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Market and sustainability potential for algal bioplastics in Australia

The University Technology Sydney Institute for Sustainable Futures and The Climate Change Cluster

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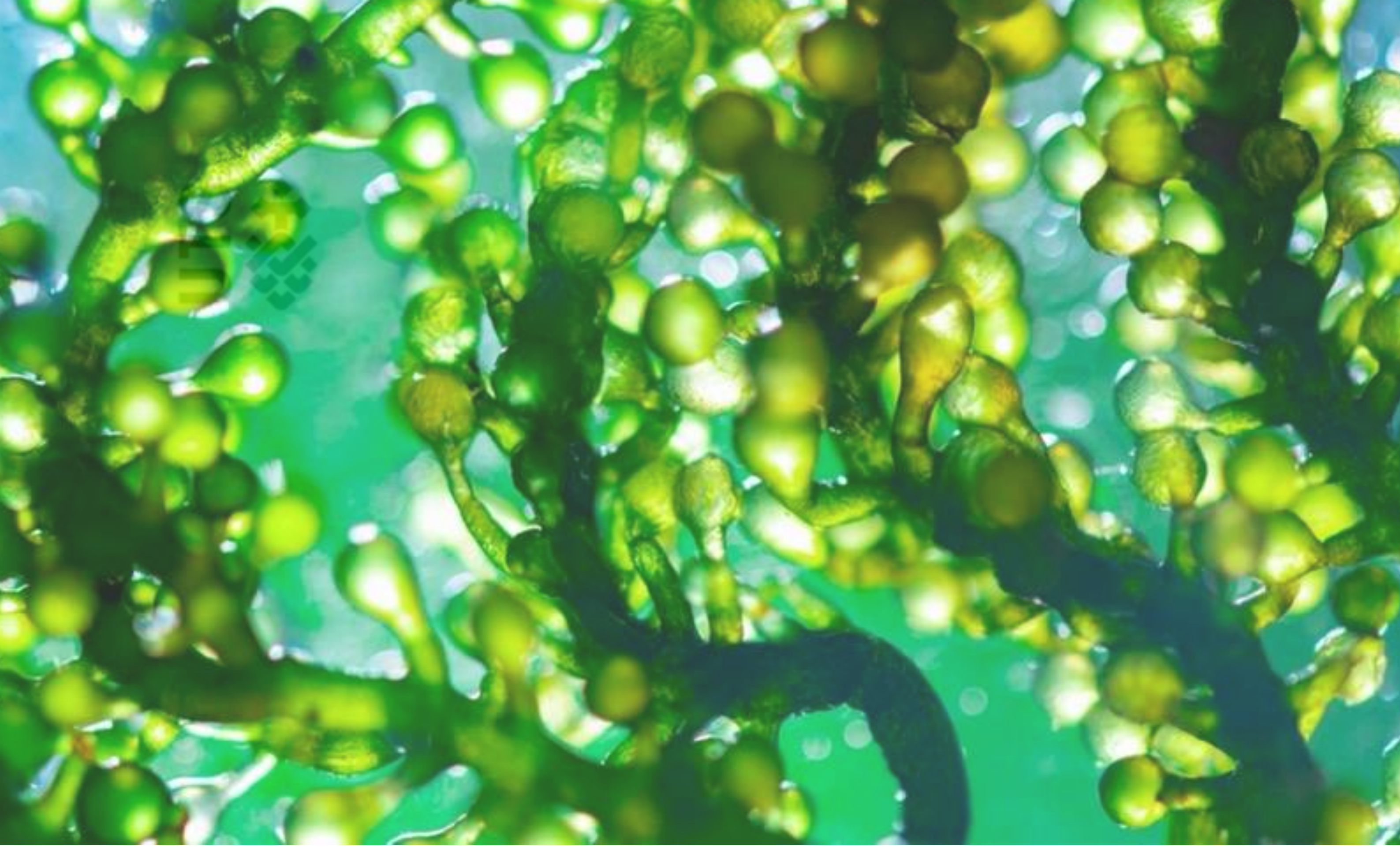

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About the authors

The Institute for Sustainable Futures is an independent research institute within the University of Technology Sydney. We conduct transdisciplinary, project-based research in line with our vision of creating positive change towards sustainable futures.

The Climate Change Cluster (C3) produces new insights into problems facing marine ecosystems by working at the intersection of the physical and life sciences.

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Executive Summary

This paper has been developed by the Institute for Sustainable Futures and the Climate Change Cluster (C3) at the University of Technology Sydney. UTS's Climate Change Cluster (C3) are developing flexible bioplastics from algae which have a range of potential applications, in particular to replace petroleum-based plastics and potentially offer a more sustainable alternative.

This report aims to provide:

- a brief primer on the potential market for algal bioplastics
- identification of key hotspots for sustainability considerations in product design
- a discussion of the current policy context and how this will influence bioplastic development, and
- recommendations for product developers.

This paper has been written for investors, government, researchers and the general public, to provide information on the sustainability opportunities and constraints of algal bioplastics in a circular economy.

Algal bioplastics at UTS

C3 is isolating polysaccharides from both micro and macroalgae to create polymer blends. While microalgae are small and invisible to the naked eye, they grow faster and can be commercially cultivated in ponds or tanks. Macroalgae or seaweed can be harvested from wild or farmed crops. C3 have developed green chemistry methods for extraction, thus minimising the use of hazardous chemicals and producing minimal chemical waste. It is expected that extracted polysaccharides will be mixed with biodegradable polymers in the presence of green additives to generate biodegradable polymers.

Market for algal bioplastics

The bioplastics sector is small, and algal bioplastics are part of the latest third generation of bio-feedstocks under development which can be used to make both rigid and flexible bioplastics. There is high demand for biodegradable flexible packaging and this is a key driver of bioplastics industry growth. In addition to packaging, bioplastics are used in catering products, consumer electronics, the automotive sector, agricultural applications, toys and textiles. They are more expensive than petroleum-based plastics due to higher feedstock costs.

The current challenges to producing algal bioplastics at scale include technical issues such as identifying the most suitable algae to produce polymers and designing those polymers with the required characteristics of resilience, biodegradability and so on. In addition, the production technology for bioplastics is not yet market ready. Cost is also a challenge, particularly alongside the availability of inexpensive petrochemical plastics and there are many trade-offs to consider in large scale cultivation of algae with regard to cost, productivity and contamination risk. There is only a small seaweed cultivation industry in Australia, and this is not currently used for the production of bioplastics.

Sustainability hotspots

This report reviewed the available literature regarding the life cycle of algal bioplastics in order to identify key sustainability hotspots to be considered in product development. The life cycle begins with the cultivation and harvesting of the crop, and includes four key phases: pre-production and product design, production, retail and use and finally, the product end-of-life. The sustainability issues considered follow a life cycle sustainability framework including four key dimensions: resource use, climate change, human health impacts and ecosystem quality.

The key sustainability hotspots to consider in the pre-production phase are aquatic ecosystems in which seaweed is harvested and grown; the potential for uptake of toxic water pollutants depending on where they are grown; the impacts of land use and harvesting in nearshore areas and potential competing uses for arable land and for fisheries. Also, in the pre-production phase is product design which is a critical hotspot to plan for life cycle sustainability and end of life. Sustainability hotspots in the production phase relate to the energy and water consumption which may be high, depending on the process used.

In the retail and use phase, hotspots include adequate labelling and appropriate use, for example to ensure algal bioplastics are correctly disposed of and separated and to ensure they are used in settings where appropriate collection systems are available. End of life is a critical sustainability hotspot in terms of whether the algal bioplastic can be completely composted or recycled or is disposed of in landfill or incinerated. Critical to this is whether there are collection and sorting systems that enable composting or recycling, as the collection system alone may pre-determine the fate of the bioplastic. Consumer awareness also plays a key role in the end of life pathways for algal bioplastic.

Policy context

At both the National and State or Territory level, significant policies have been implemented to phase out Single Use Plastics (SUPs). Key goals of the National Plastics Plan are to reduce plastic waste and plastics going into the environment and to find alternatives for plastic products where possible. The plan also seeks to phase out products that are called 'degradable' but are not compostable. The National Packaging Targets set ambitious goals to increase the volume of packaging that is reusable, recyclable, or compostable, to increase recycled content and phase out problematic packaging. There are also goals to provide consistency in types of compostable packaging with the APCO National Compostable Packaging strategy. Each state and territory has now implemented Single Use Plastic bans, typically including thin plastic bags as well as plastic cutlery, stirrers and straws. In many states, bans implemented since 2018 also apply to bio-based, biodegradable and compostable items. This reflects the difficulty in appropriately managing the end of life for these items, and demonstrates policy barriers for the commercialisation of many algal bioplastic products. In conclusion, bioplastics have limited potential to replace single use plastics in the current policy context. There may be change in the future depending on the availability of appropriate collection and processing infrastructure. For example, if certified compostable bioplastics can be collected and composted safely and reliably, or where kerbside recycling of soft plastics becomes available.

Conclusions

Where the end-of-life impacts of bioplastics can be similar to conventional plastics, they are regarded as similarly damaging for the environment by governments, and consequently they have been included in plastic bans. Ensuring bioplastic products have an end-of-life pathway that contributes to a circular economy (either through mechanical recycling or composting) will be important for enabling their widespread application and acceptance. In addition, greater uniformity and labelling of bioplastics, greater uptake of standards for compostability of bioplastics and their characteristics will facilitate their adoption and acceptance within regulatory frameworks. As such, it may be incumbent on industry to demonstrate the sustainability and safe end-of-life for algal bioplastics so that they may be exempted from bans in the future.

Considering the key sustainability hotspots in product design will contribute to developing a more sustainable product that could be widely adopted.

The waste sector is currently facing significant challenges with regard to managing recyclables and has limited capacity to invest in new infrastructure. In order for bioplastics to be accepted in the waste system and by regulators, they may need to be readily recyclable, that is made of PET, HDPE or PP or be certified compostable with an appropriate technology to manage them. Finally, consumer awareness and understanding of the diversity of plastic types and end-of-life collection needs is limited, consequently it will be beneficial to have standardised labelling and information and education for consumers as well as greater simplicity in the characteristics of bioplastics and their waste system requirements.

Recommendations

Product Developers

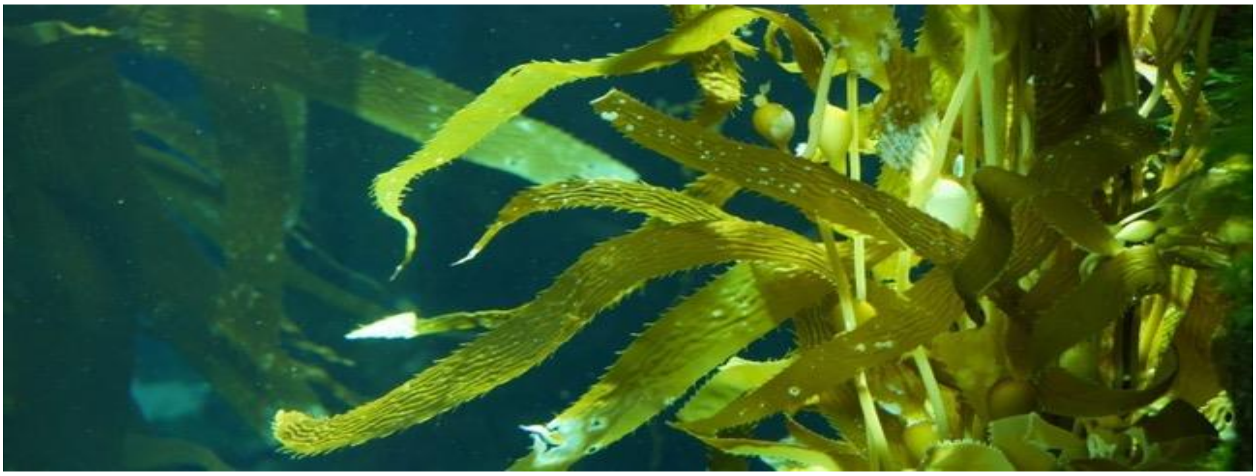
- By addressing the sustainability hotspots in this report, product developers and designers can ensure the sustainability of algal bioplastics
- New products should seek certification for Australian home and industrial composting (and international certifications for marine, land and soil degradability) prior to commercialisation or being sold to market
- Algal bioplastic products should be labelled and marketed correctly to avoid confusion with the consumer (using the term compostable rather than biodegradable or bioplastic)
- Niche applications in which the use and disposal of the products are contained can be an area of focus (e.g. food courts, hospitals, precinct developments, government procurement schemes) and their disposal in relevant composting facilities (e.g. industrial composting)

Research Community

- Research should be carried out to identify how waste management systems can overcome barriers to receiving and processing bioplastics and compostable plastics
- Life cycle assessments and peer-reviewed methodologies of bio-based plastics should be supported to clearly demonstrate the impacts from the overall life cycle. This could help to demonstrate safe end of life outcomes to improve suitability as an alternative to single use plastics.

Government

- Governments could clarify potential future requirements (such as standards) for bioplastics, so that innovators can work towards those requirements (e.g. certified home compostability)
- Regulate consistent labelling requirements for bioplastics, such as verification of compostable products and use of the Australasian Recycling Label (ARL) to enable their integration into waste systems
- Improved consumer education around the use and disposal of bioplastics, in collaboration with improved labelling by industry, would help to facilitate correct separation and disposal



Contents

1. Innovating plastic packaging

1.1 Objectives of this report

In response to the significant environmental impacts caused by single use plastics, innovative bioplastics have been developed with the aim of providing a more sustainable alternative. Bioplastics have been synthesised from a variety of biological sources such as corn, sugar and organic farm residues. In this report we consider the sustainability potential of bioplastics more broadly as well as the algal-derived bioplastics being developed by UTS's Climate Change Cluster.

