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Review

Bridging Science and Strategy: The Emerging R&D Portfolio of the Australian Seaweed Industry

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Abstract: The Australian seaweed industry is poised for transformative growth, driven by its potential economic, environmental, and health benefits. Some native seaweeds have emerged as promising sources of novel feed and food additives, showing strong potential for the development of innovative bioproducts. To fully unlock this potential, it is crucial to establish a robust industrial and social ecosystem that positions seaweed as a cornerstone of Australia's blue and circular economy development. At present, the industry is focusing on scaling up biomass production through initiatives that address societal challenges, such as climate change and environmental degradation, alongside the broader goal of promoting economic independence. This article outlines a comprehensive portfolio developed for the Australian seaweed sector, identifying strategic priorities and emerging needs within the industry. It outlines key research and development (R&D) challenges, opportunities and expected outcomes. This article also provides commentary on the issues and gaps within the current R&D landscape, along with targeted recommendations to support the industry's future development. The information can be used to coordinate national R&D practices and help focus targeted investments to better support the growth and advancement of the seaweed industry.

Keywords: seaweed; emerging industry; research investment optimisation; innovation and collaboration

1. Introduction

The global seaweed industry is experiencing accelerated growth with production tripling over the last two decades. Traditionally centred in Asia for human consumption and hydrocolloid extraction, the sector has diversified considerably and extended into pharmaceuticals, nutraceuticals, cosmetics, bio-packing, animal feed and renewable energy. To date, seaweed farming represents a pivotal strategy to sink carbon, support marine biodiversity, employ women, build a world free of poverty, and together generate value and uplift communities [1]. The global seaweed market, valued at approximately $25.5 billion (AUD) in 2021 [2], is projected to exceed $83.7 billion (AUD) by 2040 [3]. This expansion reflects a convergence of consumer preferences, government investment in bioeconomy initiatives, consistent research support and international policy commitments to climate change mitigation.

In recent years, commercial seaweed aquaculture has become prevalent in Europe and North America, largely driven by increasing demand for sustainable, functional and plant-based products. However, seaweed production is still mainly concentrated in East and Southeast Asian countries, which collectively account for ~86.6% of global production [4]. Seaweed has become a cornerstone of coastal economies in these regions, contributing significantly

to food security, industrial applications and environmental services. They have large-scale mariculture systems, established supply chains, and sustained investment in breeding and processing technologies. Moreover, integrated value chains have been well established to link smallholder farmers with processing plants and export markets, sustaining millions of livelihoods. Although the economies of scale, technological know-how and government support have enabled rapid growth of seaweed industries, their intensive cultivations have also raised ecological concerns, such as habitat degradation, nutrient imbalance and disease outbreaks [5].

By contrast, Australia is an emerging but underdeveloped participant in the global seaweed economy. National production is below 1% of global volumes and mainly reliant on small-scale wild harvest rather than established aquaculture. Nevertheless, the Australian seaweed industry has several comparative advantages. Australia's extensive coastlines encompass diverse native species across tropical to temperate bioregions, providing a rich source of untapped commercial potential. In addition, Australian waters are renowned for the pristine quality, with heavy metal levels in harvested seaweed reported to be over two times lower than those found in imported seaweed products [6]. This premium quality, together with a growing blue economy agenda, will position Australia to differentiate itself in high-value niche markets. Moreover, based on the lessons from established international industries, Australia is able to pursue a "quality over quantity" pathway, harnessing the unique environmental conditions and scientific innovation to achieve sustainable goals of the seaweed industry.

Although production is limited, the potential value of Australia's seaweed industry has been demonstrated by several successful examples. Bull kelp (*Durvillea Pototorum*) from King Island in Tasmania (TAS), supplies approximately 5% of the global natural alginate market, generating an income of about $2.5 million (AUD) per annum [7]. More recently, the red seaweed genus *Asparagopsis* (order *Bonnemaisoniales*) has attracted global attention for its capacity to reduce methane emissions from ruminants by over 80% when included as a small proportion of feed additive [8]. This discovery has placed Australia at the forefront of a rapidly expanding international effort to develop seaweed-based climate solutions. Other native seaweed species, such as *Ecklonia radiata* and *Ulva* spp., are increasingly popularised for biostimulants, functional foods and bioremediation applications, expanding the reach and impact of the Australian seaweed industry both domestically and globally. These findings indicate that the Australian seaweed sector can produce high-impact, high-quality products, even at relatively small production scales.

The strategic significance of seaweed aquaculture has been included and clarified in national policy frameworks. For example, the *National Aquaculture Strategy (2017–2027)* sets a goal to double the current value of the aquaculture industry, and identifying diversification (incl. seaweeds) is a key mechanism to achieve this ambition [9]. Similarly, the *National Marine Science Plan 2015–2025* also emphasises the blue economy as a driver of sustainable growth, innovation and regional employment [10]. As reported, a mature Australian seaweed sector could create more than 8500 jobs and contribute $5–10 billion (AUD) in gross value of production (GVP) by 2050 [2]. Cultivation activities are expected to occur in southern subtropical and temperate regions, where environmental conditions are favourable to the growth of diverse native taxa. Meanwhile, seaweed aquaculture aligns well with multiple UN's Sustainable Development Goals (SDGs), including SDG 2 (Zero Hunger), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Sustainable Production and Consumption), SDG 15 (Life on Land), and SDG 14 (Life Below Water) [11]. There is no doubt that targeted R&D support is needed in this sector to achieve these goals.

Actually, seaweed aquaculture has been recognised as a potential and emerging food industry opportunity for Australia since 1997 [3,6]. However, this sector confronts some structural deficits. Apart from regulatory hurdles, investments have been fragmented, with limited continuity in breeding programs, cultivation technology trials, downstream processing innovation and environmental assessment. The absence of a coordinated research and development (R&D) framework has impeded systematic progress in this sector. There is a pressing need to establish targeted and coherent R&D strategies to guide the future development of the Australian seaweed industry. The purpose of this article is therefore twofold: (1) to analyse the status of current Australian seaweed industry in relation to global benchmarks, and (2) to identify and prioritise R&D strategies that can support its long-term development. Through analysing literatures, scientific, technical and institutional developments, this article reviews current progress, identifies knowledge gaps, and proposes a roadmap to strengthen the R&D portfolio as a driver of sustainable blue bioeconomy growth in Australia.

2. Industry Landscape

To date, approximately 50 companies are dedicated to seaweed business development in Australia, with more than half being family-based SMEs and startups (Figure 1). In addition to a few established businesses harvesting beach-cast seaweed, Australia's seaweed industry is growing quickly with significant private investments supporting

this burgeoning market. To gain a better understanding of these, the following will present an overview of the Australian seaweed industry, summarizing it into five focus areas based on the functions and objectives of businesses.

