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RESEARCH

Regulatory ecosystem services through large-scale commercial farming of *Kappaphycus alvarezii*: Pan-India potential estimates

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Abstract

For more than a billion years, seaweeds have been a segment of marine primary productivity this fact must be contemplated while considering emerging conceptual frameworks such as the "blue economy". This sector not only has the potential to provide renewable feedstock but its cultivation and processing ticks an important box for sustainable development. Seaweed cultivation in India is gaining momentum and great attention is being given to developing the infrastructure. A flagship program 'Pradhan Mantri Matsya Sampada Yojana (PMMSY)' has provided adequate budgetary allocation to achieve a production of 11.2 Mt (fresh) feedstock. However, the scheme seems to focus only on material benefits (product development) and the ecosystem services, especially regulatory services have seldom been taken into consideration. Thus, the present article tries to address the estimation of potential regulatory ecosystem services [capture carbon, uptake nutrients and heavy metals (Cr, Co, Cd)] met through *Kappaphycus alvarezii* farming, at the Pan-India level. The estimates were made for both tube net and raft cultivation methods separately. The farm cover was estimated to be around 700,000 ha supporting approximately 780,000 farmers for tube net, while it was 56,000 ha supporting ~ 1.25 million farmers for raft cultivation. A total number of tube nets that would be put to use would be 140 million and 56 million in the case of rafts. Once the target is achieved India would have gained the ability to annually capture approximately 600,000 t of carbon, 22,000 t of nitrogen, and 2000 t of phosphorous and absorb more than 1000 t of heavy metals cumulatively. Nevertheless, a monetary valuation of ecosystem services is needed to arrive at rational decisions by policy-makers and resource managers.

Keywords Carbon capture · Ecosystem services · Heavy metal absorption · Nutrient uptake · Regulatory services · Seaweed cultivation

Introduction

Marine ecosystems are among the most productive habitats across the globe. They are responsible for providing varied economic and social benefits, which contribute to the blue economy of any nation. The major contributors to the blue economy come through fisheries, coastal tourism, and maritime transport sectors. But in recent times marine aquaculture—in particular seaweed farming—is on the rise globally, as it also contributes significantly to food supplies in addition to other ecological benefits.

Historically, seaweeds have been used in food, feed and other non-food applications for hundreds of years especially in Asian countries like Malaysia, Indonesia and China (Tiwari and Troy 2015). Of late, their cultivation has gained huge momentum which has resulted in the production of 35 million tonnes of farmed seaweed in 2019. This is more than three times the seaweed biomass produced in 2000 (FAO 2021). This boom in seaweed cultivation aligns with many sustainable development goals (SDG) identified by United Nations as its applications cater to not only material benefits but also act as a strong ecological reinforcement. The benefits obtained from the marine or coastal ecosystem are termed as 'Ecosystem Services' (ES). Commercial seaweed cultivation can be a major contributor to ES as seaweeds are

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already being pitched as the sustainable future feedstock for various applications (Blikra et al. 2021; Duarte et al. 2022). The services provided by the ecosystem are generally characterized into four categories i.e. provisioning, regulating, supporting and cultural services. Provisioning services provided through seaweed farming include the material benefits availed for example biomass, biofuel, hydrocolloids, food etc. Maintaining soil health and quality, providing drought and disease tolerance to crops, carbon sequestration, and absorption of excess nutrients are some of the regulating services provided by seaweeds. Seaweed farming activity often results in providing habitat to various flora and fauna, besides breeding grounds for these organisms, and helps in biogeochemical cycling. They also act as the major source of primary production, therefore come under supporting services. Lastly, cultural services include non-material benefits like cultural identity, tourism, recreation etc. Nevertheless, regulating services are often unnoticed, by mainstream scientists and policy-makers but any drastic change in these can result in irreversible damage.

The economics of ecosystem services (ES) especially marine ecosystems is being extensively determined in a few European (Bermejo et al. 2022) countries like Sweden (Hasselström et al. 2018), Norway (Gundersen et al. 2021) and African and East Asian countries, South Africa (Blamey and Bolton 2018) and Korea (Park et al. 2021). Various methods have been employed to arrive at economic gains like Delphi technique. Nevertheless, in India this evaluation is still in its nascent stage. The countries mentioned above have also started to specifically evaluate the ES of proposed seaweed cultivation programs, which remains a distant dream under the Indian scenario. Though there are many reports on the evaluation of ES of the terrestrial ecosystem in India, very few reports attempted to cover the marine counterpart thereby underlining the urgency of its assessment (Chopra et al. 2022). One of these few reports, published recently, estimates the value of ES to be ₹ 1,895.42 billion (approximately 22.9 billion US$) at 2012–13 prices (Kumar et al. 2022). The estimation of ecosystem services was made using three scientific methods i.e. direct market valuation, travel cost method and benefit transfers. But it still remains grossly underestimated as they have not included the economics of supporting ecosystem services.

One of the main regulatory ecosystem services provided by seaweed farms is carbon capturing. It is the process of capturing atmospheric or anthropogenic CO_2, from large-scale sources like in this case the marine ecosystem. The carbon sequesters act as a sink for atmospheric carbon and can hold it for a long duration of time and is not recycled back to the ecosystem. This could be achieved either by dumping the biomass into deep soil/water or by converting the biomass into a product that could lock in the captured carbon for decades if not more. Seaweeds act as one such carbon sink, which can address the rapid rise in CO_2 emissions thereby aiding to mitigate climate change and providing a significant ecosystem service. The extent of this valuable carbon sink can be understood from the fact that in 2009, the global seaweed carbon sink had captured carbon equivalent to 4.67 million t of CO_2 (Hu et al. 2022). Nevertheless, the terms 'carbon capture' or 'carbon fixation', and 'carbon sequestration' or 'carbon sink' have essentially different scientific connotations but are used analogously. The carbon capture or fixation is simply the trapping of emitted carbon, while carbon sequestration or sink refers to the next stage where the captured carbon is stored into the environmental reservoirs (Nayak et al. 2022). It is pertinent to understand that farmed seaweed biomass clearly 'captures' or 'fixes' carbon but this does not necessarily lead to 'sequestration' or 'sinking'. The idea of farming seaweeds and then sinking to the deep ocean floor has been mooted for achieving carbon sequestration (Troell et al. 2022). The mathematical assessment in Canada—where the carbon tax scheme was piloted—revealed that, the value of seaweeds for carbon sequestration does not match the price of feedstock for other markets (Chopin 2021). Further, most of the current seaweed biomass is used to make crop bio-stimulants, food, and feed ingredients that rapidly cycle elements from the sea, and back into terrestrial ecosystems. However, the life-cycle impact assessment of bio-stimulant production was found to have a very low carbon foot-print at the factory-gate in India (Ghosh et al. 2015). Thus, this feedstock can be considered, at the most, for efficient 'carbon capturing' rather than 'carbon sequestration'.

