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Integrated macroalgae production for sustainable bioethanol, aquaculture and agriculture in Pacific island nations

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Abstract: The Philippine Biofuels Act of 2006 mandates domestic gasoline blending with bioethanol at a rate of 5% by 2009 and 2010, and 10% by 2011 (by volume). Akin to most biofuel policies, the Act aims to increase fuel supply security, reduce emissions, and stimulate regional development. However, the majority of biofuels blended are imported due to conventional food market demand for biofuel feedstocks, and limited domestic biofuel production capacity. A promising alternative domestic bioethanol feedstock is macroalgae (seaweed) species, of which the Philippines is already a major global commercial producer. The advantages of using particular non-food macroalgae as a bioethanol feedstock include zero competition with agricultural food production, no freshwater requirement, high yields per area, zero fertilizer applications, and the pre-existing markets for bioethanol macroalgae wastes. Adaptation of existing macroalgae farming methods, customized to high-yielding non-food bioethanol precursor species, can enable rapid expansion into industrial-scale biofuel production, far exceeding terrestrial bioethanol yields in terms of per unit area. This work identifies the regional availability and supply of appropriate macroalgae species suitable for bioethanol production, and explores integrated production synergies and challenges for an environmentally sustainable macroalgae bioethanol industry suitable for a number of Pacific island nations.
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Keywords: macroalgae; biofuel, ethanol; Pacific; energy security

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Introduction

Akin to many Pacific island nations, the Philippines is heavily dependent on imported energy to supply domestic liquid fuel and electricity needs.[1] Currently, Shell Philippines and other petroleum companies import bioethanol from Brazil to meet the Philippine Biofuels Act (2006) blending requirements, as sufficient domestic bioethanol processing capacity is low.[2,3] Similarly, the current domestic bioethanol feedstock supply exhibits high seasonal and geographical variability, and the corresponding price is highly variable over the year.[4] Whilst most bioethanol feedstock is sugar or starch food/feed grade products, the Philippines will require non-food/feed bioethanol input feedstocks to prevent domestic food price inflation, as the Philippines is a sizable net food importing nation with a sizeable rural poor population sensitive to food prices.[5–7] This work assesses the availability of farming macroscopic marine brown macroalgae (seaweed) species (*Sargassum spp.*), due to their natural abundance in Pacific regions and potential suitability as a current non-food bioethanol feedstock,[8] in the Philippines and other Pacific island nations generally who seek to balance energy and food security.

Macroalgae represent a diverse range of photosynthetic marine organisms,[8] and more than 800 known species of benthic marine macroalgae (attached to the ocean floor) exist in the Philippines alone.[9,10] Benthic macroalgae are important primary biomass producers in shallow coastal areas on which the ecosystems depend directly and indirectly.[11,12] Macroalgae are also a major global aquacultural/maricultural industry[13] with 90% of the 15.7 million wet tonnes (approx. 1 million dry weight) harvested worldwide derived from nearshore farmed mariculture production.[14] Industrial algal production can reduce land competition between current biofuel systems and conventional food production by an order of magnitude.[15–17] Whilst terrestrial-based microalgae (single-celled algae) have received much recent focus for their high productivity, and despite literally billions of US dollars (USD) invested in R&D in terrestrial microalgae, the terrestrial production processes remains fundamentally reliant on the application of the inorganic elements which constitute the cells, including nitrogen, iron, and phosphorus, which are generally supplied as conventional fertilizer inputs.[13,17] Industrial microalgae production is particularly limited by the decrease in quality and the increasing price of non-renewable sources of mined phosphate rock, resulting in production cost increases.[18] In a similar manner to mineral oils, modern agricultural sources of phosphorus are geographically concentrated and may be depleted well before the next century, and microalgae biofuels may be a very large new consumer which accelerates demand.[18,19] Whilst technologies exist to recover much microalgal nutrients from production wastes, macroalgae production needs no conventional nutrient input, is already used as an agricultural organic fertilizer, and also an excellent source of micro-elemental nutrition for land animals.[8,20–22] From a macronutrient perspective, there is a low dry weight phosphorus content (0.78–1.53%) relative to the high nitrogen content (34.31–56.34%) for most marine macroalgae.[*23] Nonetheless, harvesting marine algae may still provide a means of recovering both phosphorus and nitrogen from saline wastewater,[24] or even the ocean. In theory, this could reverse some of the existing nutrient flows into coastal waters and coral ecosystems from terrestrial agricultural runoff, using a method comparable to phytoremediation.

