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REVIEW

Selection of marine macroalgae for nutrient biofilter and bioproduct trials in the coastal waters of Queensland, Australia

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Abstract

The capacity of many macroalgae to rapidly absorb soluble inorganic nutrients and convert them into primary biomass provides opportunities for their use in the bioremediation of nutrient-enriched waters. Marine-based macroalgal cultivation has the potential to target diffuse source nutrient discharges and produce valuable bioproducts such as fertiliser, soil conditioning agents and agricultural feed additives and phycocolloids. Whilst macroalgal diversity offers benefits for improving and maintaining healthy marine ecosystems, it also presents a challenge for determining the best candidate species for cultivation as a nutrient biofilter and, ultimately, a source of bioproducts. We developed and applied a multi-criteria selection model to identify likely candidate macroalgal species for cultivation in Queensland's coastal waters for biofiltration and bioproduct development, focusing on native species and product development for the agronomical and horticultural sectors. From a species database of 1380 macroalgal species, candidates were initially selected based on their regional abundance, distribution and morphological characteristics considered amenable to in-situ cultivation and harvesting. From a resulting shortlist of 17 species, five systematic literature searches were applied to identify biofilter potential, bioproduct potential and current cultivation status. Of the shortlisted species, *Ulva lactuca*, *Gracilaria edulis* and *Hypnea cervicornis* ranked most highly in the multi-criteria analysis, with several other species showing good potential, but requiring further investment in understanding key biological processes and the development of cultivation protocols.

Keywords Algaculture · Biofilter · Great Barrier Reef · Mariculture · Species selection · Systematic review

Abbreviations

GBR	Great Barrier Reef
DW	Dry weight
FW	Fresh weight

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DIN Dissolved inorganic nitrogen
DIP Dissolved inorganic phosphorous
PP Particulate phosphorus

Introduction

Marine macroalgae are ubiquitous and essential components of coastal environments, creating important habitats for a diverse community of marine species (Fulton et al. 2019; Ravaglioli et al. 2021) while also providing foundational energy resources that support complex food webs (Vinagre et al. 2018; Zheng et al. 2020). Macroalgae often exhibit rapid and opportunistic growth, particularly in response to the enrichment of water column inorganic nutrients (Vaughan et al. 2021; Mercado et al. 2022). This capacity of many macroalgae to rapidly absorb inorganic nutrients and convert them into biomass provides opportunities for their use in the bioremediation of eutrophic waters, both in coastal zones and in ponds as part of integrated aquaculture operations (Xiao et al. 2017; Aquilino et al. 2020). This same capacity can also lead to some species of macroalgae bioaccumulating water-borne contaminants such as heavy metals, arsenic, pesticides and herbicides (Holdt and Kraan 2011; Devault et al. 2021). As such, in-situ bioaccumulation of such compounds should be assessed and considered with respect to their intended end-use, particularly with respect to food and feed applications.

Macroalgal biomass has successfully been converted into valuable bioproducts, such as the use of *Asparagopsis* spp. as a functional feed supplement for cattle to mitigate enteric methane (CH_4) emissions (Roque et al. 2019; Ridoutt et al. 2022), and the application of macroalgal fertilisers as biostimulants in horticulture and agronomy (El Boukhari et al. 2020). The broad range of secondary metabolites produced by macroalgae, coupled with the relatively new exploration of macroalgae in the context of bioprospecting, suggests that many additional, and potentially valuable biotechnological applications of macroalgae remain to be discovered and developed (Pereira and Costa-Lotufo 2012). However, it is crucial that macroalgal bioprospecting also considers the amenability of candidate species to cultivation, to help promote the sustainable development of these emerging industries.

Cultivation of macroalgae needs to be economically viable to be successful (Kang et al. 2013). A comprehensive modelling exercise for the economic, social and environmental opportunities for macroalgal culture in Australia was carried out, suggesting the potential for a AUD $1.5 billion industry by 2040 (Kelly 2020). Australia boasts an enormous diversity of marine macroalgae with over 2000 species currently recorded, many of which are endemic (Huisman 2018; Hurd et al. 2023; Guiry and Guiry 2024). Such diversity offers benefits for maintaining healthy marine ecosystems (Stachowicz et al. 2008; D'Archino and Piazzi 2021) and developing mariculture, but also presents a challenge in identifying the most promising native species for cultivation as a nutrient biofilter and, ultimately, a source of bioproduct. Ideally, species used for biofiltration should remove a significant fraction of the pollutant of concern at a high areal rate, produce a high yield of biomass, have a nutritional profile or bioactive compounds applicable to an end-user product and should have established techniques in place for life-cycle control (Neori et al. 2004).

In the state of Queensland, financial incentives in the form of nitrogen credits are available for the provision of bioremediation solutions for the Great Barrier Reef (GBR) World Heritage Area (Kelly 2020). In the GBR, mean-annual nutrient loads from land-based runoff have increased following widespread immigration of European settlers in the 1860s

(Furnas 2003). River-nutrient loads are estimated to have increased by a factor of 5.7 for total nitrogen and 8.9 for total phosphorous, rising from respective pre-European levels of 14,000 and 1,800 tonnes per year to recent levels of 80,000 and 16,000 tonnes per year (Kroon et al. 2012). In recent years, nutrient loads to the GBR in the form of dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorous (DIP), the forms most readily available for algal growth (Hurd et al. 2014), accounted for 22% and 16% of total nitrogen and total phosphorous discharges (Bartley et al. 2017). Excess nitrogen and phosphorous loading may have negative effects on reef calcification rates (Silbiger et al. 2018), while excess nitrogen has been suggested to exacerbate the severity of coral bleaching by lowering the temperature threshold for severe bleaching events (Donovan et al. 2020). However, further research is needed to quantify the effects of catchment loads on the susceptibility to, and recovery from, coral bleaching (Hughes et al. 2017; Baird et al. 2021). Increased nutrient loading can also compromise coral health by enhancing macroalgal and turf algal growth on coral boundaries and bleached coral, resulting in competition with, or overgrowth of corals, particularly in habitats of low herbivory (McCook 1999; Williams et al. 2019; Adam et al. 2021). Elevated nutrients have also been linked to outbreaks of crown-of-thorns starfish *Acanthaster planci*, a significant contributor to the loss of hard coral cover in the GBR (Brodie et al. 2017). These collective impacts associated with excessive nutrient loading from land-based runoff have the potential to impact the health of the GBR and its resilience to stress events, potentially rendering the reef more vulnerable to impacts associated with ocean acidification and extreme weather events (Waterhouse et al. 2017).

Elevated nutrients in flood plumes as a result of heavy rainfall in GBR catchments can lead to temporary eutrophic conditions, associated with noticeable surface phytoplankton blooms (McKinnon et al. 2013). The development of ocean-based macroalgal cultivation in the GBR lagoon may represent a commercially viable mechanism for the mitigation of coastal nutrient enrichment associated with excess runoff, via the biofiltration of excess nutrients (Kim 2014; Xiao et al. 2017). Despite the fact that algaculture has been identified as a key emerging industry for Queensland (Naughtin et al. 2021), at present there are no commercial ocean-based algaculture operations and only two land based facilities located there (Kelly and Macleod 2023). As a form of extensive aquaculture in which interventions such as supplemental feeding and aeration are not required (Martínez-Curci et al. 2023), algaculture in the GBR may be permitted within designated zones under a Marine Parks permit from the Great Barrier Reef Marine Park Authority (Queensland Government 2024b). These designated areas are classified as General Use, Habitat Protection and Conservation Park zones, accounting for approximately 32.6%, 28.0% and 1.5% respectively of the 345,000 km^2 marine park (Queensland Government 2024a). Marine spatial planning for algaculture in the GBR will also need to consider bathymetry and environmental parameters to maximise biofiltration services (Roleda and Hurd 2019), avoid conflict with existing industries such as shipping, and minimise potential environmental impacts (Racine, Marley, Froehlich et al. 2021).

Land-based algaculture represents an alternative means for the biofiltration of nutrients from estuarine and marine sources in areas of the GBR which experience high nutrient runoff. Land-based cultivation offers the potential to achieve high yields of commercially valuable species and the benefits of traceability and consistent biomass and product quality (Mata et al. 2016; Wu et al. 2022). The Queensland Department of Agriculture and Fisheries (2018) has identified six potential sites for locating and operating land-based aquaculture facilities in Queensland based on a range of economic, environmental and constraints mapping, spanning a total of 7,048 ha. Despite the benefits associated with land-based

algaculture, this mode of cultivation requires access to water and significant investment in infrastructure, maintenance and energy and thus poses significant technical, logistical and economic constraints (Kelly 2020). Therefore, the scope of this review and analysis will focus on ocean-based cultivation. Ocean-based cultivation accounts for the majority of seaweed production globally, and typically focuses on low-cost production of large quantities of monospecific harvestable biomass for feed or food. However, with a growing market for bioactive algal compounds, ocean-based cultivation may be better suited to the grow-out of large mature fronds than land-based systems (Hafting et al. 2015).

Achieving meaningful nutrient reductions in the GBR will be largely dependent on significant development of ocean-based algaculture (Kelly 2020) with an estimated collective macroalgal cultivation footprint of 87.7 km^2 required to meet respective DIP and DIN reduction targets in GBR catchments (Table 1). The estimates provided in Table 1 are based on calculations of nutrient removal capacity per km^2 of macroalgal cultivation for total macroalgal culture in China, with species composition dominated by *Saccharina japonica* (69.4%) and to a lesser extent, *Gracilariopsis* species (13.4%) (Xiao et al. 2017). However, in-situ nutrient uptake rates in the GBR will be dependent on cultivation species and local conditions, including temperature, irradiance, stocking density, hydrodynamics and herbivory pressure (Roleda and Hurd 2019); therefore, refining these estimates will require consideration of these factors, for example within a numerical ocean model approach.

Here, we present the results of a three-phased methodology for the selection of candidate, native macroalgal species for the purposes of biofiltration and bioproduct development, with a focus on (a) product development for the agronomical and horticultural sectors; and (b) species with demonstrated presence of bioactive metabolites or evidence of bioactivity, with potential to span a range of product areas in major markets, including pharmaceuticals, feed additives, manufacturing, food processing and cosmetics (Buschmann et al. 2017; Kelly 2020).