In addition to being an efficient carbon fixer, the seaweed farms also act as filters to various nutrients like inorganic phosphate (P_i) and nitrogen (N), which runoff from the terrestrial ecosystem via streams and sewage canals. The excess of these nutrients in the shallow coastal water results in eutrophication, which can in turn affect the natural populations of marine flora and fauna by creating hypoxic conditions, adversely affecting the economics of the region (Le et al. 2022). The removal of these nutrients by the farmed seaweeds has resulted in the increase of ES value from US$ 1.30 million in 2000 to US$ 5.66 million in 2019 in just one Chinese province (Hu et al. 2022).

India is on the cusp of expanding seaweed farming activities. Currently, three products (alginate, mannitol, and plant bio-stimulant) are obtained from two alginophytes namely *Sargassum* and *Turbinaria*; two products (carrageenan and plant bio-stimulant) from *K. alvarezii*, while only one product (agar) is obtained from various agarophytes namely *Gelidiella acerosa*, *Gracilaria edulis*, *Gracilaria debilis* and *Gracilaria dura*. The agar and alginate industries are still solely dependent on natural resources available near islands as well as the mainland coastal region of the Gulf of Mannar on the southeast coast of India (Shah et al. 2022). *Kappaphycus alvarezii* owing to its economic value remained the only species that has been commercially farmed. However, the farming activities are currently restricted to only four districts of Tamil Nadu. The ambitious seaweed production aspirations have been made from time to time by private/public seaweed farming pioneers since the year 2000 in India. Despite diligent efforts by several entities, extensive farming of red seaweeds has failed repeatedly (especially agarophytes). Nevertheless, the Government of India has renewed its interest in commercial farming of seaweeds and introduced the ambitious project named "Pradhan Mantri Matsya Sampada Yojana (PMMSY)". This project is managed by the Department of Fisheries under the Ministry of Fisheries, Animal Husbandry and Dairying, with the highest-ever investment of ₹ 200.5 billion (~ 2.4 billion US$). This commercial investment comprises of Central share of ₹ 94.07 billion (~ 1.1 billion US$), State share of ₹ 48.80 billion (~ 590 million US$) and beneficiaries contribution of ₹ 57.63 billion (~ 700 million US$). The seaweed feedstock production target under this project is 11.2 million t in incremental proportions of 15, 15, 20, 20, 30% each year respectively for five years. (Mantri et al. 2022). Besides, the Fisheries Department of Central and State government, different line ministries namely, the Ministry of Agriculture & Farmer Welfare, Ministry of Micro, Small and Medium Enterprises, Ministry of Shipping, Ministry of Rural Development, Marine Products Export Development Authority, Indian Council of Agriculture Research, Council of Scientific and Industrial Research, have also been involved for Policy, Convergence and Technology Hand-holding. Currently, viable farming technologies have been developed for few species of agarophytes namely *Ge. acerosa* (Ganesan et al. 2009), *Gr. edulis* (Ganesan et al. 2011), *G. dura* (Mantri et al. 2020), *G. debilis* (Veeragurunathan et al. 2019) besides *K. alvarezii* (Mantri et al. 2017) in Indian waters. Although the project is not aimed at farming any specific species, we in this case have assumed the farming of *K. alvarezii* at Pan-India scale. This assumption is made only for arriving at uniformity in calculations, and similar proposition can also be made for other species mentioned above. We do understand that the calculations depends primarily on the location or site-specific to be more realistic. However, the estimates for growth were considered based on our experience in Tamil Nadu, as the specific locations or site-specific data for Pan-India is not available in the published literature. Nevertheless, the projection presented here is very critical for formulating domestic policies. The present study thus investigates regulatory ecosystem services in terms of (i) carbon capture; (ii) inorganic phosphate (P_i) and nitrogen (N) removal capacity; (iii) cadmium, cobalt and chromium absorption capacity through large-scale commercial farming to be implemented in all coastal states and union territories of India. This is the first-ever study to document regulatory ecosystem services of seaweed farming in the Indian subcontinent which often go unnoticed, by mainstream scientists and policy makers.

Materials and method

In the present study, the data shown is the extrapolation/ estimation made in accordance with the targeted *Kappaphycus* production aimed by PMMSY over a period of five years. The targeted biomass production given under PMMSY was in 'tonnes dry weight', which was converted to 'tonnes fresh weight' by multiplying the dry weight data with a factor of 10 (fresh to dry weight ratio arrived at by personal communication with commercial fishermen). The main reason for using *Kappaphycus* for this study is that it is the top-most commercially cultivated seaweed species in India, due to which its cultivation technologies, expertise, and infrastructure have already been successfully standardized for Indian coastal waters. All the calculations are based on certain assumptions namely: (i) It was assumed that per year minimum of three cycles (about 45 days each) of cultivation are possible in most Indian coastal states and union territories [except Kerala, Tamil Nadu and Andaman where five cycles and Puducherry where four cycles were presumed considering different prevailing climatic conditions], (ii) Two main commercially successful *Kappaphycus* cultivation methods in India viz. tube net and raft, were taken into consideration, where seeding density was kept at 20 kg tube net^{-1} and 40 kg raft^{-1} respectively, (iii) The initial *Kappaphycus* biomass to be seeded was calculated in accordance to the production target set for each year for respective states and union territories (Supplementary Table 1–13). (iv) About 1000 rafts or 200 tube nets were considered to cover area of one hectare. The part of the biomass produced at the end of each cycle was then used for the next cycle. It is pertinent to mention here that, despite repeated attempts at numerous locations since the late 1980s, extensive commercially successful tube net farms have never developed anywhere in the world. However, considering the success of pilot-scale farming of *K. alvarezii* by tube net method along the west coast, we decided to generate such data. Furthermore, on comparing to an established seaweed forest that grows for several months or even years before being harvested or utilized, a 45 days growth cycle is very short. Nevertheless, various reports suggest a significant uptake of atmospheric carbon by cultivated seaweeds (Mashoreng et al. 2019). It is also possible that some of the farm biomass will break free and drift and/or sink, and some may undergo further processing that sequesters carbon, but the proportion of drifting fragments is very minuscule. Moreover, the farmers use old fishnet at the bottom of the raft to protect the crop from grazing, and tube net holds great promise in minimizing drifting (Mantri et al. 2017). However, as stated above, this feedstock when farmed at a very large-scale – as per the targets fixed under PMMSY scheme – can be considered for efficient carbon capture or carbon fixation.

Total carbon captured was calculated as per the formula:

$$\textit{Carbon capture potential}\ (t) = \frac{52.92 \times \textit{weight of fresh biomass in t}}{1000}$$

where 52.92 mg g^{-1} fr. wt is the amount of C captured per cycle of 45 days @ 1.176 mg g^{-1} fr. wt day^{-1} (Mashoreng et al. 2019).

