities across the value chain are subsequently outlined below (see also results from the stakeholder consultation session 3). For completeness, we include identified challenges and, in some instances, recommendations raised by the Summit attendees. Table 2 below is broken into three "value chain" sections (as above in "Algae Value Chain"); issues concerning the supply of algae, issues around end products and applications of algae, and generalised issues. These are summarised in the context of commercial opportunities, policy and regulatory frameworks, research and development (R&D), and social context.

**Table 2: Summary of key challenges and investment priorities in the algae value chain.**

| Value Chain Element | Commercial | Policy/Regulatory | R&D | Social |
|---|---|---|---|---|
| **General** | Lack of shared marketing strategy within the industry | Lack of adequate legal and policy frameworks at international or national/ regional levels<br>Quantification of environmental services (carbon sequestration - blue carbon credits) and standards harmonization are required | There is a focus pull between applications of nutrient absorption, habitat creation or restoration, and coastal resilience<br>Lack of targeted funding e.g. for the construction of innovative bio-refineries | Lack of consumer awareness and acceptance of algae products, and their nutritional value |
| **Supply: Issues surrounding the growth and processing of algae and derived products** | | | | |
| **Cultivation** | Lack of supply/producers<br>High production cost<br>Mapping location of remote and regional cultivation areas<br>Existing large-scale facilities distribute their produce to only established business<br>Lack of scaling-up and limited supply of algae biomass and algae-based products (high price)<br>Lack of access to marine space, non-arable land, infrastructure, and technology | No adequate legal and policy frameworks at regional /state levels<br>Uncoordinated funding initiatives | Choice of algae strains; opportunity to expand these to include more diverse strains, engineered strains, etc.<br>Opportunities to address water pollution and eutrophication<br>Gaps in cultivation systems, biorefinery processing into multiple products<br>Advantages and negative impacts and risks of cultivation and harvesting | Lack of trained/skilled workers in regional areas<br>Improve opportunities for interaction and collaboration with Traditional owners for knowledge translation |
| **Biorefinery** | Ability to demonstrate at pilot-scale the sustainability improvements for technical, economic, environmental, and social sustainability | Policy to incentive co-location of businesses involved in biorefinery from upstream to downstream | Design and develop processing technologies, to eliminate the high-energy, water, and chemical-requiring processes to be clean and green | N/A |

| Value Chain Element | Commercial | Policy/Regulatory | R&D | Social |
|---|---|---|---|---|
| **Algae Applications: Issues surrounding the application and use of algae end-products** | | | | |
| **Biofuels** | High production cost<br>Low supply | N/A | Efficient biomass production is necessary to achieve a profitable microalgal biofuels | N/A |
| **Feeds** | Improve feed conversion ratios<br>Availability of supply | Economic incentives for farmers could improve usage and production for other applications | No market size data is available | Increased overall perception of benefits of natural alternatives has improved market pull |
| **Food and Nutraceutical** | Availability of algae supply is limited<br>Expensive niche market | Complex rules and regulations on novel food products constrain use of new ingredients / strains | Quality and certification of nutrition claims has some issues and constraints around it | Acceptance in the general population as nutraceutical / ingredient is gaining traction<br>A good nutritional ingredient with diverse applications |
| **Bio-fertiliser** | Limited transportation and storage space | Weak and fragmented labelling of bio-fertiliser goods<br>Enact legislation to screen biofertilisers | Inaccessibility of suitable strains<br>To reduce impacts and check stated soil and natural situations | Exposure among end users (farmers) is needed |
| **Biomaterials** | Competition with other sustainable products<br>Availability of supply/ low cost for large-scale production | Improve labelling and standards frameworks are needed to drive market pull | More research to improve the performance of algae-based materials | Improve public perception of algae as a good biomaterial alternative |

# Stakeholder Consultation

The stakeholders' consultation (SC) was carried out on Tuesday 30 May 2023 at UTS via the Algae Business Summit. The purpose of the SC was to gather insights from a broad range of stakeholders and address the pressing need for the progression of the Australian algae industry. The SC aimed to identify key opportunities and roadblocks and create an environment for knowledge-sharing collaboration, and collective problem-solving.

The consulted stakeholders include companies that currently work in the Australian algae industry, research and academia, public authorities, and NGOs (Fig.7).

In total 71 responses were submitted. All questions were asked to all stakeholder categories and did not depend on previous answers. However, not all respondents answered all the questions. Specific responses were categorised and synthetised for better visual analysis Companies and business organizations with academia were the largest group, consisting of 88% (44% each) of all respondents, followed by business associations (10%) and public authorities (1.4%). The smallest groups represented were NGOs with one (1) respondent.