Characterisation of Queensland's coastal waters

Located in northeast Australia, Queensland's mainland coastline extends from latitude 28° to 10° south, spanning 6,967 km with a further 6,385 km of island coastline, including the GBR (Geoscience Australia 2024). Whilst Queensland's seafood aquaculture industry is valued at AUD $94.5 million, there are no ocean-based macroalgal culture operations and only a small number of land-based operations in the region (Department of Agriculture and Fisheries 2016a; Kelly 2020; FAO 2022). Queensland's coastal climate ranges from sub-tropical to tropical, with average water temperatures ranging 23–31 °C in the north to 19–27 °C in the south (Bureau of Meteorology 2001; Meynecke and Lee 2011). The wet season occurs primarily from October–April with average annual rainfall ranging from 700 to 1,500 mm (Meynecke and Lee 2011). Much of this rainfall is channelled to the GBR lagoon through sizeable river catchments that have seen expansive land modification for agricultural and horticultural purposes, e.g. approximately 40% land clearance for cattle grazing and sugarcane farming (Furnas 2003). Sugarcane farming is the primary contributor of dissolved inorganic nitrogen to GBR catchments, and cattle grazing is the primary contributor of sediment and particulate nutrient discharge through sub-surface erosion (Waterhouse et al. 2017). Catchment modelling estimates that 55.0 kt of total nitrogen and 13.4 kt of total phosphorous are delivered to the GBR per year, of which 53% and 66% respectively is attributed to anthropogenic changes in land use and management

Table 1 The estimated footprint of macroalgal aquaculture (km^2) required to meet the dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorous (DIP) removal targets for catchments in the Great Barrier Reef (GBR) (MCL = maintain current load)[a]

Region	Catchment/basin	Water quality targets for GBR catchments:			Macroalgal biofilter area required to achieve targets:		
		DIN removal (tonnes $year^{-1}$)	PP removal (tonnes $year^{-1}$)	Estimated DIP removal (tonnes $year^{-1}$)	Aquaculture footprint for DIN removal (km^2)	Aquaculture footprint for DIP removal (km^2)	Aquaculture footprint for combined DIN and DIP removal (km^2)
Cape York	Normanby	MCL	5.0	1.1	MCL	0.1	0.1
Wet Tropics	Mossman	52.0	MCL	MCL	0.9	MCL	0.9
	Barron	52.0	MCL	MCL	0.9	MCL	0.9
	Mulgrave-Russell	300.0	19.0	4.0	5.0	0.5	5.0
	Johnstone	350.0	250.0	52.6	5.8	6.9	6.9
	Tully	190.0	23.0	4.8	3.2	0.6	3.2
	Murray	120.0	11.0	2.3	2.0	0.3	2.0
	Herbert	620.0	57.0	12.0	10.3	1.6	10.3
Burdekin	Ross	74.0	No data	No data	1.2	No data	1.2
	Haughton	640.0	MCL	MCL	10.6	MCL	10.6
	Burdekin	100.0	440.0	92.6	1.7	12.2	12.2
	Don River	MCL	43.0	9.1	MCL	1.2	1.2
Mackay / Whitsunday	Proserpine	110.0	MCL	MCL	1.8	MCL	1.8
	O'Connell	130.0	120.0	25.3	2.2	3.3	3.3
	Pioneer	140.0	23.0	4.8	2.3	0.6	2.3
	Plane	260.0	MCL	MCL	4.3	MCL	4.3
Fitzroy	Fitzroy	MCL	380.0	80.0	MCL	10.5	10.5
	Calliope	MCL	54.0	11.4	MCL	1.5	1.5
	Boyne	MCL	5.0	1.1	MCL	0.1	0.1

Table 1 (continued)

Region	Catchment/basin	Water quality targets for GBR catchments:			Macroalgal biofilter area required to achieve targets:		
		DIN removal (tonnes year^{-1})	PP removal (tonnes year^{-1})	Estimated DIP removal (tonnes year^{-1})	Aquaculture footprint for DIN removal (km^2)	Aquaculture footprint for DIP removal (km^2)	Aquaculture footprint for combined DIN and DIP removal (km^2)
Burnett Mary	Baffle	16.0	15.0	3.2	0.3	0.4	0.4
	Kolan	34.0	5.0	1.1	0.6	0.1	0.6
	Burnett	150.0	29.0	6.1	2.5	0.8	2.5
	Burrum	93.0	3.0	0.6	1.5	0.1	1.5
	Mary	180.0	160.0	33.7	3.0	4.4	4.4
Total:		**3,611.0 tonnes**	**1,642.0 tonnes**	**345.7 tonnes**	**59.9 km^2**	**45.5 km^2**	**87.7 km^2**

[a] Water quality targets are predictions by State of Queensland (2018) for the year 2025. DIP removal targets were estimated from particulate phosphorus (PP); calculated from total monitored phosphorus load (composed of 76% particulate phosphorous, 8% dissolved organic phosphorus, 16% dissolved inorganic phosphorous) (State of Queensland 2018). Nutrient removal capacity per km.^{2} of macroalgal cultivation was calculated using estimates by Xiao et al. (2017)

(Waterhouse et al. 2017). This land modification, paired with the region's seasonal and highly variable runoff and groundwater, has led to a substantial increase in the discharge of fertilisers, sediment, freshwater, pesticides and herbicides and increased exposure of acidic soil over the last 50–150 years, impacting the water quality of GBR lagoon (Hutchings et al. 2005). Intensive agriculture is largely responsible for pesticide loading in the GBR catchments; predominantly sugarcane, which contributes the majority of photosystem II inhibiting herbicides (ametryn, atrazine, diuron and hexazinone) and, to a lesser extent, cattle grazing (tebuthiuron) (Devlin et al. 2015).

The GBR region contains a diverse and complex assemblage of macroalgae, with species assemblage and macroalgal cover linked to variation in the physical environment of the seabed and environmental conditions (Diaz-Pulido et al. 2016; Fabricius et al. 2023). Within the GBR region, macroalgae occupy a wide range of habitats, including shallow and deep coral reefs, deep inter-reef areas, seagrass beds, mangrove forests, sandy bottoms and rocky intertidal zones (Diaz-Pulido et al. 2007).

Materials and methods

A three-phased methodological approach for selection of marine macroalgal species for nutrient biofilter and bioproduct trials in Queensland's coastal waters was developed as outlined below.

Phase 1: assembling the species database

A database of all marine macroalgae recorded in Queensland's waters as of November 2020 was amalgamated from online databases maintained by AlgaeBase and Atlas of Living Australia (Atlas of Living Australia 2024; Guiry and Guiry 2024). Database records were searched by defining the geographic area as 'Queensland' and habitat as 'marine' and the species group as 'algae'. Duplicate records among online databases were removed and non-native species were excluded. Selecting only native species for cultivation in the GBR may help to maintain biodiversity by minimising the risk of of disease and pest transfer associated with the cultivation of non-native or invasive species (Campbell et al. 2019).

Phase 2: multi-criteria selection of species

The second phase of the selection process was the application of multi-criteria to the database to identify potential candidate macroalgal species suitable for commercial ocean-based cultivation in Queensland using a series of pre-requisite criteria. The criteria were determined through consultation with an independent science panel with significant experience in phycology, policy, sustainability, fisheries resource management, business strategy and commercialisation. The selection criteria were endorsed by industry partner The Australian Seaweed Institute and advocacy group The Australian Sustainable Seaweed Alliance. Using a quantitative approach, criteria were designed to ensure that the short-listed species possessed sufficient biomass to maximise the commercial viability of ocean-based cultivation and were relatively abundant and widely distributed, to enable cultivation within the GBR at a wide special scale.

The following criteria were sequentially applied to the species database (Fig. 1):

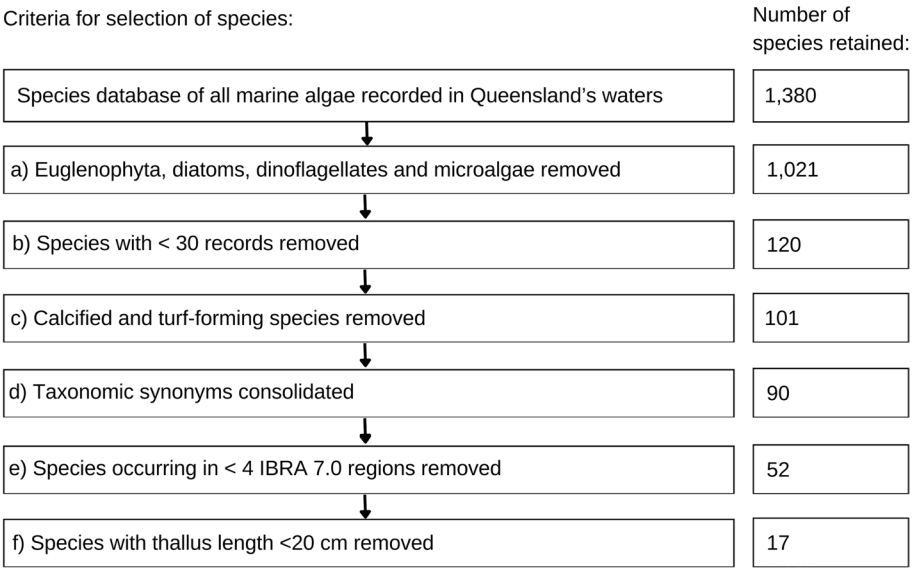


Fig. 1 Flowchart of multi-criteria selection process (Phase 2) for the identification of potential candidate species suitable for commercial macroalgal cultivation in Queensland's coastal water

(a). Must be a marine macroalgal species; this excludes euglenophyta, diatoms, dinoflagellates and microalgae which are not amenable to ocean-based cultivation.

(b). Species must be relatively abundant throughout Queensland's coastal waters, defined by an arbitrary cut-off of ≥ 30 records from Queensland waters (The Australasian Virtual Herbarium 2024). According to the Great Barrier Reef Marine Park Authority (2004), broodstock must be collected from the nearest viable population, taking account of cross-shelf, latitudinal and bioregional differences. To improve the likelihood of reliable access to source material for research and establishing nurseries, a cut-off of ≥ 30 records from Queensland's waters was selected. This cut-off was based on the distribution of the data by visualising the spread of values on a histogram; 57.3% of species had less than 10 records in Queensland's waters, with the number of records ranging from 1 to 365 and the average number of records per species being 18.

(c). Species must not have a calcified thallus (e.g. encrusting coralline algae, *Halimeda*) or be turf-forming (e.g. *Feldmannia*, *Ceramium*). Although turf-forming algae are capable of acquiring a significant proportion of nutrients from episodic runoff events and are thus a crucial component of nutrient recycling in coral reef ecosystems (den Haan, Huisman, Brocke et al. 2016), their morphology and small biomass is not suited to ocean-based aquaculture.

(d). Taxonomic synonyms checked and consolidated.