Total nutrient uptake was calculated as per the formula:

$$\textit{Nitrogen uptake}\ (t) = 0.2\%\ \textit{of weight of fresh biomass in t}$$
$$\textit{Phosphorous uptake}\ (t) = 0.019\%\ \textit{of weight of fresh biomass in t}$$

For calculating heavy metal biosorption, the formula used was:

$$\textit{Biosorption of cadmium}\ (kg) = \frac{3.064 \times \textit{weight of fresh biomass in t}}{100}$$

where 3.064 mg (100 g).$^{-1}$ fr. wt is the absorption rate of Cd (Kumar et al. 2007)

$$\textit{Biosorption of cobalt}\ (kg) = \frac{3.365 \times \textit{weight of fresh biomass in t}}{100}$$

where 3.365 mg (100 g).$^{-1}$ fr. wt is the absorption rate of Co (Kumar et al. 2007)

$$\textit{Biosorption of chromium}\ (kg) = \frac{2.799 \times \textit{weight of fresh biomass in t}}{100}$$

where 2.799 mg (100 g).$^{-1}$ fr. wt is the absorption rate of Cr (Kumar et al. 2007)

To achieve the target set under PMMSY, the seaweed cultivation if carried out throughout India, in its entirety using tube-net method, the initial fresh weight required would be more than 120,000 t, and approximately 140 million tube nets would be required and around 780,000 fisher people would need to be employed to manage them for the whole cultivation season. The area covered by the seaweed farm would be approximately 700,000 ha. Similarly, for the raft cultivation method, more than 60,000 t of initial fresh weight would be required and since the rafts are reusable, the number of rafts required would be significantly less i.e. ~ 56 million. Over different cultivation cycles, more than 1.2 million fisher people need to be employed to manage the seaweed farms. The raft cultivation method would cover approximately 56,000 ha with seaweed farms for the whole cultivation season. The complete data for each state is listed in Table 1.

Results

The analysis was carried out to study the extent of ecosystem services especially the regulating services, to be rendered by the successful implementation of the National Seaweed Mission under Pradhan Mantri Matsya Sampada Yojana (PMMSY). Assuming that the biomass produced at the end of each cultivation year meets the target set for the respective

Table 1 Estimated requirements in terms of number of tube nets manpower and area under the farm for successful implementation of seaweed cultivation under PMMSY

State/ UT	Tube Net			Raft		
	Number of tube nets required (20 kg tube net^{-1})	Manpower needed (4 tube net person^{-1} day^{-1})	Area covered	No of rafts required (40 kg raft^{-1})	Manpower needed (1 raft person^{-1} day^{-1})	Area covered (hectare)
Gujarat	25,000,000	138,889	125,000	10,000,000	222,222	10,000
Maharashtra	12,500,000	69,444	62,500	5,000,000	111,111	5000
Goa	2,500,000	13,889	12,500	1,000,000	22,222	1000
Karnataka	6,250,000	34,722	31,250	2,500,000	55,556	2500
Kerala	6,250,000	34,722	31,250	2,500,000	55,556	2500
Tamil Nadu	37,500,000	208,333	187,500	15,000,000	333,333	15,000
Andhra Pradesh	18,750,000	104,167	93,750	7,500,000	166,667	7500
Odisha	12,500,000	69,444	62,500	5,000,000	111,111	5000
West Bengal	12,500,000	69,444	62,500	5,000,000	111,111	5000
Diu	1,250,000	6944	6250	500,000	11,111	500
Puducherry	2,500,000	13,889	12,500	1,000,000	22,222	1000
Lakshadweep	1,250,000	6944	6250	500,000	11,111	500
Andaman and Nicobar	1,250,000	6944	6250	500,000	11,111	500

Table 2 Estimated values of carbon capture, nutrient uptake and heavy metal absorption by *Kappaphycus alvarezii*, cultivated at various coastal states and UTs of India

State/UT	Production targets as per PMMSY (tonnes)	Carbon Capture (tonnes)	Nutrient Uptake (tonnes)		Heavy Metal Absorption (Kg)		
			Nitrogen	Phosphorous	Cadmium	Cobalt	Chromium
STATES							
Gujarat	2,000,000	105,840	4000	400	61,280	67,300	55,980
Maharashtra	1,000,000	52,920	2000	200	30,640	33,650	27,990
Goa	200,000	10,584	400	40	6128	6730	5598
Karnataka	500,000	26,460	1000	100	15,320	16,825	13,995
Kerala	500,000	26,460	1000	100	15,320	16,825	13,995
Tamil Nadu	3,000,000	158,760	6000	600	91,920	100,950	83,970
Andhra Pradesh	1,500,000	79,380	3000	300	45,960	50,475	41,985
Odisha	1,000,000	52,920	2000	200	30,640	33,650	27,990
West Bengal	1,000,000	52,920	2000	200	30,640	33,650	27,990
UNION TERRITORIES							
Diu	100,000	5292	200	20	3064	3365	2799
Puducherry	200,000	10,584	400	40	6128	6730	5598
Lakshadweep	100,000	5292	200	20	3064	3365	2799
Andaman and Nicobar	100,000	5292	200	20	3064	3365	2799

states/UTs, the rate of carbon capture, nutrient removal and heavy metal absorption was calculated.

For India, the overall carbon capture rate is reported to be approximately 600,000 t CO_2 cycle^{-1} either by tube net or raft cultivation method. The nitrogen and phosphorous removal capacity is calculated to be 22,400 t cycle^{-1} and 2,240 t cycle^{-1}, respectively. Similarly, the absorption of the heavy metals Ca, Co, Cr by seaweeds cultivated by tube net method was calculated to be 343.17 t cycle^{-1}, 376.88 t cycle^{-1} and 313.49 t cycle^{-1}, respectively irrespective of the cultivation methods used. The state wise calculations are represented in Table 2 and Figs. 1, 2, 3, 4, 5, 6, 7.

Discussion

According to FAO data, India stands at the 13th position in global seaweed production with the contribution of just 0.02% seaweed biomass (Mantri 2022). Despite having more than 7500 km long coastline, this sector remained largely unexplored. The seaweed cultivation in India has gained more attention in the last few years with the Union Government earmarking funds as well as targets to achieve significant growth in this sector.

The analysis done in this manuscript was to evaluate the specific regulatory services viz. carbon capture, nutrient removal and heavy metal absorption provided by the *Kappaphycus* cultivation done using two different methods. It was observed that in all the parameters the tube net method fared better than the raft method, which is directly related to the growth rate in each method. However, the factor that has to be kept in consideration is the environmental impact and the carbon footprint left by the non-reusable tube nets (Behera et al. 2022). There are far more advantages of the tube net method like the ability to withstand rough seas, and the higher retention capacity of seaweed material (Reis et al. 2015). This makes it imperative to look for ways to address the adverse environmental impact or find an eco-friendly way to dispose of the used nets.

Carbon capture

Global CO_2 emissions have been increasing at an alarming rate and have reached more than 36 gigatonnes in 2021 according to IEA (IEA 2021). In addition to reducing the emissions, the capturing of already released carbon needs to be addressed as well. Marine photosynthetic organisms are the largest contributors to capturing atmospheric carbon. They are perceived as a critical resource against global warming and one major group of these photosynthetic organisms—seaweed, is no different. The estimates revealed that common seaweeds growing in temperate regions can fix more than 100,000 t of carbon year^{-1} in 5000 ha of kelp farms (Blamey and Bolton 2018).