Conventional ethanol feedstocks and the Philippines Biofuel Act

Bioethanol can be produced through fermentation of biological feedstocks that contain appreciable amounts of sugar, or any material that can be converted into sugar.[25,26] The three major classifications of bioethanol feedstocks are sucrose-containing feedstocks (i.e. sugarbeet, sweet sorghum, and sugarcane), starchy materials (i.e. wheat, corn, and barley), and lignocellulosic biomass (i.e. agricultural residues like wood, straw, and grasses).[25,27,28] Whilst this diversity of available feedstocks provides flexibility, seasonal availability is an issue in many regions.[4,27] As with most governments of Pacific island nations, the government of the Philippines has identified risks to expansion of the bioethanol-gasoline blending program, including the security of the biofuel precursor feedstocks over time, public acceptance of the blended fuel, the absence of domestic blending standards,

* Macroalgae nutrient contents are also seasonally variable, with generally higher contents in May, and lower contents in November.[23]

engines able to accept blends beyond 10% bioethanol (by volume), and insufficient investment in domestic production facilities.[29] Table 1 shows the volume of agricultural common crops produced in the Philippines (which are also common to many Pacific island nations) that may be utilized as feedstocks for bioethanol production.

The Philippines currently grows enough bioethanol feedstock domestically for local facilities to produce the volume of fuel necessary to meet the 10% gasoline-bioethanol blend mandate. The theoretical potential volume of bioethanol that can be produced from these feedstocks is shown in Table 2. To meet the Philippine Biofuels Act of 2006 target, only around 5% of the total annual crop production was required to meet the 2010 demand for ethanol. Whilst this does not seem like much, this would have reallocated approximately 0.6 million t of corn, or 3.2 million t of sugarcane from the food supply chain into the fuel sector. Thus, for a large net food importing developing country like the Philippines, this would be a major issue in terms of food security and local food price stability, particularly for the millions of rural poor families who are unable to afford sufficient food for extended periods of the year.[5–7] In stark contrast, native non-food macroalgae species are suitable technical and economic substitutes to displace food-crop bioethanol feedstocks as they exhibit high levels of structural polysaccharides, zero lignin (or extremely minor levels), and similar species are currently produced using existing cost-effective methods.

Characteristics of macroalgae and current uses

Macroalgae are historically divided into three major groups based on their photosynthetic pigments: Chlorophyta (green algae), Rhodophyta (red algae), and Phaeophyta (brown algae).[8,31] The distinct brown color of the Phaeophyta is due to the predominance of xanthophylls pigments, and their cell walls are composed of alginic acid, cellulose, and other polysaccharides, with the plant storing energy as laminarin and mannitol.[32,33] About 365 species of marine benthic macroalgae are commercially farmed in the Philippines, although the most common are food-grade red macroalgae which are often grouped by their major uses; agarophytes (agar-producing); carageenophytes (carageenan-producing); alginophytes (alginate-producing), and; other uses.[34] The commercial red species (*Eucheuma)* commonly grown domestically include *E. cottonii* and *E. spinosum* (for carrageenan), and *E. gracilaria and E. gelidium* (for agar agar). The other major commercial macroalgae in the Philippines are *Kappaphycus*, *Gracilaria,* and *Caulerpa* species, with smaller commercial operations producing *Codium*, *Gelidiela, Halymenia*, *Porphyra* and *Sargassum* species.[10,31]

Table 1. Volume of agricultural crop production 2005–2009.[29]

	Production in MT				
Crop	2005	2006	2007	2008	2009
Corn	5 253 160	6 082 109	6 736 940	6 928 225	7 034 033
Cassava	1 677 564	1 756 856	1 871 138	1 941 575	2 043 719
Sugarcane	22 917 674	24 345 106	22 235 297	26 601 384	22 932 819
White Potato	70 160	69 461	118 497	121 311	119 159

Table 2. Potential ethanol production from agricultural crops.