The key objectives of this report are to:

- Provide a brief primer on the challenges for single use plastics and the potential market for algal bioplastics
- Assess sustainability across the lifecycle of bioplastics to identify key hotspots for sustainability considerations during product design
- Discuss the current policy context and how this will influence bioplastics development
- Provide recommendations for bioplastics developers

In Section 1 we briefly highlight the key issues with regards to current plastics usage and provide an overview of bioplastics development in general. In Section 2 we provide further detail about bioplastics from algae, and in Section 3 set out an overview of the bioplastics market. In Section 4 we take a deeper dive into the sustainability of bioplastics with reference to algal bioplastics. Here we explain our sustainability framework and consider each phase of the product life cycle in turn. This leads to the synthesis in Section 5 which highlights the key sustainability considerations in the design of new bioplastic products. Following this we have explained the Australian policy context in Section 6 with regards to single use plastics and bioplastics and discuss how this affects their development. In Section 7 we provide some conclusions and recommendations for bioplastics producers.

1.2 Plastics pose challenges throughout the life cycle

Plastic packaging use is growing

The convenience of plastic packaging has allowed for a range of products to be provided to customers hygienically and conveniently at a relatively low cost. Our use of plastic is increasing and globally plastic use is predicted to double by 2040 (DAWE, 2021).

Disposable, long-lived plastics are increasing in landfill and the environment

In 2018-19 Australia used 3.4 million tonnes of plastic, of which 1 million tonnes were plastic packaging (APCO, 2021). Around 84% of all plastic is sent to landfill and approximately 130,000 tonnes leaks into the Australian environment annually, much of this ingested by marine life and seabirds (DAWE, 2021).

Plastic packaging is mostly made from unsustainable fossil fuels

Plastic manufacturing processes use non-renewable resources, such as oil, and release greenhouse gases into the atmosphere contributing to climate change (UNEP, 2014). Most plastic packaging is made from HDPE, LDPE, PP and PET with 0.6% made from bioplastics (APCO, 2021).

A third of plastic packaging is soft plastics, mostly going to landfill

Soft plastics (plastic you can scrunch into a ball such as food wrappers) represent about a third of plastic packaging placed on the market in Australia – around 70 billion pieces per year made up of a large amount of LDPE (DAWE, 2021). The food and beverage sector is the largest single user for soft plastics including bubble wrap, pallet wrap, films and food packaging and other uses include retail carry bags and distribution packaging.

A small amount of soft plastics are being recovered, mostly by commercial and industrial operators

In 2017-18, about 27 000 tonnes of soft plastics were recovered (approximately 6%), predominantly from commercial and industrial (C&I) sources, and this was mainly LDPE or LLDPE (Retamal et al, 2019). Post-consumer soft plastics have poor recovery rates, with only 1% being captured at supermarket drop-off facilities and a small number of kerbside collection trials (Retamal et al, 2019). Considering that 87% of plastic packaging is used for business to consumer, and 13% from business to business, there is significant gap in recycling post-consumer soft plastics. Currently, there is also a very limited end market for recycled soft plastics in Australia.

Strong policy responses are limiting use of single use plastics

Many state, territory, and local governments have already banned certain problematic and unnecessary single-use plastics and plastic packaging. The summary of single use plastics bans and bioplastic relevant policy is provided in Section 6. Many businesses are also taking proactive steps to phase out problematic plastic packaging (DAWE, 2021). Examples can be found in Section 3.

Some system and product-level changes are underway

To address the problem of plastic packaging accumulating in landfills and the environment, local governments and recyclers are investigating and investing in better sorting technology to separate more types of plastics, and enable more recycling. With some types of plastics being banned and phased out, packaging companies are also developing substitutes for plastic. Bioplastics are becoming a popular alternative to conventional plastics. This paper provides more information and analysis of the advantages and disadvantages of bioplastics in Section 2.

1.3 Types of bioplastics

Bioplastics have a wide variety of feedstocks

Feedstocks for bioplastics can be defined as first, second or third generation as follows:

- 1st Generation feedstock: carbohydrate-rich plants such as corn or sugar cane that can also be used as food or animal feed currently, the most efficient feedstock as it requires the least amount of land to grow and produce the highest yields

- 2nd Generation feedstock: feedstock not suitable for food or feed. It can be either non-food crops (e.g. cellulose) or waste materials from 1st generation feedstock (e.g. waste vegetable oil)
- 3rd Generation feedstock: biomass from algae (which have a higher growth yield than 1st and 2nd generation feedstock) and from waste streams such as CO_2 or methane (Bioplastics Magazine, 2021).

Bioplastics vary significantly in terms of origin and end-of-life

Bioplastic is often used as a broad term for plastics that are made from biologically derived feedstocks called 'bio-based', biodegradable or both (APCO, 2021). Bioplastics typically fall into one of three groups:

- Bio-based and biodegradable
- Bio-based (but not biodegradable)
- Biodegradable (but not bio-based).

Conventional polymers (e.g. PET and HDPE) can also be fully or partially bio-based (APCO, 2021).

Bio-based plastics are those with building blocks that are derived partly or wholly from plant-based feedstocks (APCO, 2020). The term ***biodegradable*** is a generic term that can refer to the ability of the material to decompose or break down but does not specify how decomposition happens - the length of time it takes or the environment in which it is decomposing. APCO have advised that biodegradable is "best avoided as a term for plastic materials as it infers a general behaviour of the material and could mislead users to think that something will automatically biodegrade in a reasonable timeframe whereas in practice it may only be under specific controlled conditions" (APCO, 2020, p5).

The following table from ABA (2021) highlights the differences between conventional plastics and the three types of bioplastics. While some are recyclable, others are compostable and can contaminate recycling systems, therefore understanding life cycle impacts are important to overall sustainability.

Table 1 – Characteristics of different plastics and bioplastics (Source: ABA, 2021)

Plastic type	Building Block	Example	Cost	Recyclable	Biodegradable
Conventional plastics	Fossil Fuels	PE, PET, HDPE, PP	Low	Yes	No
Bio-based but not biodegradable	Biomass	Bio-based polyethylene (PE), polyethylene terephthalate (PET), bio-based technical performance polymers, such as polyamides (PA), or (partly) bio-based polyurethanes (PUR)	Higher	Yes	No
Bio-based and biodegradable	Biomass	Polylactic acid (PLA), polyhydroxyalkanaoates (PHA), polybutylene succinate (PBS), and starch blends;	Higher	No, and can contaminate recycling stream	Yes – some can be composted at home, others only through industrial composting facilities
Fossil-based and biodegradable	Biomass	PBAT and PCL	Higher	If added in high percentage could contaminate recycling stream	Yes - Home or Industrial Composting

In this report, when we refer to bioplastics, it includes those plastics that are bio-based (whether biodegradable or not).

2. Bioplastics from Algae

Bioplastics can be produced from seaweed or algae

Algae are the earliest ancestors of all plants, first appearing around 2.5 billion years ago. Algae can be micro or macro. Macroalgae are complex and made of many cells and consist of species such as red seaweed and kelp (which can reach lengths of nearly 60m). Microalgae are tiny cells, invisible to the naked eye and smaller than the diameter of a human hair (Climate Change Cluster, 2022).

Macroalgae (or seaweeds) are classified into three major groups: brown algae (Phaeophyceae) often called kelp, green algae (Chlorophyta), and red algae (Rhodophyta) (Dang et al, 2022). Seaweeds are important sources of polysaccharides from marine environments, and form the building blocks for bioplastics. Red seaweeds are generally rich in agar, brown seaweeds in alginate and some green seaweeds in ulvan (Zerrouki and Henni, 2019) which can be extracted. These polysaccharides extracts can be used to create bioplastics with a wide range of properties (European Commission, 2016).

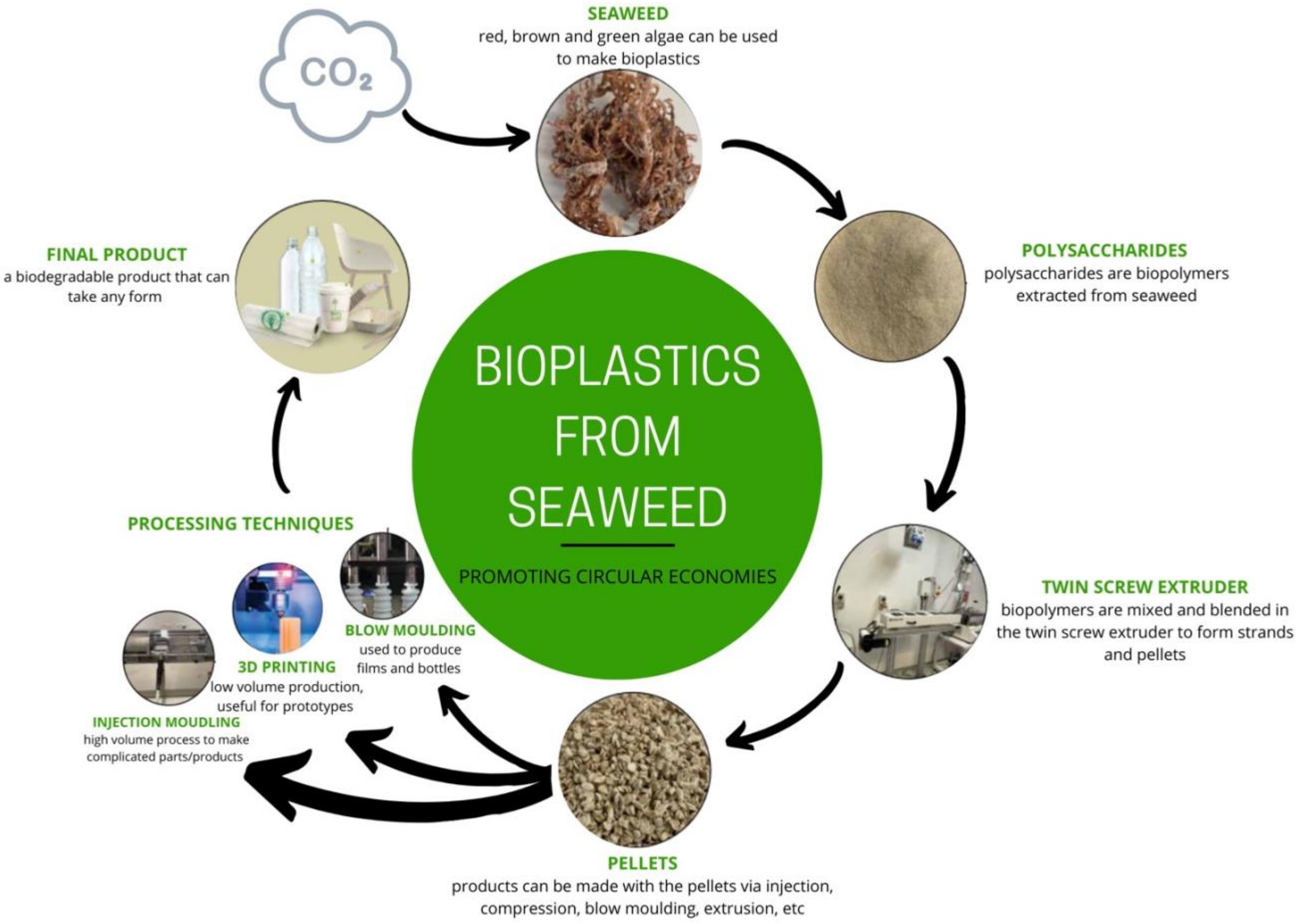


Figure 1 – Bioplastics from Seaweed process (Source: C3, 2022)

Microalgae species usually grow faster than freshwater/marine macroalgae species (Dang et al, 2022). Microalgae systems can use saline and/or wastewater and enable effective recycling of nutrients (e.g., nitrogen and phosphorous) in contained systems (Karan et al, 2019). Their low lignin content make them a good choice for biomass conversion technology for creating bioplastics (John et al., 2011).

Algae-based industries are emerging and there is a growing interest in bioplastic production. Algae biomass possesses specific characteristics (e.g. a low percentage of lignin, long-chain hydrocarbons, economical extraction of pure cellulose) making it an ideal feedstock for bioplastics (Zanchetta et al., 2021).

C3 Algal Bioplastic Prototypes

C3’s work in Algal Bioplastics

The UTS Climate Change Cluster (C3) produces new insights into problems facing marine ecosystems by working at the intersection of the physical and life sciences. C3 is working on a range of uses for algae as a new, sustainable raw material substitute for what are now petroleum-based products (UTS, 2022).

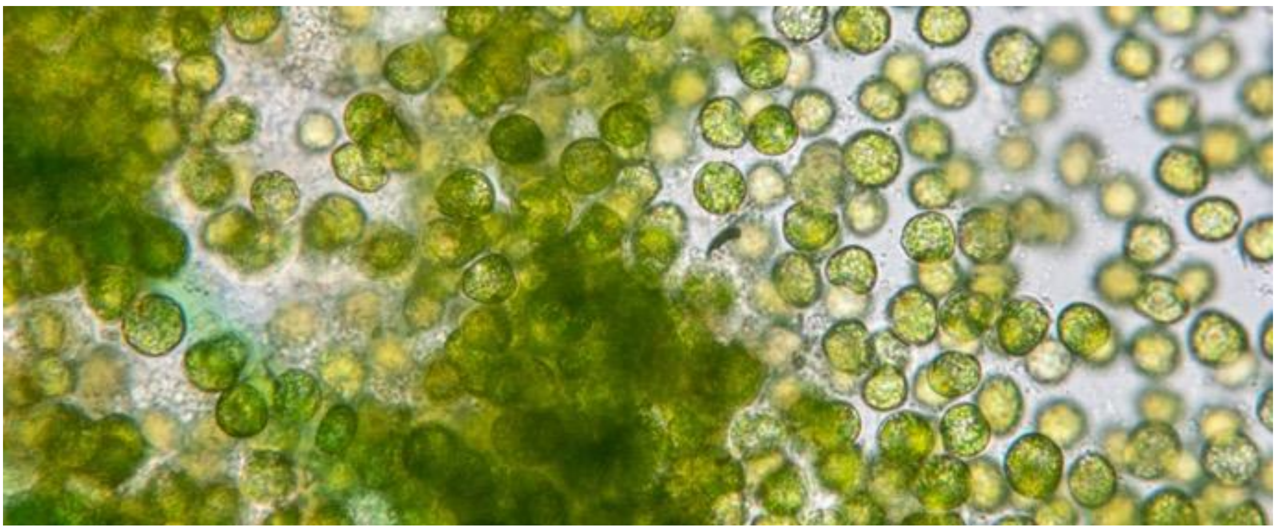
C3 performs bio-prospecting to identify algal strains with potential polysaccharide composition that can be utilised to produce polymer blends. Studies to prepare polymers/blends using ulvan, carrageenan and alginate are in progress. Specifically, C3’s bioplastic projects are based on polysaccharides isolated from selected macroalgae and microalgae. These species are sourced through partner institutes, commercial sources or internally grown.