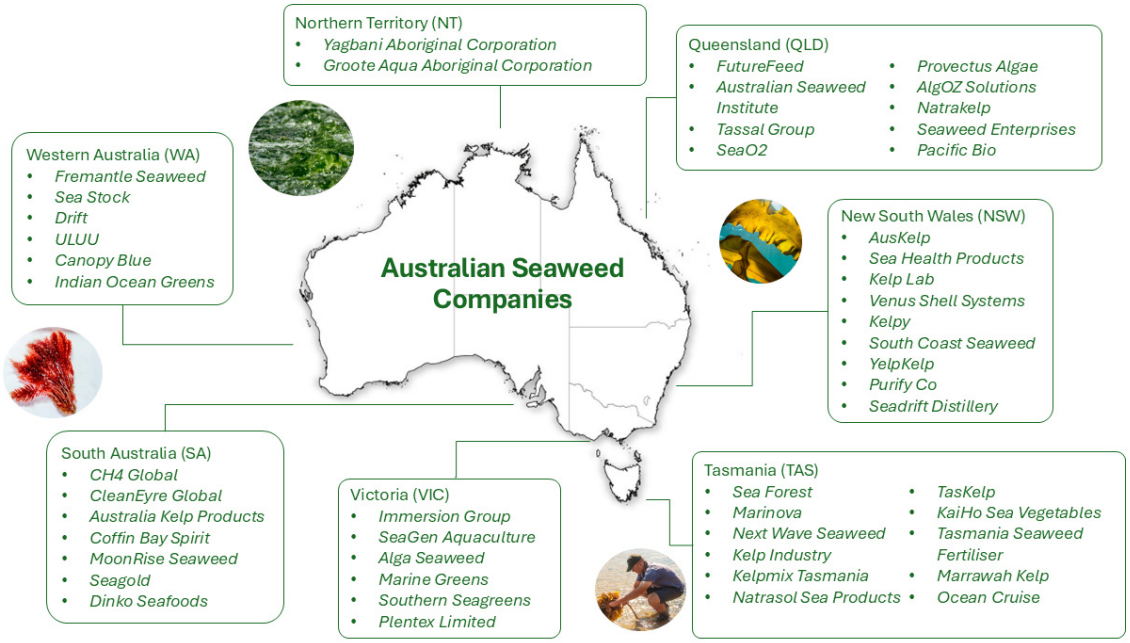

Figure 1. The landscape of Australian seaweed companies.

2.1. Feed Additives for Enteric Methane Reduction

The majority of Australian seaweed providers are largely focused on the red seaweeds *Asparagopsis armata* and *A. taxiformis* for their methane-reducing properties in livestock feeds. *Asparagopsis* spp. are potent inhibitors of enteric methane due to their production and storage of bromoform, the bioactive secondary metabolite within cells [12,13]. Their anti-methanogenic activity at <2% of dry matter in feed can reduce enteric methanogenesis by up to 98% in ruminants [14–17]. Some studies have also reported that *Asparagopsis* supplementation can have significant productivity benefits in feedlot beef [13,16,17]. Since Australia has already committed to the voluntary global methane reduction pledge aiming to slash emissions by 30% by 2030 [18], progressing *Asparagopsis* aquaculture can directly support the national commitment to reducing methane in agriculture.

There is growing interest in commercially cultivating *Asparagopsis* seaweeds to supply the livestock industry in Australia and overseas [19], expanding from Australia to New Zealand, Asia, America, and Europe. The Australian has become a frontrunner in harnessing *Asparagopsis* biomass to mitigate the pressure of livestock methane emissions. *Asparagopsis*-based commercial products have already reached the market, well known of Sea Forest's livestock additive SEAFEED™ and CH4 Global's Methane Tamer™. In response, research is also advancing rapidly to target large-scale *Asparagopsis* cultivation, aiming to secure a high-quality and consistent supply chain. For example, the Australian Government has committed $8.1 million (AUD) to advance research for seaweed commercialisation through the establishment of a peak body for the Australian Seaweed industry, the Australian Sustainable Seaweed Alliance (ASSA), and the launch of two National Hatchery Hubs to support *Asparagopsis* aquaculture [20]. Several seaweed companies focus on *Asparagopsis* cultivation, and some have been widely recognised through various environmental, business, and innovation awards (Table 1).

Notably, FutureFeed holds the global intellectual property (IP) and several patents for the use of *Asparagopsis* as a livestock feed ingredient to reduce methane emissions in ruminants. They have licensed nine partners across Australia, New Zealand, the US, Canada, and Europe to drive the development and commercialisation of *Asparagopsis* technology and build carbon markets for enteric methane [21]. CH4 Global was named to the Global Cleantech 100 as an exceptional innovator in the race to net zero emissions. They have commissioned their first full-scale land-based facility, proving the value of their promising business model. In 2024, the startup had raised $47 million (AUD) from venture capital funds [22]. Initial customers include *CirPro Australia, Ravensworth* and *Lotte International.* Similarly, CleanEyre Global (CEG) has also focused on land-based production of *Asparagopsis* but in uptight bag systems with both indoor and outdoor facilities. As part of the business plan, CEG plans the feedlot trials on their seaweed products in collaboration with *EnviroBeef* in the US. Immersion Group has built a new pilot production facility in Victoria (VIC), conducting trials with tertiary education institutions,

beef feedlots and dairy processors. With the investment of *Nissui Corporation* (Japan), their partnership has expanded and included several research partners and seaweed companies [23]. Sea Forest is a science-based environmental technology company in TAS. They have a 1600 ha marine lease and a land-based High-Rate Algae Pond (HRAP) facility for *Asparagopsis* cultivation and production. The company has partnered with different industries, such as the national burger chain Grill'd to produce a beef burger with up to 67% less methane emissions of beef production, and the M.J. Bale for carbon neutral wool, as well as with 4 Pines Brewing Co. to produce climate-conscious beer [24]. In WA, SeaStock owns the provisional patent for novel *Asparagopsis* culture method and dual extraction method and has entered an agreement with Regis Resources Ltd. to cultivate *Asparagopsis* in Mine Pit Water [25]. Fremantle Seaweed has a fully approved 32 ha aquaculture lease in Western Australia (WA) and their business is dedicated to harnessing the rich marine resources of the region, sustainable seaweed cultivation, and high-quality seaweed production of *Asparagopsis* [26]. As a consulting company, Drift is proactively engaged with various seaweed businesses to develop and implement hatchery and seedling cultivation techniques for *Asparagopsis* and many other seaweed species. Meanwhile, the QLD-based startups Australian Seaweed Institute and Provectus have also begun investigating *Asparagopsis* cultivation through different approaches and platforms. The effort on *Asparagopsis* also includes Plentex Limited, which is an Australian-registered aquaculture company aiming to cultivate *Asparagopsis* in the Philippines [27].

Table 1. Awards summary of some Australian seaweed companies on *Asparagopsis* business (as of publishing time).

Company	Awards
FutureFeed	• Food Planet Prize winner 2020 • Eureka Prize finalist 2021 • Australian Financial Review Sustainability Leaders 2022 • BloombergNEF Pioneers Award 2023 • Banksia Sustainability Awards finalist 2023 • 2024 Indo Pacific Climate Tech 100 Company
CH4 Global	• Global CleanTech Top 100 list in 2022 and 2023 • Norrsken top 100 Impact Award 2023 • Eco Innovation Award 2023 • SA Climate Leaders Award 2023 • "AgTech Sustainability Solution of the Year" in 2024 AgTech Breakthrough Award • Fast Company's Next Big Things in Tech 2024 Award • One of America's Top GreenTech Companies by TIME Magazine 2024, 2025 • THRIVE Top 50 AgTech Awards 2024, 2025
CleanEyre Global	Member of the 2023 Sparklabs Cultiv8 Cohort start-up accelerator program.
Sea Forest	• Finalist in the 2023 Earthshot Prize • Telstra business awards in Australia and Tasmania • Numerous agritech innovation awards in Australia and Tasmania • 2024 Alliance Award of American Chamber of Commerce in Australia
SeaStock	• MassChallenge 2023 Louis Dreyfus Climate Resilience Prize • Runner up of the Rio Tinto Emerging Innovation Award 2024
Provectus Algae	Carbon Reduction Solution of the Year by CleanTech Breakthrough Awards

Note: These awards were conferred in recognition of the *Asparagopsis'* anti-methanogenic efficacy, either through associated business initiatives or the development of seaweed-derived products.