	2009 Total Production[10] (t)	Average 2005-2009 yield[30] ($t\ ha^{-1}\ yr^{-1}$)	Conversion Efficiency[30] ($L\ t^{-1}$)	Ethanol Yield[30] ($L\ ha^{-1}\ ha^{-1}$)	Potential Ethanol Production[30] (ML)
Corn	7 034 033	2.46	350–460	917–1206	2462–2947
Cassava	2 043 719	8.87	180	1704	368
Sugarcane	22 932 819	61.17	68–70	3860–3973	1559–1666
White Potato	119 159	14.14	100	1508	12
Total					4401–4993

Philippine commercial macroalgae production development

During the mid-1960s, the abundant natural supply of *Eucheuma* species in the Sulu Archipelago and Eastern Visayas in the Philippines became scarce due to unsystematic and uncontrolled harvesting. In 1966, commercial propagation commenced, selecting commercially productive species to satisfy growing demand.[35,36] In 1969, a large successful *Eucheuma* plantation around Tapaan Island, Siasi, Jolo was established in the Central Visayas.[32] Today, macroalgae farms are common in the coastal areas of Jolo, Tawi-tawi, Zamboanga del Norte, Zamboanga del Sur, Palawan, Bohol, and around the Visayas and Mindanao. More recent total macroalgae industry production in the Philippines from 1997 to 2008 is shown in Fig. 1. The steady increase in production is attributed to high market demand, improving prices, and a suitable natural climate.[10] According to the Philippine Department of Agriculture (2010), the marked increase in macroalgae output in 2008 was due to improved planting and farming techniques, materials, and management, together with the newly opened areas in Palawan.[37] In 2008, macroalgae represented the largest aquacultural production (around 1.7 million wet tonnes), representing 69% of total Philippine production by fresh weight.[37] Macroalgae exports include raw (fresh or dried), or processed (alkali-treated chips, semi-refined chips/carrageenan, and refined carrageenan).[36] The major importing countries of Philippine macroalgae products (primarily food-related uses) are France, Korea, China, the USA, and Germany,[10] which generated an export income of almost 5.4 million Philippine Pesos (PHP) in 2008 (Table 3). The possibility of shipping additional macroalgae for biofuel production remains as an export opportunity in the Philippines.[38] The relatively low current market value per tonne for the variety of macroalgal biomass exports (~USD7.5 – 1.5 t^{-1}) relative to other biomass is likely to facilitate new markets, and potentially provide a cost-effective new supply of biofuel feedstock for importing nations. (As of early 2011, 1 USD was worth roughly 44 PHPs).

Potential Philippine macroalgae ethanol production estimates

Research results by Aizawa *et al.* stated that 1 t of dried and fermented raw *Sargassum* (90% moisture, 5.8% carbohydrate) produced 29.6 kg, or approximately 38 L of bioethanol (0.38% conversion efficiency). The waste products include 900 kg of water, and around 70 kg of mineral supplements or fertilizers.[39] Using these simple conversion rates, if the entire 2008 commercial Philippine macroalgae production of 1 666 556 t was processed into bioethanol, it could produce around 63 million L. This is approximately equal to around one-third (29%) of the 5% (by volume) 2010 bioethanol requirement. However, as the current macroalgae production is predominantly food species, an alternative means to supply biomass feedstock is the under-utilized *Sargassum* species.