C3 develop green chemistry methods for extraction techniques, thus minimising the use of hazardous chemicals and producing minimal chemical waste. It is expected that extracted polysaccharide will be mixed with biodegradable polymers in the presence of green additives to generate algae based biodegradable polymers.

Some of the prototypes developed include carrageenan-glycerol, carrageenan- water, ulvan-starch, polyvinyl alcohol-carrageenan-glycerol.

These prototypes possess physio-mechanical properties which can be utilised to produce materials for film type applications such as packaging films and cellophane films. C3 polymer chemists routinely work towards improving the properties of prototypes by adjusting the blend ratios, mixing techniques, additives etc to meet specific industry requirements.

Figure 2 – C3 algal bioplastic prototypes (Source: C3, 2022)



3. Market overview for bioplastics

It is difficult to determine if any algal bioplastics are currently being processed or manufactured in Australia, however, there are prototypes being developed by C3 and other organisations. For example, a company ULUU is developing a natural polymer from seaweed, seawater and saltwater microbes to replace plastics (ULUU, 2022).

Other products are being manufactured from seaweed in Australia, for example Seasol, who make a biofertilizer from Australian Bull Kelp, and Marinova who manufacture fucoidan extract from largely imported seaweeds for the health and nutrition market (Kelly, 2020). Smaller food producers such as Alg Seaweed use imported and some Australian seaweeds (Kelly, 2020).

3.1 Bioplastic Sources

Bioplastics are made mostly from starch feedstocks

Approximately 80% of bio-based plastics being manufactured at the moment use starch as a feedstock (or 1st generation feedstocks) sourced from maize, potatoes and cassava (APCO, 2020). Arrowroot, barley, some varieties of liana, millet, oats, rice, sago, sorghum, sweet potato, taro and wheat could also be used as feedstocks (APCO, 2020).

The bioplastic sector is small but growing

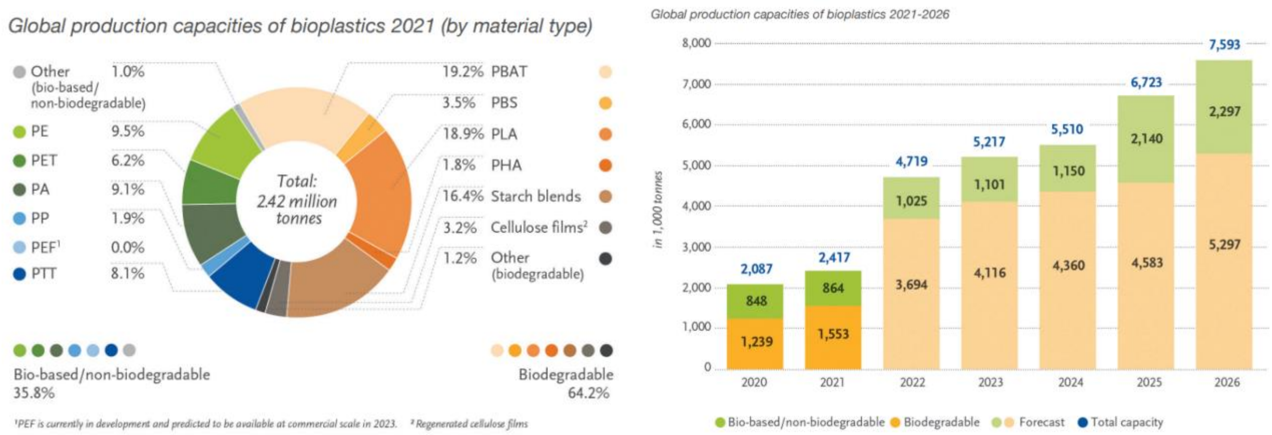


Figure 3 – Production capacities of bioplastics (Source: European Bioplastics, 2021)

European Bioplastics (2021) estimate that of the 367 million tonnes of plastic produced annually, bioplastics currently represent less than one percent. Interestingly, while there is growth in the market for bioplastic, there is a decrease in conventional plastic production (European Bioplastics, 2021).

There is high demand for biodegradable flexible packaging

Bio-based plastics globally are produced largely for rigid packaging, textiles, flexible packaging and automotive and transport sectors. However, biodegradable plastics are produced predominantly for flexible packaging. Increasing demand for environmentally-friendly plastics from the packaging industry is a key driver of growth (Fortune Business Insights, 2022).

In Australia the amount of bioplastics placed on the Australian market in 2018-19 was 6000 tonnes (of the total 1 million tonnes of plastic packaging placed on the market), 5000 tonnes of this was rigid plastic and 1000 flexible (APCO, 2021).

A very small proportion of bioplastics contain recycled content and are recycled in Australia

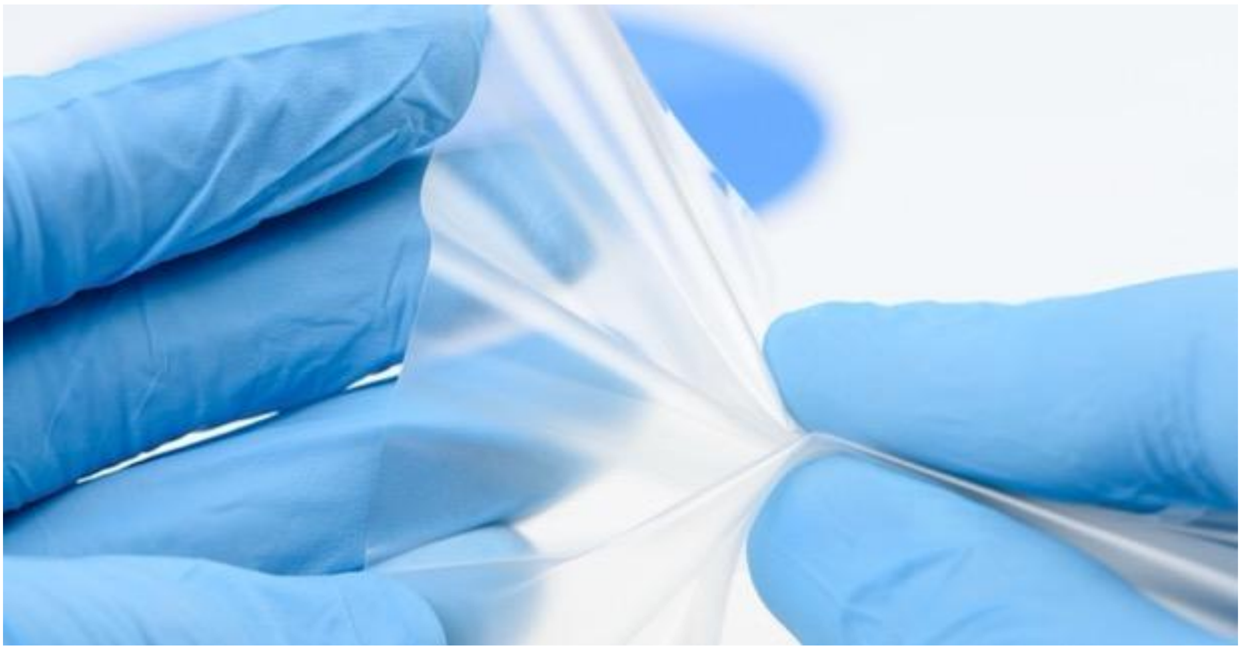
In total approximately 4.8% of bioplastic content was recycled in 2019-20 in Australia (O'Farrell et al, 2021). Of the small quantity of bioplastics placed on the market, 12% are from pre-consumer recycled content and 88% are from a virgin source of bioplastic from biologically derived feedstocks (APCO, 2021). Note that biodegradable plastics cannot be recycled in kerbside systems.

Bioplastics offer a range of product types, but are more expensive

Bioplastic products are created for a range of industries and uses including packaging, catering products, consumer electronics, automotive, agriculture/horticulture, toys and textiles (ABA, 2022b). It is predicted the price of bio-based plastics will continue to be higher than conventional plastics given the higher cost of feedstocks (O'Farrell et al, 2021).

Rigid bioplastics – Manufactured products that are durable including car interiors, mobile phones and bottles are built from bioplastic materials (ABA, 2022b).

Flexible bioplastics - Biofilms are defined as "flexible films prepared from biological materials such as proteins and polysaccharides that act as barriers to outside elements" (Seixas et al, 2013, p1). These materials have potential application in medical, pharmaceutical and food sectors (Chandra and Rustgi, 1998). Often the most common application of bioplastic materials is for products with a short life such as packaging for food, insulation or hygiene products (ABA, 2022). Bioplastic materials, such as PLA, also have properties to extend the life of food products by keeping them fresh (Van den Oever et al, 2017).



3.2 Algal Bioplastic Markets

Algal bioplastics face challenges with being produced on a large scale

For packaging, production of algal bioplastics to meet the market demands in terms of material properties, production costs, and required quantities is not yet possible at the scale required to replace conventional plastics (Schmidtchen et al, 2022).

The current challenges with large scale commercialization and production of algal bioplastics production include:

- **Algae biomass composition** – to create various properties required for different bioplastic polymers, the most suitable algae needs to be identified (Chia et al, 2020)

- **Polymer selection** - during design, the resilience, biodegradability, feedstock renewability, degradation rate, brittleness, polymer size, molecular weight and moisture content must all be considered for the appropriate polymer and its application (Chia et al, 2020)
- **Consumer awareness and acceptability** – often consumers are unfamiliar with the term "bioplastics", are unsure about their use and can often assume bioplastics are more expensive as they are from bio-based sources (Chia et al, 2020)
- **Production technology** - unlike other bio-based industries, the technology development for bioplastics is not yet market ready
- **Cost –** as there is an abundance of fossil-based materials, conventional plastics can be produced at a lower cost (Schmidtchen et al, 2022)
- **Varying cultivation requirements –** to produce algal bioplastics often requires large-scale algae cultivation systems with varying methods and costs, maintenance requirements, scaling ability, productivity and risk of contamination (Chia et al, 2020)

The seaweed/algae industry is relatively new in Australia, especially as feedstock for bioplastics

Worldwide, algae (primarily seaweeds) make up approximately 30 percent of aquaculture production (Cai et al, 2021). Compared to Asia, Europe and the U.S., Australia currently has a lower commercial seaweed production with nascent industry development. This is despite "being historically used extensively as wild catch by Indigenous Australians" (Kelly, 2020, pp. vii).

Most algae products in Australia are imported, not grown locally, and not used to make algal bioplastics

Australian production of seaweed is a small industry and the majority is produced by Kelp Industries Pty Ltd on King Island in Tasmania, who collect storm-cast Bull Kelp (Durvillea pototorum) which is mostly exported for manufacturing alginate and biofertiliser products (Kelly, 2020). Australia is a net importer of seaweed and our consumers pay a premium for tonnes of fresh and frozen seaweed for both human and non-human consumption (Kelly, 2020).

Australia's commercial seaweed operations are limited to two small land-based operations for Ulva spp. cultivation in Shoalhaven, NSW (Venus Shell Systems) and Ayr, QLD (Pacific Biotechnology) with less than five hectares of seaweed under production (Kelly, 2020) and no commercial ocean seaweed farms.

Kelly (2020) found from stakeholder interviews a significant increase in parties interested in obtaining aquaculture licenses for seaweed ocean farms in most Australian states. This is assumed to be driven by interest in adding seaweed to cattle feed to reduce methane production and experimentation of 'seaweed permaculture'.

Microalgae is a small but growing sector, with opportunities similar to macroalgae

Compared to macroalgae species, microalgae species grow faster and are therefore targeted for starch production (Dang et al, 2022). However, microalgae cultivation is lower than macroalgae (seaweeds) contributing less than 0.2 percent of global algae cultivation tonnage in 2019 according to FAO statistics (Cai et al, 2021).

4. Life cycle sustainability considerations

To assess the sustainability of a product, it is important to consider its whole life cycle. The life cycle of bioplastic begins with crop cultivation and harvesting and ends with an end-of-life option (Wellenreuther and Wolf, 2020).

Life cycle thinking and assessment are established approaches to understanding environmental sustainability of products, and these methods typically involve the analysis of a variety of “impact categories”, such as: climate change, resource depletion, land use, water use, human toxic effects, ozone depletion, photochemical ozone creation, ecotoxicity, eutrophication, acidification and biodiversity (Jolliet et al., 2003a; UNEP SETAC, 2011). These impact categories also align with the planetary boundaries framework which sets out nine critical earth systems which determine the safe operating space for humanity (Rockström et al, 2009). These impact categories reflect four key areas of potential environmental damage including: human health, ecosystem quality, climate change and resources (Jolliet et al., 2003a; UNEP SETAC, 2011).

The European Commission’s framework for assessing consumption impacts includes these impact indicators and considers them over the life cycle of a product including: design, resource extraction, farming, processing, manufacturing, transportation, retail, use, disposal, recycling and energy recovery (European Union, 2022). We have clustered the life cycle into four main phases: pre-production, production, use and end of life. To consider environmental sustainability over the lifecycle, we have drawn together these four key phases along with the four major areas of environmental damage to create a framework for analysis in Figure 4. We use the life cycle phases and key environmental dimensions to structure our qualitative analysis of life cycle sustainability, based on the existing literature.