Although recent studies have revealed that no bromoform residue was detected in meat and offal [13], there are still many debates regarding the safety issue of *Asparagopsis'* bromoform to animal health [28]. Inthis regard, some seaweed companies (like FutureFeed) have already started working with the Australian Pesticides and Veterinary Medicines Authority (APVMA) on relevant regulatory compliance. Meanwhile, a new standard framework (AS 5404:2025) has been published to ensure the safe and effective supply of methane-reducing feed additives for agriculture [29]. According to the Meat & Livestock Australia (MLA), methane abatement appears to offer the greatest potential for achieving the 2030 target for national methane reduction, and *Asparagopsis* has been included in the nation's emissions reduction toolbox. Although there is also some concern regarding the cost viability of *Asparagopsis* [30], these positive feedbacks and progresses will create more opportunities, moving *Asparagopsis* feed additives closer to global commercialization. They can also empower seaweed farmers to explore new revenue channels and promote sustainable farming practices, thereby bolstering efforts to combat global greenhouse gas emissions. It is anticipated that there will be a leap forward in driving the adoption of the *Asparagopsis* feed additive in the years to come.

2.2. Nutrition Products for Agriculture, Feed, Food and Health Applications

This area encompasses the most diverse seaweed business activities. Considerable focus in Australia has been directed towards the harvesting and processing beach-cast seaweeds, especially kelp. The use of kelp for fertilisers and animal feed supplementation is still the mainstream in Australia, while kelps nutritional value and culinary versatility are also increasingly recognised. Some interesting health products (e.g., Boost's seaweed smoothies, Phycohealth's seaweed snacks and pasta) have become popularised in society, showing a broader trend towards healthier and more sustainable end choices of innovative seaweed-based organic products.

In TAS, there are three major kelp-related industries: alginates, fertilisers and feeds for agriculture, and fucoidan bioactive compounds [7]. The alginate and fertiliser industries have been primarily driven by the collection of beach-cast bull kelp (mainly *Durvillaea* spp.) since the 1970s by Kelp Industries Pty Ltd. It has exported more than 80,000 tonnes of dried bull kelp, with the majority purchased by FMC Biopolymer, one of the world's largest alginate producers [31]. Other enterprises that collect bull kelp for fertilisers and animal feed, albeit in smaller amounts, include Natrasol Sea Products, Tasmania Seaweed Fertilisers, TasKelp Ltd., Marrawah Kelp and Kelpmix Tasmania. Most of their products have been certified as organic products by the National Association for Sustainable Agriculture Australia, and the distribution network now extends to overseas markets. Meanwhile, market testing by KaiHo Sea Vegetables Tasmania on local seaweed species has shown a strong interest in high-quality food products [7]. Now, this company still operates as a seaweed supplier to the local market, including to AlgSeaweed in VIC. The Next Wave Seaweed is also dedicated to the development of seaweed food and other products, as well as the design and management of seaweed farms. Marinova Pty Ltd. is an Australian biotechnology company specialising in seaweed fucoidan extract and supplying over 35 countries worldwide. In 2024, Marinova completed a $5 million (AUD) expansion of its extraction facility, tripling its production capacity to meet growing global demand [31]. Marinova has shifted from harvesting local wakame *(Undaria pinnatifida)* to using imported kelp (*Fucus vesiculosus*) from Canada in recent years.

In South Australia (SA), the Australian Kelp Products (AKP) has been licensed for commercially collecting beach-cast kelp in the Limestone Coast area. Now, AKP's business focuses on converting the collected kelp biomass (mainly bull kelp) into various bioproducts to supply local markets, such as SOS® liquid kelp for fertilisers and SeaBiscuit® StockAid for animals. Seagold is another company that has been running its seaweed business on beach-cast algae since 1986. They also have imported seaweed extract fertilisers to supplement their products, which are sold at approximately 50 stores across Australia. Based on the hand-foraged approach, Coffin Bay Spirit has added golden kelp, *Codium* green seaweed and other native species into their recipe for the new gin products. An indigenous, family-based startup, MoonRise Seaweed produces a variety of seaweed-based food products by collecting beach-cast seaweed. Their current business priority is to build seaweed cultivation capacity and strengthen their partnership with First Nations communities, supported by scientific research from Flinders University.

In Queensland (QLD), imported seaweed *Ascophyllum nodosum* appears to dominate the food, feed, and fertiliser markets. Seaweed Enterprises Australia **(**also known as Seaperia) supplies a variety of seaweed-based products under its brand of Seagreens (through partnership with Seagreens UK) and Seaperia. Their seaweed business originated in the 1970s. Another family-based business, Natrakelp**,** has manufactured seaweed-based fermented biostimulants and conditioners for plants, soil and animals since 1987, offering a range of liquid and nutrient boosted products (incl. Tasco®) [32]. AlgOZ Solutions is a biotechnology startup in partnership with the University of the Sunshine Coast (USC), targeting the processing techniques for high-value bioproducts from farmed seaweeds in Australia.

In Victoria (VIC), there are various seaweed-based food products on the market, mainly supplied by three local seaweed companies. AlgSeaweed started the seaweed business on processing Tasmanian hand-harvested wakame for culinary nutrients in 2017 and has already launched a range of food products, including the Rainbow Seaweed™. Marine Greens from Snowy River Station supplies high-quality edible seaweeds (incl. Ulva and Nori) to restaurants, resorts and chefs worldwide, based on the fresh biomass harvested from the pristine Snowy River. In addition to diving for introduced Wakame in the water, the Southern Seagreens has successfully cultivated giant kelp (*Macrocystis pyrifera*) on their sea farm at Flinders. Now they plan to cultivate golden kelp (*E. radiata*) in the near future, aiming to establish a new supply chain.

In New South Wales (NSW), Sea Health Products has been hand-harvesting golden kelp for over 50 years of experience in processing dried biomass and producing a range of organic products for cooking and self-care. With farming support from the Kelp Lab, the company has built its own kelp farm close to Port Lincoln in SA. Still based on beach collection of golden kelp, Seadrift Distillery has started adding seaweed to make non-alcoholic spirits [33]. Another startup, Purify Co. has produced different skin care products from seaweed extracts, while YelpKelp has launched its own brand of YELPKELP® dog food. AusKelp initiated the first commercial-scale

seaweed farming trial in NSW, with a preliminary approval from the Department of Primary Industries (DPI) on a 200-hectare ocean lease to grow golden kelp. Meanwhile, AusKelp is currently investigating additional locations in Australia and New Zealand for the licensing of commercial brown kelp farms.

Sea lettuce (*Ulva*) is another promising species for future protein food and functional sources [34] and has been cultivated successfully onshore. In NSW, Venus Shell Systems Pty Ltd. utilises clean CO_2 to rapidly grow *Ulva* and extracts tailored biomass for use in biomaterials, cosmetics, dermatological care, food, nutraceuticals and pharmaceuticals. They have now established two brands of PhycoHealth and PhycoLife, targeting the applications of existing and new seaweed ingredients, respectively. PhycoHealth has over 20 products including a range of award-winning foods and supplements (e.g., Gold—*Seaweed Dhukka Blends*, Silver—*Seaweed Protein*, and Bronze—*Seaweed Pasta* at the Australian Food Rewards in 2016). They have built Australia's first and largest land-based *Ulva* cultivation farm, with a capacity of 40 tons for wet production, generating over $600,000 in revenue for FY22/23 [35]. Moreover, they have secured partnerships with retailers like *Harris Farm Markets* and *Holland & Barrett* in the UK.

