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How profitability assessment parameters score under large-scale commercial cultivation of different agarophyte seaweeds along south-eastern coast of India

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Abstract
Mass mortality of *Kappaphycus alvarezii* in India has severely hindered the employment opportunity of fishermen by diverting them to less-remunerative seaweed collection sector. The depletion of resources due to over-harvesting coupled with ongoing global supply chain crisis offers excellent opportunity to initiate commercial farming of agarophytes. The productivity and financial implications in terms of profitability assessment parameters have not been attempted before for Indian agarophytes. The comparison between four species, namely *Gelidiella acerosa*, *Gracilaria debilis*, *G. dura* and *G. edulis* under deployment scenarios (1TPD and 5 TPD), revealed *G. debilis* as productive spices in terms of requirement of rafts (9,000–163,636), area under farming (3.6–65.45 ha) and persons involved (100–1,818). It reported minimum payback period of 0.3 years, breakeven point of 66.56 tons of biomass with and highest internal rate of returns of 237.6% for high range yield scenario. All the agarophytes except *G. acerosa* registered profit, with maximum (0.46 million USD) reported for *G. dura*, followed by *G. debilis* (0.19 million USD) under yield scenario of 5-TPD. Thus, the present investigation confirms that commercial cultivation of *G. debilis* farming can be viable alternative to the fishermen along the south-eastern coast of India due to low skill set and small investment.

Keywords Agarophyte cultivation · Breakeven point · Internal rate of returns · Payback period · Productivity

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Introduction

South-eastern coast of India has long history of seaweed trade especially agarophytes (Mantri 2019). After the World War II, when import of specialty chemicals has been severely impeded, active steps have been taken by then Board of Scientific and Industrial Research to manufacture agar within the country. The University of Travancore at its Research Department between 1942 and 1946 made small quantities of agar to cater for the cholera vaccine production (c.f. Subba Rao and Mantri 2006). The agarophyte resources have been thus explored in the 1960s, and subsequently their export to foreign nations has flourished. This has led to establishment of commercial seaweed landing centres along the Gulf of Mannar (GoM) between Rameswaram and Kanyakumari as well as Sethubavachatram in Palk Bay (Krishnamurthy 1971). *Gracilaria edulis*, *G. salicornia*, *G. debilis*, *G. verrucosa* and *Gelidiella acerosa* are commercially used for agar production in India (Ganesan et al., 2017). Despite the requirement of agar is 400 tonnes year^{-1} in the country, barely 150 tonnes year^{-1} is currently produced (Johnson and Ignatius 2020). Besides agar, market potential for colorants (R-phycoerythrin and R-phycocyanin), minerals, proteins, lipids and cellulose derived from this feedstock also exists (Baghel et al., 2014). Nevertheless, industrial production of this economically lucrative commodity still relies heavily on natural exploitation (Johnson et al. 2017; Sambhwani et al. 2020).The operating cost involved in seaweed collection has doubled between 2012 and 2015 but the net profit has marginally increased (Johnson et al. 2017). The landing of agarophyte taxa has been consequently reduced during the decade 2005–2015 (Mantri et al., 2019). The trend has continued even today. In order for the industry to sustain, the production has resorted to import the entire quantity of raw material from Morocco, Sri Lanka, Indonesia, etc. (Ganesan et al., 2017).

The experimental or pilot-scale trials of agarophyte seaweeds have been successfully conducted in India including Lakshadweep waters. The yield of 3.5 to 4 kg fresh weight m^{-1} length rope harvest^{-1} has been reported (Kaladharan et al. 1996; Oza et al. 1994; Raju and Thomas 1971; Subbaramaiah and Thomas 1990; Umamaheswara Rao 1974). The poor biomass yield coupled with cumbersome seeding and aggravated epiphytic infestation associated in long line, single rope floating technique, net method, coral stone or concrete block, etc. (Ganesan et al., 2009) has culminated into adopting floating bamboo raft method for pre-commercial trials along south-eastern coast of India (Ganesan et al. 2011a, 2015a, b; Veeragurunathan et al. 2015a, b). The trials have been conducted at Mandapam coast using raft of 2 × 2 m length in all the reported studies. The cultivation of *Ge. acerosa* has yielded 18 t dry wt ha^{-1} year^{-1} biomass in three harvests (Ganesan et al., 2009). The same was 35 t dry wt ha^{-1} year^{-1} biomass in six harvests in *G. edulis* (Ganesan et al., 2011a); 11.5 t dry wt ha^{-1} year^{-1} biomass in five harvests in *G. dura* and 56.7 t dry wt ha^{-1} year^{-1} biomass in six harvests in *G. debilis* (Veeragurunathan et al., 2015a, b; Veeragurunathan et al. 2019). However, the yield for other species of *Gracilaria* under various farming systems has also been reported in the literature, namely 47 t dry wt ha^{-1} year^{-1} for *G. gracilis* from South Africa by suspended rope technique (Wakibia et al., 2001); 18–29 t dry wt ha^{-1} year^{-1} for *G. tikvahiae* from Florida, USA, in pond culture (Hanisak and Ryther, 1986); 84–132 t dry wt ha^{-1} year^{-1} for *G. chilensis* (now *Agarophyton chilensis*) from Chile in sea bottom culture (Buschmann et al., 1995); and 40 t dry wt ha^{-1} year^{-1} for *G. gracilis* from Saldanha Bay, South Africa, by raft method (Anderson et al. 1996).