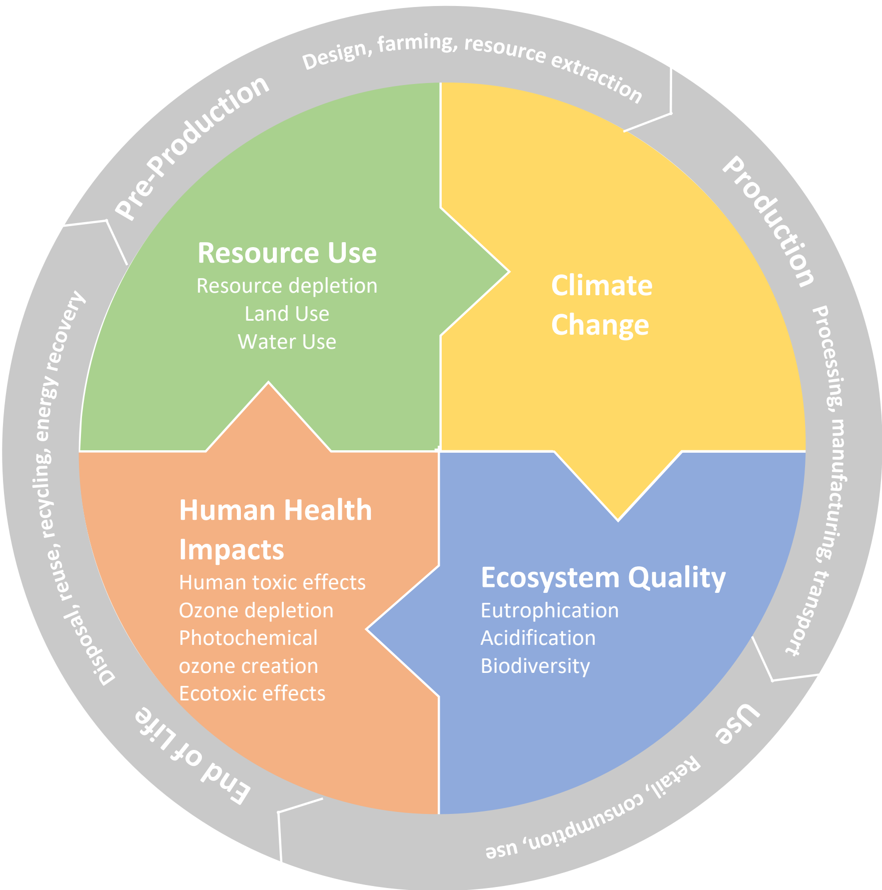


Figure 4 – Life cycle sustainability framework (adapted from Jolliet et al., 2003a; UNEP SETAC, 2011; European Union, 2022)

This framework focuses on environmental sustainability, as in this study we are focusing on the potential for algal bioplastics which are still in the product development phase. No supply chain has been established, so it is difficult to consider the social dimensions at this stage. Raworth (2017) provides a valuable extension of the planetary boundaries framework, by including the 'social foundation' in addition to the 'ecological ceiling', which includes: health, education, income and work, peace and justice, political voice, social equity, gender equality, housing, networks, energy, water and food. These social sustainability dimensions can be further considered in the future.

4.1 Pre-Production

The pre-production stage involves product design, farming the algae (resource extraction) and processing of algae. This differs for micro vs macroalgae and for the type of bioplastic being produced. Macroalgae are harvested either from wild or farmed crops. Seaweed commercial production occurs globally in approximately 35 countries in cold to tropical waters and harvesting occurs by hand or mechanically by boat (McHugh, 2003).

Microalgae can be grown in photobioreactors (tanks or closed systems), open pond systems (shallow ponds) where nutrients come from runoff water or from sewage/water treatment plants (Carlsson et al, 2007). To harvest micro-algae, conventional processes include concentration through centrifugation, foam fractionation, flocculation, membrane filtration and ultrasonic separation. The micro-algae are small and require large volumes of water. The harvesting method is dependent upon species, cell density and often culture conditions (Carlsson et al, 2007).

There are trade-offs with different microalgae cultivation systems, where lower cost open pond systems are more prone to contamination risk and are lower productivity, while higher cost closed pond systems are at lower risk of contamination and achieve higher productivity but also face higher scale up costs (Chia et al, 2020).

Sustainability challenges

Collection of seaweeds in Australia is limited by the availability of beach-cast seaweed, its quality and seasonality, as well as community concerns and permits (Kelly, 2020). While some see extensive coastal areas and open ocean as an unexploited and under-utilised feedstock (Zerrouki and Henni, 2019; Lawton et al, 2013), others think the wild ocean harvest of seaweed can have harmful environmental impacts and not enough research is available on regrowth potential (Kelly, 2020). For example, seaweed plays a pivotal role in the aquatic food chain, producing up to 50% of Earth's oxygen (NOAA, 2022). It is unknown how the large-scale cultivation and harvesting of seaweeds will affect aquatic ecosystems. A study by Ögmundarson et al (2019) looking at the life cycle impacts of macroalgae as a PLA feedstock found environmental impacts are highly influenced by the way feedstock is "mowed" (harvested) with regard to impacts related to terrestrial acidification and marine eutrophication.

The land for growing the current level of bio-based plastics globally is about 0.02% of agricultural area (European Bioplastics, 2022). To replace the current fossil-plastics production with land-based biomass feedstock, 5% of the total amount of biomass produced and harvested each year would be required for plastics production (Van den Oever et al, 2017). This raises an issue for land-based bioplastic feedstocks, as this land use would compete with agricultural demands for food and fibre. However, algae production could involve the use of ocean area instead or a combination of the ocean for macroalgae and land-based production in ponds.

To produce 500 million tons dry weight of macroalgae in the ocean would require 0.03% of the earth's ocean area but would require expansion of worldwide large-scale cultivation of current coastal areas close to the shore (Schmidtchen et al, 2022). This suggests limitations in ocean area that can be used due to the logistical practicality of global scale nearshore production and the many competing uses of nearshore areas, including for fisheries.

Microalgae biomass production has some challenges. For example microalgae biomass grown on digestate and flue gas can have high nutrient loadings, possible toxic compounds and could affect productivity and stability of algae growth (Wageningen University, 2022). This has production implications and may also affect algal quality and potential contamination. Some seaweeds have the capacity to absorb from polluted water heavy metal ions like zinc and cadmium (McHugh, 2003).

Sustainability benefits

Macroalgae is a renewable resource, with a very high growth rate and yield compared to other crops (Konda et al., 2015). Other sustainability benefits of macroalgae is that it does not compete for arable land, or require fertilisers or pesticides (Dang et al, 2022). Macroalgae can grow in fresh or salt water and under polluted conditions, and can even improve water quality by taking up excess nitrogen and CO_2 (Schmidtchen et al, 2022). This can improve water quality in marine coastal areas, where runoff from aquaculture or agriculture has increased nutrient levels.

When fossil-based plastics are replaced by bio-based plastics, this typically leads to less use of non-renewable energy and consequent greenhouse gas emissions (Van den Oever et al, 2017). GHG emission reduction can be considered through a simple analysis or include factors such as direct and/or indirect land-use change and comparison to emissions from what may be produced by similar feedstocks such as biofuels (Van den Oever et al, 2017). In the case of algal bioplastics, the impacts from land-use change are significantly lower due to the use of ocean area for cultivation. Microalgae can fix carbon dioxide from different sources including atmospheric CO_2, CO_2 from industrial exhaust gases such as flue or flaring gas and soluble fixed CO_2 (carbonates) (Wang, 2008). Algae also enables CO_2 uptake from the ocean which is a GHG benefit (Gao and Beardall, 2022).

The majority of LCA studies conclude that bioplastics based on first-generation bio-plastics feedstocks (from starch crops such as corn and sugarcane) are not always more environmentally friendly than fossil alternatives, especially due to intensive agriculture, use of pesticides, fertilizers, land and water and competition with food production. Wellenreuther and Wolf (2020) highlight the potential for higher food prices resulting from an increase in demand for corn and sugar from bioplastics production. Considering this, algal-based bioplastics offer significant advantages due to the fact that pesticides, fertilisers and freshwater resources are not being used.

4.2 Production

To prepare raw bioplastic material from macroalgae, there are a number of production processes including drying, chemical treatment, extraction and purification. Each step in the production process requires increasing resources including labour, chemicals, energy and water (Schmidtchen et al, 2022). Very few life cycle assessments have been conducted for algal bioplastics, so the impacts of production are still being determined as their processing is being refined.

Sustainability challenges

Water-soluble polysaccharides from macroalgae (or seaweed) are extracted during several hours under conventional heating using hot water (European Commission, 2016), which is energy intensive. The conventional process of solution casting polymers is both water and energy intensive, where 6-18 kg of water must be evaporated from each 1kg of plastic. However, a process involving semi-dry extrusion uses much less water and energy than solution casting and can be used as an alternative (Schmidtchen et al., 2022). Scientists at C3 have developed a green process for the extraction of sulphated polysaccharides from algal biomass. The new extraction method is less energy intensive and does not use traditional, toxic chemicals and has resulted in high yield and purity.

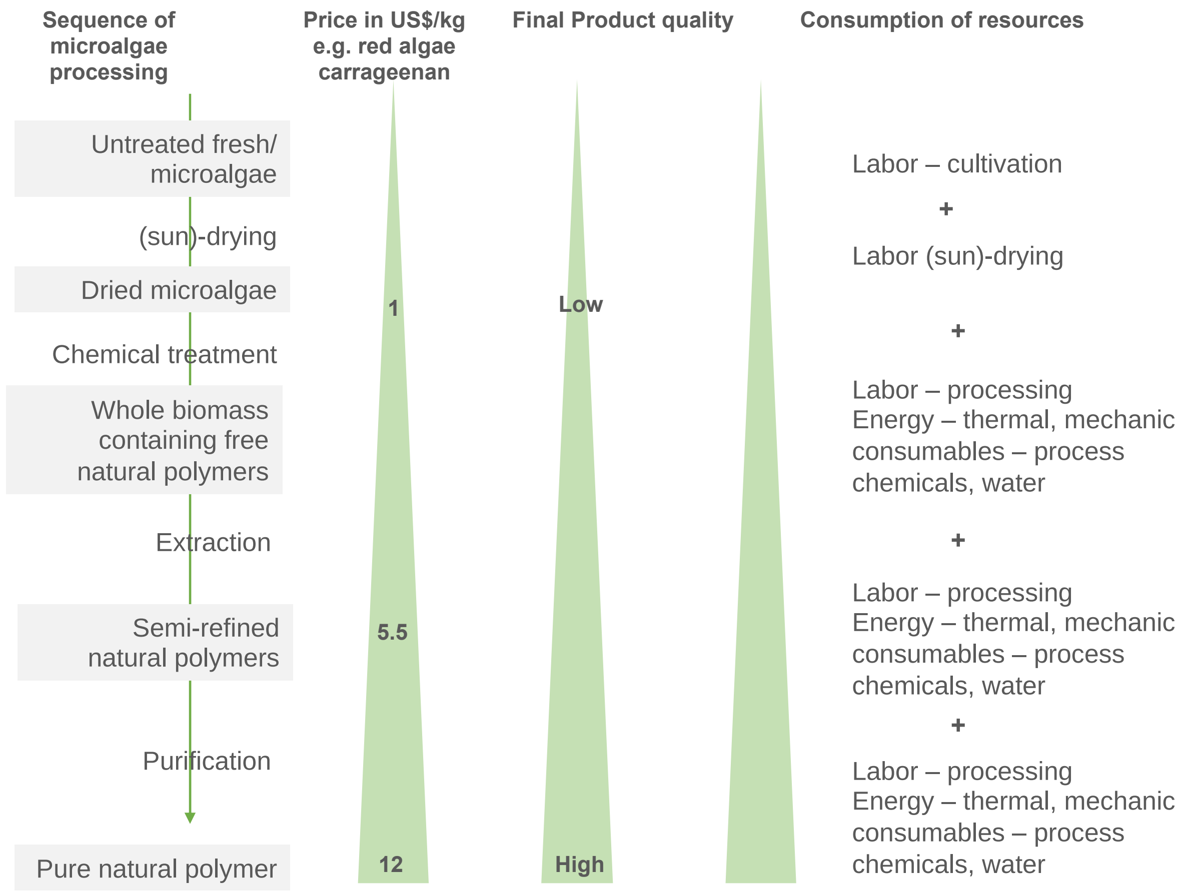


Figure 5 – Macroalgae processing, price, product quality and consumption of resources (Source: Schmidtchen et al, 2022)

Similar to other plastic manufacturing processes, algal bioplastics may also use fossil fuel derived energy during manufacture, which release greenhouse gases into the atmosphere (UNEP, 2014). As the technology used to process macroalgae is in its infancy, the refinery stages require high inputs of energy and the optimal treatment methods for specific processes are still uncertain (Wellenreuther and Wolf, 2020).

A study by Ögmundarson et al (2019) looking at Environmental Life Cycle Assessments for macroalgae (brown algae) as a PLA feedstock compared to corn stover found that biomass production and refinery stages of the lifecycle have higher impacts (particularly in relation to the energy required to dry the biomass), compared to polymerization and end of life stages. Similarly transporting wet macroalgae has higher transportation impacts with respect to energy and pollution. The impacts were lower for marine eutrophication, freshwater ecotoxicity, marine ecotoxicity, and human non-carcinogenic toxicity, because of the difference in the composition of the energy mix used in the LCA model (Ögmundarson et al, 2019). Enabling fermentation of alginate (without the need to dry the feedstock) was identified as drastically reducing environmental impacts (Ögmundarson et al, 2019). However, uncertainty was reported to be a function of technological maturity as macroalgae as feedstock in biorefineries is not yet a common practice (Ögmundarson et al, 2019).