In tropical region like India, *Kappaphycus* remains the commercially important seaweed, which is being cultivated since 1980s. On comparing the carbon- capture potential of seaweeds with other photosynthetic organisms associated with marine environments like mangroves or seagrasses, the contribution by former is significantly higher. The seaweeds e.g. *Kappaphycus*, as per the data in this article, can

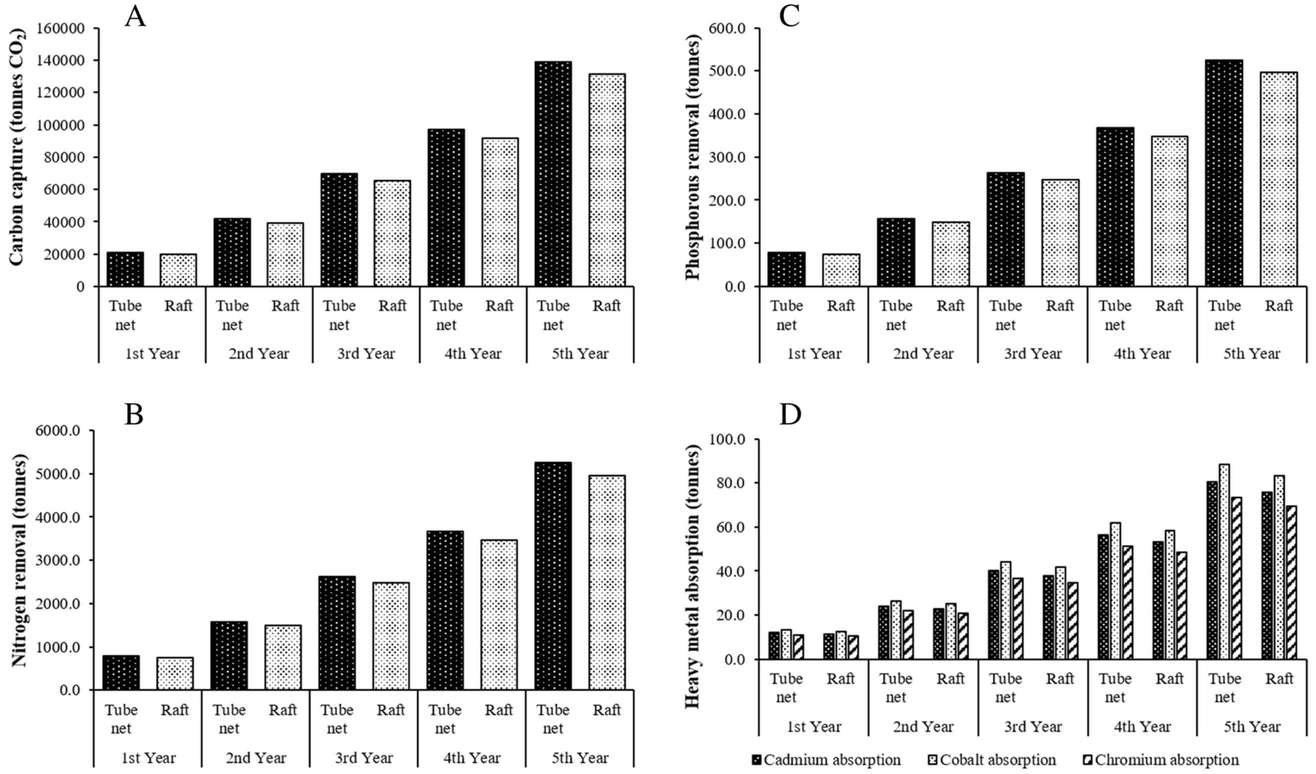

Fig. 1 Regulatory ecosystem services: **A**) carbon capture, **B**) nitrogen and **C**) phosphorous removal, and **D**) heavy metal (Cd, Co, Cr) absorption by *Kappaphycus* cultivation at Gujarat, India

capture more than 0.84 t carbon per hectare from tube net farms and 10.5 t carbon per hectare from raft method each year whereas the mangroves all over India, have the capacity to capture 0.36 million t per year (Chatting et al. 2022). Nevertheless, the fact is that mangroves occupy close to 0.5 million hectares, and the per hectare capture comes out to be 0.7 t carbon. This value is significantly lower than that of the values reported in our study for seaweeds. On the other hand, kelps, which are one of the largest canopy-forming seaweeds can capture a huge amount of carbon up to 60 t per hectare annually (Yoshida et al. 2019). *Sargassum* can annually capture up to 16 t per hectare (Yoshida et al. 2019), *Ulva* on the other hand cannot directly contribute to carbon capture and storage as it is composed of labile carbon which can easily be broken down by microbes (Kwan et al. 2022). Thus, in tropics like India, the species of *Sargassum* and *Ulva* which have pan India distribution and are able to form a significant canopy may contribute to capturing carbon significantly. However, the main bottleneck in large-scale cultivation of these species is that their propagation is mainly spore based which needs land-based hatcheries and technical expertise to operate (Largo et al. 2020). Although *Sargassum* can also be multiplied by fragmentation—its complex life cycle requires it to undergo sexual as well as asexual reproduction, which is critical component and integral to its commercial cultivation program.

The carbon captured by seaweeds like *Kappaphycus* can remain stored in the feedstock. Even though such storage is not the long-term approach, the end product of such biomass is like plants bio-stimulants have shown to significantly reduce carbon footprint by reducing the use of chemical fertilizers and pesticides (Layek et al. 2015). Further, the application of such bio-stimulants adds to the enhancement of carbon capture potential of the crop plants as well (Mondal et al. 2015).

Nutrient uptake

The ability of seaweeds to recycle nutrients, especially nitrogen and phosphorous, can provide a significant ecosystem service. *Gracilaria* has been reported to contribute up to 65% to the removal of total nutrients (Hu et al. 2022). Similarly, *Kappaphycus* has also been reported to contribute significantly to nutrient removal from coastal waters. Multiple coculture and IMTA studies not only report the significant nutrient removal potential of *K. alvarezii* but also the higher growth rate of such biomass (Hayashi et al. 2008; Kambey et al. 2020). The nutrient uptake is very