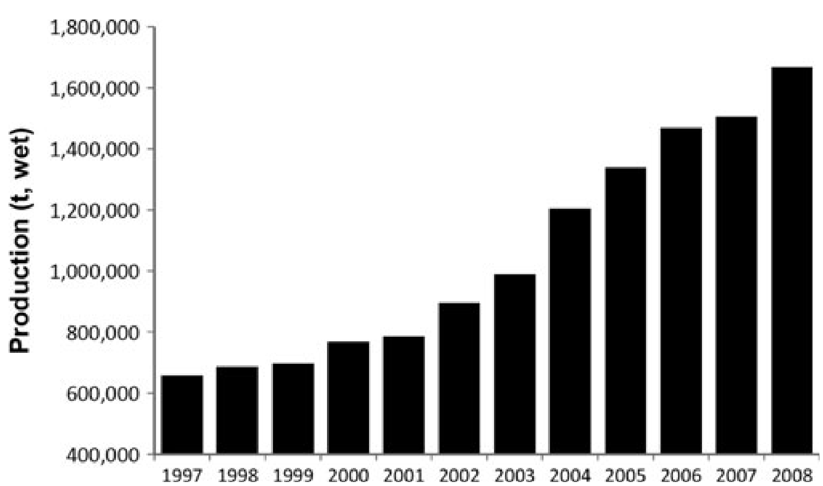

Figure 1. Macroalgae production in the Philippines 1997–2008. Note: the approximate moisture content is 90%.[10]

Table 3. Macroalgae exports in terms of value, 2008.[10]

Commodity	Quantity (t)	FOB Value (USD)	FOB Value (Pesos)
Macroalgae and microalgae	10 541	20 817	920 743
Macroalgae for human consumption	2882	4544	200 975
Carageenan	12 825	96 669	4 275 689
Total	26 248	122 030	5 397 407

Table 4. Surface area required for *Sargassum* species cultivation.[29,39]

Year	Est. Fuel Displacement (million t)	*Sargassum* Required (t)	Water Surface Area Required (in km^2)	% Total Sea Area of the Philippines (total sea area is 1 039 190 km^2)	% Total Coastal Area of the Philippines (total coastal area is 226 000 km^2)
2010	218.93	5 761 316	1721	0.172	0.76
2011	460.63	12 121 842	3620	0.35	1.6
2014	536.29	14 112 895	4215	0.41	1.9

Data presented by Aizawa *et al.* was used to approximate the ocean surface areas required for large-scale *Sargassum* farming using floating technology productivities of around 3348 t km^{-2} y^{-1} wet weight (9 g m^{-2} day^{-1}).[39] Table 4 shows the approximate sustainably farmed surface areas required to meet the bioethanol volumes required for the Philippine Biofuels Act in 2010, 2011, and the demand growth up to 2014. The Table uses the 3348 t *Sargassum* km^{-2} annual productivity, and the 0.38% conversion efficiency to bioethanol to estimate the area requirement for bioethanol production in the Philippines.† Based on Table 4 calculations and assumptions, less than 1% of the total sea area or about 2% of the total coastal area of the Philippines is required to meet the bioethanol production targets. According to 2002 estimations from the Seaweed Industry Association of the Philippines (SIAP), the potential Philippine macroalgal farmable coastal area remains at around 3550 km^2, while only about 433 km^2 were utilized at the time. Thus, the entire 2010 bioethanol requirement can be met by the *Sargassum* species cultivation without competition with existing macroalgae producers, although the 2011 and 2014 requirement will slightly exceed the existing farmable area in coastal areas. Therefore, either additional coastal areas, an increase in macroalgae farm productivity, or higher conversion efficiencies will be necessary to meet the mandated bioethanol targets post 2010 using macroalgae. Alternatively, as the open ocean may also be utilized for macroalgae,[8] new *Sargassum* cultivars cultured with existing technologies can be used to meet national bioethanol targets far in excess of current demand, without competition with any current macroalgae production.

†The authors note that as with any crop, the yield, hydrolysable carbohydrate levels, and bioethanol conversion efficiencies will vary over time, sometimes widely. Nonetheless, the authors have selected the Aizawa et al. results from Japan as an indication of realistic crop-to-ethanol expectations for large production areas in the Pacific.