Improvements to technology in the future present opportunity for emissions reductions, but current studies still lack evidence to what degree this will be (Wellenreuther and Wolf, 2020). In terms of energy, it is important to consider transport requirements from extraction/farming to processing, to manufacturing and then end markets.

4.3 Retail and use

Sustainability challenges

Currently bio-based plastics are primarily being used to replace single-use plastics, so the use phase is short-lived and mimics existing disposable practices. This can be problematic if bio-based plastics have similar disposal and end of life challenges as fossil-based plastics. Maximising the use phase of the product would be ideal, for example, enabling reuse and also ensuring environmentally safe disposal. The waste hierarchy in Figure 6 has been adapted for bioplastics by Total Corbion PLA (a bioplastics manufacturer) and illustrates that the highest priorities are prevention and reduction of plastic use followed by reuse and design for long-life and increased utilisation.

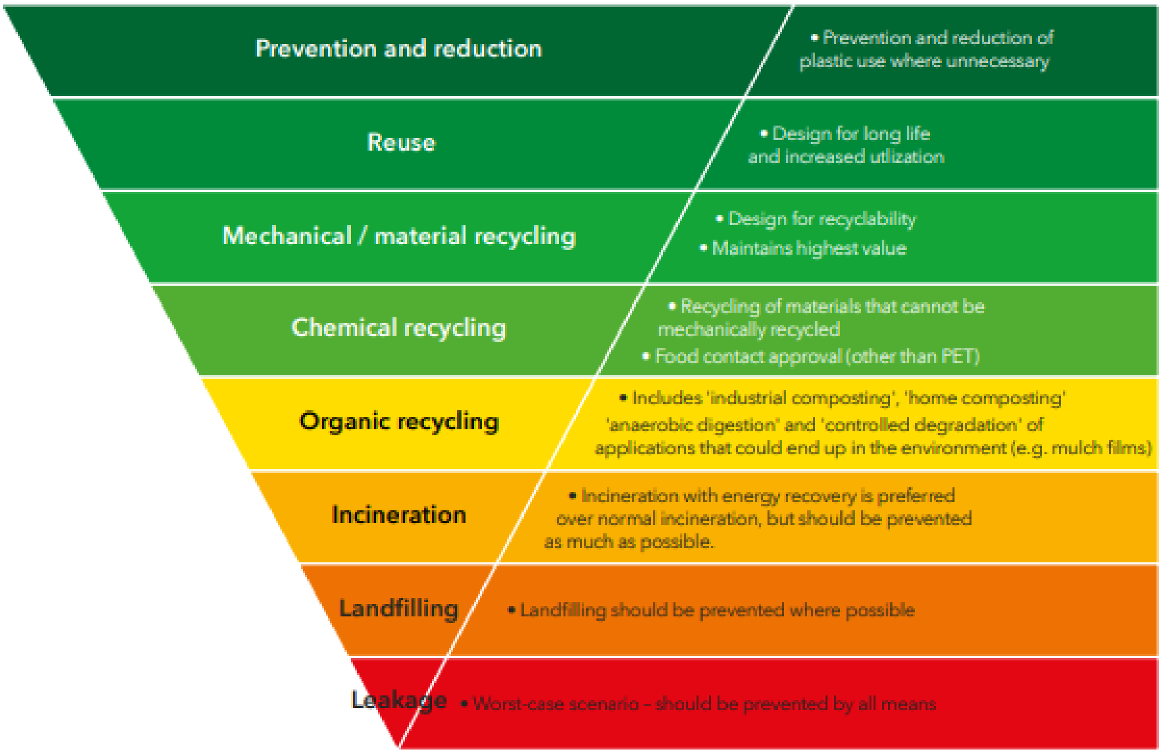


Figure 6 – Pyramid of bioplastic waste management (Source: Total Corbion PLA, 2020)

In order to reuse algal bioplastics, the durability would need to be determined. Microalgae-based bioplastics can be designed for biodegradability in natural (such as marine and soil) as well as industrial composting settings (Karan et al, 2019) which is not the case for the majority of fossil-based plastics.

Another aspect of sustainability in the use phase is consumer awareness and understanding of end of life pathways, such as whether the product is compostable or recyclable and how they need to be collected. Currently in Australia, the market share of bioplastics is very small, therefore labelling and consumer education around responsible disposal options are still in the early stages of being introduced and implemented. Australia has a voluntary certification scheme for home and industrial compostability of plastics and Europe has regulated materials standards for compostability linked to international standards. These standards can help ensure claims made about bioplastic product properties (such as compostablility) are genuine and verifiable (OECD, 2013).

4.4 End of Life

The end-of-life phase for bioplastics depends greatly on its properties and whether it is disposed of appropriately. After a bioplastic product has been used, it can be reused or disposed of along a number of waste pathways including:

- Disposal/ littering to land and aquatic environments
- Recycling (mechanical and chemical)
- Industrial composting (aerobic and anaerobic)
- Home composting
- Incineration/ energy recovery
- Landfill

Different applications, regional differences in waste collection infrastructure and future ambitions of that waste collection infrastructure could lead to different end-of-life recommendations. There are advantages and disadvantages of each end-of-life option that require careful evaluation and consideration of the application, its intended use and the existing waste collection infrastructure. Bioplastics end of life options are still being researched, due to their small volume in the waste stream. The most suitable end-of-life option for a bioplastic depends on its properties (Van den Oever, 2017), and the diversity of bioplastic types creates challenges for end of life.

Landfill and litter

Sustainability challenges arise in the disposal stage whether the bioplastic is landfilled, littered or composted, and their environmental impacts depend on their design and composition. Currently there are no algal bioplastics being disposed of in Australia, however, comparing waste pathways with other bioplastics can offer some insights into sustainability challenges.

Sustainability challenges

In 2018-19, less than 13% of plastic waste (2.54 million tonnes) was recycled, less than 3% used for its energy value with the rest sent to landfill (Pickin et al, 2020). There are at least 50 million tonnes of plastic accumulating in Australian landfills (DAWE, 2021). Plastics in landfill contribute to greenhouse gas emissions, and in 2018-19, plastics in Australia contributed 576,380 tonnes CO_2-e (Pickin et al, 2020). Therefore, plastics that accumulate in landfill also cause environmental degradation.

A large amount of plastic does not make it to the bin or landfill. Approximately 130,000 tonnes of plastic leaks into the Australian environment annually, much of this is ingested by marine life and seabirds (DAWE, 2021). European countries (such as Switzerland, Austria, the Netherlands and German) have implemented landfill restrictions for plastic waste (Total Corbion PLA, 2020).

The impact of disposal or littering of bioplastics to land and marine environments has had limited research. Any bioplastic material being designed with a view of sustainability should consider the material's biodegradation impacts such as CO_2 being released to the atmosphere during decomposition, offsetting any positive effects during manufacturing. The opportunity for recyclability of the bioplastic material is also a sustainability consideration.

There is limited research available on the characteristics of bioplastics and their degradation when disposed of to land or water. Some studies have shown that the biodegradation of bioplastics result in release of harmful gases and odours during degradation or decomposition. They recommend specific design considerations such as biodegradation conditions, disintegration processes and environmental impacts such as methane accumulation or harmful gas release (Chia et al, 2020).

Certifications have been developed in Europe for biodegradability of products to marine and land environments, these include: material standards EN 13432 or ISO 18606 or EN 14995, and are tested by official certification bodies (e.g., DIN CERTCO (Germany) TÜV Austria (Austria), etc.) to guarantee a uniform certification representative of the standard specified. Other standards include OK biodegradable MARINE and OK biodegradable SOIL which require tests for biodegradation, ecotoxicity and heavy metals content for soil and water (TUV Austria, 2022). Soil compostability standards also exist in Australia. There is a risk this could increase littering of bioplastics and, as recommended by Van den Oever et al (2017, p8) "a clear distinction should be made between certification of the claim and authorization to communicate about this certification".

Recycling

Sustainability challenges

If bioplastics are made into a recyclable type of plastic for example as bio-polyethylene or bio-PET, then those bioplastics can be recycled together with fossil-based versions (European Bioplastics, n.d.). However, only a small percentage of bioplastics are recyclable and recycled in Australia. Recovered biopolymers in Australia are used mostly in food service ware and packaging applications and less so in agricultural applications (O'Farrell et al, 2021).

If bioplastics are recycled in our current waste system, there are limitations on the types of plastics that are readily recycled. Currently just two or three types of plastic PET #1 (e.g. water or soft drink bottles) and HDPE #2 (e.g. milk and shampoo bottles) are easily recycled into new plastic containers and there is a growing market and capacity to sort PP #5 but not in all areas (Dominish et al, 2020). Apart from a small amount sent to soft plastics recycling, the remaining plastic types are currently being stockpiled or landfilled as there is currently no market for their recovery and exports are banned. However, there is an increased focus on developing infrastructure for local processing (DAWE, 2022). Given these constraints, it is recommended that bioplastics aiming for recyclability through the regular household recycling systems should be made of bio-PET, HDPE or PP.

Composting

The terms 'biodegradable' or 'bio-based' are vague and often misused to describe a variety of materials, and may falsely imply biodegradation without clarifying the environments and timeframe (APCO, 2020). The Australian Packaging Covenant Organisation (APCO) prioritise only referencing either 'certified ***compostable*** plastics' or 'conventional plastics' rather than bioplastics for maximum clarity across industry and consumers (APCO, 2020). Certified compostable plastics have obtained certification to the Australian Standard *AS4736:2006 – Biodegradable plastics: Biodegradable plastics suitable for composting and other microbial treatment (Australian Industrial Composting Standard)* or **'industrial compostable'** and *Australian Standard - AS 5810: 2010 Biodegradable plastics suitable for home composting (Australian Home Composting Standard* or **'home compostable'.**

Figure 7 illustrates the labels for these certifications.

AUSTRALIAN STANDARD INDUSTRIAL COMPOSTING LABEL

Compostable
AS 4736
ABAX 9999

AUSTRALIAN STANDARD HOME COMPOSTING LABEL

Home Compostable
AS 5810
ABAX 9999

Figure 7 – Australian Standards for compostable products

Approximately 0.1% of plastic packaging in Australia is made of compostable plastics (APCO, 2020). Aside from recycling, composting is commonly considered ideal for bioplastics disposal (Chia et al, 2020). Not all biodegradable plastics are certified compostable (ABA, 2020) and this is problematic as they therefore have no safe end-of-life pathway.

Bioplastics which are biodegradable in an optimal environment (industrial composting plant) are not necessarily biodegradable in water or soil, or a home compost bin (TUV Austria, 2022b).

Sustainability challenges

The recovery system for compostable packaging in Australia faces challenges. To begin with, there is limited access for households and businesses to organics collection services that are able to process compostable packaging.

Secondly, a challenge exists with the design of waste management infrastructure which does not enable recycling and composting of biodegradable bioplastics (O'Farrell et al, 2021). Non-compostable 'biodegradable' packaging contaminates compost and recycling waste streams (APCO, 2021b). In addition, bio-based plastics (such as bio-PET, bio-PE and bio-PP) are also recyclable but not compostable which can also contaminate composting facilities (O'Farrell et al, 2021).

APCO recommend that composting of rigid certified compostable plastic is more likely in a setting where there is a "closed" system of waste management, packaging procurement and sorting such as at festivals and within individual buildings, food courts and coffee shops (APCO, 2020). O'Farrell (2021) found that in Australia, of the 350 active reprocessing sites operating in 2020, only a small proportion (perhaps 10–20) accept certified compostable bioplastics, the majority of which are from sources that have training, labelling and designated separation and collection systems in place. Organics recyclers are also limited by the longer than standard time to process compostable packaging into quality products and reliable markets (APCO, 2021b).

With respect to algal bioplastics, the compostability is variable based on the type of algal bioplastics and the environment it degrades in – data is limited given the small amount of algal bioplastics currently being produced and disposed of. A study by Schmidtchen et al (2022, p4) found raw "macroalgal fragments, detritus and their associated polymers were completely degraded in cold polar waters within 4.5–7 weeks compared to commonly used "bioplastic" PLA (that is biodegradable at industrial composting conditions), which showed virtually no sign of degradation after 1 year in warm ocean waters". This study suggests that given this, during the process of being converted to bioplastic packaging material, the properties of macroalgal biomass are altered which can affect biodegradability, and the author suggests that further studies on such products are required (Schmidtchen et al, 2022).

APCO (2021b) have found that organics recycling technologies such as home composting, industrial facilities, anaerobic digestion, mechanical biological treatments and thermal energy recovery facilities, have varying capacities to process compostable packaging. Variables across these technologies such as temperature and exposure to air, water solubility of the packaging, length and conditions of processing can result in different success rates of the biodegradability of compostable packaging (APCO, 2021b).

Energy recovery

Sustainability challenges

Incineration and energy recovery are currently an end-of-life option for plastics. Incineration refers to the burning of plastic waste where a substantial portion of energy value in the waste plastic is not recovered (O'Farrell et al, 2021). Energy Recovery refers to the combustion of waste plastics to create heat to be used for steam production which is used in industry or to generate electricity (O'Farrell et al, 2021). There has been an increase in the use of scrap plastics for energy recovery (7% of local reprocessing in 2017–18 to 35% in 2018–19) due to additional energy recovery facilities being built in NSW (O'Farrell, 2020).

However, as a disposal option, waste incineration in some respects may hinder the transition to a circular economy. Studies comparing the alternatives to plastic incineration such as recycling plastic waste show recycling provides greater reductions in greenhouse gas emissions. In addition, incineration is associated with a long list of adverse health effects and many European countries are moving away from waste incineration (Dembek et al, 2022).

5. Summary of sustainability 'hotspots' in the algal bioplastic life cycle

The sustainability dimensions of the bioplastic lifecycle were qualitatively discussed in the previous section and here we present the key potential 'hotspots' within the lifecycle which need careful consideration in the development of a sustainable bioplastic alternative.

