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Challenges and opportunities in achieving sustainable mud crab aquaculture in tropical coastal regions

Elina Apine [a,*,1], Prashanth Ramappa [b], Ramachandra Bhatta [c], Lucy M. Turner [a], Lynda D. Rodwell [d]

[a] School of Biological and Marine Sciences, University of Plymouth, Plymouth, PL4 8AA, United Kingdom
[b] Department of Fisheries Resources Management, Karnataka Veterinary Animal and Fisheries Sciences University, College of Fisheries, Mangalore, 575002, India
[c] ICAR-Emeritus Scientist (Economics), Department of Fisheries Economics, Karnataka Veterinary Animal and Fisheries Sciences University, College of Fisheries, Mangalore, 575002, India
[d] School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, PL4 8AA, United Kingdom

A R T I C L E I N F O

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A B S T R A C T

Aquaculture plays a significant role in food security and provides livelihoods and employment for millions of people among coastal communities worldwide. However, the growing aquaculture sector has also created debates around its long-term ecological sustainability, economic viability, potential social inequalities and governance issues. We investigated the perceived challenges and opportunities to achieving sustainable mud crab aquaculture in tropical coastal regions by using the case study of coastal mud crab farms in Andhra Pradesh, India. Informed by perceptions and indicative financial data from a sample of stakeholders we investigated the potential economic outcomes under different scenarios representing varying yield levels, risk factors and project time periods. The main risks identified by the stakeholders were associated with the limited supply of mud crab seeds and the lack of access to governmental and non-governmental support schemes. There are no financial buffers, therefore major disease outbreaks or extreme weather conditions caused by climate change would lead to a loss of livelihoods. This paper also highlights the most critical factor determining the level of success of mud crab farming being the crab survival rate which is influenced by a variety of factors including increasing sea surface temperature. The results of this study show that small-scale mud crab farming has fewer risks and higher flexibility involved than large-scale mud crab farming. It could be an economically sustainable enterprise and serve as a tool for poverty alleviation in developing countries if microfinance support and training are available.

1. Introduction

Global human population growth along with increasing fishing intensity and capacity are major factors leading to the depletion of wild fish stocks, which consequently has resulted in the rapid expansion of the aquaculture sector in the last three decades in coastal and ocean regions. In 2017 global production from aquaculture was 80 million tonnes, encompassing 425 fish and shellfish species (Naylor et al., 2021). Aquaculture is now the fastest growing food production sector in the world and has a direct impact on food security and poverty alleviation of the rural poor in coastal regions (FAO, 2022). Small-scale aquaculture has been identified as one of the promising economic enterprises generating income and employment opportunities for local communities (Toufique and Belton, 2014). However, some of the farming practices, in particular, shrimp (Penaeidae) and milkfish (Chanidae) farming, are linked to the extensive destruction of mangrove forests and coastal wetlands during the 1980s and 1990s (Naylor et al., 2000). The first two decades of aquaculture sector development also saw significant problems with effluent discharge, the introduction of non-native species and extensive use of wild seed (early life stage and/or juveniles) to stock aquaculture ponds (e.g., Naylor et al., 2000; Primavera, 2006). This has been linked to weak governance mechanisms and policies supporting foreign exchange without fully assessing environmental impacts (Hishamunda et al., 2009; Genschick, 2011). In addition to the negative environmental impact, social issues such as the exclusion of small-scale fishing communities were also seen (Béné, 2015; Blythe

* Corresponding author. School of Geography and Sustainable Development, University of St Andrews, St Andrews, KY16 9AL, United Kingdom.
E-mail address: ea93@st-andrews.ac.uk (E. Apine).
[1] Present address: School of Geography and Sustainable Development, University of St Andrews, St Andrews, KY16 9AL, United Kingdom.