**SC** questions are described as follows:

## In Session 1:

### From Supply to Market: Opportunities and challenges – Case studies from across the algae industry – Current markets

Questions to address:

1 What are the challenges for upscaling algae current markets?

2 Which actions are needed to solve constraints?

## In Session 2

### Regulatory and other Frameworks to support the Australian Algae Bioeconomy and Driving a supportive business ecosystem

Questions to address:

1 Australian regulation and support frameworks in relation to algae food use, aquaculture (including collection), and investment (and other sectors):

2 Interpretation/Access/Application

3 Gaps

4 Need for additional regulation

## In Session 3

### Developing a roadmap and recommendations

Questions to address:

1 Constraints, needs, and opportunities for the sector development

2 Access to information, participation, and impact

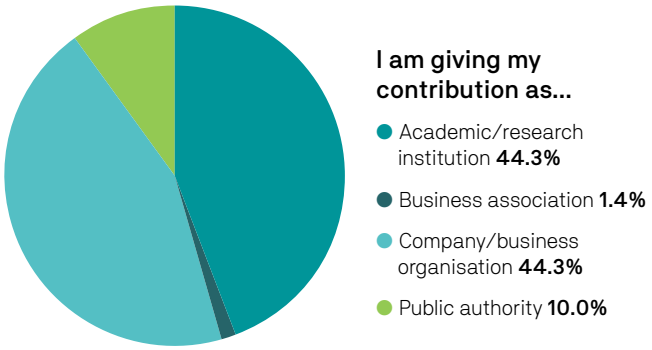
3 Interpretation/Access/Application

4 Gaps

5 Need for additional regulation/support

6 Future priority topics.

**Figure 7: Attendees and contributors to the Algae Business Summit by self-identified sector.**



# Overview of Results

The below is a summary of the key findings from the SC. Full results for each session can be found in the **Appendix** of this Whitepaper.

## Session 1:

### From Supply to Market: Opportunities and Challenges

#### Q1: Challenges for Upscaling Algae Current Markets

- Policy and Regulations: Identified as the most pressing challenge (18%).
- Access to Funding Complexities: Cited by 15% of respondents.
- "Made in Australia" Label and Engineering Challenges: Gained partial consensus at 12% and 11%, respectively.
- Resolving Status Quo Behaviour: Consistent concern throughout the session, garnering 12% agreement.

#### Q2: Actions Needed to Solve Constraints

- Regulation Inconsistency: Key identified challenge identified challenge at 38%.
- Lack of Trained Personnel: Highlighted as a hurdle by 22%.
- Knowledge Gap Around Algae Potential: Recognised by 17%.

## Session 2:

### Regulatory and other Frameworks to support the Australian Algae Bioeconomy and Driving a Supportive Business Ecosystem

#### Q1: Australian Regulation and Support Frameworks

- Shared Vision and Coordinated Funding Initiatives: Identified by 27% as key issues for improving regulatory frameworks.
- Diversity in Priorities: Responses showcased a multi-disciplinary range of challenges.

#### Q2: Gaps in Australian Regulation and Support Frameworks

- Lack of Government Roadmap: Identified by 21% as a primary challenge.
- Misallocation of Funding: Repeatedly mentioned, highlighted by 21%.
- Gaps in International Standards and Labelling: Recognised as a concern by 17%.
- Industry Still Young: Acknowledged by 17%.
- Significant Gap in Policy Development: Noted by 8%, emphasising the absence of knowledge sharing with Indigenous communities.

#### Q3: Feedback and Suggestions for Additional Regulation

- Coordinated Regulation Across States: Raised by 24%.
- Incentives for Market Access: Supported by 22%.
- Improvement in Data Sharing: Emphasised by 16%.
- Incentivisation of Carbon Capture through Algae: Mentioned by 5%.

## Session 3:

### Developing a Roadmap and Recommendations

Respondents were asked a series of questions concerning constraints, needs, and opportunities for the sector development, access to information, need for additional regulation and future topics to develop a roadmap and recommendations for the algae industry.

Most of the answers of this session were summarised and reported in the next section "**Identified Challenges and Opportunities, pg 28**".

#### Q6: Recommendations for Future Priority Topics

- Development of Robust Leadership and Roadmap: Prioritised by 29%.
- Streamlining Current Regulation: Supported by 17%.
- Circularity Principles and Guidelines: Recognised as important by 13%.

The findings reveal a complex landscape with diverse opinions, emphasising the need for a comprehensive approach addressing regulatory, financial, and knowledge-related challenges to propel the algae industry forward. Priorities include strategic leadership, regulatory coherence, and fostering circular practices for sustained growth.

# Identified Challenges and Opportunities

## Developing a roadmap and recommendations

**Industry Vision:** The vision for the Australian Algae Industry is to foster growth, innovation, and international competitiveness, leveraging its unique selling points to contribute value to the global bioeconomy.

Through the stakeholder consultation and roadmap development process, stakeholders identified three key pillars that are needed to drive the growth of the Australian algae industry. The Roadmap highlights how each pillar will contribute to scaling up the national algae industry to achieve its vision and identifies the key stakeholder actions required.

Stakeholder actions have been identified from industry input at the Algae Business Summit and post-summit Survey, and then validated through ongoing stakeholder consultation.

The pillars that emerged were; (1) Resourcing; (2) Regulations and Formalised Frameworks for Recognition; and (3) Collaboration. These are presented below, broken into key areas, with some examples given for opportunities for next steps:

## Pillar 1: Resourcing

### Workforce training

**Challenge:**

- There is a lack of skilled workers in the algae ecosystem, particularly in the space of algae growth and production.
- The current skilled personnel are mostly located in the major cities with no incentives to move to regional or remote areas where there is a shortage of trained staff.