Pre-production phase

Key sustainability issues in the pre-production stage are:

- **Aquatic ecosystems**: If seaweed (macroalgae) is harvested from the wild, further study is needed to understand the impact on aquatic ecosystems and the potential for the seaweed to regrow
- **Toxics**: The ability for algae to grow in polluted conditions (macroalgae) or via flue gas (microalgae) could mean uptake of other toxic compounds, which may affect algal growth or product quality
- **Land use:**
  - For land-based production in ponds, farming of algae may compete with other uses of arable land for example for food and fibre, and for sustainability will need to consider the impact of land and resource use as well as potential nutrient pollution
  - For use of nearshore ocean areas for farming, farming of algae may compete and impact upon other uses such as fisheries
  - There are likely to be limitations on the global scale of nearshore algal cultivation due to competing uses, and ecosystem impacts at scale
- **Product design**: needs to be designed with end of life in mind

Production

Key sustainability issues in the production stage are:

- Energy consumption:
  - Hot water is used to extract polysaccharides from macroalgae, so consideration needs to be given to the energy demands of the extraction and refining process
  - Many bioplastics are still made with fossil fuel driven energy, so consideration needs to be given to the energy source
- Resource consumption:
  - Water consumption of traditional extrusion processes can be very high
  - The energy required to transport biomass for production can contribute to pollution
  - Blending of other materials with bioplastics to improve physical and chemical properties can cause environmental impacts during production (and subsequently disposal)

Retail and use

Key sustainability issues in the retail and use stage are:

- **Resource use:** For sustainable design following the waste hierarchy, bioplastics should be designed for minimal material use, and potentially to enable reuse and longer lifespans where feasible, without compromising end of life sustainability
- **Waste management:**
  - Given the diversity of bioplastics and their differing treatment, labelling and information to the consumer is critical to ensure that bioplastics are correctly disposed of or separated by the consumer and managed accordingly at end of life

– Rigid compostable packaging is recommended to only be used in closed systems with pre-arranged composting collection for example for festivals, individual buildings and the like

End of life

Key sustainability issues in the end-of-life stage are:

- Biodegradation:
  - Degradation conditions should be considered during the design phase including in water or on land to understand implications for biodegradation, GHG emissions, ecotoxicity and heavy metals content and to identify the most appropriate end of life pathway
  - Landfill is a poor disposal option due to release of carbon emissions and the potential length of time breaking down
  - The development of biodegradable bioplastics that are not compostable and not recyclable are not recommended as they have no safe end of life pathway
- **Recyclability:** Given system constraints, if a bioplastic is being designed for recyclability, it should be made of bio-PET, HDPE or PP
- **Incineration and energy recovery:** These are the lowest priority in the waste hierarchy and have many negative aspects including health effects and increased GHG emissions, hence this is not a recommended end of life pathway

While there are a number of key points in the lifecycle to design for sustainability, there are also some sustainability benefits from algal cultivation, such as CO_2 uptake from the ocean.

6. Policy context

Policy and funding measures enacted by different levels of government will play a significant role in whether algae-based bioplastics are a viable alternative in the future bio economy (Lee et al, 2021).

Currently there is little focus on incentives to encourage bioplastic production as an alternative to fossil-based plastics, and in fact new single use plastics bans are including bioplastics and compostable plastics in their bans due to the difficulty of ensuring correct disposal. This will influence the development of bioplastics in the short-term.

6.1 National legislation and planning for phasing out conventional plastics

A range of government regulations in Australian states have been introduced to phase out single-use plastics, which affect opportunities for bioplastics.

In 2021, a communique from the Commonwealth and State and Territory Environment Ministers meeting outlined eight plastic product types for industry to phase out by 2025. This included several types of single-use plastic packaging such as lightweight plastic bags, plastic products misleadingly termed as ‘degradable’, plastic straws, EPS (expanded polystyrene) food containers loose fill and microbeads (Australian Department of Climate Change, Energy, the Environment and Water, 2021). Following this governments have continued to ramp up policy and regulation on single-use plastics (APCO, 2022) including Target 5 of the National Waste Policy Action Plan to phase out problematic and unnecessary plastics by 2025 such as EPS loose fill and moulded single-use EPS and containers and packaging not certified compostable (including oxo-degradable, landfill-degradable or other claimed degradable plastics) (Australian Department of Climate Change, Energy, the Environment and Water, 2022).

To date, South Australia, Victoria, the Northern Territory, the Australian Capital Territory, Tasmania, Queensland, Western Australia and New South Wales have all introduced legislated bans on the supply of lightweight plastic shopping bags (NRA, 2022).

6.1.1 National Plastics Plan

In March 2020, Australia’s first ever National Plastics Summit released the National Plastics Plan. Its key goals are to:

- reduce plastic waste and increase recycling rates
- find alternatives to the plastics we do not need
- reduce the amount of plastics impacting our environment.

While there is no specific reference to supporting bioplastics in the plan, there is a commitment to funding for Cooperative Research Centres, where $29.1 million will be provided to “research projects that demonstrate innovative ways to recycle plastics and reduce plastics going to landfill” (DAWE, 2021, p11).

The plan may also make headway to addressing barriers to end of life for bioplastics such as phasing out conventional plastic products and products that are labelled ‘degradable’ (but are not compostable or recyclable). By July of 2022, the Plan seeks to phase out non-compostable plastic packaging that does not meet compostable standards, which will support lower contamination of composting streams and potentially improve bioplastics disposal options.

The Australian Government will “refer companies making false or misleading labelling and environmental claims such as misrepresentation of recyclability to the ACCC for investigation” (DAWE, 2021, p8). However, this plan predominately focuses on barriers to recycling which are a priority given the make-up of the waste stream and bioplastics being a small portion.

6.1.2 National Packaging Target 2025 (APCO)

The peak body for packaging in Australia – APCO - operates with industry and government in a co-regulatory model and have been appointed by the Australian Government to facilitate a national Australian vision for all packaging (plastics, glass, paper and cardboard) (Schandl et al, 2021). The 2025 National Packaging Targets were released in September 2018 and updated in 2020. The below shows the four APCO targets, all of which are specific to plastics. Adherence to the APCO recommendations and targets is an option for companies with an annual turnover of $5 million or more. Smaller companies are not subject to the targets and some larger companies choose not to join APCO. APCO estimates their membership covers 75% of the market share (Schandl et al, 2021). By 2025:

- 100% of packaging to be reusable, recyclable or compostable
- 70% of plastic packaging recycled or composted
- 50% average recycled content across packaging
- Phase out problematic and unnecessary single-use plastic packaging

While these targets encourage compostable packaging, which may include bioplastics, it includes a wide array of packaging (not just plastic), and a focus has been on recycled content in packaging with less focus on compostable packaging. While targets are one mechanism, the issue of appropriate and available waste streams for composting, as well as collection and transportation remain.

6.1.3 APCO National Compostable Packaging Strategy

The National Compostable Packaging Strategy was developed by the Australian Packaging Covenant Organisation (APCO), the Australian Organics Recycling Association (AORA) and the Australasian Bioplastics Association (ABA) in consultation with a wide range of stakeholders from industry and government. The strategy was launched on 17 June 2021 at the AORA annual conference. It was developed to provide a clear and consistent national approach for compostable packaging in Australia. The strategy recognises that “systemic change needs to occur at three critical points in the packaging lifecycle – design, collection and recycling” (APCO, 2021b).

Key strategies proposed in the compostable packaging strategy include:

- phasing out fragmentable plastic packaging,
- clarifying product claims and labelling of products,
- educating the packaging value chain,
- minimising contamination in organics collections and
- undertaking processing trials for compostable packaging (APCO, 2021b).

6.1.4 CSIRO’s National Circular Economy Roadmap

In 2019, CSIRO was tasked to lead the development of a Circular Economy Roadmap, which reviews four materials that are common waste streams in our economy: plastics, tyres (automotive and mining), glass and paper. The roadmap has a focus on innovation and brings together industry stakeholders to explore circular economy opportunities for Australia. The roadmap suggests that a future target for the circular economy in Australia should involve a transition towards renewable feedstocks for plastics, however, the roadmap suggests that before this happens there is a need for ‘greater collection, processing and reuse’ of plastics (Schandl et al, 2021).

6.2 State legislation and planning for plastics

6.2.1 NSW Waste and Sustainable Materials Strategy 2041

The NSW Waste and Sustainable Materials Strategy 2041, Stage 1: 2021–2027 was released in 2021 and sets targets to:

- reduce total waste generated by 10% per person by 2030
- have an 80% average recovery rate from all waste streams by 2030
- significantly increase the use of recycled content by governments and industry
- phase out problematic and unnecessary plastics by 2025
- halve the amount of organic waste sent to landfill by 2030 (DPIE, 2021).

While there is nothing specific relating to bioplastics in this strategy, part of this strategy is the NSW Plastics Action Plan.

NSW Plastics Action Plan 2021

The NSW Plastics Action Plan proposes four long-term outcomes to work towards: 1) reducing plastic waste generation; 2) making the most of plastic resources; 3) reducing plastic leakage; and 4) improving understanding of the future of plastics (DPIE, 2021b). Under outcome 1, a phase out of single-use plastics commenced in June 2022 beginning with lightweight single use plastic bags. Lightweight plastic shopping bags **are those with handles that are 35 microns or less in thickness at any part of the bag and includes compostable packaging (even if certified compostable)** (DPIE, 2022). This would include lightweight bags made from bioplastics and algal bioplastics, reducing their market opportunities in NSW.

The plan suggests retailers sell reusable bags (fabric, hessian, jute or chiller bags), sustainably sourced non-plastic bags or using cardboard boxes or recycled paper bags instead. Heavyweight plastic bags (over 35 microns) are still able to be used. However, major supermarkets and stores have also announced they will phase these out as well (Powell, 2022).

The plastic bag ban is followed in November 2022 by other problematic single use plastics including:

- Single-use plastic straws, stirrers and cutlery (including forks, spoons, knives, chopsticks, and food picks)
- Single-use plastic plates and bowls (excluding bowls with a spill-proof lid)
- Expanded polystyrene foodware and cups (e.g. clamshells, cups) – this does not include other types of plastic cups
- Cotton buds with plastic sticks
- Microbeads – can be an ingredient in cosmetics and personal care products

For these products the plan suggests avoiding use and introducing reusable items, or if required, using sustainably sourced bagasse, wood, bamboo, cardboard or paper (e.g. paper straws, wooden or bamboo cutlery, or uncoated plates, bowls and clamshells made from cardboard or sugarcane pulp). **If these items contain any form of plastic, including compostable or 'plant-based' plastic, they are banned** (NSW Government and NRA, 2022). This clearly impacts the bioplastic industry in NSW and may result in retailers disposing of and/or moving these products to other states in Australia, and manufacturers also.

The NSW Plastics Action Plan includes a proposal to accelerate the transition to better plastic products such as establishing a $10 million Circular Materials Fund to help with the costs of shifting from plastic to more sustainable alternatives by supporting businesses like manufacturers, builders and retailers with projects that will: reduce the amount of virgin plastic used, reduce the amount of hard-to-recycle plastics used, and increase the amount of recycled plastic in products. There is a focus on the lifecycle of products through partnerships between producers, users and the waste and resource recovery sector. In addition, there is a $2 million commitment for a new Plastics Research Partnership to further understand the future of plastics and developing innovative solutions to manage plastic waste (DPIE, 2021b).

6.2.2 Summary of other state policies for single use plastics

While NSW has recently adopted a plastic bag ban, it is the last of the states to do so. South Australia led the way with a plastic bag ban in 2009, and the ACT and NT followed in 2011. All other states have implemented similar policies in relation to plastic bags since with some variation. The key points relevant to bioplastics are as follows:

Queensland

- In July 2018, the Queensland Government introduced a ban on lightweight plastic shopping bags less than 35 microns thick, including degradable, biodegradable and compostable bags (NRA, 2022).
- Single-use plastic items such as straws, stirrers, cutlery and plates have also been banned in Queensland since September 2021. Alternatives which contain compostable plastics must meet one of the following Australian Standards: AS 5810-2010 Biodegradable Plastics—Biodegradable Plastics Suitable for Home Composting or AS 4736-2006 Biodegradable Plastics Suitable for Composting and Other Microbial Treatment (QLD Government, 2022).

Victoria

- The Victorian Government introduced a state-wide ban on all lightweight plastic shopping bags which have a thickness of 35 microns or less, including degradable, biodegradable and compostable bags from November 2019.
- The single use plastics ban to be implemented in Victoria in 2023 with regard to straws, cutlery, plates and stirrers is proposed to include degradable, compostable, bioplastic and oxo-degradable materials (State Government of Victoria, 2022).

Western Australia

- In WA, from July 2022 all plastic shopping bags with handles were banned, regardless of thickness. This replaces the previous plastic bag ban implemented in 2018.
- Single use plastic straws, cutlery and stirrers will also be banned as part of WA's Plan for Plastics in July 2022 – this includes bioplastics (NRA, 2022)

South Australia

- In 2009, South Australia introduced a state-wide ban on lightweight plastic bags less than 35 microns thick. The ban does not include biodegradable bags.
- Since March 2021, plastic straws, cutlery and stirrers including bioplastic alternatives have also been banned in SA, exceptions include reusable and plastic-free compostable items (Government of South Australia, 2022).

Northern Territory

- In 2011, the Northern Territory introduced a state-wide ban on lightweight plastic bags with a thickness less than 35 microns including degradable bags. Biodegradable and compostable bags are permitted (NT Government, 2022).