Sea grapes *Caulerpa lentillifera* and *C. racemosa* contain high levels of phenolic and flavonoid compounds (e.g., cyanidin, malvidin, quercetin, kaempferol, and apigenin) with effective antioxidants and anti-proliferative activities. Unlike other native species, sea grapes require strict standards for freshness to ensure safe and enjoyable consumption. Fremantle Seaweed in WA planned their offshore cultivation to try cultivating this valuable species in 2024. Another start-up, SeaO2 in QLD, also evaluated its land-based cultivation trials on this seaweed a couple of years ago. In the Northern Territory (NT), a 5-year trial is underway on the oyster farm of Yagbani Aboriginal Corporation with the scientific support from USC, aiming to cultivate this delicious seaweed. According to the market feedback, the fresh and high-quality biomass is appealing to local restaurants for $100–140 (AUD) per kilogram.

In addition, Dinko Seafoods has cultivated native biofouling seaweed on their tuna farms in SA, in partnership with SARDI (South Australian Research and Development Institute) under the funding support of the Marine Bioproducts Cooperative Research Centre (MBCRC). As a value-adding strategy, the produced seaweed will be manufactured into fertiliser, chicken feed and a red pigment of phycoerythrin (worth $250,000 (USD) per kilogram) [36]. The company Sea Stock in WA also has a strong interest in producing this red pigment, but from *Asparagopsis* based on their patentable technology for cosmetic-grade red pigment extracts [37].

With an increasing focus on healthier and more sustainable lifestyle choices, Australian seaweed is naturally gaining recognition for its quality and rich nutritional profile. This burgeoning interest has spurred innovation in bioproduct development, with more Australian companies exploring ways to incorporate seaweed into a wide range of bioproducts tailored to different customers' requirements. Meanwhile, as awareness of seaweed farming's environmental benefits grows, business initiatives are helping to influence policy and drive the transition to more sustainable practice along Australia's vast coastline. Therefore, the Australian seaweed industry is witnessing a remarkable upsurge in the trend toward the development of seaweed food and nutrition products, driven by these business actors and relevant R&D supports.

2.3. Bioplastics and Innovative Materials

Similar to many other countries, the seaweed-bioplastic sector is entering a new phase of R&D and commercialisation in Australia. In WA, ULUU has developed compelling seaweed-based bioplastics. They use seaweed (such as *Gracilaria*) as the feedstock for microbes to produce PHAs (polyhydroxyalkanoates), which are natural biopolymers used in the production of biodegradable plastics [38]. With $8.6 million (AUD) from the investors, the company has built a pilot plant, finalised first-to-market agreements and developed a global brand [38,39]. In 2024, ULUU won the *Rio Tinto Emerging Innovation Award* in WA. In NSW, another startup, Kelpy, founded in 2021, makes bioplastic pellets directly from seaweed, which are compatible with standard plastic manufacturing equipment. Kelpy collaborates with major global brands to pilot marine- and home-compostable packaging materials and has also partnered internationally to utilise invasive sargassum as a feedstock. Although still at an early stage, Kelpy's R&D interests focus on the full value chain, from sustainable seaweed cultivation and feedstock characterisation to material formulation and product performance testing.

In NSW, seaweed *Ulva'*s gel-like glycan molecules (polysaccharides) have been studied and investigated thoroughly at Venus Shell Systems, especially for the efficacy to enhance both the mechanical properties and biological activity in the skin regeneration process. This research outcome has been deployed for clinical testing on 3D bioprinting [40]. The company's brand, PhycoLife, has completed another fundraising round to support its new discovery of "phyaluronic acid" for growing full-thickness 3D-printed skin. In 2024, PhycoLife won the award for Most Innovative Protein Source. Also they were shortlisted as a Finalist for 'New Technologies for Improved Health' & 'Most Sustainable Ingredient' at the International Food & Drink Event in London [41].

Australian aquaculture giant Tassal Group has leveraged the marine alga (*Cladophora*) to remove effluent nutrients released from their prawn ponds in QLD, resulting in a large amount of biomass production. They have explored the possibility of using biomass to produce algae-based packaging materials, aiming to valorise the bioremediation process. Meanwhile, PhycoForms in VIC is focusing on the usage of seaweed waste to produce homewares and furniture, and this business concept has received the *Sustainability Award* at RMIT University [41]. Overall, these initiatives represent a growing interest in Australia's emerging seaweed product innovation, even though most are still in the early stage.

2.4. Environmental Biofilters and Bioremediation

As part of nature, algae possess a great power to remove nutrients in different industrial effluents [42]. Therefore, there is a great potential to incorporate algae cultivation into different market segments to deliver added value and reduce pollution as a win-win strategy. In QLD, the Australian Seaweed Institute was founded with a clear mission to protect the health of the Great Barrier Reef (GBR), working on long-term, nature-based solutions by using native seaweed species to biofilter the precious ecosystem. The company has established a 10-year plan to achieve meaningful impact at scale to protect the GBR's ecosystem, with the partnership of the Australian Government's Reef Trust and the Great Barrier Reef Foundation [43]. In return, the harvested seaweed will be processed and sold as organic health ingredients for use in animal feeds, fertilisers and various bioproducts. Based on the bioremediation process of aquaculture wastewater, the Tassal Group also plans to utilize large-scale algae production to develop functional supplements for animal feed. Another QLD-based company Pacific Bio is developing ways to utilise green algae (incl. *Ulva*) to filter unwanted nutrients out of aquaculture and/or wastewater treatment plants. Their proprietary bioremediation solution is named RegenAqua™, with credits to help different wastewaters management achieving the balance between discharge compliance and aquatic ecosystems protection. The produced algae biomass are converted into a potent biostimulant–PlantJuice™, with great potential to replace synthetic fertilisers helping agricultural farmers [44]. These companies have engaged in different research collaborations with Central Queensland University (CQU), James Cook University (JCU) and USC, respectively.

Within this section, the integrated multi-trophic aquaculture systems (IMTA) are gaining prominence in Australia, especially combining seaweed cultivation with existing marine aquaculture operations. Moreover, forming partnerships with existing marine aquaculture leaseholders is generally regarded as a strategic shortcut for seaweed producers to enter the market [3]. Several R&D projects have been designed and conducted in Tasmanian waters, integrating kelp cultivation with fish/bivalve aquaculture [45,46]. There are also some commercial trials showcasing the practical improvement of IMTA-seaweed cultivation in other states, such as at the fish farm of Dinko Seafoods in SA, the oyster farms of Groote Aqua Aboriginal Corporation and Yagbani Aboriginal Corporation in NT. These developments demonstrate how targeted R&D and process optimisation are accelerating the integration of seaweed aquaculture technologies within IMTA systems.

2.5. Sea Forest Rehabilitation

It was reported that more than 80% of Australia's kelp cover were declined in the last 50 years, due to ocean warming, sea urchin overgrazing, and in some areas, anthropogenic pollution [47,48]. These kelp forests are unlikely to recover naturally, leaving behind barren and lifeless landscapes as "dead zones" where thriving ecosystems once existed [49]. Although the further impact on wild kelp populations remains uncertain, there are many commercial initiatives supplying seedlings and artificial planting on the impacted seafloor, with an attempt to rehabilitate the declined sea forest. These endeavours include Canopy Blue and Indian Ocean Greens in WA, SeaGen Aquaculture in VIC, and Next Wave Seaweed in TAS. In NSW, an Indigenous startup, South Coast Seaweed, organises seaweed foraging tours to reconnect people with traditional Aboriginal knowledge and raise awareness about the vital role of seaweed in the ecosystem.