Despite the fact that different agarophyte candidate species are available, coastal seaweed mariculture in India is synonymous with *Kappaphycus alvarezii*. Although *K.*

alvarezii farming has been started as lucrative industry recent mass mortality event has caused serious setback (Mantri et al., 2017). Against this backdrop, agarophyte farming is thus widely regarded as promising alternative to *K. alvarezii* cultivation in India. Techno-economic analysis (TEA) ascertains operating as well as capital cost investment to understand economic viability of the technology for determining its commercial feasibility. Ganesan et al. (2017) has provided economics of agarophyte farming for 2000 bamboo rafts occupying 1 ha area in *G. edulis*, *G. dura* and *Ge. acerosa*. They recorded net income of USD 125.4 person^{-1} month^{-1} for *G. edulis*, followed by USD 200 person^{-1} month^{-1} for *Ge. acerosa* and USD 240.8 person^{-1} month^{-1} for *G. dura* (raft method). The financial implications of farming of *G. debilis* under six harvests each have been reported (Veeragurunathan et al., 2019). The profit of USD 141 person^{-1} month^{-1} has been reported. The projections of economic evaluation of pre-commercial cultivation of *G. dura* (tube net method) have also been reported (Mantri et al., 2020). The estimated profit of USD 354.4 person^{-1} month^{-1} has been reported. The socio-demographic profiling and asset indicators of *Gracilaria* farmers from northern west coast of India has revealed that there is growing interest in stakeholders in agarophyte feedstock (Shah et al. 2022). Although these studies are indicative of preliminary cost–benefit scrutiny, more detailed analysis pertaining to profitability measurements such as total value of future net cash flow, average intrinsic profitability of the farming and time required for the recovery of capital investment are needed.

In the communication, we reported comparison of productivity of the different agarophytes, namely *Ge. acerosa*, *Gracilaria debilis*, *G. dura* and *G. edulis* in terms of infrastructure, required farming area and manpower. Furthermore, the economic feasibility analysis was carried out in terms of pay-back period, breakeven point, net-present value and internal rates of returns to understand the profit potential under family centric establishment.

Material and methods

Productivity of the different agarophytes

We proposed two deployment yield targets, namely to achieve a production of one ton (dry) biomass and five tons (dry) biomass per day (TPD) for *Gelidiella acerosa*, *Gracilaria debilis*, *G. dura* and *G. edulis*. The method of farming was 2 × 2 m floating bamboo raft in all the species (Supplementary Fig. 1). The initial seed material ranged from 0.5–3 kg fresh weight depending on the species. We considered variable yields (higher as well as lower) to bring out the best scenario for investors to understand the financial viability. In order to obtain lower as well as higher range values of biomass yield, average biomass was first computed from the reported growth data, namely 2 years for *Ge. acerosa* (Ganesan et al., 2009), 2 years for *G. debilis* (Veeragurunathan et al., 2019), two years for *G. dura* (Veeragurunathan et al., 2015b) and 3 years for *G. edulis* (Ganesan et al., 2011a). The values for the highest and lowest yield registered in these publications were taken to calculate % increase and decrease in yield, respectively. The lower as well as higher biomass yield raft^{-1}(kg. fr. wt) was finally arrived (Supplementary Table 1). These two variable yields were further used to bring-out the best scenario for investors to better understand the financial viability. The yield in dry weight was considered for all the analysis. It was based on fresh to dry weight ratio.

Number of rafts required for achieving one ton (dry) biomass day^{-1}and five tons (dry) biomass day^{-1} for all the corresponding species was computed based on the biomass yield of each seaweed. By considering that two rafts can be seeded by each person day^{-1}, manpower required was computed. As different seaweeds have different growth cycle, number of rafts required by these persons to complete one cycle was calculated (Table 1). It may be noted that each raft consists of 20 nylon ropes of 2 m length each, thus needed 40 m rope for seeding. The calculation to arrive at productivity in terms of infrastructure, required farming area and manpower was based on number of rafts and area (ha).

Economic viability of biomass production

TEA and economic viability along with economic feasibility of biomass production were analysed considering the period of available cycles or days of aquaculture required to obtain 1 TPD and 5 TPD biomass production. In order to understand the economic viability of the project without any added value, profitability assessment parameters such as payback period, breakeven point, net present value and internal rates of return were calculated as described below. The depreciation for the rafts (investment) was considered 10%, while calculating the abovementioned parameters.

Payback period (PP) elucidates the time required to attain the profit and it was evaluated by the ratio of cost incurred during investment to the annual cash flow of the project. Breakeven point (BP) was also calculated to determine the minimum seaweed biomass production required to cover the cost, considering the selling price per ton of seaweed biomass using Eq. (1) and it shall be noted that variable cost in calculating BP was considered as zero.

$$\text{Break even point (tons of biomass)} = \frac{\textit{Fixed costs}}{\textit{Selling price per unit} - \textit{Variable price per unit}} \tag{1}$$

Net present value (NPV) is a way of determining the future cash flow generated by a project, including the initial investment incurred and it was calculated using Eq. (2). NPV calculations were done considering the discount rate of 12%, as per the report of Nogueira and Henriques (2020). NPV was calculated for the period of available cycles or days of aquaculture required to obtain 1 TPD and 5 TPD biomass production. If NPV > 0, it indicates that discounted current value of the future cash flow for the project will be attractive for commercialisation.

$$\textit{Net Present Value} = \frac{\textit{Cash flow}}{(1 + \textit{Discount rate})^{i}} - \textit{Initial investment} \tag{2}$$

Internal rate of return (IRR) is a rate of return of an investment employed in capital budgeting to determine and compare the profitability of investment, and hence, it was determined to understand the economic viability of seaweed production. Mathematically, IRR is the interest rate received for an investment made in a project and the cash flow occurred during a given period. For NPV > 0, IRR values were calculated as per Nogueira and Henriques (2020).