(e). Species must be relatively widespread throughout Queensland's waters to enable widespread cultivation across varying water temperatures, and reduce the risks associated with translocation activities (Great Barrier Reef Marine Park Authority 2007). Therefore, a cut-off was imposed, requiring the availability of species records in ≥ four biogeographic regions, out of a maximum of six such regions in Queensland's coastal waters. Regions were defined by the Interim Biogeographic Regionalisation for Australia version 7.0 (IBRA). IBRA represents a landscape-based approach to classifying

Australian habitats, with each region reflecting a unifying set of major environmental influences which shape biodiversity and its interaction with the physical environment (NSW Government 2016). The cutoff of ≥ four biogeographic regions was selected based on the distribution of the data by visualising the spread of values on a histogram; retaining species with a distribution spanning of ≥ four biogeographic regions preserved 58.2% of the species remaining in the database.

(f). Species must possess an average thallus length of ≥ 20 cm, with thallus length acting as an indication of biomass, given that thallus length and biomass have been shown to be highly correlated (r = 0.90) in a number of phylogenetically distinct macroalgae (Scrosati 2006).

Phase 3: systematic review of shortlisted species

The third phase of the selection process was to systematically review the existing body of literature for each of the species shortlisted in Phase 2 ($n = 17$), with respect to five research areas: (1) nutrient uptake rates; (2) growth rates; (3) bioproduct potential, with a focus on applications in agronomy and horticulture; (4) identification of bioactive primary and secondary metabolites; and (5) current status and scale of cultivation. Searches for the above research areas were conducted between April 2021 and May 2023 using the online database Scopus by searching within article title, abstract and keywords (Table 2). Duplicate records were removed from the database. Peer-reviewed journals and industry or government reports were eligible for inclusion in the review. A date cut-off or geographical limitation was not applied. Searches were carried out on both the accepted name of the species and homotypic and heterotypic synonyms, as defined by the World Register of Marine Species (2024) and Guiry and Guiry (2024); note, references to the shortlisted species hereafter include eligible records pertaining to synonymous species. In cases where more than 50 records were returned from a single search, results were sorted according to the 'relevance' function in Scopus and the first 50 records were screened for eligibility according to criteria detailed in Table 2. Although the focus of this study is on the development of ocean-based cultivation, cultivation studies conducted on land were eligible for inclusion, in order to capture reproductive biology and nursery studies, and experimental-scale cultivation studies conducted in tank-based systems.

For each research area, specific metrics were extracted from the eligible literature records. For research area one (nutrient uptake), the extracted metrics were tissue nutrient content (nitrogen and phosphorous) on a dry weight (DW) basis, nutrient uptake rate (ammonium, nitrate and phosphate) on a DW and fresh weight (FW) basis, the experimental setting (tank, field or pond-based) and the inclusion of additional explanatory variables. Extracted metrics for research area two (growth rate) were peak relative growth rate, peak biomass on a FW and DW basis, the experimental setting and the inclusion of additional explanatory variables. Ideally, records pertaining to nutrient uptake and growth would be restricted to in-situ studies of ocean-based cultivation, preferably within the GBR, as variation in temperature, among other factors such as irradiance and stocking density will affect these metrics (Roleda and Hurd 2019). Even on a small geographic scale, site-specific variation, seasonality and differences in cultivation techniques will affect nutrient uptake and growth rates among studies. However, further refinement of the selection criteria was not possible due to a scarcity of eligible records for these research areas with respect to the shortlisted species. For research area three (applications within agronomy and horticulture), data were collected on the range of applications identified and the scale of study

Table 2 Search strategy used in systematic review of shortlisted algal species (Phase 3)

Search number	Search description	Search terms	Inclusion criteria	Exclusion criteria
1	Quantitative examples of nutrient (particularly nitrogen and phosphorus-based compounds) uptake rates by algal species shortlisted in Phase 2	(Insert relevant species name) AND (nutrient* OR nitrogen OR nitrate OR nitrite OR NOx OR phosphorus OR phosphate OR organophosphate) AND (uptake OR assimilation) AND rate	Studies that provide a quantitative measurement of nutrient (nitrogen or phosphorous based compounds) or uptake/ assimilation rates for the selected algal species	Studies that do not provide a quantitative estimate of uptake/ assimilation rates
2	Quantitative examples of the growth rates of algal species shortlisted in Phase 2	(Insert relevant species name) AND (growth OR biomass OR length OR size) AND rate	Studies that provide a quantitative measurement of growth/ biomass accumulation rates for the selected algal species	Studies that do not provide a quantitative estimate of growth/ biomass accumulation rates
3	Examples of fertilizer-oriented bioproducts developed from algal species shortlisted in Phase 2	(Insert relevant species name) AND (bioproduct* OR bioactiv* OR fertilizer* OR fertiliser* OR mulch OR compost* OR soil enrichment OR plant stimulant OR agricultur* OR horticultur*)	The study must demonstrate the development and/ or use/ application of a fertilizer-oriented bioproduct from the selected algal species	Studies that focus purely on bioproducts that are not oriented toward fertilizers, and studies that purely describe methods of compound extraction from algae, and studies that focus purely on the economic cost/ benefits of algal bioproducts
4	Evidence of metabolites/ compounds present in algal species shortlisted in Phase 2, which have potential for bioproduct development	(Insert relevant species name) AND (metabolite* OR secondary metabolite* OR compound* OR analyte* OR bioactive* OR natural product*)	The study must demonstrate the presence of a compound within the algal species and demonstrate/ describe its potential use in at least one bioproduct. Studies that do not directly demonstrate the presence of the compound within the algae but instead focus only on the use of that compound in a potential bioproduct are also eligible for inclusion	Studies that focus purely on compound extraction methods

Table 2 (continued)

Search number	Search description	Search terms	Inclusion criteria	Exclusion criteria
5	Examples of laboratory culturing or aquaculture techniques for the cultivation of algal species shortlisted in Phase 2	(Insert relevant species name) AND (cultivat* OR cultur* OR aquaculture* OR farm* OR propagat* OR maricultur*)	Studies that demonstrate/ describe the production of selected species of algae through an intervention approach (e.g. laboratory culturing, sea farming etc.)	Studies that demonstrate/ describe the increased production of natural wild stocks of algae (e.g. during eutrophication). Also, studies that purely focus on environmental factors that influence algal growth

(laboratory scale, greenhouse scale or in-situ field scale). Within research area four (evidence of bioactive metabolites), data were collected on the range of bioactive primary and secondary metabolites reported and the associated applications that were demonstrated. Finally, within research area five (current status and scale of cultivation), data were collected on the range of response and explanatory variables assessed, the experimental scale (laboratory or pilot) and the experimental setting (ocean, pond or tank based). Data visualisation and figure creation was conducted in R version 4.0.4 (R Core Team 2021) using the ggplot2 package (Wickham 2009).

Finally, all shortlisted species were scored within a multi-criteria analysis with respect to the five key research areas, to aid decision in prioritising which species to carry forward to cultivation trials in the GBR as biofilters and for bioproduct development. The scoring criteria used in the multi-criteria analysis framework are presented in Supplementary Information Table S1. The weighting of the multi-criteria analysis considers the strength of advantageous metrics within each of the five key research areas (accounting for 66.6% of weighting per research area). To a lesser extent, the weighting considers the availability of scientific data within the five key research areas (accounting for 33.3% of weighting per research area) to account for the robustness of conclusions drawn. Furthermore, an additional weighting was applied to each research area, placing emphasis on the suitability of a given species for biofiltration and commercial cultivation, the key focus of this study. In research area one (nutrient uptake), only four eligible records were identified with respect to phosphate uptake rate; therefore, this variable was not included in the multi-criteria analysis as it would not provide a meaningful comparison, although these records were included in the total numbers of studies identified.

Results

Phase 1: assembling the species database

Searches of Algaebase and Atlas of Living Australia yielded 1,375 and 348 results respectively. The amalgamation of these records without duplicates resulted in a working database of 1,380 species.

Phase 2: multi-criteria selection of species

The number of species retained in the database throughout the multi-criteria selection process is displayed in Fig. 1. Seventeen species remained (Table 3) at the end of Phase 2. Regarding global marine macroalgal cultivation of these shortlisted species, at the family level, only Bonnemaisoniaceae, Caulerpaceae, Gracilariaceae, Sargassaceae, Solieriaceae and Ulvaceae have been cultivated to date (note that FAO (2022) production statistics are only classified to a family level for some entries, inhibiting the ability for direct species comparisons). The historical global production of these families, in terms of volume and value, is outlined in Fig. 2, and shows a particularly strong increase in both volume and value for Solieriaceae, and, to a lesser extent, Gracilariaceae, over the past 20 years. Of the Solieriaceae cultivated in 2020 for which a species name was reported, *Kappaphycus alvarezii* accounted for 92% on a wet weight basis, *Eucheuma denticulatum* for 8% and *Eucheumatopsis isiformi* for less than 1% (FAO 2022). All of the Gracilariaceae cultivated in 2020 belonged to the genus *Gracilaria*, although species names were not reported (FAO 2022).

Table 3 The shortlisted species remaining at the end of the Phase 2 multi-criteria selection process outlined in Fig. 1. Note that species are listed alphabetically and in no way reflect any selection preference with respect to suitability as candidate species for cultivation in Queensland's coastal waters

Species name (authority)	Family	Taxonomic phylum	Thallus morphology
Asparagopsis taxiformis	Bonnemaisoniaceae	Rhodophyta	Erect
Caulerpa taxifolia	Caulerpaceae	Chlorophyta	Erect, foliose
Cladophoropsis vaucherii-formis	Boodleaceae	Chlorophyta	Branched, filamentous
Gracilaria edulis	Gracilariaceae	Rhodophyta	Erect, simple terete branching
Halymenia durvillei	Halymeniaceae	Rhodophyta	Erect, foliose, branched
Hormophysa cuneiformis	Sargassaceae	Ochrophyta; Phaeophyceae	Erect, branching
Hydroclathrus clathratus	Scytosiphonaceae	Ochrophyta; Phaeophyceae	Spherical
Hypnea cervicornis	Hypneaceae	Rhodophyta	Erect, branching
Laurencia obtusa	Rhodomelaceae	Rhodophyta	Branched
Sarconema filiforme	Solieriaceae	Rhodophyta	Erect, branched
Sargassopsis decurrens	Sargassaceae	Ochrophyta; Phaeophyceae	Erect, branched
Sargassum baccularia	Sargassaceae	Ochrophyta; Phaeophyceae	Erect, branched
Sargassum polycystum	Sargassaceae	Ochrophyta; Phaeophyceae	Erect, branched
Sirophysalis trinodis	Sargassaceae	Ochrophyta; Phaeophyceae	Erect, branched
Solieria robusta	Areschougiaceae	Rhodophyta	Erect, branched
Spyridia filamentosa	Callithamniaceae	Rhodophyta	Erect, branched
Ulva lactuca	Ulvaceae	Chlorophyta	Erect, foliose

Phase 3: systematic review of shortlisted species

Literature searches returned 267 (nutrient uptake), 862 (growth), 593 (bioproduct potential for agronomy and horticulture), 706 (bioactive metabolites and applications) and 1,888 (current status of cultivation) records for each research area respectively (Table 4). Of these records, 16, 45, 52, 186 and 57 items met the eligibility criteria for each research area, respectively and were included in the review. Eligible records were only identified across all research areas for *Ulva lactuca* Linnaeus, *Gracilaria edulis* (S.G.Gmelin) P.C.Silva 1952 and *Hydroclathrus clathratus* (C.Agardh) M.Howe. In contrast, no eligible records were identified within any of the research areas for *Cladophoropsis vaucheriiformis* (Areschoug) Papenfuss and *Sargassopsis decurrens* (R.Brown ex Turner) Trevisan 1843.