**Opportunity for next steps:**

- Improvement in training for algae workers and the availability of qualifications in algae aquaculture (e.g. TAFE) for future students is necessary to provide pathways for the new industry.

### Need for a biorefinery and piloting facilities

**Challenge:**

- Access to downstream processing facilities is unsatisfactory for startups and universities

**Opportunity for next steps:**

- Development of an Australian biomanufacturing pilot facility or Centre of Excellence (CoE) with access, support and incentives for businesses or universities
- Bioeconomy strategy from the Commonwealth.

# Pillar 2: Regulations and Formalised Frameworks for Recognition

## Provenance of Australian produce

**Challenge:**

- According to the reviewers, there are inconsistencies with product labelling processes, with items being made overseas and packaged onshore still receiving the label, misleading buyers, and therefore damaging small aquaculture and nutraceutical companies that make all their products in Australia.
- There is a vast opportunity to be had to deploy strains with elite qualities (faster growing, etc.); however regulatory bottlenecks and impacts on the ecosystem need further understanding.
- Environmental Impact Statements (EIS) and other regulatory approvals come with significant investment, which hinders industry collaboration and progression.

**Opportunity for next steps:**

- As a nation, Australia is known and vetted as a desired market, with internationally respected high standards. It also provides many Australian species with unique qualities to be explored in different sectors (e.g., manufacturing, fibre, feed, food). Therefore, the "Made in Australia" label process needs to better align with such good practices.
- Investigation is needed to understand how to deploy "elite" strains of seaweed into the ocean; with further understanding required of the regulatory bottlenecks and any impacts on the existing ecosystem.
- Consultation with a broader network or assistance in meeting regulatory approval requirements (ex. microalgae or seaweed association) would help to streamline processes such as approvals and EIS requirements.

## Inconsistent regulation across states and the need for a state-based information officer

**Challenge:**

- There is inconsistency in the regulations governing the sourcing, growth, and production of algae across different Australian states/levels of government without a clear national rulebook.
- Unclear regulatory approval processes deter investors and create barriers to investments of State-based approvals, limiting market opportunities and the creation of new startups.
- Some Australian states are more advanced than others in their regulatory processes (see SA/TAS for marine zoning or QLD/NT for access/benefit sharing). Currently, this is an identified barrier for NSW not being allowed to do ocean trials of seaweed/macroalgae cultivation.

**Opportunity for next steps:**

- Regulation should be a nationwide standard, or streamlined to eliminate bottlenecks.
- A designated seaweed officer in each state/government department to assist in the industry would also be beneficial.
- A common point of discussion was to have an independent advisory board or algae peak body; to guide companies in understanding regulation or to establish aquaculture zoning but also to connect companies to investors, or companies or trained staff.

## Link between algae, decarbonisation, and carbon credits

**Challenge:**

- Currently, it is unclear how algae fits within existing carbon markets; at the moment, no standards exist in Australia.
- Clear opportunities lie in implementing algae in circular systems – by growing off waste (i.e. wastewater, carbon dioxide); however, implementation of these schemes has limited examples in Australia.

**Opportunity for next steps:**

- Co-location of industries to co-enable circularity and incentivise carbon capture through algae.
- There is a need for non-involuntary (voluntary) carbon markets for algae claims; this will further add financial motivation for the implementation of algae into circular systems, and assist with the financial viability of some product ranges.

## Risk Assessment and Risk Aversion

### Challenge

- It was raised several times during the summit that there was expected to be production of algae before investment or supply contracts (such as for pharmaceuticals) would be considered.
- Large-scale production was not able to occur until investment had been raised. The risk aversion of potential investors is not enabling progress to occur.

### Opportunity for next steps:

- Need a roadmap to provide a shared vision and coordinated support for new and emerging algae research/company.
- Looking to the USA as a case study: How insurance of algae farms is managed or regulated by government bodies with improvements in requirements criteria provides a map for opportunities in Australia
- Analysis and evaluation of the EU market, especially the successful collaboration between different countries.
- Funding and cost and risk assessments for investors (coastal license/development planning opposes) could offer more favourable opportunities to investors

# Pillar 3: Collaboration

## Algae has an image problem

### Challenge:

- Public perception of algae is negative or neutral and needs a better story to motivate investors emphasising algae's role as a nutrient-dense and photosynthetic sustainable resource.
- Academics and engineers are good at producing data/results but may not be the ones to lead and encourage a change in public opinion surrounding algae.

### Opportunity for next steps:

- Marketing strategies are needed to address these issues. Community engagement is also needed to discuss concerns and feedback on algae farming.
- To achieve market attractiveness, there needs a clear focused communication strategy such as rebranding biotechnology policy changes and aligning common objectives.

## Indigenous opportunities in the seaweed industry

### Challenge:

- Missing opportunity to include Indigenous people and knowledge sharing.

### Opportunity for next steps:

- Better consultation and collaboration with Indigenous people.