Table 1 Basic production data including market value and infrastructure cost of different agarophytes at 1 tons per day (1 TPD) and 5 tons per day (5 TPD) dry biomass with low and high range yield scenario

Parameters	*Gelidiella acerosa* Ganesan et al. 2009				*Gracilaria debilis* Veeragurunathan et al. 2019				*G. dura* Veeragurunathan et al. 2015b				*G. edulis* Ganesan et al. 2011a			
	1 TPD		5 TPD		1 TPD		5 TPD		1 TPD		5 TPD		1TPD		5 TPD	
	Yield scenario				Yield scenario				Yield scenario				Yield scenario			
	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range
Seed biomass (kg) raft^{-1}	0.5	0.5	0.5	0.5	3	3	3	3	1	1	1	1	1	1	1	1
Yield (kg) raft^{-1} @ 90 days *Ge. acerosa* @ 45 days *G. debilis*, *G. dura*, *G. edulis*	5	6	5	6	14	43	14	43	2	10	2	10	6	28	6	28
Yield after deducting seed material for subsequent crop raft^{-1} (kg)	4.5	5.5	4.5	5.5	11	40	11	40	1	9	1	9	5	27	5	27

Table 1 (continued)

Parameters	*Gelidiella acerosa* Ganesan et al. 2009				*Gracilaria debilis* Veeragurunathan et al. 2019				*G. dura* Veeragurunathan et al. 2015b				*G. edulis* Ganesan et al. 2011a			
	1 TPD		5 TPD		1 TPD		5 TPD		1 TPD		5 TPD		1TPD		5 TPD	
	Yield scenario				Yield scenario				Yield scenario				Yield scenario			
	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range
Dry to fresh weight ratio (Water content)	4	4	4	4	8	8	8	8	7	7	7	7	10	10	10	10
Dry weight (kg)	1.12	1.38	1.12	1.38	1.38	5	1.38	5	0.14	1.29	0.14	1.29	0.5	2.7	0.5	2.7
Number of rafts required for @ 1 TPD or @ 5 TPD	889	727	4,444	3,636	727	200	3,636	1,000	7,000	778	35,000	3,889	2,000	370	10,000	1,852
Number of people required for seeding @ 2 rafts day^{-1} $person^{-1}$	444	364	2,222	1,818	364	100	1,818	500	3,500	389	17,500	1,944	1,000	185	5,000	926

Table 1 (continued)

Parameters	*Gelidiella acerosa* Ganesan et al. 2009				*Gracilaria debilis* Veeragurunathan et al. 2019				*G. dura* Veeragurunathan et al. 2015b				*G. edulis* Ganesan et al. 2011a			
	1 TPD		5 TPD		1 TPD		5 TPD		1 TPD		5 TPD		1TPD		5 TPD	
	Yield scenario				Yield scenario				Yield scenario				Yield scenario			
	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range
Number of rafts growth cycle^{-1} @ 90 days *Ge. acerosa* @ 45 days *G. debilis*, *G. dura*, *G. edulis*	80,000	65,455	4,00,000	3,27,273	32,727	9,000	1,63,636	45,000	3,15,000	35,000	15,75,000	1,75,000	90,000	16,667	4,50,000	83,333
Area required (ha)	32	26.18	160	130.90	13.09	3.6	65.45	18	126	14	630	70	36	6.667	180	33.33

Table 1 (continued)

Parameters	*Gelidiella acerosa* Ganesan et al. 2009				*Gracilaria debilis* Veeragurunathan et al. 2019				*G. dura* Veeragurunathan et al. 2015b				*G. edulis* Ganesan et al. 2011a			
	1 TPD		5 TPD		1 TPD		5 TPD		1 TPD		5 TPD		1TPD		5 TPD	
	Yield scenario				Yield scenario				Yield scenario				Yield scenario			
	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range
Total days of farming year-1 @ 3 harvests of 90 days for *Ge. acerosa* @ 6 harvests of 45 days for *G. debilis* and *G. edulis* @ 5 harvests of 45 days for *G. dura*	270	270	270	270	270	270	270	270	225	225	225	225	270	270	270	270
Total days of obtaining harvest	180	180	180	180	225	225	225	225	180	180	180	180	225	225	225	225

Table 1 (continued)

Parameters	*Gelidiella acerosa* Ganesan et al. 2009				*Gracilaria debilis* Veeragurunathan et al. 2019				*G. dura* Veeragurunathan et al. 2015b				*G. edulis* Ganesan et al. 2011a			
	1 TPD		5 TPD		1 TPD		5 TPD		1 TPD		5 TPD		1TPD		5 TPD	
	Yield scenario				Yield scenario				Yield scenario				Yield scenario			
	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range
Total produce year^{-1} (tons)	180	180	900	900	225	225	1125	1125	180	180	900	900	225	225	1125	1125
Market value of biomass tons^{-1} as prevailing rates (Million USD) @ USD 1603 for *Ge. acerosa* @ USD 601 for *G. debilis* @ USD 534 for *G. edulis* @ USD 1336 for *G. dura*	0.29	0.29	1.44	1.44	0.14	0.14	0.68	0.68	0.24	0.24	1.20	1.20	0.12	0.12	0.60	0.60