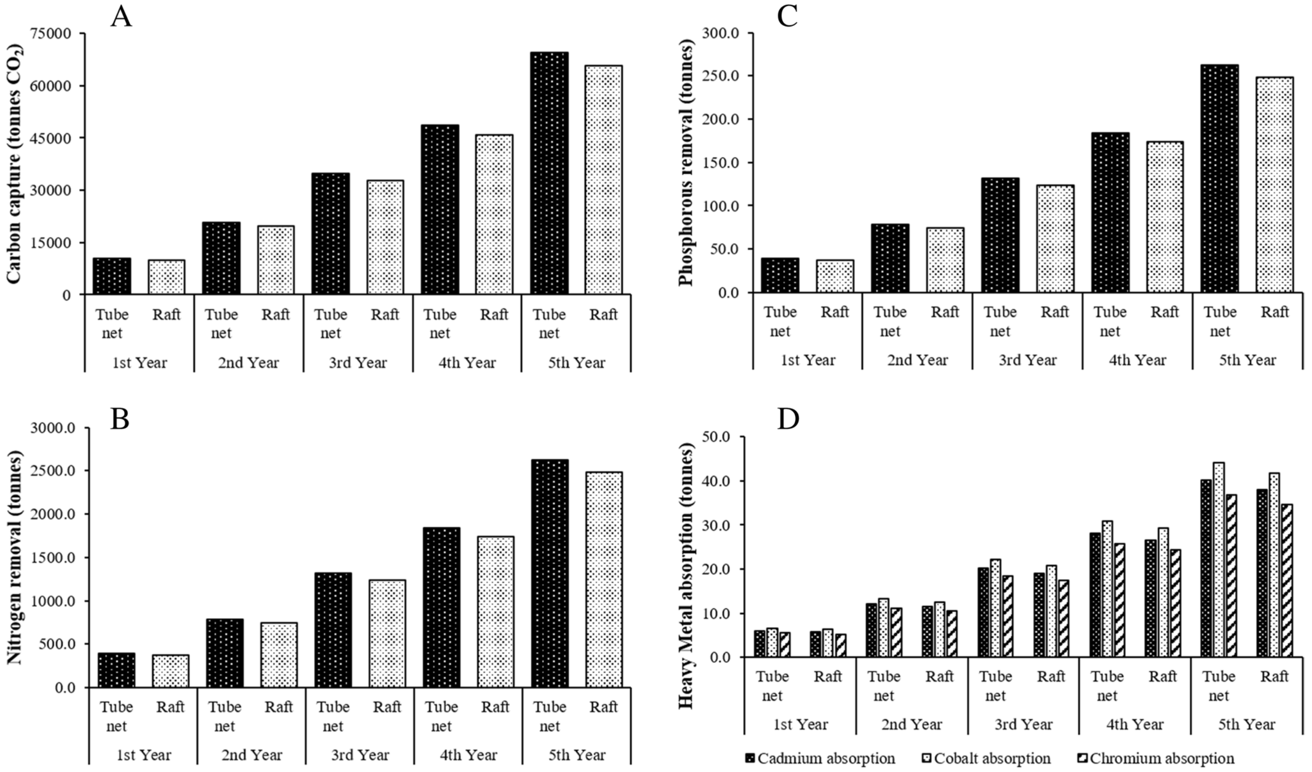

Fig. 2 Regulatory ecosystem services: **A**) carbon capture, **B**) nitrogen and **C**) phosphorous removal, and **D**) heavy metal (Cd, Co, Cr) absorption by *Kappaphycus* cultivation at Maharashtra, Odisha and West Bengal, India

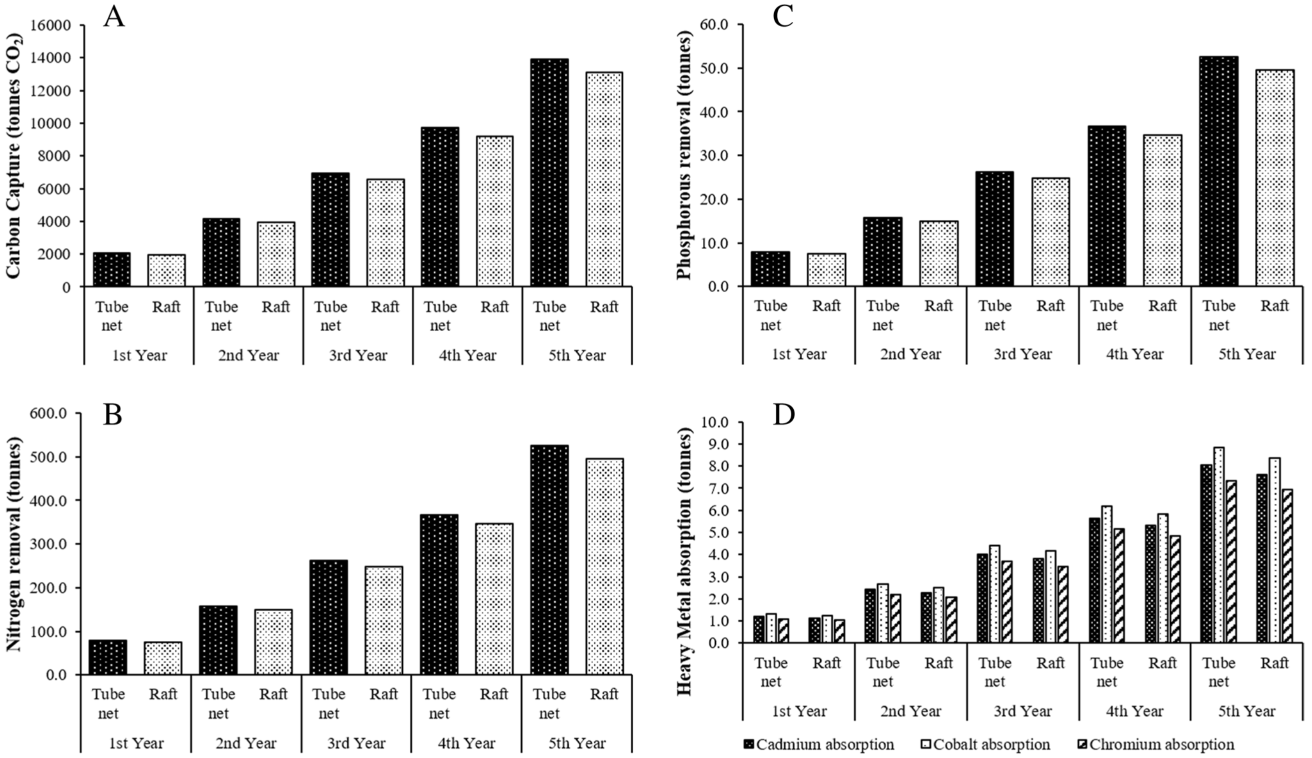

Fig. 3 Regulatory ecosystem services: **A**) carbon capture, **B**) nitrogen and **C**) phosphorous removal, and **D**) heavy metal (Cd, Co, Cr) absorption by *Kappaphycus* cultivation at Goa and Puducherry, India