## Improved communication across and within the algae community; including improved data and knowledge exchange

### Challenge:

- There is a lack of algae knowledge and recognition within the government, leading to a lack of recognition in relevant guidelines and governance.
- Lack of guidance/interest for regional centres where there are clear opportunities for circular economy, linked by regional development strategies.

### Opportunity for next steps:

- An advisory network or individuals could be established to knowledge share and advise on the science around algae.
- Case studies of successful businesses from overseas with different uses/applications of algae are needed. These could include a focus on end products, and connecting with customers about the product and market drivers.
- Sharing data and information across sectors/companies and universities to get broader benefits. This could include the sharing of non-confidential data and the benefits of increasing public awareness and perception.
- The circular economy should be a priority. This includes determining what it means to make sure the industry is using a position statement, and showing clear alignment with areas such as biotechnology, circular economy, agriculture/food, bioengineering

# What's Next: Development of an Australian algae bioeconomy

Algae have been recognised as one of the most promising resources of the blue bioeconomy (e.g. "*by definition, 'blue bioeconomy' incorporates any economic activity associated with the use of renewable aquatic biological resources to make products*" [3].

Further, while each algae application has been described individually, a strong advantage of algae is that it can simultaneously service multiple sources of demand. Thus, in practice, a single cultivation plant could provide secure agreements in several applications depending on suitable infrastructure, policy, and demand requests.

Barriers to the activation of the algae market stem from a lack of supporting infrastructure for algae domestic supply to the inconsistency of state regulation (evidence from Q2-Session 1). However, both barriers could be overcome via a series of strategic investments along the value chain from both the private and public sectors (A snapshot of the underpinning algae value chain is set out on page 24).


It is expected, however, that the development of an appropriate national bioeconomy strategy framework/ roadmap could create a market pull for algae with investment in infrastructure, algae production, and startups that are likely to follow [3].The competitiveness of algae against other resources is likely to then improve when considering factors such as access to non-arable land, localization and automation of supply chains, renewable energy supply, and carbon risk as well as the establishment of an algae export industry.

### Opportunities to leverage Australia's unique resources

In Australia, most microalgae production is completed in raceway systems (i.e. Biogenesis, AlgaePharm). This method utilises Australia's environmental strengths, (lots of sun and space) and is low cost, however, product utilisation is limited (food, feed, biomaterials). (Spencer-AgriFutures, 2021)

Currently, nine microalgae production companies operate in Australia, but one multinational company (BASF), dominates most of the Australian production.

Macroalgae (seaweed) can be farmed in both on-land ponds and offshore farms. Most macroalgae are cultivated on offshore farms, however regulation across different states can limit ' access to offshore options.

# Looking Forward: Paving the path and unlocking the growth and innovation of the Australian algae industry

To drive the Australian algae industry into a future of sustainable growth and innovative product diversification, strategic measures and collaborative initiatives are essential.

For companies seeking to scale and diversify their product offerings into high-value markets, prioritisation of de-risking strategies is required. A common theme echoed at the Algae Business Summit (ABS) was the need for centralised services (**Pillar 1: Resourcing**), such as biorefineries or pilot facilities. These facilities play a pivotal role in processing algae biomass and the development of high-value products.

Centralising services can significantly mitigate capital expenditure (CAPEX) for individual businesses while concurrently facilitating their entry into high-value markets, including cosmetics, nutraceuticals, supplements, and pharmaceuticals. Notable examples, like Bondi Bio, underscore the current challenges faced by companies managing biomass across multiple states for varied processing. Streamlining this process through centralised facilities would streamline production, enhance efficiency, and unlock new revenue streams, particularly in waste valorisation. Drawing inspiration from successful models like the Bio Base Europe Pilot Plant, a unique facility for process development, scale-up, and custom manufacturing of biobased products, offers a blueprint for this type of facility.

A critical need exists to better outline, streamline, and standardise regulatory requirements (**Pillar 2: Regulations and Formalised Frameworks for Recognition**). Industry players would greatly benefit from clear guidance and recommendations on connecting with the circular economy and leveraging carbon credits. Establishing a regulatory framework that aligns with sustainable practices and economic circularity is imperative for industry-wide success.

Moreover, recognising the multifaceted nature of algae production, it is advisable for producers with limited resources or a reduced need for waste biomass, to consider collaborating with existing producers rather than independently developing production farms (**Pillar 3: Collaboration**). This collaborative approach ensures access to established resources, knowledge, and infrastructure, addressing challenges related to time, research, and finance. By fostering partnerships within the industry, companies can harness collective expertise, optimise resource utilization, and navigate the complex landscape of algae production more effectively.