Table 1 (continued)

Parameters	*Gelidiella acerosa* Ganesan et al. 2009				*Gracilaria debilis* Veeragurunathan et al. 2019				*G. dura* Veeragurunathan et al. 2015b				*G. edulis* Ganesan et al. 2011a			
	1 TPD		5 TPD		1 TPD		5 TPD		1 TPD		5 TPD		1TPD		5 TPD	
	Yield scenario				Yield scenario				Yield scenario				Yield scenario			
	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range	Low range	High range
Infrastructure cost (Million USD) @ USD 8.016 $raft^{-1}$	0.64	0.52	3.21	2.62	0.26	0.07	1.31	0.36	2.52	0.28	12.65	1.40	0.72	0.13	3.61	0.69
Total investment (Million USD) @ 50% subsidy from Fisheries Department Government of Tamil Nadu	0.32	0.26	1.60	1.31	0.13	0.04	0.66	0.18	1.26	0.14	6.30	0.70	0.36	0.07	1.80	0.34

Economic feasibility of biomass production

In this model, biomass values (dry wt ton^{-1}) as per the prevailing market rate for different seaweeds were considered @ USD 1603 for *Ge. acerosa*, @ USD 601 for *G. debilis*, @ USD 534 for *G. edulis* and @ USD 1336 for *G. dura* and it is assumed to remain constant throughout the year. The infrastructure cost was considered @ USD 8.016 raft^{-1}, while investment for the farmer was considered only half of the total economic cost considering benefit of 50% subsidy that can be availed from Fisheries Department Government of Tamil Nadu.

Total cost

In this model, we assumed that the main economic cost is the capital cost (fixed cost) since there is no other cost associated with seaweed production in this study. The seaweed farming is being carried out by individual fishermen we have not considered labour cost.

$$Total\ cost\left(\frac{USD}{year}\right) = \frac{Total\ rafts \times Cost\ of\ one\ raft\ (USD)}{Number\ of\ years\ in\ consideration} \quad (3)$$

Total revenue

The seaweed revenue is dependent on the existing price of seaweed, production and the number of cycles or days available for aquaculture during a year. The total revenue was calculated as:

$$Revenue\ \left(\frac{USD}{year}\right) = \frac{Price\ \left(\frac{USD}{Ton}\right) \times Production\ (Tons)}{Number\ of\ years\ in\ consideration} \quad (4)$$

Profit

Profit is equal to farm revenue minus total cost. The total cost used in this study is inclusive of 10% depreciation associated with the fixed cost.

$$Profit\left(\frac{USD}{year}\right) = Total\ revenue\left(\frac{USD}{year}\right) - Total\ cost\left(\frac{USD}{year}\right) \quad (5)$$

Results

Productivity of the different agarophytes

The comparison between productivity of farming system in terms infrastructure (number of rafts) (Fig. 1), required farming area (Fig. 2) and manpower (Fig. 3) essential for achieving 1 TPD and 5 TPD harvest was given. The productivity varied widely among all the four agarophytes, namely *Ge. acerosa*, *Gracilaria debilis*, *G. dura* and *G. edulis*. The lower values were for yield in high range under 1 TPD scenario while higher