Macroalgae farming methods and construction requirements

Almost 90% of macroalgae production in the Philippines is derived from farming, while the remaining 10% is wild harvested.[36] Traditional macroalgae species are grown in nearshore coastal waters, with some smaller operations even occurring on land in ponds. Coastal farming systems commonly occur in shallow habitats (<500 m depth) which enable a sheltered growth environment, while offshore systems are an emerging macroalgae culture technology with water depths of between 500 and 3000 m. In the Philippines, two main shallow farming systems are presently used by macroalgae farmers; the fixed off-bottom monoline, and the floating methods.[10,40]

In the 'off-bottom' fixed monoline method, the construction of the farm support system requires the creation of holes in the substratum to affix support stakes. The monoline is attached to the stakes and the tension is adjusted between stakes to prevent algal exposure to the air, and unsuitable depths during changing tides. Each parallel monoline is generally aligned with the direction of the current or waves.[40] The floating method is used in either deepwater and shallow waters, with low water velocities, or where the substrata topography is irregular. In the floating raft method, the monolines are attached to a floating frame parallel to the length of the frame. The macroalgae plantlets are cultured on ropes slung between mooring. (Fig. 2).[8,34] In both methods, farm maintenance consists primarily of weeding out epiphytes (non-parasitic plants) associated with the crop such as competing macroalgae, removal of sand and organic litter, culling poorly growing macroalgal stocks, replacing lost or culled macroalgae with more productive stocks, removing benthic grazers, and repairing the farm support system.[8,34]

Uses of macroalgae post-ethanol processing, with a focus on *Sargassum spp.*

Both upstream and downstream of the algae fermentation process, waste macroalgal biomass may be used to produce several useable substances that lower the total production costs of the primary fuel.[17,41,42] Currently, the most common use of *Sargassum* species in the Philippines is as a wrap

Figure 2. Coastal macroalgae farming facility. Courtesy of Inland Fisheries and Aquaculture Division, BFAR.

to maintain the freshness of fish and other marine animals, although in coastal agricultural regions, fresh *Sargassum* is also used as a feed for pigs and cattle, while bleached and powdered *Sargassum* is exported as animal feed.[9,43] In the Visayas and Mindanao regions where there are influences of the Cebuano culture, *Sargassum* is also used as a fertilizer by mixing salt-free macroalgae with the soil or potting media.[43] Montaño and Tupas demonstrated that *Sargassum* contains plant growth promoting hormones such as auxin, gibberelin, and cytokinin.[44] *Sargassum* can also be a source for the manufacture of alginate, a polysaccharide that absorbs large quantities of water.[13,32,34] However, the species of *Sargassum* which are harvested from warmer waters usually provide only low yields of lower quality alginate.[45] Furthermore, there is little commercial production of alginate in the Philippines, possibly due to the low viscosity of the extracts from local seaweed alginate.[34] Whilst *Sargassum* species culture is undeveloped relative to other local macroalgae species, the common existence of several *Sargassum* species on rocky coastal habitats suggests the available farming sites could be very large and a massive new source of cost-effective non-food biomass.[32] Montaño reported that there are at least 50 natural distribution sites for *Sargassum* in the Philippines alone (Fig. 3).[46]

Protecting wild macroalgae and the ecological impact of farming

The commercial production of macroalgae from both harvesting natural stocks or through farming in the Philippines is regulated by the Fisheries Administrative Order (FAO) No. 146 Series of 1983.[47] The FAO provides for the conservation of the natural macroalgae beds, in addition to promoting sound management of farming areas. The harvesting of macroalgae in restricted areas declared by the Bureau of Fisheries and Aquatic Resources (BFAR) requires a permit. Likewise macroalgae farmers also require a permit from BFAR, and farm sizes are limited based on the legal entity status, with 30 ha allowed for a corporation, association, or company, and only 1 ha allowed for a private citizen.[32]

Highly productive macroalgae farms are generally located in areas with good currents or a moderate wave action, appropriate salinity levels, sufficient depth, fertile (although unpolluted) waters with diverse local flora and fauna.[40] Such areas often attract additional farms which can negatively