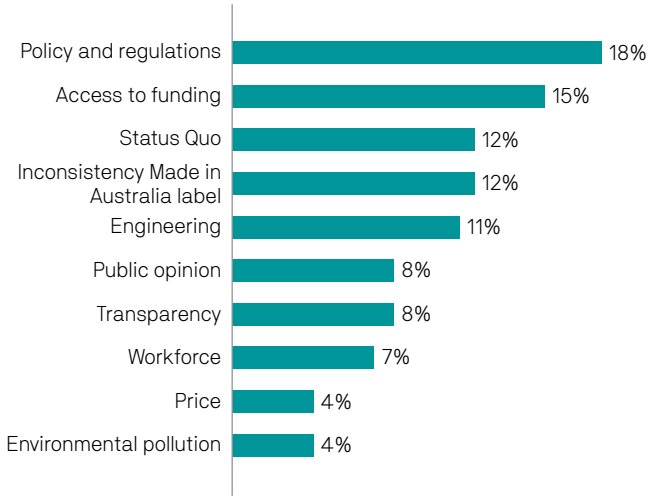
For the Australian algae industry to reach its full potential, lies in strategic collaboration, innovative facilities, and regulatory frameworks that support sustainability. Embracing centralised services, learning from successful models, and fostering collaboration are crucial steps toward unlocking the full potential of the algae industry and driving it toward a sustainable and diversified future.

# Appendix: Methods and Results from Stakeholder Consultation

## In Session 1:

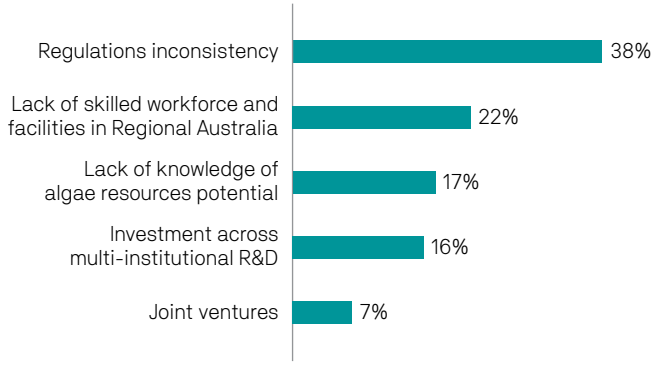
### From Supply to Market: Opportunities and Challenges Case studies from across the algae industry – Current markets

**Q1 asked respondents "What are the challenges for upscaling algae current markets?" (Respondents could write their own opinion).**




After reviewing and categorising the answers by keyword / topic, the most frequently selected challenges to upscale the markets were to improve policy and regulations (18%) followed by access to funding complexities (15%). Improving the "Made in Australia" label process and engineering challenges also received partial consensus (12%) and (11%). Resolving Status Quo behaviour (12%) appears to be a consistent argument throughout the session. (See graph below for further details).

**Q2 asked respondents "Which actions are needed to solve constraints?" (Respondents could write their own opinion).**

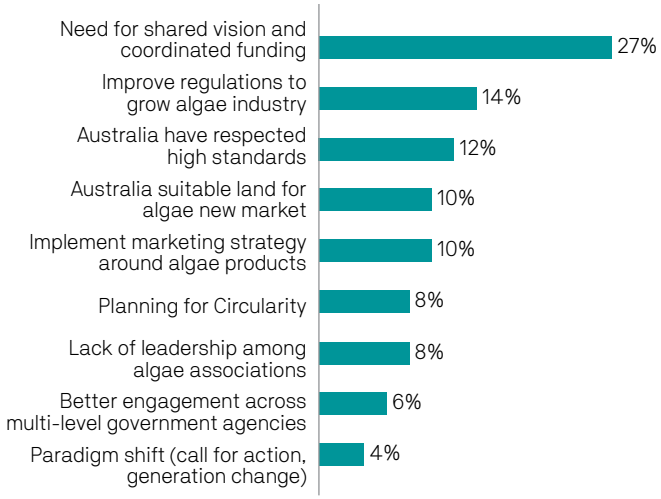



After reviewing and categorising the answers by keyword/ topic, regulation inconsistency (38%) emerged as the major identified challenge to resolving constraints to upscale the algae industry in Australia. Moreover, the lack of trained people in algae/aquaculture across the country or regional areas is another hurdle to growth (22%). Lack of knowledge around algae potential (17%) is another important topic to address especially with marketing and communication expertise. (See graph below for further details)

## In Session 2:

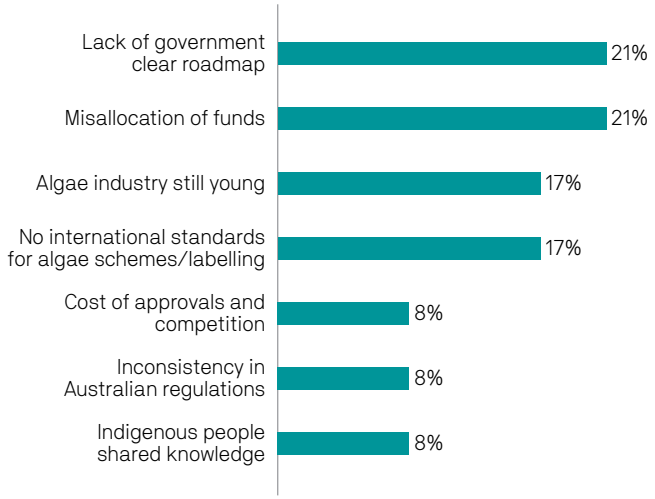
### Regulatory and other Frameworks to support the Australian Algae Bioeconomy and Driving a supportive business ecosystem.