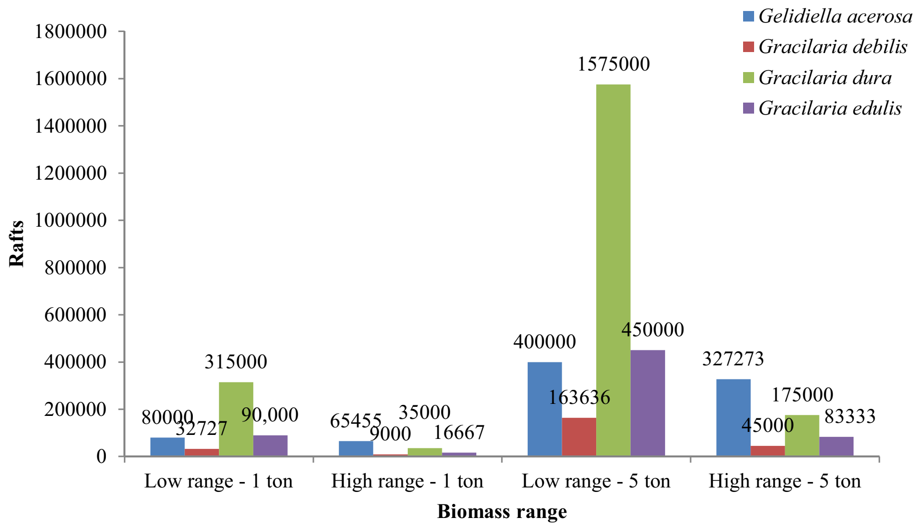

Fig. 1 Productivity of different agarophytes in terms of number of rafts

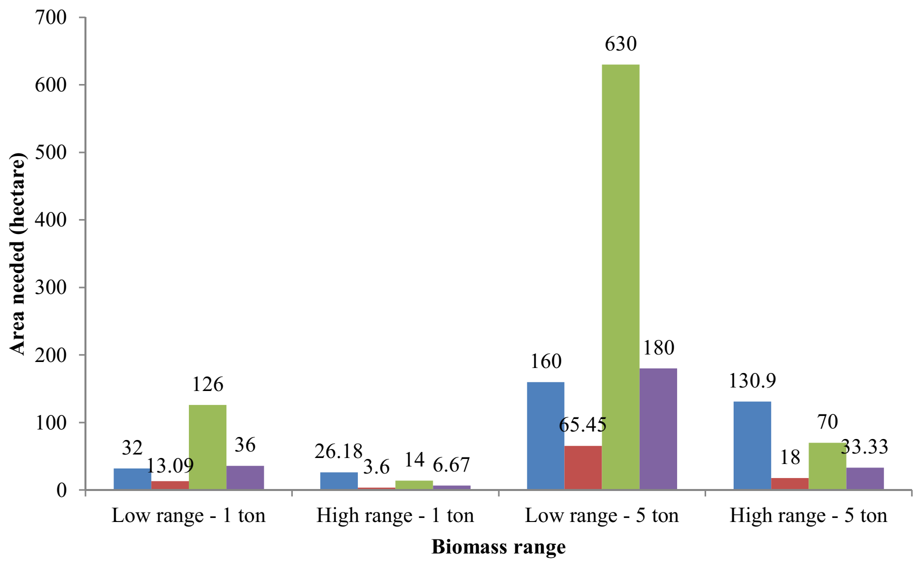

Fig. 2 Productivity of different agarophytes in terms of area under farming

values were for yield in low range under 5 TPD scenario. It was evident that, in terms of number of rafts, *G. debilis* was more productive (9,000–163,636), followed by *G. edulis* (16,667–450,000), *Ge. acerosa* (65,455–327,273) and *G. dura* (35,000–1,575,000). The estimated area under cultivation for *G. debilis* registered 3.6–65.4 ha, followed by 6.7–180 ha for *G. edulis*, 26.2–160 ha for *Ge. acerosa* and14–630 ha for *G. dura*. Nevertheless, in case of work force, *G. debilis* needed 100–1818 persons; followed by

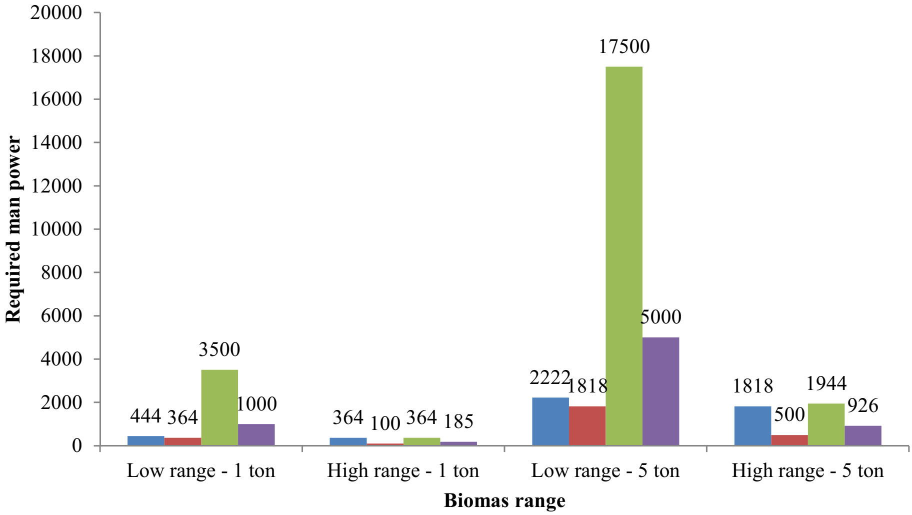

Fig. 3 Productivity of different agarophytes in terms of required manpower

185 – 5,000 for *G. edulis*, 364–2,222 for *Ge. acerosa* and 364–17,500 for *G. dura* for seeding and harvesting the crop.

Economic viability of biomass production

The economic viability of biomass production is given in Table 2. The critical economic assessment indicators reported difference in payback period, breakeven point, net present value and internal rate of return for various agarophytes. For low range scenario, a minimum payback period of 1.08 years was observed for *G. debilis* followed by *G. acerosa* (1.23 years), *G. edulis* (3.3 years) and *G. dura* (5.8 years). In case of high range yield scenario also, the minimum payback period was observed with *G. debilis* (0.3 years). Breakeven point which indicates the minimum biomass production required to cover the investment costs was found to be efficient for *G. acerosa* with 222.1 tons of biomass (low range scenario) and *G. debilis* with 66.56 tons of biomass(high range scenario).

Net present value indicates the current monetary value of a project based on the future cash flow of the project. A negative NPV value specifies non-viability of the project, whereas NPV > 0 indicates the project is acceptable and economically viable. For low range scenario, none of the seaweed species studied in this study was found to be acceptable since their values of NPV were less than zero, whereas for high range scenario, except *Ge. acerosa*, all other studied seaweed species were found to be highly favoured for commercialisation. Internal rate of return reveals the profitability of investments, and generally, the project with the higher internal rate of return (%) will be chosen for large-scale production. In this study, *G. debilis* showed the highest IRR (237.6%), followed by *G. edulis* (59.9%) and *G. dura* (54.1%).