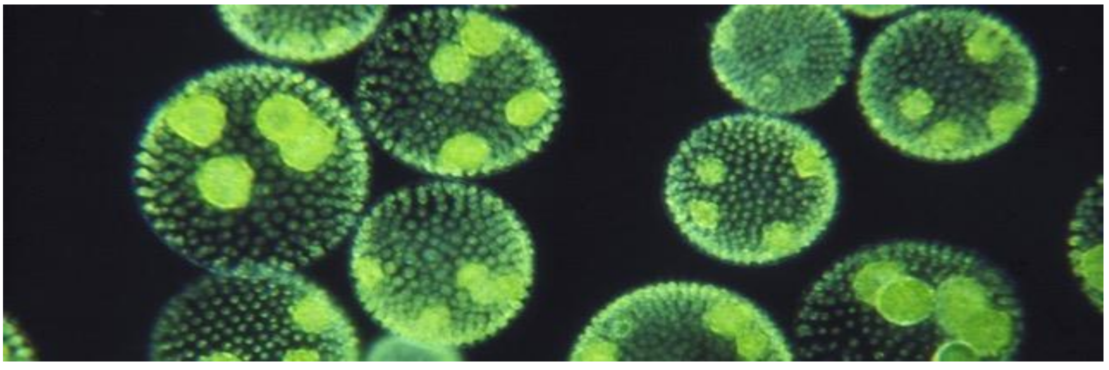
Australian Capital Territory

- In 2011, the ACT Government introduced a state-wide ban on lightweight plastic bags less than 35 microns thick. Certified compostable bags are permitted.
- From July 2021, the ACT banned single use plastic cutlery and stirrers including those made of bioplastics. The ban will also include all oxo-degradable plastics from July 2022 (ACT Government, 2022).

Tasmania

- In 2013, the Tasmanian Government introduced a state-wide ban on lightweight plastic bags less than 35 microns thick. The ban does not include biodegradable or compostable plastic bags.

In summary, most of the more recently introduced plastic bag bans (since 2018) include degradable, biodegradable and compostable bags, these are NSW, Queensland and Victoria, but not Western Australia. Recently introduced bans on single use items such as plastic cutlery and stirrers in ACT, WA and SA also include bioplastics, and a similar ban on single use items in Victoria is also proposed to include bioplastics. The Northern Territory and Tasmania are the only states where there is no legislation to ban bioplastics and compostable plastics. These regulations pose a significant challenge to the development of bioplastics as alternatives to single use items.



7. Conclusions and recommendations

7.1 Conclusions

There is a niche market for bioplastic applications in Australia

The bioplastics sector is small, and algal bioplastics are part of the latest third generation of bio-feedstocks under development which can be used to make both rigid and flexible bioplastics. There is a small seaweed cultivation industry in Australia; however, this is not currently for the production of bioplastics. Rigid compostable bioplastics are currently recommended to be used in closed systems such as events, festivals, and specific buildings where appropriate collection and disposal systems exist.

State government policy is progressively moving to ban single use plastic items and increasingly this includes bioplastic along with conventional plastics

Due to the fact that the end-of-life impacts of bioplastics can be similar to conventional plastics, they are regarded as similarly damaging for the environment by governments. While there is a lot of diversity in bioplastics and there is potential for them to be designed for more sustainable outcomes, these policies will no doubt affect their development and application in the next few years. There is potential for this to change in the future as these policies are reviewed every few years, but this may mean that bioplastics are developed for non-single use applications. Alternatively, more sustainable versions of bioplastics could be developed in the coming years, which may make them suitable as an alternative to single use plastics.

While policy currently provides a regulatory barrier for bioplastics, there is a lack of guidance on how bioplastics might be part of the solution in the future

Several states mention that certified compostable bioplastic items are permitted, so this provides an indication of what may be required of bioplastics in the future. However, currently due to complications in the waste collection system, the diversity of bioplastic types and inconsistent labelling, even compostable plastics have been seen as problematic by many states. Once there is more uniformity in bioplastic characteristics and consistent labelling, there may be improved potential for bioplastics to be used as a replacement for single use plastics. Beyond the issue of compostability, there could be clearer guidance for bioplastics producers on how they may meet with regulatory expectations in the future.

It may be incumbent on industry to demonstrate the sustainability and safe end-of-life for bioplastics in order to be exempted from bans

This report provides some sustainability design guidance which may help in the development of future bioplastics. Key issues identified as potential 'hotspots' in designing bioplastics and developing their supply chains include: a) the impacts of ocean cultivation and harvesting on aquatic ecosystems and the impact on land-use and production impacts for on-shore cultivation, b) during production the relative consumption of energy and water, c) during use, bioplastics should be designed to be used in systems where they can be safely disposed of with clear labelling on correct disposal; and perhaps most importantly, d) design needs to consider end of life outcomes with a focus on creating bioplastics that are easily compostable or recyclable.

The waste sector has limited capacity to manage a niche packaging stream, so bioplastics may need to align better with the collection and processing infrastructure that is available

The waste sector is currently facing significant challenges with regard to managing recyclables and has limited capacity to invest in new infrastructure. In order for bioplastics to be accepted in the waste system and by regulators, they may need to be readily recyclable, that is made of PET, HDPE or PP or compost well enough to be included in food and organics waste collection systems.

There is no clear labelling or certification scheme required for different types of bioplastics in Australia

The identification and disposal options of bio-based plastics that are not biodegradable and those that are compostable remains a challenge for consumers and businesses. Bioplastic manufacturers are not required to use labelling or have products certified for compostability as this is currently voluntary. Marketing of products correctly is not regulated, creating confusing messages for consumers.

Consumer awareness and understanding is limited

The majority of consumers are not aware of the types of plastics and their disposal options. Labels are confusing, the sheer number of plastic types is overwhelming and simple recycling of plastics is still challenging, evidenced by continued contamination of plastics in the waste stream. Australian consumers are also faced with challenges which lower the priority of bioplastics disposal, such as disruptions (COVID, natural disasters) which often promote or require single-use plastics (e.g. medical packaging, bottled water). There is a lack of understanding when it comes to organic waste disposal and well-intentioned consumption of bio-based plastics that are not biodegradable.

7.2 Recommendations

These findings lead to a number of recommendations for algal bioplastic producers and other stakeholders:

Product Developers

- By addressing the sustainability hotspots in this report, product developers and designers can ensure the sustainability of algal bioplastics
- New products should seek certification for Australian home and industrial composting (and international certifications for marine, land and soil degradability) prior to commercialisation or being sold to market
- Algal bioplastic products should be labelled and marketed correctly to avoid confusion with the consumer (using the term compostable rather than biodegradable or bioplastic)
- Niche applications in which the use and disposal of the products are contained can be an area of focus (e.g. food courts, hospitals, precinct developments, government procurement schemes) and their disposal in relevant composting facilities (e.g. industrial composting)

Research Community

- Research should be carried out to identify how waste management systems can overcome barriers to receiving and processing bioplastics and compostable plastics
- Life cycle assessments and peer-reviewed methodologies of bio-based plastics should be supported to clearly demonstrate the impacts from the overall life cycle. This could help to demonstrate safe end of life outcomes to improve suitability as an alternative to single use plastics.

Government

- Governments could clarify potential future requirements for bioplastics, so that innovators can work towards those requirements (e.g. certified home compostability)
- Regulation could include consistent labelling requirements for bioplastics to enable their integration into waste systems
- Improved consumer education around the use and disposal of bioplastics, in collaboration with improved labelling by industry, would help to facilitate correct separation and disposal

References

ABA (2020). Bioplastics. AORA Members Webinar August 27th, 2020. Rowan Williams, President Australasian Bioplastics Association. Accessed May 2022 at: https://www.aora.org.au/august-2020-webinar-compostable-bioplastics

ABA (2021). *Bioplastics Information Sheet*. Australasian Bioplastics Association.

ACT Government (2022). Single Use Plastics Ban – Plastic Waste Sorted. City Services. Accessed June 2022 at: https://www.cityservices.act.gov.au/recycling-and-waste/single-use-plastics

APCO (2020). *Considerations for Compostable Plastic Packaging.* Australian Packaging Covenant Organisation. Developed in partnership with the Australian Organics Recycling Association and Australasian Bioplastics Association.

APCO (2021). *Australian Packaging Consumption and Recycling Data 2018-19.* Prepared by Envisage Works, IndustryEdge, Randell Environmental Consulting and Sustainable Resource Use on behalf of Australian Packaging Covenant Organisation.

APCO (2021b). *National Compostable Packaging Strategy.* Australian Packaging Covenant Organisation. Developed in partnership with the Australian Organics Recycling Association and Australasian Bioplastics Association.

APCO (2022). *Government Update.* Australian Packaging Covenant Organisation. Accessed June 2022 at: https://apco.org.au/news/20Y9e000000001YEAQ

ABA (2022). Australasian Bioplastics Market. Australasian Bioplastics Association. Accessed May 2022 at: https://bioplastics.org.au/bioplastics/market/

Ashter, S. (2016). Overview of Biodegradable Polymers. 10.1016/B978-0-323-39396-6.00002-6.

Bioplastics Magazine (2020) *Glossary.* Bioplastics Magazine, 06/20, Vol 15 pp 54-57.

Cai, J., Lovatelli, A., Aguilar-Manjarrez, J., Cornish, L., Dabbadie, L., Desrochers, A., Diffey, S., Garrido Gamarro, E., Geehan, J., Hurtado, A., Lucente, D., Mair, G., Miao, W., Potin, P., Przybyla, C., Reantaso, M., Roubach, R., Tauati, M. & Yuan, X. 2021. Seaweeds and microalgae: an overview for unlocking their potential in global aquaculture development. FAO Fisheries and Aquaculture Circular No. 1229. Rome, FAO. https://doi.org/10.4060/cb5670en

Carlsson, A.S., van Beilen, J. B., Möller, R. and Clayton, D. (2007) Micro- and Macro-Algae: Utility for Industrial Applications. Output from EPOBIO: Realising the Economic Potential of Sustainable Resources – Bioproducts from Non-food Crops Project. September 2007, CNAP, University of York

Chandra, R. and Rustgi, R. (1998) Biodegradable Polymers. Progress in Polymer Science, 23, 1273-1335. http://dx.doi.org/10.1016/S0079-6700(97)00039-7

Chia, W. Ying Ying Tang, D. Khoo, K, Lup, A. Chew, K.W. (2020). Nature's fight against plastic pollution: Algae for plastic biodegradation and bioplastics production. Environmental Science and Ecotechnology, Volume 4, 2020, 100065, ISSN 2666-4984, https://doi.org/10.1016/j.ese.2020.100065.

Climate Change Cluster UTS (2022). *What is Algae?* Accessed May 2022 at: https://www.uts.edu.au/climate-change-cluster/our-research/deep-green-biotech-hub/education-and-outreach/what-algae

Crawford, C (2002). Seaweed Farming: An Alternative Livelihood for Small-Scale Fishers? Coastal Resources Centre Working Paper, University of Rhode Island.

Dang, B.T & Bui, Xuan-Thanh & Tran, Duyen & Ngo, Huu & Nghiem, Long & Hoang, Thi-Khanh-Dieu & Nguyen, Phuong-Thao & Nguyen, Hai & Quyen, Vo & Lin, Chitsan & Lin, Kun-Yi & Varjani, Sunita. (2022). Current application of algae derivatives for bioplastic production: A review. Bioresource Technology. 347. 126698. 10.1016/j.biortech.2022.126698.

DAWE (2022). Exports of waste plastics. Accessed June 2022 at: https://www.awe.gov.au/environment/protection/waste/exports/plastic

DAWE (2021). *National Plastics Plan 2021*. Department of Agriculture, Water and the Environment, Canberra, December.CC by 4.0.

Dembek, K, Moglia, M. Nygaard, C. Taffe, S and Woodcock, I. (2021). Is waste incineration burning a hole in our sustainable future? The Fifth Estate. 2 September 2021. Accessed May 2022 at: https://thefifthestate.com.au/columns/spinifex/is-waste-incineration-burning-a-hole-in-our-sustainable-future/

Djamal, Zerrouki & Henni, Abdellah. (2019). Outdoor Microalgae Cultivation for Wastewater Treatment. 10.1007/978-3-030-13913-1_5.

Dominish, E., Retamal, M., Wakefield-Rann, R., Florin, N., (2020) *Environmentally responsible trade in waste plastics Report 1: Investigating the links between trade and marine plastic pollution*. Prepared for the Department of Agriculture, Water and the Environment, June 2020

Downes et al (2021) A type of 'biodegradable' plastic will soon be phased out in Australia. That's a big win for the environment. The Conversation. Accessed June 2022 at https://theconversation.com/a-type-of-biodegradable-plastic-will-soon-be-phased-out-in-australia-thats-a-big-win-for-the-environment-156566

DPIE (2021). *NSW Waste and Sustainable Materials Strategy 2041. Stage 1: 2021–2027*. June 2021. State of New South Wales Department of Planning, Industry and Environment.

DPIE (2021b). *NSW Plastics Action Plan*. June 2021. State of New South Wales Department of Planning, Industry and Environment.

DPIE (2022). Phasing out Single-Use Plastics in NSW. State of New South Wales Department of Planning, Industry and Environment. Accessed June 2022 at: https://www.dpie.nsw.gov.au/our-work/environment-energy-and-science/plastics-action-plan/phasing-out-single-use-plastics-in-nsw#:~:text=A%20lightweight%20plastic%20bag%20is,from%20Australian%20certified%20compostable%20plastic.