Of the eligible records identified with respect to research area one (nutrient uptake), 75% of the studies were conducted within tank-based systems, 13% were conducted within a combination of tank and field-based systems and 12% were conducted in pond-based systems or within a combination of tank and pond-based systems. The majority (94%) of records which assessed nutrient uptake also investigated the effects of nutrient enrichment on uptake rates. Other variables which were experimentally manipulated with respect to nutrient uptake were culture density, water temperature, irradiance, salinity and CO_2 enrichment (each accounting for 6% of records). Of the species for which eligible records were returned, on average, *Caulerpa taxifolia* (M.Vahl) C.Agardh possessed the highest tissue nitrogen content, with reported values ranging from 1.17 to 5.50% DW as a percentage of dry weight (DW) (Delgado et al. 1996; Paul and de Nys 2008), whereas

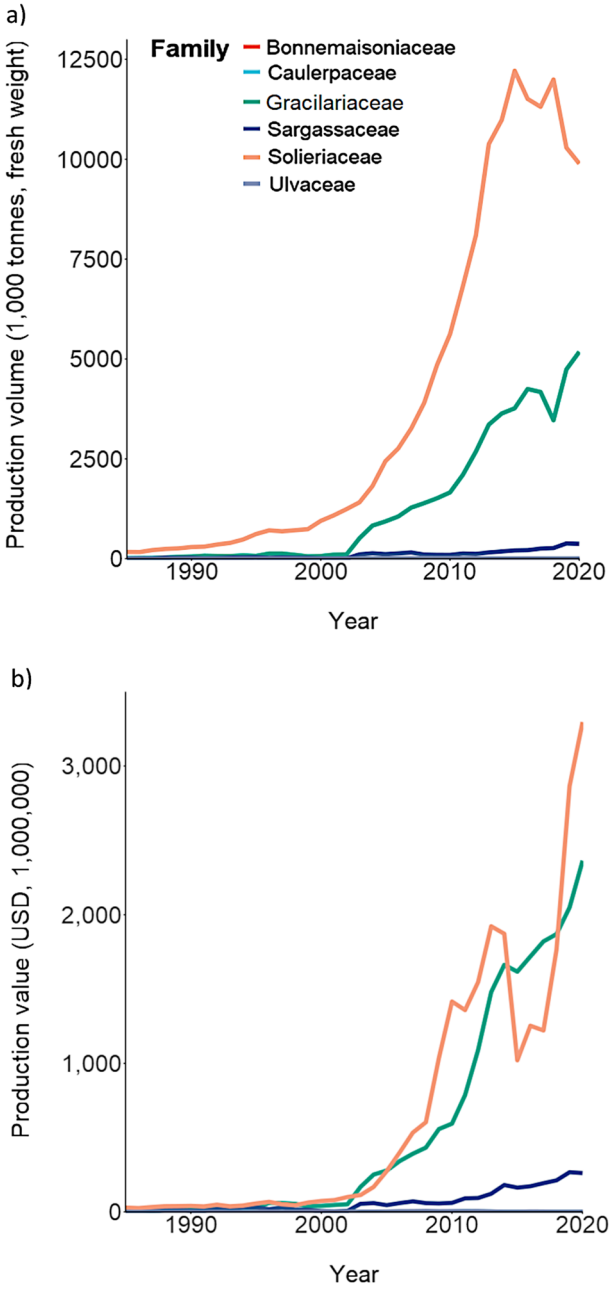


Fig. 2 Historical global production in terms of **a** volume and **b** value of Bonnemaisoniaceae, Caulerpaceae, Gracilariaceae, Sargassaceae, Solieriaceae and Ulvaceae. Data source: FAO (2022)

U. lactuca possessed the highest tissue phosphorous content, with reported values ranging from 0.10 to 0.53% DW (Van Alstyne 2018; Bews et al. 2021) (see Table 5; Fig. 3 for mean values). In terms of nutrient uptake rate on a DW basis, *Sargassum baccularia* (Mertens) C.Agardh demonstrated the greatest rates of ammonium uptake, with uptake peaking at 80.00 µmol g^{-1} h^{-1} (Schaffelke and Klumpp 1998b) and *U. lactuca* demonstrated the

Table 4 Number of records returned in the systematic review for each research area by species (Phase 3). Shown in brackets is the number of records retained after screening for eligibility. Heat map is calculated per research area based on the number of records retained after screening, with red representing minimum values, yellow representing median values and green representing maximum values, per research area

Species name (authority)	1: Nutrient uptake rate	2: Growth rate	3: Evidence of fertilizer-oriented bioproducts	4: Evidence of bioactive metabolites	5: Current status and scale of cultivation
	Number of articles returned from searches (Number of articles retained after screening for eligibility)				
Asparagopsis taxiformis	0 (0)	26 (1)	50 (1)	68 (36)	11 (3)
Caulerpa taxifolia	23 (2)	0 (0)	19 (1)	85 (10)	141 (2)
Cladophoropsis vaucheriiformis	0 (0)	2 (0)	0 (0)	0 (0)	1 (0)
Gracilaria edulis	4 (2)	37(13)	11(10)	9(5)	68(22)
Halymenia durvillei	0 (0)	4 (0)	2 (0)	4 (3)	8 (1)
Hormophysa cuneiformis	0 (0)	3 (0)	9 (4)	6 (6)	15 (1)
Hydroclathrus clathratus	3 (2)	37 (2)	31 (1)	6 (12)	77 (1)
Hypnea cervicornis	5 (0)	4 (0)	36 (6)	52 (26)	181 (11)
Laurencia obtusa	2 (0)	4 (2)	25 (6)	116 (38)	102 (1)
Sarconema filiforme	0 (0)	2 (2)	4 (0)	3 (3)	10 (2)
Sargassopsis decurrens	1 (0)	0 (0)	0 (0)	0 (0)	0 (0)
Sargassum baccularia	4 (3)	7 (2)	1 (0)	1 (0)	5 (3)
Sargassum polycystum	3 (0)	42 (4)	4 (3)	0 (0)	0 (0)
Sirophysalis trinodis	2 (0)	7 (0)	11 (0)	13 (8)	14 (0)
Solieria robusta	0 (0)	0 (0)	11 (5)	8 (7)	18 (1)
Spyridia filamentosa	2 (0)	2 (2)	8 (1)	9 (5)	29 (4)
Ulva lactuca	218 (7)	685 (17)	371 (14)	326 (27)	1,208 (5)
Total	**267 (16)**	**862 (45)**	**593 (52)**	**706 (186)**	**1,888 (57)**

greatest rates of nitrate and phosphate uptake, at 19.08 µmol g^{-1} h^{-1} and 4.93 µmol g^{-1} h^{-1}, respectively (Mhatre et al. 2018; Cartel 2020) (see Table 5 for mean values).

For research area two (growth rate), 43% of eligible studies were conducted within tank-based systems, 50% of studies were conducted in the field (of which 50% were conducted in an algaculture setting and 50% were conducted in wild populations) and 7% of studies were conducted within a combination of tank-based and field systems. The factor most commonly investigated in relation to growth was nutrient enrichment (30% of records) and, less frequently, irradiance (18%), salinity (18%), seasonality (16%) and site selection (11%). For species where data was available, the greatest relative growth rate was reported in *U. lactuca* at 54.57% FW per day (Sode et al. 2013), whereas the highest biomass was reported for *Sarconema filiforme* (Sonder) Kylin 1932 on a FW basis at 4,240 g m^{-2} (Ganesan et al. 2014) and for *U. lactuca* on a FW basis at 707 g m^{-2} (Table 6).

Of the eligible records identified for research area three (applications within agronomy and horticulture), biostimulants accounted for the largest proportion of applications identified (54% of studies), followed by biofertilisers (40%) and biofungicides (25%) (Fig. 4). The majority of studies were conducted on a laboratory scale or a small scale (76%) within pots, seed trays or hydroponic systems. By comparison, few studies assessed the efficacy of algal applications on a larger scale in-situ (24%). Further details on the applications identified in the literature concerning agronomy and horticulture are presented in Supplementary Information Table S2.