Table 2 Economic analysis of different seaweed cultivation and biomass production at 1 tons per day (1 TPD) and 5 tons per day (5 TPD) dry biomass with low and high range yield scenario

Species	Production scale (tons per day)	Payback period (years)		Breakeven point (tons of biomass)		Net present value (NPV)		Internal rates of return (%)	
		Yield scenario		Yield scenario		Yield scenario		Yield scenario	
		Low range	High range	Low range	High range	Low range	High range	Low range	High range
Gelidiella acerosa	1 TPD	1.23	1.01	222.15	181.60	−0.089	−0.030	-	-
	5 TPD			1111.11	909.06	−0.444	−0.152		
Gracilaria edulis	1 TPD	3.33	0.61	750.10	138.37	−0.264	0.030	-	59.89%
	5 TPD			3752.60	715.77	−1.321	0.139		
G. debilis	1 TPD	1.08	0.30	242.19	66.56	−0.022	0.073	-	237.60%
	5 TPD			1212.79	333.70	−0.113	0.363		
G. dura	1 TPD	5.83	0.65	1049.98	116.85	−1.069	0.053	-	54.12%
	5 TPD			5238.86	583.67	−5.333	0.264		

Economic feasibility of biomass production

The model output showed that seaweed cultivation is currently not profitable for *G. acerosa* under both low yield range and high yield range scenario for 1-TPD as well as 5-TPD production (Fig. 4). It was found that in case of high range yield scenario for 1-TPD as well as 5-TPD production, all the agarophytes except *Ge. acerosa* registered profit. Among all, *G. dura* reported maximum profit of 0.5 million USD for high yield scenario of 5-TPD, followed by *G. debilis* 0.2 million USD also for high yield scenario of 5-TPD. The cultivation of *G. edulis* incurred loss of − 1.3million USD under both low range scenario of 1-TPD and 5-TPD production. However, the same reported profit of 0.07 million USD for high range scenario of 1 TPD and 5 TPD.

Discussions

India witnessed substantial increment in agar import during the last decade, which necessitated enhanced domestic processing efforts with backword integration of cultivation. Furthermore, the limited availability of wild-stock coupled with indiscriminate harvesting opened up the prospects of commercial farming. Nevertheless, investigations on viability of the farming system as well as financial assessment are critical in the context of providing guideline on the potential commercialisation and enticing interest of investors. Zuniga-Jara and Marin-Riffo (2016) constructed a bio-economic model for individual and artisanal culture of red alga *Kappaphycus alvarezii* using raft method. The analysis revealed that net present value was positive at the 6-month mark while internal return rate was 210%. Although they hold considerable potential, agarophyte species are not yet subjected to this

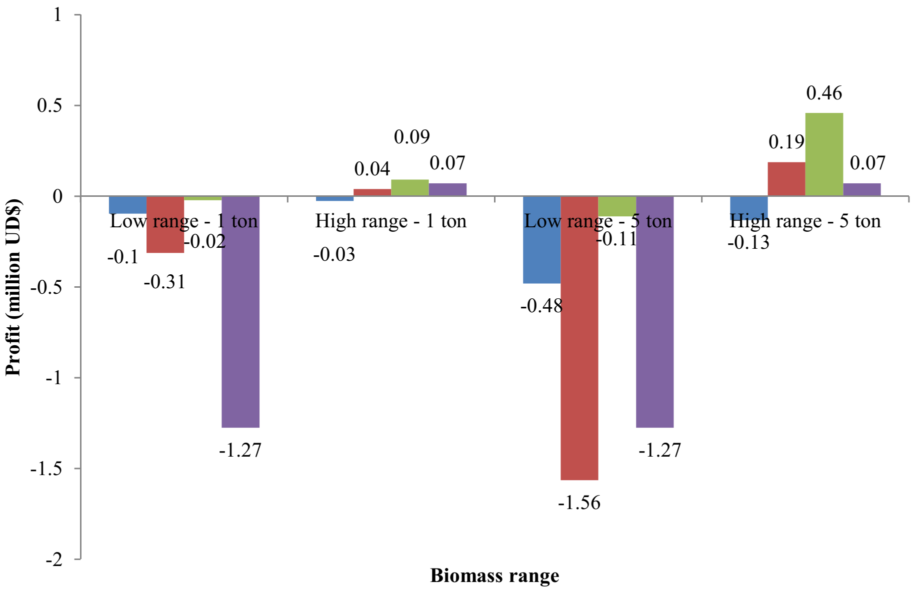

Fig. 4 Prediction of the profit using the economic feasibility analysis

kind of analysis. The motivation to this study was to evaluate comparative efficiency and profitability assessment based on payback period, breakeven point, net present value and internal rates of return to understand techno-economics that can provide clarity to investors and policy makers.

The productivity of raft method of farming was found to be variable among different agarophytes tested. The difference between productivity values for *G. debilis*, *G. edulis* and *G. dura* was mainly due to the different initial biomass and differential daily growth rate (DGR) exhibited by these seaweeds. However, it may be noted that the initial biomass has been standardised for each seaweed in previous studies. The current DGR values for these seaweeds varied from 2.5–2.8% day^{-1} for *Ge. acerosa*, 3.98–7.4% day^{-1} for *G. edulis*, 3.4–5.9% day^{-1} for *G. debilis* and 1.4–5.1% day^{-1} for *G. dura*. DGR considered in the present investigation was corresponding to the actual values reported in the field trials along the south-eastern coast of India by previous workers (Ganesan et al. 2011a, 2015a, b; Veeragurunathan et al. 2015a, b; 2019). DGR affects the overall yield obtained from the raft and thus affects the productivity in terms of number of rafts, length of cultivation ropes and area under farming and labour required to achieve 1TPD and 5 TPD production. Furthermore, there is also scope of improving the yield raft culture by changing the orientation (Ashok et al. 2016), using different substratum (Ganesan et al., 2011b), etc. The different trend of comparatively less manpower required (211–1,335) for seeding the raft in *Ge. acerosa* was due to the lengthy cultivation cycle (90 day) than other seaweeds where cultivation operations are limited to only 45 days. Although previous studies attempted economic evaluation, most of the data was presented in terms of production per hectare or per particular number of beneficiaries. Ganesan et al. (2017) reported estimated production of 35,000 kg dry wt ha^{-1} year^{-1}in *G. edulis*, 18,000 kg dry wt ha^{-1} year^{-1} in *Ge. acerosa* and 10,000 kg dry wt ha^{-1} year^{-1} in *G. dura*, from 2,000 floating bamboo rafts making *G. edulis* farming as the most productive system. The production of 56.7 tons dry wt. using 2,700 floating rafts was reported in *G. debilis* (Veeragurunathan et al. 2019). Although direct comparison is not possible in previous studies due to parameters such as number of rafts and people engaged in the farming varied between the species, *G. debilis* appears to be most remunerative in terms of yield, which was also the case in present analysis.