European Bioplastics, n.d., Mechanical Recycling, https://www.european-bioplastics.org/bioplastics/waste-management/ European Bioplastics (2021) Bioplastics Market Development Update. European Bioplastics Conference 2021. Accessed May 2022 at: https://docs.european-bioplastics.org/publications/fs/EUBP_FS_End-of-life.pdf

European Bioplastics (2022) How much agricultural area is used for bioplastics. Accessed online October 2022 at: https://www.european-bioplastics.org/faq-items/how-much-agricultural-area-is-used-for-bioplastics/

European Commission (2016) SEABIOPLAS: Seaweeds from Sustainable Aquaculture as Feedstock for Biodegradable Bioplastics. Final Report. Accessed May 2022 at: https://cordis.europa.eu/project/id/606032/reporting

European Union (2022). Consumption footprint: assessing the environmental impacts of EU consumption, Science for policy briefs, https://eplca.jrc.ec.europa.eu/uploads/JRC126257_science_for_policy_brief.pdf

Fortune Business Insights (2022) Green Packaging Market Size, Share and Covid-19 Impact Analysis. Accessed May 2022 at: https://www.fortunebusinessinsights.com/green-packaging-market-105113

Gao, K and Beardall, J. (2022) Using macroalgae to address UN Sustainable Development goals through CO2 remediation and improvement of the aquaculture environment, Applied Phycology, DOI: 10.1080/26388081.2022.2025617

Government of South Australia (2022). Replace the Waste. Accessed June 2022 at: https://www.replacethewaste.sa.gov.au/

John, G Rojan & Gs, Anisha & Nampoothiri, K. Madhavan & Pandey, Ashok. (2011). Micro and macroalgal biomass: a renewable source for bioethanol. Bioresour. Technol.. 28. 384-410.

Jolliet, O., Margni, M., Charles, R. et al. IMPACT 2002+: A new life cycle impact assessment methodology. Int J LCA 8, 324 (2003). https://doi.org/10.1007/BF02978505

Karan H, Funk C, Grabert M, Oey M, Hankamer B. (2019) Green Bioplastics as Part of a Circular Bioeconomy. Trends Plant Sci. 2019 Mar;24(3):237-249. doi: 10.1016/j.tplants.2018.11.010. Epub 2019 Jan 3. PMID: 30612789.

Kelly, J (2020) *Australian Seaweed Industry Blueprint – A Blueprint for Growth.* Publication No. 20-072. Project No. PRJ-012324. Agrifutures Australia.

Konda, N.V.S.N.M., Singh, S., Simmons, B.A. et al. (2015). An Investigation on the Economic Feasibility of Macroalgae as a Potential Feedstock for Biorefineries. Bioenerg. Res. 8, 1046–1056 (2015). https://doi.org/10.1007/s12155-015-9594-1

Lawton RJ, de Nys R, Paul NA (2013) Selecting Reliable and Robust Freshwater Macroalgae for Biomass Applications. PLoS ONE 8(5): e64168. doi:10.1371/journal.pone.0064168

Lee, T. Wearne, S. Wakefield-Rann, R and Crosby, A. (2021) Scoping Algae Futures: Scoping a Circular Algae Bioplastics Industry in Regional NSW. Faculty of Design, Architecture and Building, Climate Change Cluster and Institute for Sustainable Futures at University of Technology Sydney. Accessed May 2022 at: https://scoping-algae-futures.com/

McHugh, D (2003) A guide to the seaweed industry FAO Fisheries Technical Paper 441. School of Chemistry, University College University of New South Wales and Australian Defence Force Academy Canberra Australia. Food and Agriculture Organization of The United Nations. Accessed May 2022 at: https://www.fao.org/3/y4765e/y4765e00.htm

NRA (2022). Bag Bans Across Australia. National Retail Association. Accessed June 2022 at: https://bagban.com.au/

NRA (2022b). WA fast-tracked plastics ban – what you need to know. Accessed June 2022 at: https://www.nra.net.au/wa-fast-tracked-plastics-ban-what-you-need-to-know/#:~:text=Stage%20one%20includes%3A&text=single%2Duse%20plastic%20cutlery%20%E2%80%93%20bioplastics,Bioplastics%20not%20mentioned%20as%20exempt.

NOAA (2022). How has the ocean made life on land possible? NOAA Ocean Exploration. National Oceanic and Atmospheric Administration. U.S. Department of Commerce. Accessed June 2022 at: https://oceanexplorer.noaa.gov/facts/oceanproduction.html

Northern Territory Government (2022). Plastic Bag Ban. Accessed June 2022 at: https://nt.gov.au/environment/environment-protection-recycling-waste/plastic-bag-ban#:~:text=Northern%20Territory%20(NT)%20retailers%20must,own%20bags%20to%20shop%20with.

NSW Government and NRA (2022). Single Use Plastic Ban Guide for Businesses. NSW Government

OECD (2013). Policies for Bioplastics in the Context of a Bioeconomy. OECD Science, Technology and Industry Policy Papers, No. 10, OECD Publishing, Paris. http://dx.doi.org/10.1787/5k3xpf9rrw6d-en

O'Farrell, K (2020). 2018–19 Australian Plastics Recycling Survey National report – Final report. Produced by Envisage Works for Department of Agriculture, Water and the Environment.

O'Farrell, K. Harney, F. and Chakma, P (2021). *Australian Plastics Flows and Fates Study 2019–20*. Produced by Envisage Works for The Department of Agriculture, Water and the Environment

Ögmundarson Ó, Sukumara S, Laurent A, Fantke P. (2020) Environmental hotspots of lactic acid production systems. GCB Bioenergy. 2020;12:19–38. https ://doi.org/10.1111/gcbb.12652

Pickin, J. Wardle, C. O'Farrell, K. Nyunt, P. and Donovan, S. (2020). National Waste Report 2020. Prepared by Blue Environment for the Department of Agriculture, Water and the Environment Status

Powell, D (2022). Woolworths, Big W to phase out reusable plastic bags. Sydney Morning Herald. June 3, 2022. Accessed June 2022 at: https://www.smh.com.au/business/companies/woolworths-big-w-to-phase-out-reusable-plastic-bags-20220603-p5aqt6.html

QLD Government (2022). About the Ban. Accessed June 2022 at: https://www.qld.gov.au/environment/management/waste/recovery/reduction/plastic-pollution/single-use-plastic-products-ban/about#:~:text=From%201%20September%202021%20we,for%2Dprofit%20organisations%20and%20businesses.

Raworth, K. (2017). A Doughnut for the Anthropocene: humanity's compass in the 21st century. The lancet planetary health, 1(2), e48-e49.

Retamal, M, Florin, N, Wakefield-Rann, R, Dominish, E, Madden, B, Gee, M, Davidian, D and Braun, J (2019). *Transition Pathways to Deliver Resource Recovery Systems for Used Packaging Materials in Australia.* Prepared by the Institute for Sustainable Futures UTS and MRA for APCO.

Rockström, J., W. Steffen, K. Noone, Å. Persson, F. S. Chapin, III, E. Lambin, T. M. Lenton, M. Scheffer, C. Folke, H. Schellnhuber, B. Nykvist, C. A. De Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P. K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R. W. Corell, V. J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley (2009). Planetary boundaries:exploring the safe operating space for humanity. Ecology and Society 14(2): 32. [online] URL: http://www.ecologyandsociety.org/vol14/iss2/art32/

Schandl H, King S, Walton A, Kaksonen AH, Tapsuwan S and Baynes TM (2020) National circular economy roadmap for plastics, glass, paper and tyres. CSIRO, Australia.

Schmidtchen, L. Roleda, M, Y. Majschak, J and Mayser, M. (2022). Processing technologies for solid and flexible packaging materials from macroalgae. Algal Research, Volume 61, 2022, 102300, ISSN 2211-9264, https://doi.org/10.1016/j.algal.2021.102300.

Seixas, F., Turbiani, F., Salomão, P., Souza, R., & Gimenes, M. (2013). Biofilms composed of alginate and pectin: effect of concentration of crosslinker and plasticizer agents. The Italian Association of Chemical Engineering, 32.

State Government of Victoria (2022). Single Use Plastics Ban. Accessed June 2022 at: https://www.vic.gov.au/single-use-plastics

Total Corbion PLA (2020). End-of-life options for bioplastics. Accessed May 2022 at: https://www.totalenergies-corbion.com/media/bm1p2dwl/totalcorbionpla_whitepaper_end-of-life-201127.pdf

TUV Austria (2022). OK biodegradable SOIL, OK biodegradable WATER & OK biodegradable MARINE. Accessed May 2022 at: https://www.tuv-at.be/green-marks/certifications/ok-biodegradable/

TUV Austria (2022b). OK compost and seedling. Accessed October 2022 at: https://www.tuv-at.be/green-marks/certifications/ok-biodegradable/

https://www.tuv-at.be/green-marks/certifications/ok-compost-seedling/

ULUU (2022) ULUU What we Do. Accessed October 2022 at: https://www.uluu.com.au/what-we-do/

UNEP (2014) *Valuing Plastics: The Business Case for Measuring, Managing and Disclosing Plastic Use in the Consumer Goods Industry*.

UNEP-SETAC (2011), Towards a life cycle sustainability assessment: Making informed choices on products, Life Cycle Initiative, ISBN: 978-92-807-3175-0, https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2011%20-%20Towards%20LCSA.pdf

UTS (2022) *Algae cures popular brewers carbon hangover*. Accessed May 2022 at: https://www.uts.edu.au/research-and-teaching/research/explore/impact/algae-cures-popular-brewers-carbon-hangover

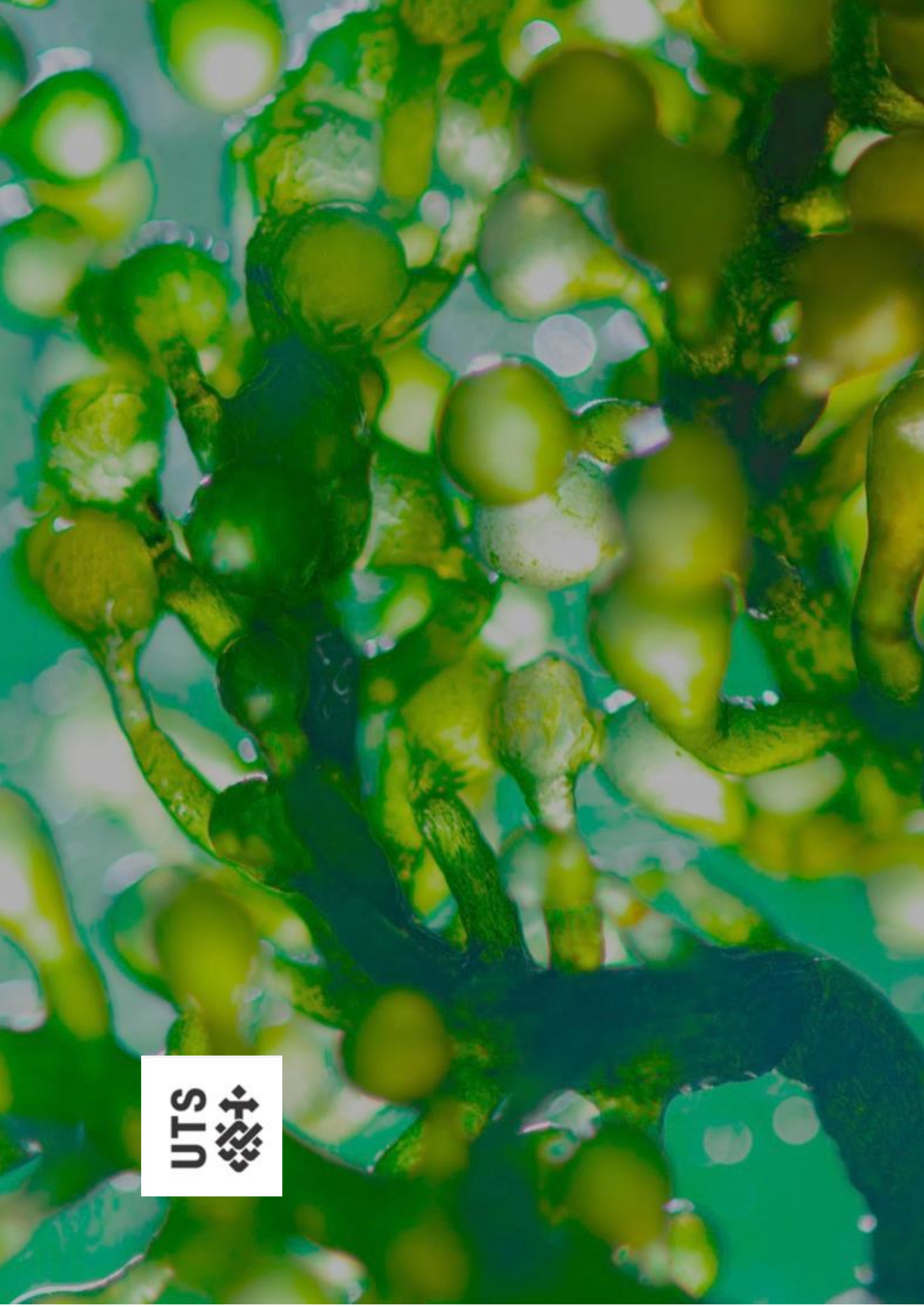
Van den Oever, M. Molenveld, K. van der Zee, M and Bos, H. (2017). Bio-based and biodegradable plastics - Facts and Figures. Wageningen Food & Biobased Research number 1722. ISBN-number 978-94-6343-121-7. http://dx.doi.org/10.18174/408350

Wageningen University (2022). Microalgae Biorefinery 2.0. Accessed May 2022 at: https://www.wur.nl/en/project/microalgae-biorefinery-2.0-mab-2.0-.htm

Wang B, Li Y, Wu N, Lan CQ. (2008) CO(2) bio-mitigation using microalgae. Appl Microbiol Biotechnol. 2008 Jul;79(5):707-18. doi: 10.1007/s00253-008-1518-y. Epub 2008 May 16. PMID: 18483734.

Wellenreuther, C and Wolf, A. (2020). Innovative feedstocks in biodegradable bio-based plastics: a literature review. Hamburg Institute of International Economics (HWWI) Research Paper 194 for BIO-PLASTICS EUROPE and the EU Horizon 2020 programme.

Zanchetta, E, Damergi, E Patel, B Borgmeyer, T Pick, H Pulgarin, A Ludwig, C. (2021) Algal cellulose, production and potential use in plastics: Challenges and opportunities, Algal Research, Volume 56, 2021, 102288, ISSN 2211-9264, https://doi.org/10.1016/j.algal.2021.102288.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