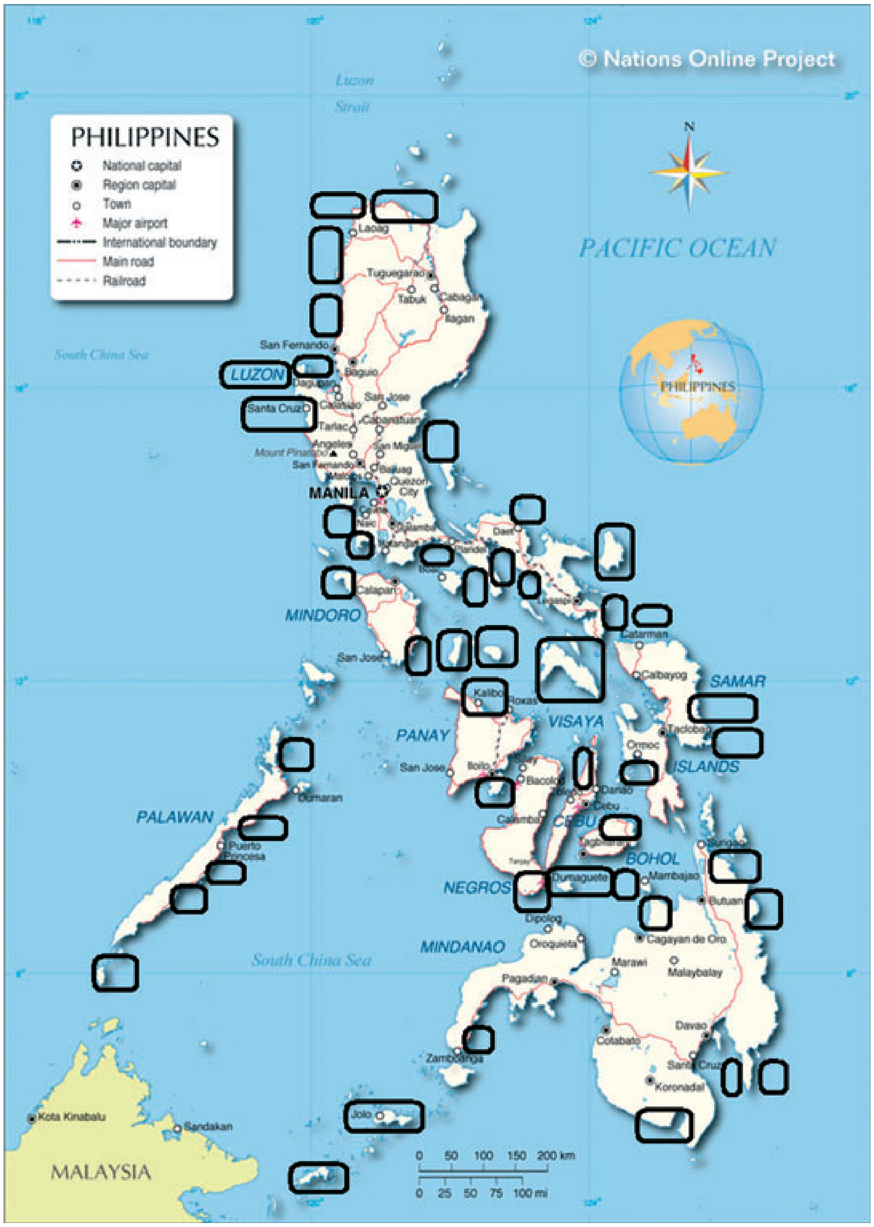

Figure 3. Approximate *Sargassum* species distribution sites in the Philippines. Source: *Sargassum spp.* distribution site data was adapted from Montaño.[46] The Philippines map is courtesy of the Nations Online Project www.nationsonline.org.

influence the local hydrology. Water movement in algae farms is important for aeration, transport of nutrients, and mixing to prevent stratified water temperatures.[32,47] When water movement is highly reduced due to over-concentration of adjacent macroalgae farms, the resulting decreased water nutrient concentrations and increased water temperatures during periods of high irradiance results in decreases in overall macroalgal productivity per unit area.[40] Furthermore, regions with excessive numbers of monoculture macroalgae farms increase the occurrence of macroalgae pathogens, competitors, and grazers which can reduce yields below commercial quantities and quality.[8] Therefore, the commercial imperative of maintaining healthy coastal marine areas to maintain high productivity are synergistic with environmental objectives. This is especially significant since many coastal areas in the Philippines have been devastated by poor fisherman illegally using cyanide and dynamite to catch the dwindling fishery resources. In some regions the local fishermen are now growing macroalgae, doubling their previous wage, and those who do use cyanide or dynamite now risk inadvertently killing their macroalgae farms. These now subsistence fishermen and macroalgae farmers are adding to the growing number of local people who are becoming a variety of natural surveillance and patrol to protect coastal areas against such harmful fishing methods.