Within research area four (evidence of bioactive metabolites), terpenes and terpenoids accounted for the largest proportion of bioactive secondary metabolites reported (35%),

Table 5 Mean nutrient tissue content and nutrient uptake rates for the shortlisted species, ± standard deviation (SD). Data was obtained from the eligible records identified within the systematic review (Phase 3). All values provided in the records were used in the calculation of means. NA values are present where data was unavailable. Nutrient uptake rates are provided per dry weight (DW) where available; where conversion factors were available within a record then fresh weight (FW) values were converted to DW to aid comparison. Where conversion factors were not present the FW values are provided

Species	Mean nutrient tissue content (% DW) ± SD		Mean nutrient uptake rate (μmol g^{-1} h^{-1}) ± SD			Source	Study locations
	Nitrogen	Phosphorous	Ammonium	Nitrate	Phosphate		
Caulerpa taxifolia	3.43 ± 1.40	0.24 ± 0.13	NA (FW) NA (DW)	NA (FW) NA (DW)	NA (FW) NA (DW)	Delgado, Rodriguez-Prieto, Gacia et al. (1996), Paul and de Nys (2008)	Australia, France
Gracilaria edulis	2.80 ± 0.00	NA	2.18 ± 0.00 (FW) NA (DW)	0.11 ± 0.00 (FW) NA (DW)	0.13 ± 0.00 (FW) NA (DW)	Jones, Dennison,Preston (2001); Mawi, Krishnan, Din et al. (2020)	Australia, Malaysia
Hydroclathrus clathratus	0.57 ± 0.01	0.08 ± 0.01	NA (FW) NA (DW)	NA (FW) NA (DW)	NA (FW) NA (DW)	Schaffelke (1999),	Australia
Sargassum baccularia	1.37 ± 0.60	0.11 ± 0.04	NA (FW) 50.34 ± 34.14 (DW)	NA (FW) 0.88 ± 0.59(DW)	NA (FW) 0.08 ± 0.13 (DW)	Schaffelke (1999), Schaffelke and Klumpp (1998a), Schaffelke and Klumpp (1998b)	Australia
Ulva lactuca	3.36 ± 1.41	0.29 ± 0.16	NA (FW) 28.24 ± 9.41 (DW)	1.07 ± 0.75 (FW) 7.79 ± 7.29(DW)	NA (FW) 2.84 ± 2.02 (DW)	Bews et al. (2021), Cartel (2020), Shpigel, Guttman, Ben-Ezra et al. (2019), Van Alstyne (2018), Lubsch and Timmermans (2018), Tremblay-Gratton et al. (2017), Mhatre et al. (2018)	Canada, India, Israel, Netherlands, Philippines, USA

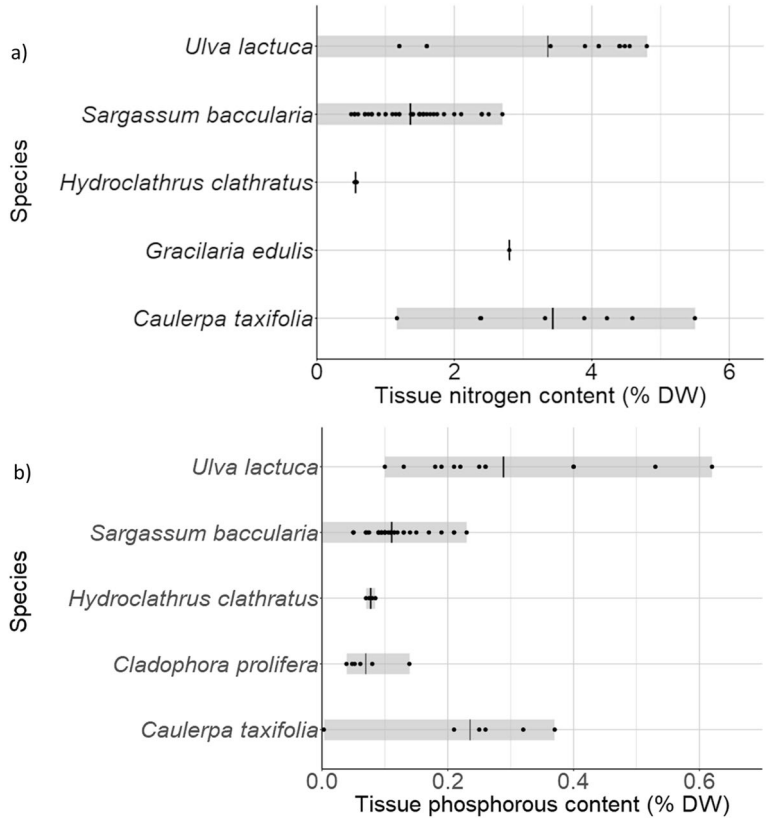


Fig. 3 Tissue **a** nitrogen; **b** phosphorous content (% dry weight (DW)) according to shortlisted species. Data points are obtained from the eligible records identified in the systematic review (see Table 5). The range of values is represented by the grey bar, with the black bar representing the mean

followed by halogenated compounds (16%) (Fig. 5b). References to primary metabolites with associated bioactivity were also reported but to a lesser extent, including polysaccharides and fatty acids (28% and 25% of records, respectively, Fig. 5a). However, in the majority of studies, the bioactivity of these compounds was not examined in isolation, but as part of an extract of a range of compounds (Fig. 5b). The majority of proposed or demonstrated applications of these bioactive compounds relate to human health (Fig. 5c), with reported antibacterial, anticancer, antifungal, antiprotozoal, antiviral, antioxidant and anti-inflammatory activity. The greatest number of proposed or demonstrated applications within the human health sector were for *U. lactuca* (31 reported applications), followed by *Hypnea cervicornis* J.Agardh and *Laurencia obtusa* (Hudson) J.V.Lamouroux (24 and 21 applications respectively). Aquaculture, including finfish, shellfish and prawns, represents an additional sector for which significant applications have been proposed or demonstrated, including as an antibacterial agent, immunostimulant and growth promoter (Mani 2021; Vijayaram et al. 2024).

Of the eligible records identified with respect to research area five (current status and scale of cultivation), irradiance, nutrient provisioning and water temperature were the most commonly assessed experimental variables (Fig. 6). Growth rate or yield was the

Table 6 Mean peak relative growth rate and biomass (dry weight (DW) or fresh weight (FW) basis) for the shortlisted species, ± standard deviation (SD). Data was obtained from the eligible records identified within the systematic review (Phase 3). Only the peak values provided in the records were used in the calculation of means. NA values are present where data was unavailable

Species	Mean peak relative growth rate (% day^{-1}) ± SD	Mean peak biomass (gDW m^{-2}) ± SD	Mean peak biomass (gFW m^{-2}) ± SD	Source	Study locations
Asparagopsis taxiformis	13.59 ± 0.0	NA	NA	Mata et al. (2017)	Australia
Gracilaria edulis	10.1 ± 13.4	NA	9,581.4 ± 3,299.1	Raikar, Iima,Fujita (2001); Ganesan, Sahu,Eswaran (2011); Yu, Lim,Phang (2013); Lavania et al. (2014); Mantri et al. (2015); Ashok et al. (2016b, a); Ashok et al. (2016b, a); Veeraguruna-than et al. (2016); Ganesan, Eswaran,Reddy (2017); Mantri et al. (2017); Mawi, Krishnan, Din et al. (2020); Kuragodage, Cumaranatunga,Deepananda (2022); Panja et al. (2022)	India, Japan, Malaysia, Sri Lanka Thailand
Hydroclathrus clathratus	NA	NA	370.0 ± 0.0	Delgado and Lapointe (1994); Marquez et al. (2014)	Philippines, USA
Laurencia obtusa	NA	18.0 ± 19.4	NA	Creed and Amado Filho (1999); Abomohra, El-Naggar,Baeshen (2018)	Brazil, Saudi Arabia
Sarconema filiforme	13.2 ± 0.0	NA	3,105.0 ± 1,605.0	Ganesan et al. (2014); Ganesan and Monisha (2017)	India
Sargassum baccularia	6.8 ± 4.0	NA	185.0 ± 0.0	Schaffelke and Klumpp (1997, 1998b)	Australia
Sargassum polycystum	4.3 ± 3.0	NA	450.0 ± 0.0	Hwang, Tsai,Lee (2004); May-Lin and Ching-Lee (2012); Zou, Xing, Su et al. (2018); Kavale, Alexander, Malarvizhi et al. (2021)	China, India, Malaysia, Taiwan

Table 6 (continued)

Species	Mean peak relative growth rate (% day^{-1}) ± SD	Mean peak biomass (gDW m^{-2}) ± SD	Mean peak biomass (gFW m^{-2}) ± SD	Source	Study locations
Spyridia filamentosa	20.0 ± 0.0	NA	NA	Amado Filho et al. (1997)	Brazil
Ulva lactuca	24.0 ± 14.7	318.8 ± 339.5	829.5 ± 961.0	Anderson, Monteiro,Levitt (1966); Niesenbaum (1988); Geertz-Hansen, Sand-Jensen, Hansen et al. (1993); Pérez-Lloréns et al. (1996); Salomonsen, Flindt,Geertz-Hansen (1997); Lee (1998); Ganesan et al. (1999); Salomonsen et al. (1999); Mallo et al. (2007); Ale, Mikkelsen,Meyer (2010); Nielsen et al. (2011); Sode et al. (2013); Chen and Zou (2015); Chávez-Sánchez, Piñón-Gimate, Serviere-Zaragoza et al. (2017); Brundu and Chindris (2018); Mhatre et al. (2018); Dinesh Kumar et al. (2023)	Cuba, China, Denmark, India, Italy, Spain, South Africa, Taiwan, USA

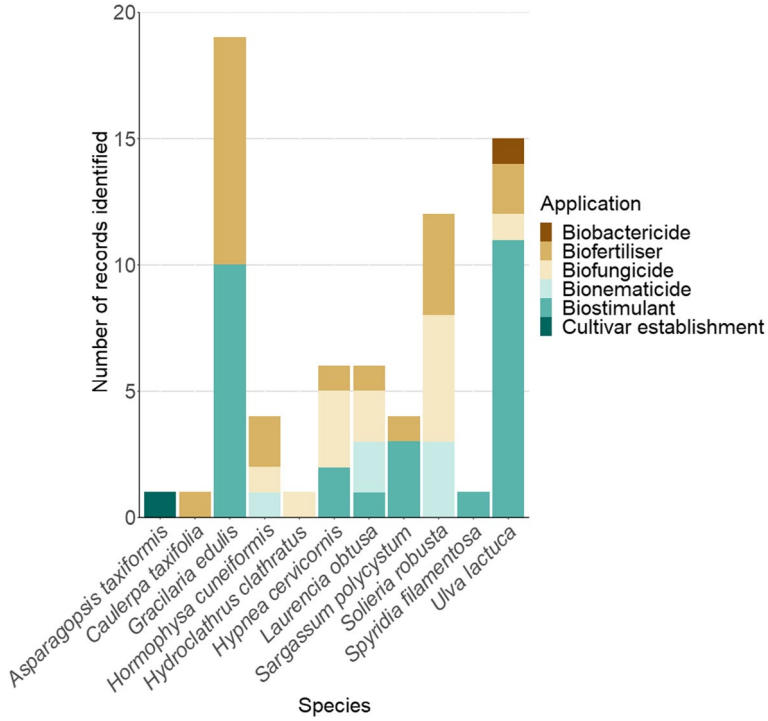


Fig. 4 Number of records identified per application (within agronomy and horticulture) per shortlisted species

most commonly assessed dependent variable, accounting for 78% of studies, followed by primary metabolite content (18%), photosynthetic pigment content (12%), secondary metabolite content (9%) and reproductive output (9%). Morphology, nutrient uptake rate, herbivory and photosynthetic rate was rarely assessed (collectively accounting for 16% of records). The majority of studies were conducted on a laboratory scale or within tank-based systems (64%), with 36% of studies being conducted in pond or ocean-based systems on a pilot scale. Of the 21 pilot scale studies, 18 were conducted in ocean-based systems, the largest of which comprised cultivation of *S. filiforme* on 1,000 m of rope using floating rafts (Ganesan et al. 2014). Three pilot scale studies were conducted in pond-based systems; the most extensive study comprised of *H. cervicornis* cultured on ropes and in baskets, within two ponds with a combined area of 5,400 m^2 (Friedlander and Zelikovitch 1984).