Moreover, there are more non-profit organisations involved in the sea forest rehabilitation, such as Tasmania Sea Vegetables, the Green Gravel Action Group, and the Kelp Forest Alliance, as well as numerous Indigenous conservation activities around Australia. Recently, the Australian Government has invested $15 million (AUD) in the Coastal Marine Ecosystems Research Centre at CQU, to support science improving long-term resilience of GBR [44]. This includes seagrass restoration to protect and restore the GBR ecosystem, and establish a seaweed hatchery to support seaweed mariculture research. These parties have made tremendous contributions to marine ecosystem protection and sea forest rehabilitation. As this is not the task outlined in this article, these efforts and other relevant bodies will not be elaborated here.

3. Challenges and Opportunities for R&D

The Australian seaweed industry is experiencing a paradigm shift alongside the increased societal awareness of seaweed importance. This is driven by a confluence of political, economic, and sociocultural factors [3,50], encompassing both challenges and opportunities. Typically, targeted financial support is crucial for fostering the sustainable growth of the seaweed industry, in the form of grants, loans, and concessionary capital, particularly patient R&D investment. However, the primary condition is to identify gaps and then establish baseline market demand and strategic research insights for informed decision-making [6]. Therefore, this section will focus on some critical priorities, identified through literature review studies and numerous communications with stakeholders across academia, industry and government.

3.1. Regulatory Hurdles

In a recent seaweed webinar, approximately 100 seaweed experts and stakeholders voted "regulatory hurdles" as the biggest challenge for the current seaweed industry's growth in Australia [51]. This is consistent with the viewpoint outlined in the *Australian Seaweed Industry Blueprint* (published in 2022) that regulatory consistency and designated aquaculture zones could significantly improve the efficiency and success of seaweed farming in Australia [3]. Although there are some ocean leases available for seaweed aquaculture, there is no standards or frameworks dedicated to seaweed aquaculture operations in Australia [50]. Moreover, existing seaweed management plans appear to be weighted in favour of resource sustainability and ecological evaluation for marine and fishery communities [6]. Therefore, it is difficult to understand the current regulatory landscape and the legal frameworks for seaweed commercial cultivation and production, especially for new entrants.

For seaweed aquaculture, Australian stakeholders who want to establish and operate cultivation facilities often need to navigate a dual-layered regulatory framework that combines state and, in some cases, federal requirements [50]. Seaweed farming is primarily regulated at the state or territory level, as most activities occur within coastal waters. At the federal level, the Department of Agriculture, Fisheries and Forestry (DAFF) provides national coordination on aquaculture policy and biosecurity assessment. And the Department of Climate Change, Energy, the Environment and Water (DCCEEW) administers environmental approvals under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). The Australian Fisheries Management Authority (AFMA) manages Commonwealth wild-capture fisheries and has limited connection to aquaculture, unless the activities occur in offshore waters or interact with fisheries resources. State fisheries departments administer aquaculture licences and leases under their respective legislation and may collaborate with federal agencies on biosecurity and environmental assessment matters (Table 2). Environmental impact assessments are typically conducted under state law, with federal referral required only when a project may significantly affect a matter of national environmental significance. Despite growing policy recognition of seaweed's potential, complex and fragmented approval processes continue to hinder the commercial expansion of seaweed industry development in Australia [50], and this has also been reported in New Zealand [52]. At the time of writing, commercial and research permits for Australian seaweed farming are still authorised on a case-by-case basis, reflecting the absence of a streamlined and standardised approach.

As noted in a recent seaweed governance report [50], the governance and policy practices associated with seaweed sectors are not evenly developed across Australia states. For example, WA has dedicated aquaculture zones for seaweed, while QLD and VIC have no seaweed-specific strategy. TAS has formal management provisions under the *Living Marine Resources Management Act 1995* (amended 2017), governing the collection of beach-cast and pest species for commercial use. SA and WA are currently the only states with dedicated strategies and policies supporting seaweed aquaculture. In some jurisdictions, governance approaches are evolving to meet the needs of the emerging seaweed industry. For an instance, Regional NSW has recently launched a new seaweed prospectus [53], offering fresh momentum and strategic direction for advancing the regional seaweed industry. However, seaweed aquaculture in Australia remains largely confined to research and pilot-scale levels, and the related regulatory frameworks are still in the nascent stages of development (Table 2).

In Australia, the *National Aquaculture Strategy* 2017–2027 emphasises the importance of a transparent and consistent regulatory framework, with particular focus on supporting industry stakeholders. Regulatory certainty can enhance investor confidence and encourage innovation in the seaweed sector. It was recommended that the governance structures should be flexible and responsive to emerging industry needs of seaweed aquaculture [9]. Although the concept of a "one-stop shop" for aquaculture management has been proposed, the rapid development of seaweed cultivation suggests that a hybrid approach may be more effective. This would involve fast-tracked approval pathways for research and pilot projects, coupled with adaptive, science-based policies for subsequent commercial expansion. Such a framework would enable early-stage operations to proceed efficiently while

maintaining the capacity to adjust regulations in response to new evidence, technological advances, and evolving environmental and economic conditions [54]. In this way, governance can move beyond a prescriptive model to one that actively supports sustainable industry growth and innovation.

Table 2. Comparison of governance for seaweed aquaculture development between different states in Australia.

State	Current Policy & Governance Status	Key Gaps	Opportunities
WA	• Established aquaculture development zones (ADZs) for seaweed • Licensing managed by DPIRD [1] • Clear zoning and pre-approved sites	• Expansion of ADZs • Approvals still complex • Scaling investment	• Blue carbon integration • Indigenous partnerships • Bioproduct R&D
NSW	• No seaweed-specific framework • Under general aquaculture and environmental planning (EP&A Act) • License via DPI [2] Fisheries • Assessment by multiple departments	• No aquaculture zones for seaweed • Fragmented permitting	• NSW Seaweed Prospectus (2023) • Future regulatory reforms • Potential for IMTA
QLD	• No seaweed-specific framework • Seaweed under general aquaculture law (DAF [3] & DES [4]) • No dedicated seaweed zones	• Lengthy, unclear permitting • GBR marine park restrictions • Limit infrastructure for seaweed	• QLD Aquaculture Strategy 2024–2034 includes regulatory reform • R&D scaling
SA	• Seaweed is regulated under general aquaculture (PIRSA [5]) • Emerging commercial interest	• No designated seaweed aquaculture areas • Unclear sustainable practical protocols	• Co-location with shellfish/finfish farms • Ecosystem services
TAS	• Seaweed is licensed under general aquaculture by NRE Tas [6] • Relatively transparent licensing pathways • Good species list	• Limited dedicated seaweed zoning	• Native species commercialisation • Potential for IMTA
VIC	• No seaweed-specific framework • Seaweed under aquaculture policy, but no formal strategy • Licensed by DEECA [7]	• Lack of zoning • Limited policy clarity	• Urban seaweed farming • Restoration-oriented initiatives • Carbon and nutrient offset potential
NT	• Limited activity • Seaweed is covered under general aquaculture and land-sea use laws • Managed by DITT [8]	• Regulatory and R&D capacity lacking • Remoteness limits investment • No Commercial operations	• Indigenous-led enterprises • Tropical biodiversity potential

[1] DPIRD, Department of Primary Industries and Regional Development. [2] DPI, Department of Primary Industries. [3] DAF, Department of Agriculture and Fisheries. [4] DES, Department of Environment and Science. [5] PIRSA, Primary Industries and Regions SA. [6] NRE Tas, Department of Natural Resources and Environment Tasmania. [7] DEECA, Department of Energy, Environment and Climate Action. [8] DITT, Department of Industry, Tourism and Trade.