**Q1 asked respondents to "Describe how Australian regulation and support frameworks in relation to algae food use, aquaculture (including collection), and investment (and other sectors) in terms of *Interpretation/Access/Application*" (respondents could write their own opinion).**




After reviewing and categorising the answers by keyword/ topic, approximately a third of the participants (27%) agree that the need for a shared vision among stakeholders and coordinated funding initiatives would be the main issues to improve regulatory frameworks and support an Australian Algae bioeconomy ecosystem. The answers provided to the question show diversity in priorities and feedback which proves the multi-disciplinary range of the challenge (see graph above).

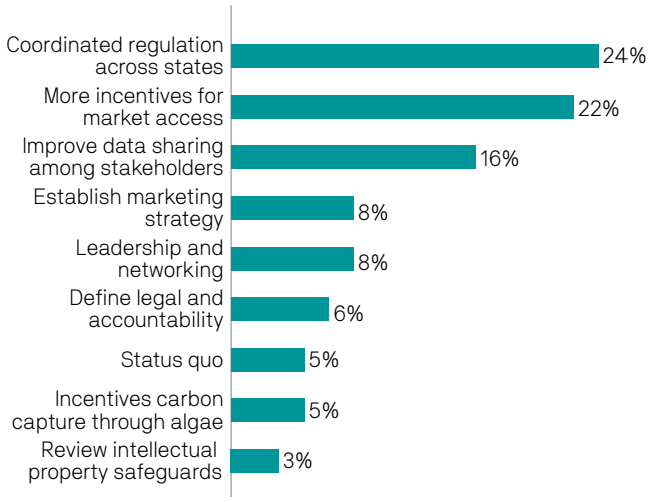
**Q2 asked respondents "Which are the *gaps* in Australian regulation and support frameworks in relation to algae food use, aquaculture (including collection), and investment (and other sectors)" (respondents could write their own opinion).**




After reviewing and categorising the answers by keyword/ topic, one-fifth of the participants (21%) indicated that the lack of a government roadmap for the algae industry is the main challenge to overcome together with the misallocation of funding (an item which repeatedly appeared during the various sessions). Gaps in international standards and labelling and the realization that the algae industry is still young (17% both) are also important statements among the participants that channel the focus of those topics. With 8% identifying that the graph below highlights that there is a significant gap in the success of policy development due to the absence of knowledge sharing with Indigenous communities.).

**Q3 asked respondents to "Provide their feedback and suggestions regarding the need for additional regulation" (respondents could write their own opinions).**

After reviewing and categorising the answers by keyword/ topic, respondents showed a diverse range of suggestions. As repeated constantly during the workshop, coordinated regulation across the states (24%) and more incentives for market access (22%) are the most selected topics to add to the regulation's agenda. Another important key point is the improvement in data sharing among stakeholders (16%) also repeated various times during the sessions. Interesting to notice that a small percentage (5%) also incentivisation of carbon capture through algae, another hot topic for further discussion (see graph below).



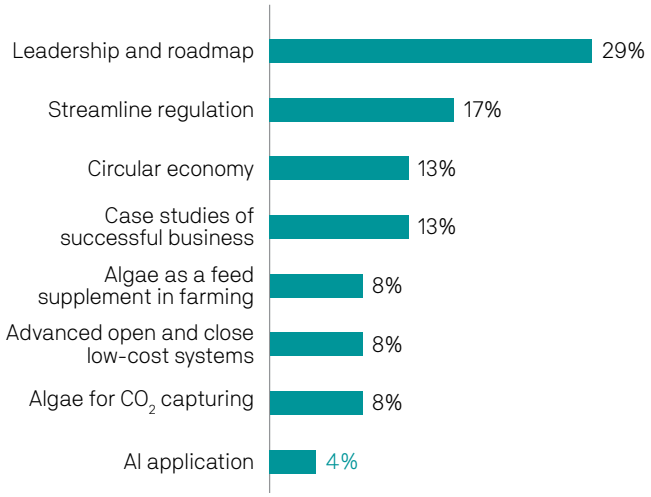
# In Session 3:

## Developing a roadmap and recommendations

Respondents were asked a series of questions concerning constraints, needs, and opportunities for the sector development, access to information, need for additional regulation and future topics to develop a roadmap and recommendations for the algae industry. The answers show a range of diverse opinions, reaching multi-disciplinary levels from regulation concerns to industry optimization making it difficult to summarize graphically. The Q6 relating to future priority topics was the only one that showed graphics attributes. Most of the answers of this session were summarized and reported in the next section "**Identified Challenges and Opportunities**".

Approximately one-third of the participants (29%) agree that priorities for the algae sector lie in the development of a robust leadership and roadmap around algae initiatives and the streamlining of the current regulation to attract new investments and startups (17%). Circularity (13%) principles and guidelines appear to be another topic that future discussion links with the algae bioeconomy.