Within the multi-criteria analysis, *U. lactuca* ranked most highly with a score of 3.33, followed by *G. edulis* and *H. cervicornis* with respective scores of 3.06 and 2.07 (Fig. 7; Supplementary Information Table S3). *Asparagopsis taxiformis* (Delile) Trevisan, *S. filiforme*, *S. baccularia*, *Spyridia filamentosa* (Wulfen) Harvey and *Solieria robusta* (Greville) Kylin achieved scores ranging from 0.99 to 1.31. *Caulerpa taxifolia*, *Halymenia durvillei* Bory, *H. cuneiformis*, *H. clathratus*, *S. decurrens*, *Sargassum polycystum* C.Agardh and *Sirophysalis trinodis* (Forsskal) Kützing achieved scores ranging from 0.06 to 0.97. *Cladophoropsis vaucheriiformis* scored 0.00 due to data deficiency.

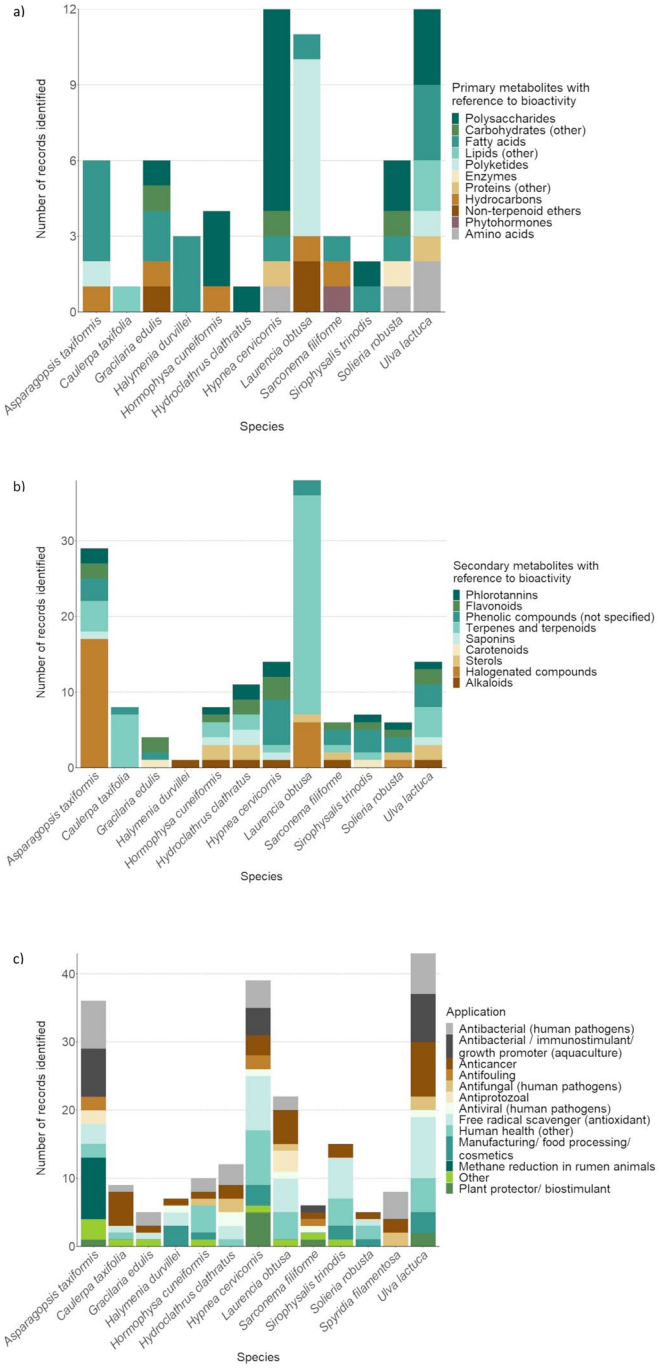


Fig. 5 Number of records identified pertaining to **a** bioactive primary metabolites; **b** bioactive secondary metabolites; and **c** proposed or demonstrated applications for bioactive compounds per shortlisted species

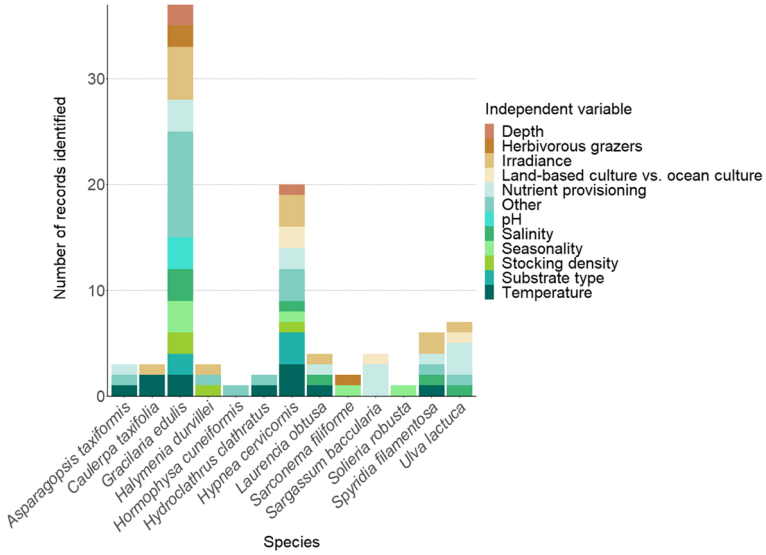


Fig. 6 Independent variables assessed with respect to cultivation per shortlisted species. Variables for which less than three records were identified were classified as 'Other'. 'Other' included supplementation with hydrogen peroxide (*Asparagopsis taxiformis*); provision of low-dose radiation (*Ulva lactuca*); water motion (*Halymenia durvillei*); site and strain selection (*Hypnea cervicornis*, *Gracilaria edulis*); fragmentation method (*Hormophysa cuneiformis* (J.F.Gmelin) P.C.Silva); pH (*Hydroclathrus clathratus*, *Spyridia filamentosa*), agar concentration in axenic culture (*H. cervicornis*), harvesting method, co-culture with bacteria, raft design and presence of epiphytes (*G. edulis*)

Discussion

Marine-based macroalgal cultivation may represent a commercially viable mechanism for the bioremediation of eutrophic coastal waters and a source of material for bioproducts (Neori et al. 2004; Duarte et al. 2021). However, the high degree of algal diversity in Queensland, coupled with gaps in our understanding of their physiology, presents challenges to determining the most promising candidate species to take forward for cultivation. We addressed this issue of species selection using a multi-criteria selection methodology to shortlist 17 species as potential candidates for cultivation. After conducting systematic literature searches across these shortlisted species with respect to their cultivation potential for biofiltration and bioproduct development, we employed a multi-criteria approach to prioritise these candidates according to the strength of advantageous metrics and, to a lesser extent, the availability of scientific data in these research areas. The multi-criteria analysis revealed that *U. lactuca*, *G. edulis*, *H. cervicornis* and *L. obtusa* appear to show the greatest promise in terms of their combined attributes of high levels of nutrient uptake, relatively fast rates of growth and biomass production, their demonstrated or potential bioproduct applications and the relatively established status of cultivation protocols. The occurrence records for these species in Queensland's coastal waters are displayed in Fig. 8.

Taking a quantitative approach to the prioritisation of the shortlisted species based on the data generated in the literature review enables an objective and transparent decision-making process with which to inform the subsequent direction of research and development and pilot scale cultivation. The engagement of stakeholders in the formulation of

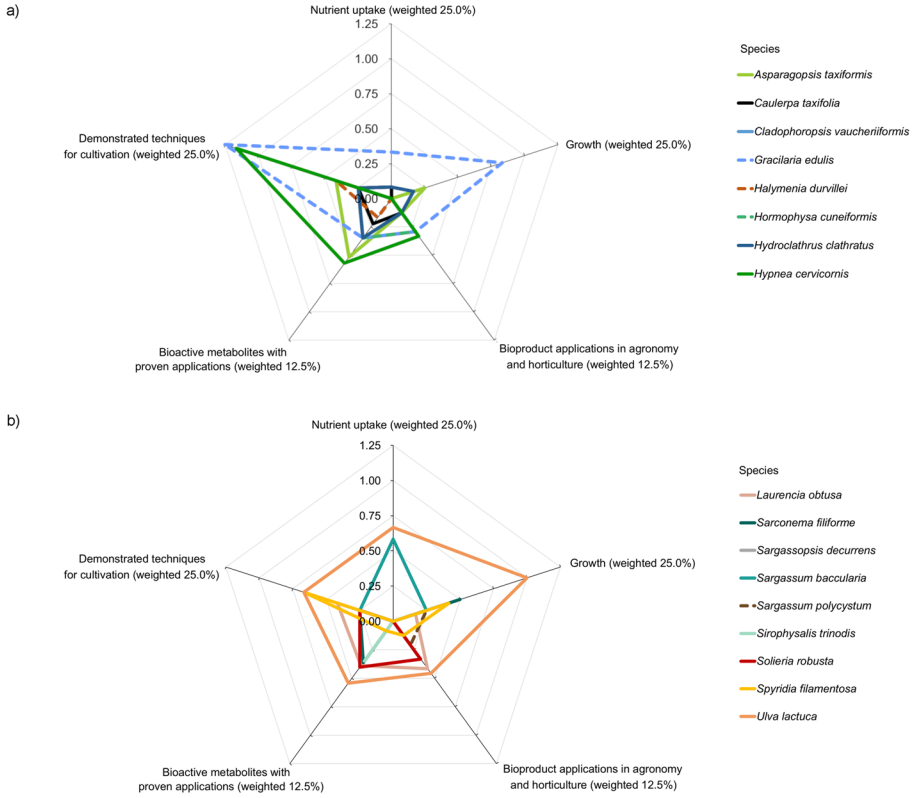


Fig. 7 Scoring of the shortlisted species within the multi-criteria analysis, with respect to the five research areas. The scoring within each research area has been adjusted by the weighting criteria, displayed in brackets. Species have been split across two graphs **a** and **b** to facilitate viewing

criteria is key to account for the preferences and priorities of the industry (Esmail and Geneletti 2018); in our case, stakeholder consultation ensures that the scope of our analysis is aligned with the needs of the emerging Australian algaculture industry.