3.2. Market Uncertainties

Despite regulatory hurdles, the sector continues to face substantial market-related uncertainties that may constrain growth and investment. These uncertainties arise from structural inefficiencies within supply chains, limited consumer awareness, the absence of standardised quality control measures, and competitive pressures from imported products. These factors influence the scalability of seaweed aquaculture, investor confidence, and the commercial viability of domestic seaweed production. The following discussion explores some potential strategies to address these concerns.

A survey of industry members voted "Opportunity" as the best word to describe the Australian seaweed sector in 2024 [51]. However, seaweed experts noted several structural market uncertainties that constrain growth, in particular of a fragmented supply chain, poor market transparency and limited market access. In Australia, only 20% of potential seaweed production is reaching viable markets [3]. This mostly reflects the systemic inefficiencies in the distribution networks. Establishing durable, mutually beneficial relationships with buyers is therefore critical to enhancing market confidence and profitability. The industry should prioritise the development of a robust and integrated market infrastructure. This involves establishing industry associations, creating platforms for connecting producers with buyers, targeted branding and certifications (e.g., organic or carbon-neutral) and implementing standardised quality control measures to enhance product traceability and build consumer trust. Similar to Norway's *National Algae Strategy* and the EU's *Algae Initiative* (2022), Australia could

establish a coordinated roadmap to connect coastal communities, First Nations enterprises and private investors to create a more inclusive and efficient value chain. Such a roadmap would provide direction on priority species, bioregional development zones, and investment in enabling infrastructure.

Limited public awareness and acceptance of seaweed's nutritional and functional properties represent another major challenge to market growth. Due to less familiarity with its nutritional benefits, many Australians are hesitant to consume seaweed, and often associate it primarily with sushi [55]. In 2022, a market survey showed that Australian consumers have less interest in the culinary and nutritional potential of seaweed than in other countries [56]. For investors, less consumer demand and uncertain market trajectories can lead to hesitation in funding new ventures. This is particularly challenging to small and medium-scale enterprises. Countries like France and the United States have invested in public education campaigns and certification systems (e.g., Blue Food Partnership and OceanWise labelling) to highlight seaweed's sustainability and nutritional benefits. Australian markets also require targeted marketing campaigns, public awareness programs, and strategic collaborations with chefs, food influencers, and/or retailers to showcase the versatility and appeal of seaweed in various culinary applications. Developing a "clean and green" Australian seaweed brand could also increase domestic consumption and support international competitiveness.

The absence of standardised quality control measures can further exacerbate market uncertainty and impede consumer trust. In Australia, seaweed is only being tested under the *Imported Food Inspection Scheme* through the Department of Agriculture, Fisheries and Forestry (DAFF). However, this scheme focuses only on imported brown and Hijiki seaweed products, whereas domestic production does not require testing under the *National Residue Survey*. Although Australian seaweed is widely recognised for its quality, the lack of uniform contaminant monitoring in seaweed products limits their export readiness. From a food safety perspective, there is a clear need for a safety framework, incorporating stringent quality control measures throughout the entire production chain from cultivation and harvesting to processing and storage [57]. Australia could learn from the regulatory experience of regions such as the EU, Japan and South Korea, where seaweed safety, labelling, and residue monitoring systems are well established. These examples demonstrate how clear quality standards support industry innovation and build consumer trust.

Innovation is pivotal to maintaining Australia's competitiveness in the rapidly evolving global seaweed market. Australian seaweed products face significant price pressure from international competitors. Current domestic market is heavily dominated by imported seaweed products, with an estimated value exceeding $40 million AUD [57]. Regardless of competing on price, the industry must strategically differentiate itself. Australia has comparative advantages in unique native species (such as *Asparagopsis*, *E. radiata*, and *Caulerpa*) in pristine marine environments and robust environmental management frameworks, which well align with premium sustainability branding. Similar strategies have successfully employed in Norway, where kelp products are marketed for traceable, low-impact cultivation. Also in South Korea, proprietary processing technologies have transformed seaweed into high-value functional foods and cosmetics, highlighting the important value of research–industry partnerships and cross-sector innovation platforms in driving product diversification and competitiveness. With this reference, Australia can expand its innovation ecosystem and enhance its competitiveness in global markets.

Furthermore, incorporating Indigenous knowledge and cultural heritage can enrich product narratives, enhance environmental management and offer both ethical and strategic advantages that appeal to discerning global consumers. International precedents, such as Māori aquaculture enterprises in New Zealand, demonstrate how traditional resource management frameworks like *Kaitiakitanga* have been effectively integrated with modern aquaculture operations, generating culturally grounded value chains that attract premium markets. Similarly, in Canada, Indigenous-led kelp farming projects have established co-management models that unite traditional ecological insights with contemporary science, strengthening both environmental and community outcomes. In Australia, this will also provide a foundation for inclusive growth of the seaweed industry, enabling Indigenous participation and leadership in the emerging blue economy. Such integration aligns with national reconciliation goals and supports the development of place-based, sustainable aquaculture practices. Ultimately, Indigenous knowledge should not be viewed solely as cultural heritage but as a vital component of an innovative and competitive Australian seaweed industry.

3.3. Seaweed Aquaculture Demands

In Australia, although there are strong initiatives for the development of product innovation and commercial cultivation, the scientific and technical foundations for seaweed aquaculture expansion remain underdeveloped. Therefore, it requires strategic R&D supports to bridge knowledge gaps across production ecology, system

optimisation and value-chain integration. The following priorities reflect key scientific and institutional demands as identified through stakeholder engagement and comparative experience.

(1) Increasing investment in R&D infrastructure and long-term strategy: There is a pressing need for a long-term national strategy to increase public and private R&D investment in seaweed aquaculture. To date, funding bodies such as the Fisheries Research and Development Corporation (FRDC), the Blue Economy CRC, and the MBCRC programs have already funded several industry-oriented projects for seaweed aquaculture. The Commonwealth Government has also committed $8.1 million (AUD) to support ASSA in building the Australian commercial seaweed industry. Although these supports have generated important R&D programs for seaweed aquaculture, the lack of coordinated, long-term infrastructure limits the sector's technical improvement and scientific accumulation in the field. Strategic funding should sustain advanced hatchery facilities, genomic and breeding programs, nutrient modelling, large-scale and collaborative field trials to explore site-specific cultivation practices, as well as investments in advanced processing technologies. At this point, the "*Blue Growth*" initiative in Norway can be considered a good reference, as it has provided a solid foundation for promoting the development of seaweed aquaculture by supporting both basic and applied research more broadly. A systemic and persistent investment model can be considered as Australia's future approach, especially by integrating national funding streams to support end-to-end R&D pipelines.