The economic analysis of commercial seaweed farming has been emerging recently that can help in developing and expanding regional seaweed aquaculture efforts. Zuniga-Jara and Marin-Riffo (2016) attempted bio-economic analysis of small-scale cultures of *Kappaphycus alvarezii* in India, while similar studies on *Macrocystis pyrifera* cultivation (Zuniga-Jara et al. 2016) and *Agarophyton chilensis* both in northern Chile (Zuniga-Jara and Contreras 2020) are available. Camus et al. (2019) analysed a model that tested economic profitability, of pre-commercial farming of *Macrocystis pyrifera* at 21-ha pilot farm installed in southern Chile. Roesijadi et al. (2008) attempted the economic as well as technical feasibility of seaweed cultivating in off-shore areas to produce biofuels. The study encompassing economic modelling to ascertain feasibility of seaweed farming in off-shore waters in the North Sea was also carried out (van den Burg et al. 2016). Similarly, techno-economic analysis studies were also concentrated on energy applications such as biofuel production (Dave et al. 2013; Fasahati et al. 2012; Krastina et al. 2017; Soleymani and Rosentrater 2017). The techno-economic analysis of carrageenan seaweed farming from six countries reported large differences in economic performance (Valderrama et al., 2015). The estimated deployment and operating costs and profitability ratios were calculated for *K. alvarezii* under large-scale versus family-sized system production along the southeastern coast of Brazil. The internal rates of return (IRR) of 38.2%, 70.7% and 87.8% and a payback period (PP) of 31, 17 and 14 months with a breakeven point (BP) at 78.4 tons of fresh weed were reported (Nogueira and Henriques, 2020). Nevertheless, high market value of biomass in case of *G. dura* coupled with 50% subsidy from the Fisheries Department of Tamil Nadu made it economically viable seaweed in terms of pay-back period (0.65 years), breakeven point (116.85 and 583.67 tons) and internal rates of return (54.12%). The comparative data from other such analysis is not available from Indian coast. Nevertheless, return on investment on hanging long line method of farming of *K. alvarezii* in the Philippines was 227% with corresponding pay-back period of 0.4 years (Hurtado et al. 2001). That was only under high yield scenario (peak month of farming). *Macrocystis pyrifera* farming in Chile reported USD 15,448 NPV, 15% IRR and 7.2 Payback time (PB) with total annual income of USD 111,600 (Camus et al. 2019).

It was evident from the study that raft cultivation of *G. debilis* is promising for commercialisation, in terms of higher internal rate of return (237.6%), payback period (0.3 years) and breakeven point (66.6 ton dry wt biomass for 1 TPD and 333.7 ton dry wt biomass for 5 TPD), as compared to other agarophytes. In case of low-range yield scenario, none of the cultivated seaweeds shown commercial implications, considering their critical economic assessment parameters. Zuniga-Jara and Contreras (2020) reported profit in *A. chilensis* after 8 years which indicated farming of this alga as a long-term investment, requiring more time for the income to recover the investments. Although a direct comparison cannot be made between the present study and values reported by Zuniga-Jara and Contreras (2020), it can be deduced that the NPV of *G. debilis* shown positive, i.e. 0.073 for 1 TPD (high-range yield scenario). Contrarily, the agarophyte cultivation along the southeast coast of India is a family-run enterprise, seed material is collected from natural habitat, lower water level in the intertidal areas where cultivation is happening requires no boat and industry is willing to go pick-up the harvested biomass from production site of individual fisherman, making no transportation-related expenses. As it is family centric, there are no wages or administrative expenditure or salaries to be paid. Similarly, there is no charge toward sea-front use or government fee for leasing sea area. Therefore, the operating cost is nil in the family centric model. Furthermore, there is no technology transfer fee directly charged to the farmers, as skill set development is taken as national initiative by various relevant agencies, in this case the National Fisheries Development Board.

It was reported in *G. dura* that other methods of farming such as monoline or long line, hanging rope techniques, net and net pouch method could be economically viable. Veeragurunathan et al. (2015a) reported that less manufacturing cost for these methods than floating raft method in *G. dura* resulted in higher profit. Hurtado et al. (2001) reported that 5 tons (dry) was found to be financially advantageous for commercial success of *K. alvarezii* in the Philippines (Hurtado et al. 2001). The highest cost in the commercial farming of *K. alvarezii* was attributed to labour (40%), followed by capital outlay (22%), materials (21%), seedlings (12%) and expedite towards interest (5%) (Hurtado et al. 2001). Camus et al. (2019) reported farming of *Macrocystis pyrifera* profitable during 10-year evaluation period considering the price over US$ 87 wet t^{-1}, keeping the yield at 12.4 kg m^{-1} in a 10-ha cultivation system. This was feasible due to about 1.5–3.5 times higher net value of biomass per ha obtained with new configuration of the culture system. Zuniga-Jara et al. (2016) reported that in *Macrocystis pyrifera* farming in northern Chile, the 28% of the total annual expenditure corresponded to lease of the sea area (18.7% for government fees and 9.3% for market premium fees). Nevertheless, it may be noted that such costs are not applicable in India, rather, there is 50% subsidy offered by the Department of Fisheries on the infrastructure cost; thus, the whole method can be profitable. Prediction of the profit using the economic feasibility analysis model deciphered the differences in profit margins of different agarophytes under both low and high range scenarios of 1 TPD and