Although the 17 species shortlisted in Phase 2 may hold potential as coastal biofilters in Queensland's waters, this conclusion is based only on currently available data and current capabilities, and the systematic review process in Phase 3 highlighted the significant research gaps surrounding a number of these species. For *C. vaucheriiformis*, *H. durvillei*, *S. decurrens*, *S. polycystum* and *S. trinodis*, eligible records were identified for only two or less of the five key research areas. These data gaps present difficulties in quantifying biofilter efficacy and identifying market potential and status of existing cultivation protocols, thereby rendering commercial cultivation of these species challenging without significant prior investment in research and development activities. Our review also highlights a scarcity of ocean-based cultivation trials for many of the shortlisted species. Pond and tank-based experiments offer a controlled environment for conducting hatchery and nursery-stage research. Utilising these systems for grow-out trials may be beneficial for early stage research, as these systems are generally less costly and subject to fewer legislative restrictions and infrastructure requirements relative to open-water cultivation. However, ocean-based cultivation trials are critical to quantify in-situ nutrient uptake and biomass in the

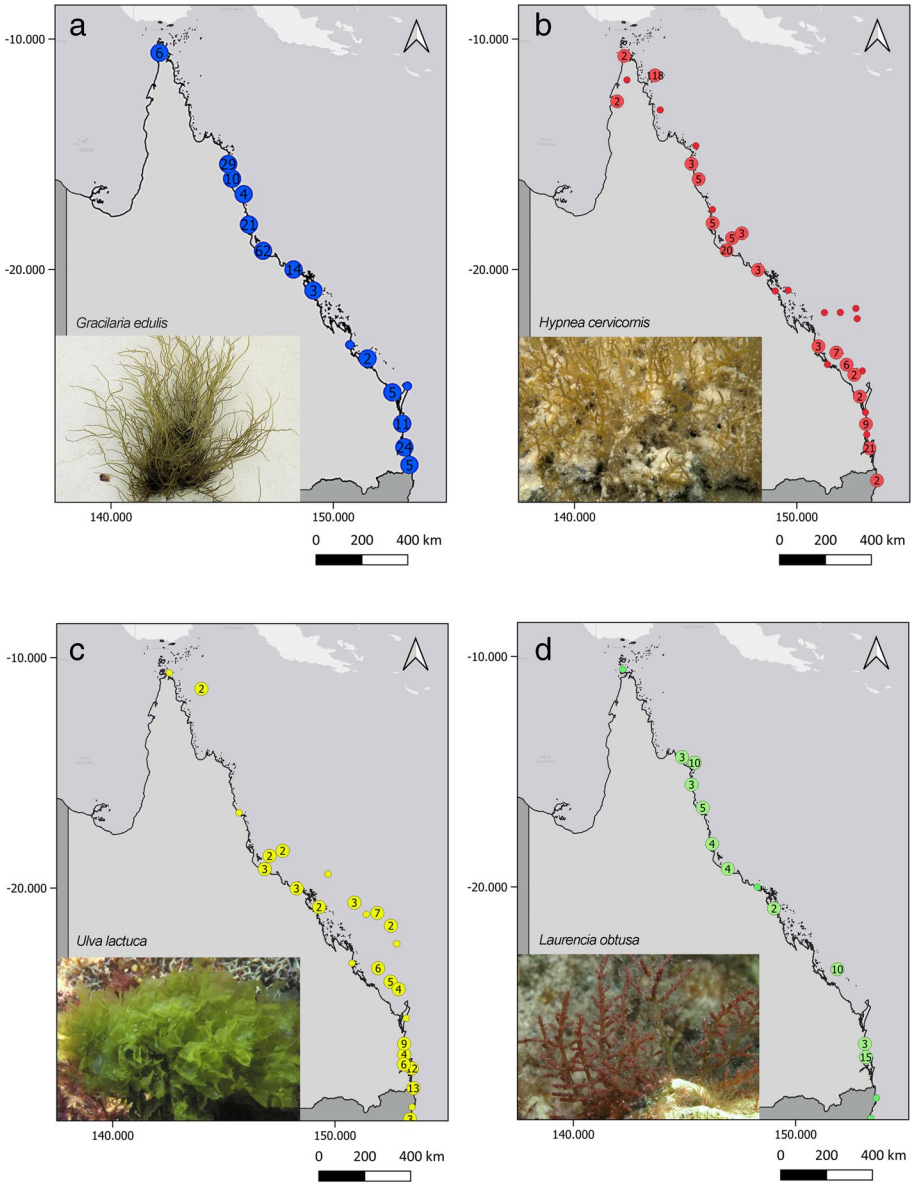


Fig. 8 Species occurrence records for the top four shortlisted species within Queensland. Multiple records are indicated with numbered text. Records were obtained from Atlas of Living Australia (2024) and mapping was conducted using the Atlas of Living Australia spatial portal. Occurrence records for **a** *Gracilaria edulis*; **b** *Hypnea cervicornis*; **c** *Ulva lactuca*; **d** *Laurencia obtusa*. Images are by K. Østerlund, N.D., J.M. Huisman, 2011, J.M. Huisman, 2011, and M. Vestjens & A. Frijsinger, 2011, respectively, and were obtained from Algaebase (Guiry and Guiry, 2024)

ocean grow-out stages. Furthermore, ocean-based cultivation trials are valuable in highlighting areas which require development to enable scaling, from farm management strategies and grow-out protocols to infrastructure and technology developments (Visch et al. 2023).

Within the systematic literature review, eligible records were identified across all five research areas for only three of the shortlisted species; *H. clathratus*, *U. lactuca* and *G. edulis*. *Ulva lactuca* represents a promising candidate for development of commercial cultivation in Queensland, ranking most highly within the multicriteria analysis. *Ulva lactuca* exhibited the greatest biofilter potential of the shortlisted species, ranking highest in terms of mean nutrient tissue contents, mean nutrient uptake rate and mean relative growth rate and ranking third in terms of mean peak biomass per m^2. Further, *U. lactuca* ranked most highly of the shortlisted species in terms of bioproduct applications in agronomy and horticulture, with demonstrated activity as a biostimulant, bactericide, fungicide and biofertiliser (Ibrahim et al. 2014; Amin 2019; Rajan et al. 2020). Bioactivity of *U. lactuca* has been demonstrated in a number of species currently cultivated in Queensland, including corn, tomato, capsicum, wheat and mung bean, with applications in promoting growth and increasing mineral content and salinity stress tolerance (Ibrahim et al. 2014; Department of Agriculture and Fisheries 2016b; Castellanos-Barriga et al. 2017; Rajan et al. 2020; El Boukhari et al. 2021; Hamouda et al. 2022). On a local scale, valorising the biomass of promising biofilters such as *Ulva* for biofertiliser applications has the potential to substitute mineral fertilisers and contribute towards reducing marine and aquatic enrichment of nitrogen and phosphorus in catchments (Seghetta et al. 2016). However, achieving a significant contribution to circular nutrient management on a national scale would require vast macroalgal supply. Furthermore, pre-treatment is generally required to utilise macroalgae as biofertilisers, the associated costs of which will need to be considered in economic viability assessments. Pre-treatment steps may include rinsing biomass to reduce salt content, chopping or further extraction processes to produce enriched subfractions (Nabti et al. 2017).

Ulva lactuca also shows potential outside of the agronomy and horticulture market, ranking second among the shortlisted species in terms of evidence and applications of bioactive primary and secondary metabolites, following *H. cervicornis* (Fig. 7). The human health and aquaculture sectors represent promising growth areas for *U. lactuca* bioproduct development, with studies frequently reporting antioxidant, anticancer, immunostimulatory and antibacterial activity of *U. lactuca* extracts (Zhong et al. 2014; Dominguez and Loret 2019). To date, the culture of *Ulva* spp. has primarily been limited to onshore cultivation in tanks or ponds, with the entirety of global aquaculture production in 2021 (2,882 tonnes) occurring in raceway ponds in South Africa in integrated aquaculture with the abalone *Haliotis midae* (Steinhagen et al. 2021; FAO 2022; Msuya et al. 2022). Despite this, a growing number of pilot studies are assessing the feasibility of cultivating *Ulva* spp. in coastal or offshore waters using suspended long-lines, nets or cages, suggesting that coastal cultivation of *U. lactuca* may be possible following research and development activities (Chemodanov et al. 2019; Steinhagen et al. 2021). *Ulva* (also *Gracilaria* and *Sargassum* species) are commonly used in bioplastic production due to their high polysaccharide content, offering additional commercial bioproduct pathways (Lim et al. 2021).

Within the scope of this review, species names are based on those reported in the literature. However, misidentification and taxonomic confusion due to variable morphological characteristics and high phenotypic plasticity are common within complex genera such as *Ulva*, particularly among foliose species (Dartois et al. 2021). Indeed, despite the presence of widespread Australian records of *U. lactuca* based on morphological identification, several studies using molecular identification have found *U. lactuca* to be absent within surveys (Kraft 2010; Kirkendale et al. 2013), suggesting that *U. lactuca* may be frequently misidentified when based on morphology alone (Gabrielson et al. 2024). Therefore, molecular identification of *Ulva*, among other candidate species, will be essential to

allow confident selection of native species and strains prior to the commencement of cultivation trials in Queensland. Although Queensland does not have a history of green tides (Ye et al. 2011), close monitoring of ocean-based *Ulva* cultivation and appropriate strain selection will be essential as some *Ulva* species are capable of proliferating rapidly under eutrophic conditions, which can lead to severe environmental and economic issues (Kang et al. 2021; Han et al. 2022).

Gracilaria edulis ranked second among the shortlisted species in the multicriteria analysis, placing first in terms of demonstrated techniques for cultivation, third in terms of nutrient uptake and second in terms of growth. Containing approximately 200 species (Guiry and Guiry 2024), the genus *Gracilaria* holds substantial economic importance as an agarophyte, of which many species are widely exploited for agar production (Vuai 2022). Further, widespread cultivation of *Gracilaria* in China has been recognised for its positive impacts in mitigating eutrophication in coastal areas (Yang et al. 2015). In the ocean, *G. edulis* is commonly cultivated using ropes or tube nets suspended close to the surface, often attached to floating bamboo rafts, although bottom cultivation is also widely practiced (Yang et al. 2015; Ashok et al. 2016b, a; Mantri et al. 2017). The commercial potential of *G. edulis*, paired with established cultivation protocols and demonstrated suitability as a biofilter in open-ocean environments suggests that *G. edulis* is a promising candidate for algaculture development in Queensland.