(2) Establishment of industry-academia-government collaborations: Collaboration across sectors and disciplines is critical to addressing multifaceted R&D challenges. Establishing a national research network will facilitate sharing knowledge and resources, while public-private partnerships can accelerate innovation and commercialisation [58]. Platforms for knowledge exchange, such as research consortia or industry forums, should be designed and organised specifically to facilitate communication between seaweed stakeholders. These communications and collaborations can expedite the development of potential local supply chains, commercialisation of seaweed-based products, cultivation and processing technologies, as well as marketing analysis. For example, the *"Seaweed for Food and Feed*" initiative in the UK is a good model, as government-backed funding has facilitated cross-sector cooperations to support seaweed farming and seaweed applications in food and animal feed products. For Australia, a formalised collaboration mechanism led by ASSA is to build a thriving and sustainable commercial seaweed industry. As a non-profit organisation, ASSA has formed a good foundation for Australian seaweed aquaculture but would need further government support to continue its mission and escalate to the next level.

(3) Focus on integrated IMTA systems for seaweed farming: It is still an early stage in Australia for scientific exploration of IMTA combining seaweed with finfish, shellfish and/or crustaceans, even though the integration of seaweed cultivation with other mariculture can reduce the environmental footprint or existing businesses and achieve both higher productivity and profitability in a sustainable manner [58,59]. Evidence from Canada, China, and Chile shows that IMTA paradigm can improve nutrient recycling efficiency, reduce eutrophication, and enhance system resilience to environmental variability. Moreover, IMTA could offer a reasonable and effective way to establish specific seaweed farming zones, by authorising seaweed farming permits and commercial aquaculture licenses within existing aquaculture leases. Australian research should therefore focus on quantifying biophysical interactions (e.g., nitrogen uptake kinetics, hydrodynamic influence on growth rates and/or site carrying capacity) and modelling ecosystem services to justify spatial planning and licensing decisions. It is essential to have such empirical foundations before IMTA transitions from concept to commercial operation.

(4) Development of biosecurity frameworks and disease management systems: Pathogen surveillance and biosecurity are critical components of sustainable aquaculture management. Seaweed diseases have caused major losses in Asian production systems, such as epiphyte infestations, ice-ice syndrome and bacterial rot. However, their presence and transmission dynamics have not yet been documented in Australian waters. Perhaps it is relevant to the limited commercial scales and production of current seaweed aquaculture. However, targeted R&D should focus on early-warning monitoring frameworks, including diagnostic tools and genetic screening for disease-resistant strains [50]. This could be implemented in a similar way as the biosecurity measures in the Australian prawn aquaculture, where molecular epidemiology and risk-based surveillance have been formalised and institutionalised for both domestic and imported products. Incorporating similar scientific rigor into seaweed aquaculture would strengthen industry resilience and protect ecosystem integrity.

(5) Expanding training, capacity building and knowledge integration: Human capital development always remains central to the growth of the Australian seaweed industry. Training programs should be designed to enhance the technical capabilities of local farmers, researchers, and industry stakeholders [9], such as practical trainings in seaweed cultivation techniques, biosecurity measures, post-harvest processing technologies and marketing strategies. Ideally these training courses can be embedded within tertiary education and vocational systems. From a broader social-ecological perspective, the integration of Indigenous knowledge presents an opportunity for both

innovation and reconciliation. Incorporating traditional knowledge into modern farming practices can yield culturally grounded, foster innovation of Australian seaweed aquaculture, and contribute to social licence to operate [60]. Furthermore, socio-economic studies should explore the broader benefits of seaweed aquaculture for coastal and Indigenous communities, including governance models for equitable benefit-sharing and cultural heritage alignment.

The future of seaweed aquaculture in Australia depends on integrating scientific knowledge, infrastructure development and institutional coordination support to transform small-scale trials into commercially viable and environmentally responsible operations. As highlighted in the previous Australian seaweed industry reports [3,6], these efforts must be embedded within an enabling governance environment that aligns regulatory certainty with innovation incentives, thereby accelerating the translation of research outcomes into practice. As an emerging market, it is pivotal to employ a collaborative, well-funded and strategically focused R&D approach to unlock the full potential of Australia's seaweed resources. By combining rigorous science, adaptive management, and inclusive capacity building, Australia can position its seaweed aquaculture sector as a model of resilient, knowledge-driven blue industry development.

3.4. Concerns of Seaweed Carbon Credits for Climate Change

Rising concerns over climate change shed light on promising opportunities for Australian seaweed industry, particularly in the context of mitigating agriculture greenhouse gas emissions and carbon sequestration. Seaweed-based strategies offer both innovative and practical solutions, as agriculture is a major source of methane emissions and national targets aim for carbon neutrality by 2030. Focusing methane mitigation through *Asparagopsis* supplementation and the broader carbon sequestration potential of seaweed farms provides a pathway to critically evaluate scientific, economic and policy dimensions. Meanwhile, it also highlights opportunities, limitations, and research gaps essential for guiding R&D and informing the emerging blue carbon market.

As the third biggest beef exporter in the world, methane from ruminant livestock accounts for Australia's major agricultural carbon footprint [61]. Within MLA's toolbox, the mitigation strategies like methane-reducing feed supplements (e.g., Bovaer) and forage feeds (e.g., *Desmanthus* and *Leucaena*) have demonstrated partial effectiveness [20]. However, the red seaweed *Asparagopsis* has shown an outstanding capacity of suppressing enteric methane production by over 80%, mediated through its bromoform content to inhibit methanogenesis in the rumen [14–17]. Scaling up *Asparagopsis* cultivation in Australia has been supported through initiatives such as *Securing Raw Materials Program* ($9.3 million AUD) for CH4 Global in regional SA, and Sea Forest in collaboration with the University of Tasmania [20]. While these efforts indicate strong commercial and research momentum, critical scientific questions remain regarding sustainable cultivation, consistent bioactive compound yield, and integration into livestock systems at scale.

Beyond the methane mitigation, seaweed aquaculture offers an effective approach to carbon sequestration, contributing to the emerging blue carbon economy. It was estimated that seaweed could sequester approximately 173 Mt CO2 yr^{-1} globally, equivalent to the emissions of 8.65 million people living in the US [62]. On a seaweed farm, a square kilometre of area could sequester approximately 1500 t CO_2 yr^{-1}, which could offset the emissions of 75–300 people depending on regional per-capita footprints [63]. It was predicted that expanding sustainable seaweed farming to 13–25 million hectares by 2050, could capture an additional 2.5–4.7 Gt CO_2 to create additional feedstock for other solutions at a net lifetime cost of approx. $5.0–9.4 trillion (USD) for 2020–2050 [64]. To date, Japan has begun incorporating the carbon sequestration of wild seaweed and seagrasses into national emissions accounting [65]. This action may set a groundbreaking precedent, likely revitalising the blue carbon credit market through the expansion of seaweed farming and opening potential pathways for integrating it into blue carbon regulatory frameworks.

However, to realise the climate-mitigation potential of seaweed, it faces multiple challenges. Standardised methodologies for measuring, verifying and certifying carbon offsets remain underdeveloped. Biomass fate is critical as much of the carbon in harvested seaweed may return to the atmosphere when used for food, feed, fertiliser or other short-lived products [66]. Long-term sequestration is more plausible in applications such as biochar production, durable bioplastics or incorporation into sedimentary deposits. However, there is little empirical data on their permanence and efficacy. Further research is required to quantify species-specific sequestration rates, the proportion of carbon exported to deep ocean reservoirs, and life-cycle emissions associated with cultivation and processing.