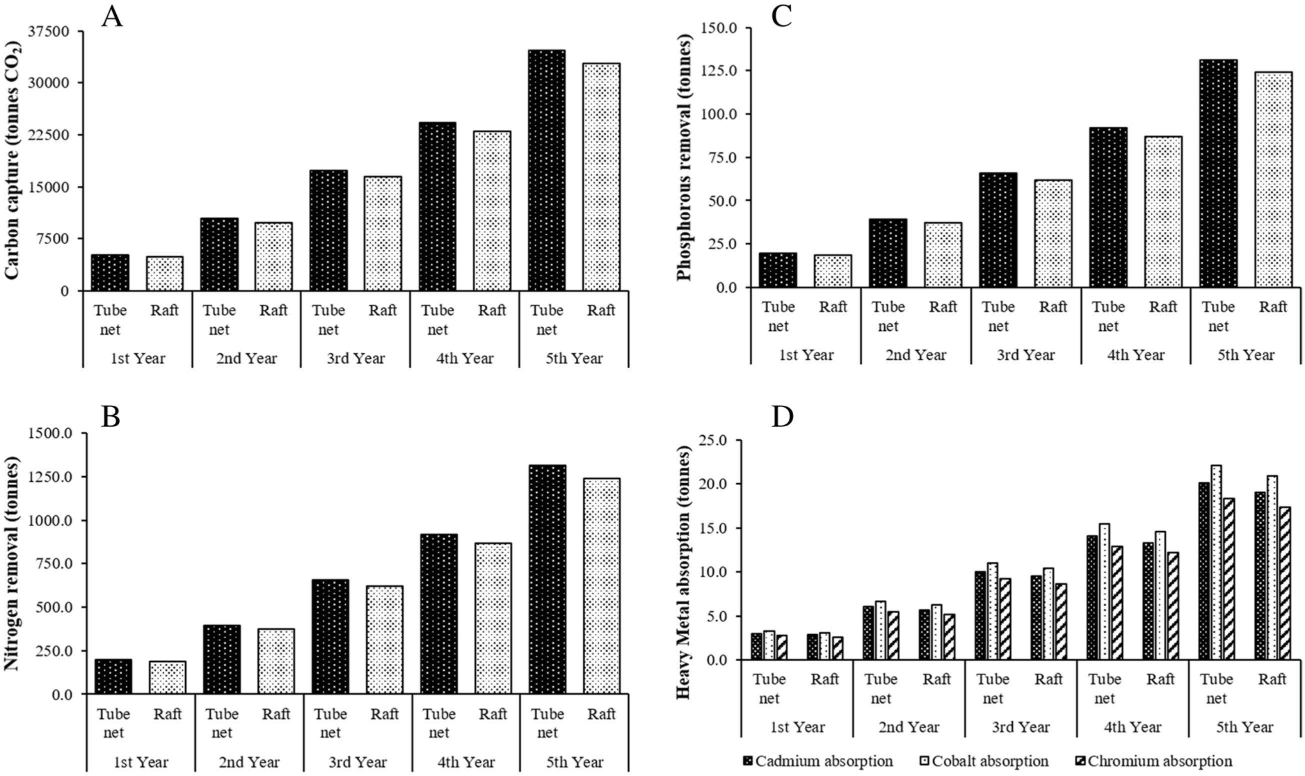

Fig. 4 Regulatory ecosystem services: **A**) carbon capture, **B**) nitrogen and **C**) phosphorous removal, and **D**) heavy metal (Cd, Co, Cr) absorption by *Kappaphycus* cultivation at Karnataka and Kerala, India

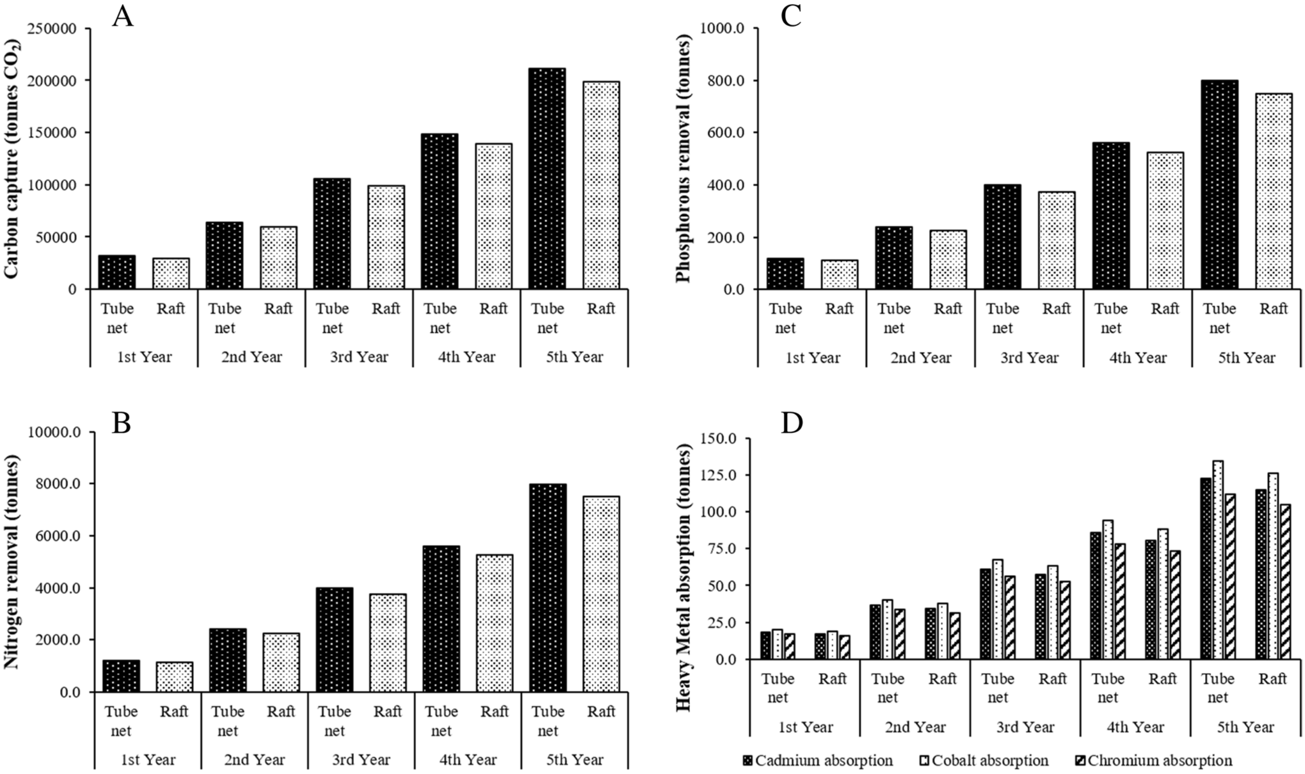

Fig. 5 Regulatory ecosystem services: **A**) carbon capture, **B**) nitrogen and **C**) phosphorous removal, and **D**) heavy metal (Cd, Co, Cr) absorption by *Kappaphycus* cultivation at Tamil Nadu, India