5 TPD production. The economic feasibility analysis showed how the economic consequences of difference in prevailing market value of seaweed biomass as well as different yields resulted into different profit in case of *Ge. acerosa*, *G. debilis*, *G. dura* and *G. edulis*. Although profitability assessment parameters such as payback period, breakeven point, net present value and internal rates of return supported, *G. debilis* and *G. dura* reported maximum profit. This disparity can be primarily explained in the farm gate value of the biomass. It may be noted that prevailing market rate of the biomass of *G. dura* is 2.2 fold higher than the *G. debilis*. It may also be noted that there is no substantial change in market selling price in agarophyte seaweeds in India (Johnson et al. 2017). Furthermore, unlike *K. alvarezii*, where secondary market in the form of plant bio-stimulant from fresh biomass has been developed in last one decade besides carrageenan, no such opportunity exists for agarophyte seaweeds. It has been observed that secondary market helps in elevating the prospects of economic profitability as observed in *Macrocystis pyrifera* (Camus et al. 2019).

It was evident that several publications and project documents project an overly positive sketch of agarophyte seaweed cultivation but there is an urgent need to make comparison based on several economic attributes for commercial success. It is also clear that economic impact of farming depends largely on farm gate values, which are usually fixed with no scope to increase. Therefore, economic viability of agarophyte farming largely depends on adopting new farming methods such as triangular rafts (Mantri et al., 2015), vertical alignment of rafts (Ashok et al. 2016) and suspended stone method (Ganesan et al., 2011b). Furthermore, scaled-up operational and improved farm maintenance capabilities, shared worked responsibilities and enhanced farm management skills are also needed. Besides, technological interventions made in product profile would also help to realise the profit in terms of value addition of farmed resource (Reddy et al. 2016). Furthermore, adoption of agarophyte farming by the people residing along the GoM, south-eastern coast of India, would bring new remunerative benefits which are depending on only seaweed collection and cannot take up *K. alvarezii* farming due to impending government restrictions (Johnson et al. 2017). Furthermore, under ‘Pradha Mantri Matsya Sampada Yojana’ a flagship project proposed by Ministry of Fisheries, Animal Husbandry and Dairying, Government of India where ambitious target of 10 million tons of seaweed production has been fixed for year 2024–2025, such analysis assumes considerable importance (Ministry of Fisheries, Animal Husbandry and Dairying 2020).

Conclusions

The considerable cut in legal annual harvest of *Gelidium* by Moroccan government coupled with enforced trade limits on export has put the already constrained Indian agar industry in perils. It is thus pivotal to have comparative management and economic potential of agarophyte farming in Indian waters to attract investors to boost indigenous production. In farming, productivity determines the final production, which is of considerable importance to the growers. The data or assumptions made in the current investigations were derived from our past studies. Techno-economic analysis of farming of four common agarophytes was presented to encourage stakeholder investment in these species. Among the four agarophytes tested, *G. debilis* was found to be more productive in terms of infrastructure and area under farming, while in terms of manpower requirement, *Ge. acerosa* was productive. It may be noted that *G. debilis* showed promising implications for commercialisation, in terms of higher internal rate of return, minimum payback period and breakeven point. *G. dura* can also be considered a candidate species due to its higher profit margins. However, one should be ready to investment substantially high cost towards infrastructure. The study confirmed profitability of farming of all agarophytes except *Ge. acerosa* under high range scenario for both 1 TPD and 5 TPD production. With this information being made available to the fishermen and potential investors, the agarophyte farming in India can be a viable alternative due to low skill set and small investments.

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Author contribution Vaibhav A. Mantri: Conceptualising and planning of the work, data analysis and interpretation and manuscript preparation; Ramalingam Dineshkumar: Data analysis for profitability assessment parameters, namely payback period, breakeven point and net present value, interpretation of results and manuscript preparation; Anshul Yadav: Data analysis for payback period, breakeven point and net present value, interpretation of results and manuscript preparation, economic feasibility total cost, total revenue and profit; V. Veeragurunathan: Data collection and processing for 1 tons per day (1 TPD) and 5 tons per day (5 TPD) dry biomass through aquaculture of *Gracilaria debilis* and *G. dura*; M. Ganesan: Data collection and processing for 1 tons per day (1 TPD) and 5 tons per day (5 TPD) dry biomass through aquaculture of *Gelidiella acerosa*; K. Eswaran: Data collection and processing for 1 tons per day (1 TPD) and 5 tons per day (5 TPD) dry biomass through aquaculture of *Gracilaria edulis*; S. Thiruppathi: Data collection and processing for high and low yield scenario.

Availability of data and material Main primary and secondary data used for this study are already included in tables inserted in the manuscript.

Code availability Not applicable.

Declarations

Ethics approval This article does not contain any studies with animals performed by any of the authors.

Consent to participate Not applicable.

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Conflict of interest The authors declare no competing interests.

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