**Q6 asked respondents about their "Recommendations for Future priority topics"**




# References


1. Shalaby, E.A., *Algae as promising organisms for environment and health.* Plant Signal Behav, 2011. **6**(9): p. 1338-50.
2. Barsanti, L. and P. Gualtieri, *Algae: Anatomy, Biochemistry, and Biotechnology, Second Edition*. 2 ed. 2014, Baton Rouge: CRC Press.
3. European Commission, Directorate-General for Maritime Affairs and Fisheries,Blue bioeconomy report, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2771/223072.
4. Fabris, M., et al., *Emerging Technologies in Algal Biotechnology: Toward the Establishment of a Sustainable, Algae-Based Bioeconomy.* Front Plant Sci, 2020. **11**: p. 279.
5. Sanchez Lopez, J., et al., *Brief on jobs and growth of the EU bioeconomy 2008-2017.* 2020.
6. Hoffman, J., et al., *Techno-economic assessment of open microalgae production systems.* Algal Research, 2017. **23**: p. 51-57.
7. Gao, K. and J. Beardall, *Using macroalgae to address UN Sustainable Development goals through $CO_2$ remediation and improvement of the aquaculture environment.* Applied Phycology, 2022. **3**(1): p. 360-367.
8. Spencer, A., *The algae and seaweed opportunity: An Australian prospect*. 2021: AgriFutures, https://agrifutures.com.au/product/the-algae-and-seaweed-opportunity-an-australian-prospect/
9. Sharma, N.K. and A.K. Rai, *Biodiversity and biogeography of microalgae: progress and pitfalls.* Environmental reviews, 2011. **19**(NA): p. 1-15.
10. Llewellyn, C.A. *Microalgae is nature's 'green gold': our pioneering project to feed the world more sustainably*. 2022.
11. Hermans, S. *Seaweed State of the Industry*. 2023; Available from: https://phyconomy.net/articles/2022-seaweed-review/.
12. Zur, T. *Australia's marine bioproducts industry is about to boom*. 2021; Available from: https://agfundernews.com/marine-bioproducts-australia-industry-is-about-to-boom.
13. Dawson, F. *America aims to boost aquaculture with SEAfood Act*. 2023, Available from: https://seawestnews.com/america-aims-to-boost-aquaculture-with-seafood-act.
14. Hatch Innovation Services 2023; Available from: https://hatchinnovationservices.com/.
15. Show, P.L., *Global market and economic analysis of microalgae technology: Status and perspectives.* Bioresource Technology, 2022. **357**: p. 127329.
16. Garrido-Cardenas, J.A., et al., *Microalgae research worldwide.* Algal Research, 2018. **35**: p. 50-60.
17. Murata, M.M., et al., *What do patents tell us about microalgae in agriculture?* AMB Express, 2021. **11**(1): p. 154.

18. Iijima, M., J.F.o.N.G. Biofuels, Editor. 2014, USDA Foreign Agricultural Services: Global Agricultural Information Network.

19. Enzing, C., et al., *Microalgae-based products for the food and feed sector: an outlook for Europe.* Institute for Prospective Technological Studiesfashion nutraceuticals, 2014: p. 1017-1024.

20. Stengel, D.B. and S. Connan, *Marine Algae: a Source of Biomass for Biotechnological Applications.* Natural Products From Marine Algae, 2015: p. 1-37.

21. de Vrije, G.J., Siegers-Budde, M. A. W., Hou, X., Bjerre, A.-B., & Lopez Contreras, A. M. , *Production of fuels and chemicals from Seaweeds*, in *FEMS 2019, 8th Congress of European Microbiologists*. 2019: Glasgow, Scotland, .

22. Fish Net, *US Congress considers SEAfood Act to advance offshore aquaculture in US waters*. 2023; Available from: https://thefishsite.com/articles/us-congress-considers-seafood-act-to-advance-offshore-aquaculture-in-us-waters.

23. Herkenrath, P. and J. Harrison, *The 10th meeting of the Conference of the Parties to the Convention on Biological Diversity—a breakthrough for biodiversity?* Oryx, 2011. **45**(1): p. 1-2.

24. Kelly,J. and Macleod, C., *Seaweed aquaculture governance in Australia: A review of state and Northern Territory seaweed aquaculture policy* 2023: AgriFutures Australia

25. IDEA, *IDEA position paper – Algae value chains* 2023; Available from: https://vb.nweurope.eu/media/17469/idea-position-paper-value-chains-v8.pdf.

26. Vasudevan, P.T. and M. Briggs, *Biodiesel production – current state of the art and challenges.* J Ind Microbiol Biotechnol, 2008. **35**(5): p. 421.

27. Sivaramakrishnan, R., et al., *Microalgal Biorefinery Concepts' Developments for Biofuel and Bioproducts: Current Perspective and Bottlenecks.* International journal of molecular sciences, 2022. **23**(5): p. 2623.

28. Poggi-Varaldo, H.M., et al., *Biohydrogen, biomethane and bioelectricity as crucial components of biorefinery of organic wastes: A review.* Waste Management & Research, 2014. **32**(5): p. 353-365.

29. Singh, S., et al., *Carbon credit market and Algae-based CO2 sequestration technology: A Review*. 2011.

30. Jönsson, M., et al., *Extraction and Modification of Macroalgal Polysaccharides for Current and Next-Generation Applications.* Molecules (Basel, Switzerland), 2020. **25**(4): p. 930.

31. Baghel, R.S., C.R.K. Reddy, and R.P. Singh, *Seaweed-based cellulose: Applications, and future perspectives.* Carbohydrate Polymers, 2021. **267**: p. 118241.