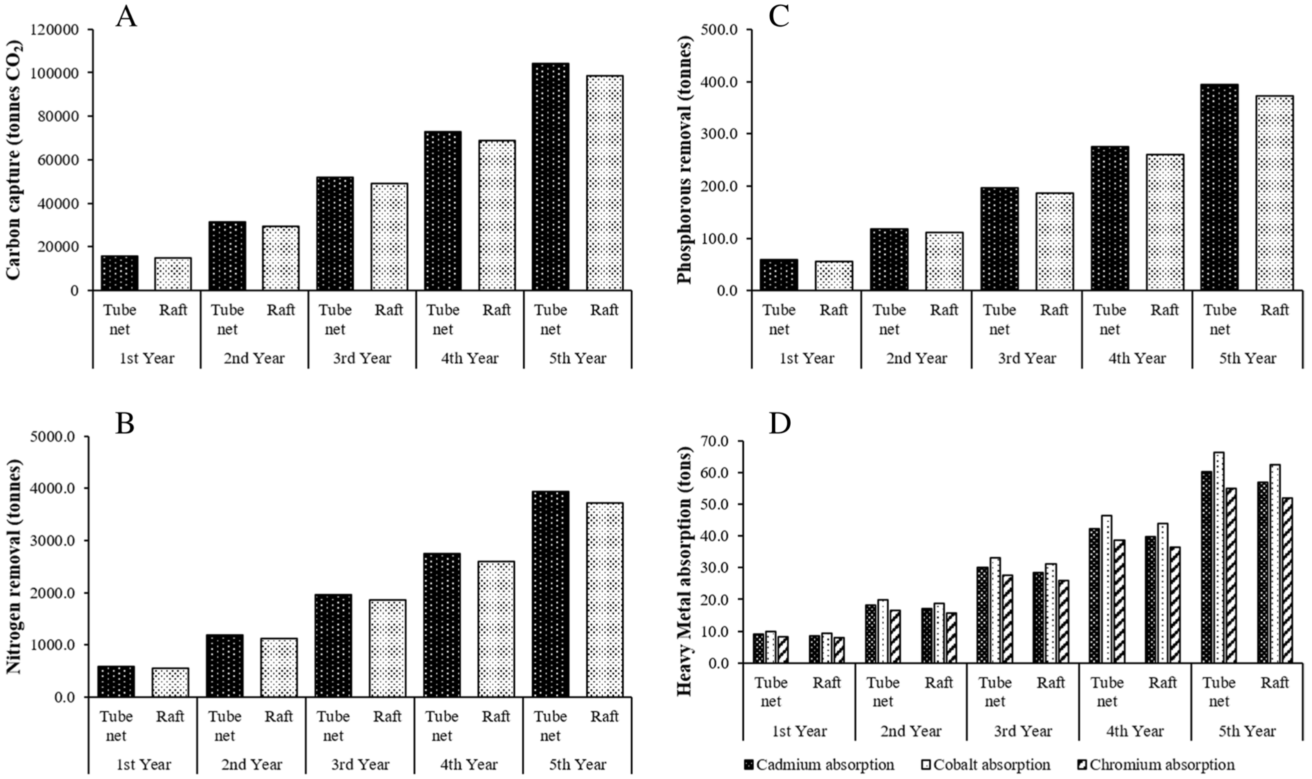

Fig. 6 Regulatory ecosystem services: **A**) carbon capture, **B**) nitrogen and **C**) phosphorous removal, and **D**) heavy metal (Cd, Co, Cr) absorption by *Kappaphycus* cultivation at Andhra Pradesh, India

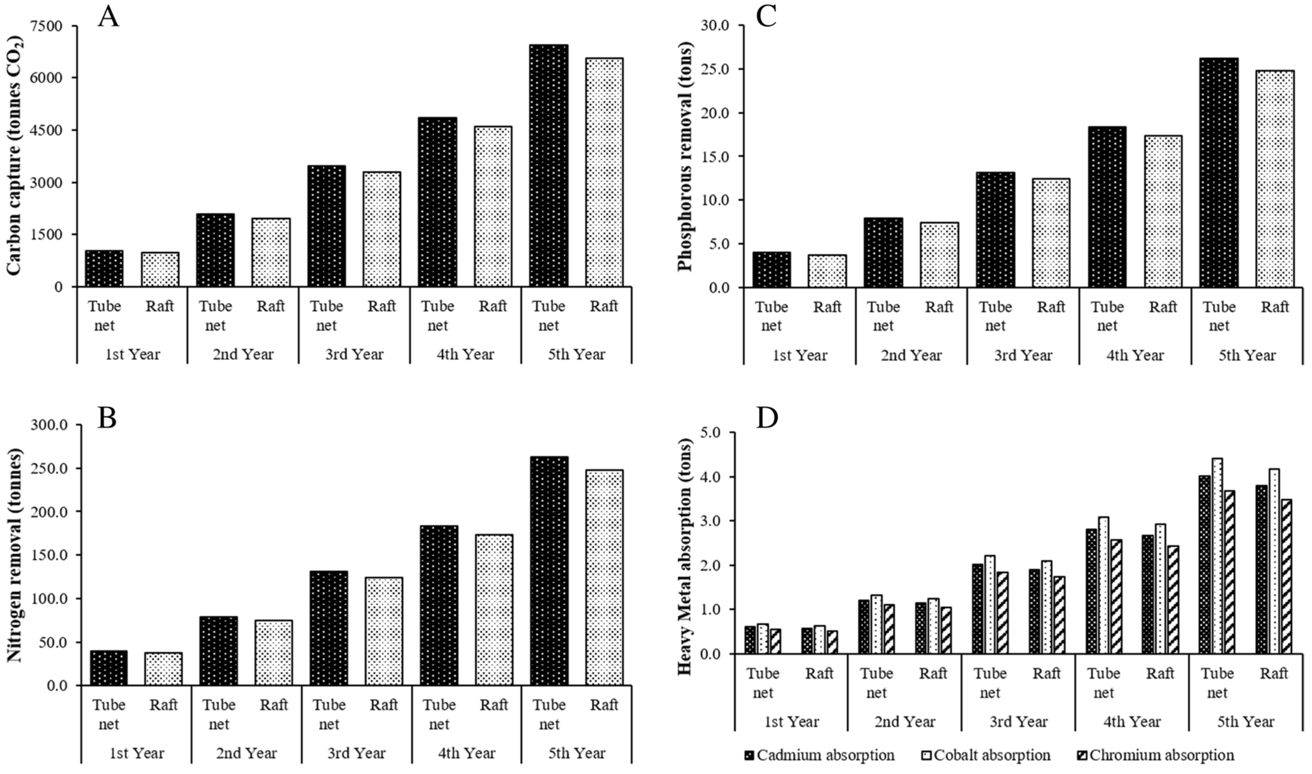

Fig. 7 Regulatory ecosystem services: **A**) carbon capture, **B**) nitrogen and **C**) phosphorous removal, and **D**) heavy metal (Cd, Co, Cr) absorption by *Kappaphycus* cultivation at Diu, Lakshadweep and Andaman and Nicobar, India

important, especially in coastal areas with high population density. This results in high N and P-content through the terrestrial discharge, leading to eutrophication and fouling of the nearby coasts. Such discharge is not an occasional occurrence, but the nutrient load has been ever increasing as reported from various locations across India (Sawant et al. 2007). Eutrophication not only reduces the penetration of sunlight but also creates hypoxic conditions, which is detrimental to the native marine flora and fauna (Nwankwegu et al. 2019). The present study has unequivocally confirmed that, commercial large-scale cultivation of *K. alvarezii* has good potential of nutrient remediation. Hayashi et al. (2008) have reported that integrated cultivation of *K. alvarezii* with fishes in re-circulating water facilitates enhanced nutrient uptake as well as commercial production of carrageenan.