Following *U. lactuca* and *G. edulis*, *H. cervicornis* ranked third highest among the shortlisted species within the multi-criteria analysis. Castelar et al. (2016) demonstrated that *Hypnea musciformis*, synonym of *H. cervicornis* (Guiry and Guiry 2024), grows well in eutrophic medium and acts as an effective biofilter, achieving daily growth rates of 10.8% per day in-vitro. Despite ranking second highest among the shortlisted species in terms of availability of literature on culture methodologies, ocean-based cultivation of *H. musciformis*/*H. cervicornis* has only been attempted on a pilot scale to date, with methods ranging from racks, mesh bags and nets to line culture (off-bottom, submerged hanging or floating) (Camacho and Montaña-Fernández 2012; Castelar et al. 2016; Mohiuddin et al. 2023). Selecting the most viable cultivation system for *H. cervicornis* in the coastal waters of the GBR will require consideration of site-specific parameters (including depth, exposure, nutrient stratification and turbidity), the potential for scaling and mechanisation and the cost of installing and maintaining infrastructure (Tullberg 2022).

Hypnea cervicornis shows promise for bioproduct development within agronomy and horticulture, ranking third among the shortlisted species, with demonstrated activity as a biofertiliser, bio-fungicide and biostimulant (Machado et al. 2014a, b; de Carvalho et al. 2019). *Hypnea cervicornis* also ranked highest in terms of evidence and applications of bioactive primary and secondary metabolites, with human health representing a promising sector for product development, due to the widely reported presence of phenolic compounds and kappa-carrageenan associated with anti-inflammatory and antioxidant activity (Martins et al. 2012; Brito et al. 2016). Interestingly, despite the widespread availability of studies, *H. clathratus* did not score particularly highly in the multicriteria analysis, ranking eighth out of a total of 17 species (Fig. 7). Although *H. clathratus* is widely used in traditional medicine (Dumilag and Javier 2022) and is known to possess a diverse array of secondary metabolites with demonstrated bioactivity (Salosso and Jasmanindar 2018; Ahmed et al. 2020), our review identified a lack of studies with respect to nutrient uptake rates and relative growth rate and only a single study with respect to its cultivation (Kogame 1997) and horticultural/agricultural applications (Raj et al. 2019), thus contributing towards its poor performance in the multi-criteria analysis.

Laurencia obtusa and *S. filamentosa* may also represent potential candidates for cultivation in Queensland's coastal waters, ranking fourth and fifth respectively within the multi-criteria analysis. Of particular note, *L. obtusa* is a promising source of bioactive secondary metabolites, primarily sesquiterpenes, a trait shared among the *Laurencia* genus for which the presence of unique specialised metabolites with demonstrated cytotoxic, anti-inflammatory, antidiabetic, antifungal, antibacterial and anthelmintic activities is well-documented (Cikoš et al. 2021). Whilst significantly fewer bioactive applications have been reported for *S. filamentosa*, this species achieved the third-highest ranking among the shortlisted species in terms of relative growth rate, with peak daily growth of 20% per day reported under controlled conditions, although growth rates for cultivation of this species under field conditions need assessing (Amado Filho et al. 1997). Developing protocols for cultivation of *S. filamentosa* and *L. obtusa* in Queensland's coastal waters would require significant research and development; to date, there are few studies assessing their cultivation under controlled conditions, and a lack of studies documenting ocean-based cultivation, a trend which extends to the entire *Laurencia* and *Spyridia* genera (Nishihara, Terada,Noro 2004).

It is notable that *Sargassum* and *Caulerpa* species did not rank particularly highly within the multicriteria analysis, yet species within these genera are already cultivated at scale and have a demonstrated commercial potential (FAO 2022). The fact that the systematic review identified relatively few studies for *C. taxifolia*, *S. baccularia* and *S. polycystum* across all research areas suggests that considerable industry-led knowledge is yet to be preserved in the types of scientific literature used in our review. In 2020, the Philippines and Indonesia collectively produced 1,021 tonnes of *Caulerpa* on a fresh weight basis, valued at USD $623,340, and Indonesia and Korea collectively produced 80,936 tonnes of *Sargassum* valued at USD $27,317,950 (FAO 2022). Edible species of *Caulerpa* (such as *Caulerpa racemosa* and *Caulerpa lentillifera*) are predominantly cultivated for human consumption due to their palatable taste and nutritional properties, an area which falls outside of the scope of this review. Nonetheless, in conjunction with the rich chemo-diversity of this genus including bioactive compounds of nutraceutical and pharmaceutical importance (de Gaillande et al. 2016), *C. taxifolia* may represent a promising candidate for cultivation in Queensland's coastal waters. Similarly, with a history of traditional consumption for food (in particular, *Sargassum fusiforme*) and medicinal value (Kim et al. 2017) and a rich regional diversity (62 species identified in our Queensland database), *Sargassum* represents an interesting candidate for the development of coastal biofilters. However, despite historic consumption of *Sargassum*, its relatively high bioaccumulation potential for arsenic, heavy metals, iodine and organic pollutants may present obstacles to food and feed valorisation (Devault et al. 2021), requiring downstream processing to comply with regulations.

There has also been a growing global interest in the cultivation of *Asparagopsis*, following the discovery of its properties as a potent methane release inhibitor in ruminant animals (Machado et al. 2014a, b). In Australia, ruminants are estimated to account for 10% of total greenhouse gas emissions (Henry et al. 2012). While cultivation techniques are in development, further research is needed to identify methods for ocean-based cultivation of gametophytes, and to facilitate scaling to meet the volumes required for such a large-scale application (Zanolla et al. 2022). Although nutrient uptake rates for *A. taxiformis* were not identified within our systematic review, the tetrasporophyte stage of *Asparagopsis armata* has been demonstrated to have excellent capacity for biofiltration, demonstrating greater biofiltration efficiency than *Ulva rigida* in land-based culture (Mata et al. 2010).

The biofiltration capacity of the *Asparagopsis* genus, paired with the widely demonstrated applications of bioactive metabolites highlighted in our analysis and a ready market as a ruminant feed supplement makes *A. taxiformis* an interesting candidate for open-water cultivation in Queensland (Kelly 2020).

Achieving consistent bioactive profiles will represent a major challenge for producers targeting higher value markets such as functional foods or feeds, nutraceuticals, cosmeceuticals and pharmaceuticals (Hafting et al. 2015). In the extraction of bioactive metabolites from macroalgal biomass, the biorefinery concept represents a promising model for optimized valorisation (El Boukhari et al. 2020). Biorefinery processing enables the extraction and purification of high value bioactive compounds, in addition to the production of marketable products such as food, animal feed, fertiliser, chemicals, materials and energy (Filote et al. 2021). However, macroalgal biorefinery technology is still in its infancy and further research and investment is required to grow this technology beyond a laboratory scale.

The findings of this study are subject to limitations, most notably the data gaps in the scientific literature with respect to nutrient uptake rates, growth metrics and agricultural applications for a number of the short-listed species, thereby limiting the evaluative power of the multi-criteria approach. The ability to compare nutrient uptake rates and growth metrics both within and among species is further confounded by variation in geography, abiotic conditions and experimental design among primary literature. Further, the lack of recent studies for some species makes it difficult to draw accurate comparisons across species, particularly in areas such as nutrient uptake rates. Knowledge relating to growth metrics and cultivation techniques may already be in practice for some species such as *Caulerpa* and *Sargassum* which are already cultivated at scale; however, the relatively low number of research articles identified suggests that this knowledge is yet to be captured in the primary scientific literature and was thus missed by our review methodology. Indeed, expanding the literature review database to canvas industry reports, if accessible, or data relating to other species within the genus, would likely see greater confidence in the choosing of candidate species for bioremediation of eutrophic waters and/ or bioproduct potential. Further development of our multi-criteria approach could include consideration of additional metrics, such as the nutritional value of the shortlisted species for the purposes of human consumption and animal feed (e.g. *Asparagopsis* and *Caulerpa* spp.) and the commercial value per unit weight or market size of each shortlisted species.

An important next step to build upon this work is the identification of potential sites in the GBR for macroalgal cultivation, considering practical and regulatory constraints and the primary drivers of growth and nutrient uptake; light, temperature and nutrient availability (Roleda and Hurd 2019). Establishing pilot scale cultivation of one or more of the shortlisted species in these potential sites will provide important in-situ data to ground-truth the findings of our multi-criteria analysis with respect to nutrient uptake and productivity and will facilitate optimal culture site selection. Such trials should be conducted over multiple seasons, to account for spatial and temporal fluctuations in nitrogen and phosphorus, the levels of which may impact the uptake kinetics of cultivated macroalgae (Narvarte et al. 2024). Uptake kinetics of inorganic nutrients can have a direct effect on macroalgal physiology and have been shown to vary among species and strains (Narvarte et al. 2022). Research will also be needed to develop hatchery and nursery protocols, strain selection and determine local phenology, harvest schedules and stocking densities to aid commercialisation and scaling. Given the high levels of cryptic diversity present in macroalgae (Spalding et al. 2019), the employment of molecular

techniques for species identification will be crucial in the establishment of new algaculture programs in the GBR, in order to develop a clearer understanding of species distribution and populations and identify promising varieties for cultivation.

To conclude, we demonstrated the value of the multi-criteria selection approach in the face of high algal diversity to shortlist candidate species for cultivation, for the purposes of mitigating coastal nutrient enrichment in Queensland. Our review identified a shortlist of 17 species, with *U. lactuca*, *G. edulis* and *H. cervicornis* appearing particularly promising native candidates for biofilter and bioproduct development and a number of other species with good potential but requiring further investment in the development of cultivation protocols. Importantly, our review highlights key candidate species to be taken forward for pilot-scale cultivation trials in the GBR, in order to quantify growth and nutrient uptake rates in-situ and inform the business case for future commercial algaculture ventures. We also draw attention to important knowledge gaps for further research in the areas of nutrient uptake, growth, agricultural applications, bioactive metabolites and cultivation techniques. Using macroalgal cultivation to achieve meaningful reductions in nutrient concentrations across a broad ecosystem such as the GBR will require industrial-scale thinking supported by policy-makers and investors, to establish multiple cultivation sites and develop nurseries, efficient harvesting methods and bioproduct processing technologies. In addition, cost–benefit analysis and economic viability for end-use applications will need to be assessed. Considered site selection, assessment of environmental contaminants and implementation of biosecurity protocols and risk mitigation steps will be crucial to maximise the sustainability and commercial potential of this emerging Australian sector.

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Data availability No datasets were generated or analysed during the current study.

Code availability Not applicable.

Declarations

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