Further benefits of the expanding macroalgae industry are additional fishery aggregation sites, as the artificial structures provide fauna (fish and invertebrates) with artificial habitats and feeding grounds.[48] Yet, the total biomass of the macroalgae farms fluctuates significantly, being particularly small during the start of cropping (planting) and also at harvesting periods, and is relatively large during the grow-out phase. Despite the additional surface water biomass fauna habitat in the grow-out phase, in theory there may be a negative impact on shallow water coral communities below due to lower light levels. However, according to a field study in 2007 in the Philippines at Lamitan, Basilan, (supported by the Food and Agriculture Organization), coral communities located between 5 and 10 m below multiple floating macroalgae units remained robust and healthy.[40] The direct and easily measured negative impacts of macroalgae farming generally occur during establishment of the support systems in shallow areas using the fixed off-bottom monoline method. Nonetheless, this direct impact in the construction phase is relatively minor (being the driving of metal stakes into the sea bed, and the original flora and fauna recover quickly in the tropical waters.[40] Despite the potential for some minor negative ecological impacts of some farming methods in shallow waters, the further development of deepwater floating methods would enable the avoidance of important coastal ecologies altogether.

Furthermore, macroalgal farming can be integrated as a secondary product grown in polyculture specifically to remove nutrient from aquaculture systems in terrestrial ponds. For example, *Sargassum* species have been successfully cultivated in a polyculture with western king prawn (*Penaeus latisulcatus*) culture ponds. The integrated polyculture resulted in macroalgae growth rates increasing 3.16 ± 0.74% g day^{-1} above that of the monoculture rate of 5.70 ± 0.82% g day^{-1} over a 7-day period, with significantly lower ($p < 0.05$) total ammonium nitrogen, nitrite–nitrogen (NO^{2-}) and nitrate–nitrogen (NO^{3-}), dissolved inorganic nitrogen, total nitrogen, phosphate (PO_4^{3-}) and total phosphorus in the water, with no negative impact on the prawn yields.[24] Several other aquaculture fauna species are amenable to polyculture with macroalgae to mitigate high-nutrient aquacultural effluent release into aquatic systems.[49]

Conclusion

While the wild stocks of *Sargassum* and the existing production of macroalgae is insufficient to meet the growing bioethanol demands in Pacific island nations like the Philippines, such regions enjoy a natural advantage favoring commercial expansion of the industry. Algae represent a potentially large industrial developmental opportunity for Pacific island nations to meet future societal needs for renewable energy and alternative biomaterials, while also reducing biofuel development pressures on terrestrial forests and food supplies.[1,5,8,38] Fundamental constraints to industrial expansion relate to basic scientific and technological capacities, and requirements for the development of commercial farming technology and culture systems for the *Sargassum* species, akin to *Eucheuma*, *Kappaphycus*, *Gracilaria* species and *Caulerpa lentillifera* systems. As the commercial production of bioethanol from algae requires industrial-scale quantities at low cost, there is a significant associated infrastructure investment requirement, both pre- and post-farm to develop high efficiency in the production chain.[8,19] Finally, mitigating negative ecological impacts of large-scale macroalgae farming in coastal environments will require technology development, and the implementation of regulation that at least maintains the unique natural environments required to secure sustained high industry-wide productivity to provide cost-effective biofuel feedstock.

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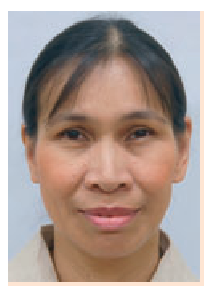

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