Seaweed aquaculture in China annually removes more than 75,000 t of nitrogen and 9500 t of phosphorous from its waters by farming *Saccharina japonica* and *Gracilariopsis* (Zheng et al. 2019). In India, once the seaweed cultivation targets are achieved, the farms, would have the ability to uptake more than 22,000 t of nitrogen and around 2,200 tonnes of phosphorous, from the coastal waters in each cultivation cycle. It is pertinent to mention that the farm area required to achieve this via tube net method is more than 12 times the area required to achieve similar results from raft cultivation method. The huge difference between the nutrient uptake in the two countries is mainly because of the farm area which reached to the tune of 760,000 ha in 2015 (Zheng et al. 2019), whereas the data for India is calculated for roughly 700,000 ha for tube net and just 56,000 hectares for raft farms.

The rate of nutrient uptake, especially nitrogen, has been reported to be much higher in seagrasses, ranging from 4.6 to 25.6 mg N g^{-1} DW h^{-1} for nitrate and ammonium (Nayar et al. 2018). Seaweeds, on the other hand, are able to uptake only around 2 mg N g^{-1} DW h^{-1}. Nevertheless, seaweeds are more versatile than seagrasses in terms of their uses, and can be commercially utilized in a range of applications domains, such as food, fuel, cosmetics, and pharmaceuticals. This versatility makes seaweed farming a more attractive preposition for investors.

Heavy metal uptake

The accumulation of various heavy metals like chromium, cadmium etc. in the soil or water has been accelerating because of rapid industrialization. The runoff from commercial factories ultimately ends up in seawater thereby posing a considerable threat to the marine ecosystem. As already explained, seaweed farms can act as bio-filters, they not only take up nutrients but are known to absorb heavy metals as well from seawater (Kang and Sui 2010). After achieving the cultivation targets under PMMSY, the *Kappaphycus* farms would be able to absorb more than 1000 t $year^{-1}$, of heavy metals cumulatively at the rate of 0.11 mg kg^{-1} FW of chromium, cobalt and cadmium. The potential is comparable to other seaweeds like *Sargassum*, *Pyropia*, *Undaria* etc., which were reported to absorb heavy metals like arsenic, cadmium etc. in the range of 0.02 to 0.2 mg kg^{-1}FW (Lee et al. 2022). It is imperative to understand at this point that the absorbed heavy metals still remain inside the seaweed tissue (cell wall matrix). They could be released again in the environment when the cell walls are disrupted and thus proper disposal of such biomass for recovery of heavy metal is needed. Nevertheless, the bio-sorption by the seaweed keeps these toxic elements aggregates to a specified area in the water thereby scrubbing the contaminated seawater off these heavy metals.

Various regulatory ecosystem services provided by the seaweed cultivation in India will add another facet to the already growing seaweed industry. India, being the third largest CO_2 producer, has committed to reduce CO_2 emissions by 50% by 2050. Recently, NITI Aayog—apex public policy think tank of the Government of India—has collaboratively developed a policy framework to address this issue. The document lists different methods, which include solvent, or adsorption-based technologies that can be deployed at the source to prevent or limit the emission (Mukherjee and Chatterjee 2022). These technologies howsoever effective are very expensive and include technical expertise for deployment and maintenance. Although, seaweed farming cannot replace these technologies per say, but such move is a cost effective against rising CO_2 emissions. This intervention may not always be deployable at the source of emission (except at the industries located in coastal areas) but has the potential to be a game changer in controlling over-all carbon emissions. *Kappaphycus alvarezii* feedstock has been used for the production of carrageenan (semi-refined or refined) world-wide. The invention of feedstock liquefication, for obtaining sap rich in potash and micronutrients (having proven efficacy) along with carrageenan, has provided a face-lift to the domestic seaweed processing industries. Further, the life-cycle impact assessment of pristine bio-stimulant production was found to have a very low carbon foot-print at the factory gate (118.6 kg CO_2 equivalents kL^{-1}) towards its production. Furthermore, the transportation of such goods by rail and sea routes was found to have the least environmental impact, than by road (Ghosh et al. 2015). In summary, the farming of *K. alvarezii* although not contributing to carbon sequestration directly, would help in reducing carbon foot-print, even during the supply chain segment. Moreover, reusing the storage containers or substituting fossil-based plastics with biodegradable products would apparently further make the process greener. Similarly, in eutrophicated coastal waters, seaweed farms can uptake excess nutrients and heavy metals. This move would be helpful in doubling the benefits by cleansing the water and increasing its own biomass. The feedstock thus generated in turn forms the raw material for the seaweed domestic processing industries. There is no doubt that the regulatory ecosystem services of commercial farming of seaweeds in India is seldom captured by policy makers. This might be due to the non-availability of such data; and absence of its direct monetary valuation and thus are not considered important in policy perspective. We feel that if these regulatory ecosystem services are examined carefully, the overall impact of the farming project would increase.

Furthermore, achieving high feedstock production targets proposed in PMMSY requires a sustainable and un-interrupted supply of quality planting material. Therefore, the establishment of germplasm or seed bank facilities at each coastal state and union territory is pivotal. The coastal territories in India are influenced either by the southwest monsoon or the northeast monsoon when farming activities come to a complete halt due to inclement weather. The preservation of seed material during monsoon in the vicinity of cultivation sites, albeit in small proportion would help in reviving commercial farming after the retreat of monsoon season. Although the sufficient fund has been allocated under PMMSY for the fishermen to procure infrastructure, they still need to invest about 40 – 50% towards the raft or tube net system, and not all the fishermen would be able to afford that. Hence, the Kisan Credit Card facility, originally initiated to aid the land-based farmers' needs, could be extended to fishermen involved in seaweed farming as has been done to other aquaculture projects. The conducive locations in each coastal state also need to be identified through on-going pre-feasibility trials that will enable the expansion of farming area (Mantri et al. 2022).

The article highlights the benefits of seaweed cultivation in terms of ecosystem services specifically regulatory services but ultimately the monetary valuation of these benefits is what drives the priorities for requisite policy and programs. Once the monetary worth of any ecosystem is evaluated, informed decisions regarding conservation or any other intervention could be made. Since this valuation forms the basis for such important policy decisions, the methods and mechanisms used for calculation become extremely important and should take care of all the aspects including the involvement all the stakeholders of that particular ecosystem. Such kind of valuation is needed in the context of seaweed farming in India as till now the focus has only been on its material benefits.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing Interest The authors declare that they have no conflict of interest. There are no known competing financial interest or personal relationships that could have appeared to influenced the work reported herein.

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