In parallel with empirical studies, economic and policy frameworks must evolve to support blue carbon markets. As for the popularised *Asparagopsis* aquaculture, it is worth noticing that market mechanisms are particularly important for incentivising livestock farming to reduce methane emissions through carbon credit

subsidies and supportive policy frameworks [67]. Similarly, integrating seaweed aquaculture into carbon credit schemes requires robust verification protocols and consideration of synergistic benefits, such as nutrient removal and ecosystem services. The current seaweed industry is witnessing a shift in cultural perceptions, from seaweed as a versatile ingredient in culinary traditions to a more accepted paradigm of sustainable bioeconomy with "zero" carbon footprint. This process offers an opportunity to align R&D, policy and industry practices towards scalable carbon mitigation solutions. Therefore, it is essential to enhance our understanding of how Australian seaweed aquaculture contributes to carbon storage under various conditions, to formally integrate seaweed farming into national and regional blue carbon strategies.

3.5. Outlook for Strategic Roadmap

In the face of these challenges and opportunities, it is essential to establish a strategic pathway to develop a scientifically informed and economically viable seaweed industry in Australia. Moreover, it is important to ensure technological innovation, regulatory reform and environmental stewardship under a unified national vision. The following framework is designed to guide research and policy interventions toward a mature and resilient sector integrated within Australia's blue and circular economy. However, the strategic pathway for Australia's seaweed sector should be viewed as an adaptive and iterative process, and improved by continuous feedback between science, policy and practice.

(1). Building a science–policy interface. Future seaweed industry development should be based on a science–policy interface for evidence-based decision making. ASSA's national R&D network and hatchery hubs developed for Australian seaweed industry are good examples. Technical platforms should be established to translate research outcomes and connect marine biotechnologists, environmental scientists, economists and regulators. This mechanism could facilitate the policy or regulatory evolving with support of scientific evidence. Moreover, it is important to integrate ecological models, life-cycle assessments and bioeconomic analyses with adaptive licensing and spatial planning based on sustainable criteria [62,68]. Such approaches have been successfully applied in Europe through the *EU Algae Initiative* (2022) and in Norway's "*Blue Growth*" strategy [69]. Establishing a national seaweed R&D hub/community with policy integration could play a similar role in Australia, ensuring that R&D outcomes are translated into clear governance mechanisms and investment priorities.

(2). Integrating technological innovation with ecological design. To scale from pilot trials to industrial operations, it requires combining advanced production technologies with ecological design principles. Precision aquaculture tools such as satellite monitoring, AI-based growth prediction, and automated modeling nutrient dynamics can improve productivity and balance ecological protection with commercial operational needs [69]. Overall, the technical transition must account for ecosystem-based management principles, ensuring that nutrient cycling, biodiversity protection and carbon storage are maintained within ecological limits [70]. With this regard, incorporating seaweed farming into IMTA systems has proven effective in mitigating eutrophication and improving yield stability in Canada, China and Chile [71,72]. For the Australian seaweed industry, it can also strengthen the environmental credentials and economic viabilities if these IMTA scientific approaches are employed within a circular bioeconomy framework.

(3). Developing a coordinated R&D and innovation ecosystem. A coordinated R&D ecosystem is vital to foster innovation across research, technical and socio-economic dimensions. As demonstrated by the UK's "*Seaweed for Europe*" and the North Sea Farm consortium in the Netherlands, cross-sector research consortia can significantly accelerate technology transfer and enhance market readiness [73]. Therefore, Australia could establish a tiered innovation network combining (i) fundamental science on breeding, physiology and biosecurity; (ii) applied research on cultivation optimisation and product engineering; and (iii) socio-economic research on consumer behaviour, value chain logistics and policy development. It is crucial to establish a multi-level funding mechanism, especially combining competitive national programs with matched industry contributions. Thus, such ecosystem can ensure long-term research continuity and reduce dependency on project-based cycles.

(4). Enabling blue carbon and climate innovation. Seaweed aquaculture can contribute significantly to Australia's climate mitigation targets through both methane abatement and carbon sequestration. Developing robust blue carbon methodologies requires interdisciplinary studies to quantify sequestration efficiency, carbon permanence, and life-cycle emissions across native taxa [64,74]. Empirical verification of carbon fluxes and sediment burial rates is important before seaweed farming can be formally integrated into national emissions accounting. Japan's inclusion of seaweed carbon sequestration within its greenhouse gas inventory provides a strong precedent [65]. UNEP (2023) and the High-Level Panel for a *Sustainable Ocean Economy* have also called for the recognition of macroalgae in global blue carbon strategies [1,75,76]. If these messages can be incorporated into Australia's Emissions Reduction Fund and/or Australia Carbon Credit Unit Scheme, seaweed cultivation

could obtain carbon credits and attract climate finance support that further encourages investment in large-scale aquaculture and habitat restoration.

(5). Empowering regional and indigenous partnerships. Inclusive industry growth depends on the participation of regional communities and Indigenous knowledge holders. By integrating traditional ecological knowledge with scientific monitoring, co-management frameworks have improved aquaculture governance in New Zealand and Canada [77]. For Australia, Indigenous-led enterprises could play an important role in seaweed farming, ensuring equitable benefit-sharing and social licence to operate. With alignment of *Caring for Sea Country* principles, integrating traditional marine resource management can improve spatial planning, biodiversity outcomes, and cultural sustainability [78,79]. Therefore, targeted programs should be designed and developed to support training, knowledge transfer and/or joint venture development, enabling Indigenous stewardship within regional blue economy hubs.

(6). Fostering a sustainable market transition. It is profoundly important to establish a transparent, traceable and quality-assured marketplace for escalating the global competitiveness of Australian seaweed products. To develop an "*Australian Seaweed Quality and Sustainability Standard*" analogous to ISO 12878 (*Seaweed Safety and Quality*) or the EU Algae Label, it can enhance product credibility and build consumer trust. Moreover, certification schemes linking origin, safety and environmental performance can differentiate Australian seaweed products in premium markets. Market diversification should prioritise bioactives, functional foods and biomaterials derived from Australian native species, based on research investigation and guidance (e.g., biochemical pathways and metabolomic profiling) [80]. Meanwhile, integrating sustainability certification with carbon neutrality and circular economy labelling will further support the development of Australian seaweed industry as an innovation-led export industry through scientific differentiation rather than low-cost competition.

4. Conclusions

The coming decade represents a unique opportunity to transform Australia's seaweed sector into a globally recognised model of sustainable innovation. This requires a coordinated national effort to unite industry stakeholders, researchers and policymakers around a shared strategic agenda [3]. It is instrumental to align R&D activities with industrial and consumer requirements. More importantly, transparent communication and shared goals will enable a unified effort to overcome existing barriers and accelerate innovation. As outlined in this article, a comprehensive strategy that combines scientific insights with practical solutions will unlock the full potential of seaweed aquaculture in Australia. Although current seaweed farming in Australia remains underdeveloped, the development vision should look beyond the objective of expanding production volumes and capacities. Through committed collaboration, cutting-edge research, and forward-thinking policies, Australia can harness the ecological and economic potential of native seaweeds to establish a resilient, sustainable industry. In doing so, the sector can deliver multiple co-benefits, including support for coastal communities, contributions to carbon mitigation, and sustainable economic growth. Ultimately, a coordinated and scientifically informed approach will enable the Australian seaweed industry to transition from a niche market into a globally recognised sustainable sector, renowned for its ecological, social and economic contributions.

Author Contributions

Y.L.: Investigation, conceptualisation, information analysis, writing original draft. M.R.: Validation, writing review and editing. S.C.: Conceptualisation, funding coordination, writing review and editing. J.Q.: Conceptualisation, writing review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest

The authors declare no conflict of interest. Given the role as Editorial Board Member, Yan Li had no involvement in the peer review of this paper and had no access to information regarding its peer-review process. Full responsibility for the editorial process of this paper was delegated to another editor of the journal.

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