32. Trica, B., et al., *Extraction and Characterization of Alginate from an Edible Brown Seaweed ( Cystoseira barbata ) Harvested in the Romanian Black Sea*. Marine drugs, 2019. **17**(7): p. 405.

33. Wolle, M.M. and S.D. Conklin, *Speciation analysis of arsenic in seafood and seaweed: Part I—evaluation and optimization of methods*. Analytical and bioanalytical chemistry, 2018. **410**(22): p. 5675-5687.

34. Fish Net, *New technology to convert waste from fish farming into seaweed*. 2023; Available from: https://thefishsite.com/articles/new-technology-to-convert-waste-from-fish-farming-into-seaweed.

35. Solvang, T., et al., *Automation Concepts for Industrial-Scale Production of Seaweed.* Frontiers in Marine Science, 2021. **8**.

36. Bruhn, A., et al., *Bioenergy potential of Ulva lactuca: Biomass yield, methane production and combustion.* Bioresource technology, 2011. **102**(3): p. 2595-2604.

37. Pittman, J.K., A.P. Dean, and O. Osundeko, *The potential of sustainable algal biofuel production using wastewater resources: Biofuels - II: Algal Biofuels and Microbial Fuel Cells*. Bioresource technology, 2011. **102**(1): p. 17-25.

38. Chiaramonti, D., et al., *Thermochemical Conversion of Microalgae: Challenges and Opportunities*. Energy Procedia, 2015. **75**: p. 819-826.

39. Hemaiswarya, S., et al., *Microalgae: a sustainable feed source for aquaculture*. World journal of microbiology & biotechnology, 2011. **27**(8): p. 1737-1746.

40. Borowitzka, M.A., *Commercial production of microalgae: ponds, tanks, tubes and fermenters*. Journal of biotechnology, 1999. **70**(1): p. 313-321.

41. Alvarez, J.S., et al., *Substitution of fishmeal with soybean meal in practical diets for juvenile white shrimp Litopenaeus schmitti* ( Pérez-Farfante & Kensley 1997 ). Aquaculture research, 2007. **38**(7): p. 689-695.

42. Hardy, R.W. and A.G.J. Tacon, *Fish meal: historical uses, production trends and future outlook for sustainable supplies*. 2002, CABI Publishing: Wallingford, UK. p. 311-325.

43. Koyande, A.K., et al., *Microalgae: A potential alternative to health supplementation for humans*. Food science and human wellness, 2019. **8**(1): p. 16-24.

44. Montero-Lobato, Z., et al., *Chemically-Induced Production of Anti-Inflammatory Molecules in Microalgae*. Marine drugs, 2018. **16**(12): p. 478.

45. Adarme-Vega, T.C., et al., *Microalgal biofactories: a promising approach towards sustainable omega-3 fatty acid production*. Microbial cell factories, 2012. **11**(1): p. 96-96.

46. Narchonai, G., et al., *Deciphering the microalgal diversity and water quality assessment of two urban temple ponds in Pondicherry, India*. Biocatalysis and agricultural biotechnology, 2019. **22**: p. 101427.

47. Chapman, R.L., *Algae: the world's most important "plants"—an introduction*. Mitigation and adaptation strategies for global change, 2013. **18**(1): p. 5-12.

48. Ammar, E.E., et al., *Algae as Bio-fertilizers: Between current situation and future prospective*. Saudi journal of biological sciences, 2022. **29**(5): p. 3083-3096.

49. Suleiman, A.K.A., et al., *From toilet to agriculture: Fertilization with microalgal biomass from wastewater impacts the soil and rhizosphere active microbiomes, greenhouse gas emissions and plant growth*. Resources, conservation and recycling, 2020. **161**: p. 104924.

50. Beckstrom, B.D., et al., *Bioplastic feedstock production from microalgae with fuel co-products: A techno-economic and life cycle impact assessment*. Algal research (Amsterdam), 2020. **46**(C): p. 101769.

51. Zeller, M.A., et al., *Bioplastics and their thermoplastic blends from Spirulina and Chlorella microalgae*. Journal of applied polymer science, 2013. **130**(5): p. 3263-3275.

52. Monshupanee, T., P. Nimdach, and A. Incharoensakdi, *Two-stage (photoautotrophy and heterotrophy) cultivation enables efficient production of bioplastic poly-3-hydroxybutyrate in auto-sedimenting cyanobacterium*. Scientific reports, 2016. **6**(1): p. 37121-37121.

53. Oliver, R. *The future of construction: living-algae buildings*. 2016; Available from: https://www.materialstoday.com/amorphous/comment/the-future-of-construction-livingalgae-buildings

54. Olson, G. *Cleaning up wastewater through algae*. 2015; Available from: https://sustainability-innovation.asu.edu/news/archive/11515-2/.

55. Harris, C. *World-first treatment technology set to tackle nutrient runoff in the Great Barrier Reef and beyond*. 2023; Available from: https://www.awa.asn.au/resources/latest-news/world-first-treatment-technology-set-to-tackle-nutrient-runoff-in-the-great-barrier-reef-and-beyond.



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