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et al., 2015). However, more recently significant steps have been taken to achieve a sustainable aquaculture sector (Eigaard et al., 2014; Naylor et al., 2021). Acknowledging the negative associations with the aquaculture sector is important for ensuring that any emerging aquaculture farms have minimal adverse environmental and social impacts. Aquaculture at the coast can pose significant governance issues as coastlines are often the least governed spaces while being used by multiple users for various purposes (Mansfield, 2004; Foley and Mather, 2019). Furthermore, being at the interface between the land and sea, governance of coastal aquaculture entails management of common pool resources (water bodies) (e.g. Osmundsen et al., 2020; Partelow et al., 2021), property rights (e.g. Tecklin, 2016), supply chains (e.g. Bush et al., 2019; Bottema et al., 2021) and competition with fisheries and agriculture (e.g. Tveterås and Tveterås, 2010).

One of the most valuable crustaceans in the Indo-Pacific region is the mud crab of the genus *Scylla*. Mud crab fishing and farming in South Asia have been practised for decades and it serves as a significant source of income for small-scale fisher communities in these regions as well as a vital protein source (Keenan, 1999). *Scylla serrata* is the most economically important species among the four *Scylla* species due to its large size and demand in the domestic and export market of many countries (Flint et al., 2021). It can be farmed in a relatively simple setup, including mangrove pens and earthen ponds previously used for shrimp farming. It is known to be hardy and it tolerates wide temperature and salinity gradients, yet its cannibalistic behaviour accounts for a relatively high mortality rate (Alberts-Hubatsch et al., 2016). Furthermore, although it is possible to rear crab larvae in hatcheries, large-scale commercial hatchery production is still limited by low survival rates (Quinitio et al., 2001), depending on the optimisation of rearing conditions, nutrition and disease management (Nghia et al., 2007) and crab farms still often rely on wild caught juvenile crabs.

A widely accepted narrative is that fish is vital for food security for rural poor communities. Small-scale aquaculture can be a subsistence activity or a form of livelihood diversification contributing to poverty alleviation (Little et al., 2010). However, the counterargument is that the fish farmed by these communities are consumed by the middle class instead and often exported to the Global North (Beveridge et al., 2013; Golden, 2016), therefore not solving local food security and/or poverty challenges. Amid these two narratives, an alternative narrative of aquaculture as a small- and medium-scale enterprise (SME) has emerged highlighting the indirect effects of aquaculture on poverty alleviation. Developing aquaculture as SME can create growth linkages – employment opportunities, demand for feed and other inputs (Filipski and Belton, 2018).

Owing to the high economic value of *S. serrata* and the prospect of environmentally sustainable farming set-ups, this study aims to: 1) determine the perceived opportunities and limitations to mud crab farming in tropical coastal regions and 2) assess the potential of mud crab aquaculture as a sustainable small- and medium-size enterprise.

2. Materials and methods

2.1. Study area and data collection

The study was conducted in Andhra Pradesh, a tropical coastal region in southeast India and the leading state of aquaculture production, contributing 40% of the total farmed fish export value for India (Subramanyam and Prasad, 2017). The main aquaculture species in this region are prawns, catfish and carp, and increasingly mud crabs. Socioeconomic data on small-scale mud crab farming were collected by using a structured questionnaire through direct face-to-face interviews in October 2019. The interviews were conducted in the local language Telugu with the aid of a translator. The questionnaire was divided into five sections – 1) stakeholder perceptions of farm management practices of mud crabs, 2) access to market and extension services (such as agencies providing information and training), 3) costs and returns of production, 4) environmental issues and 5) demographics. A snowball sampling approach (research participants help identify other potential participants) was used after the first respondents were identified by local authorities and researchers. The snowball sampling approach was chosen as no extensive registers are available for crab farms in Andhra Pradesh. Being a type of purposive sampling, this approach allows for building up a sample based on the research project's aims (Robson, 2011). In total 37 respondents were interviewed in nine locations across a 500 km transect, providing sufficient indicative perception and financial data to inform the scenario analysis (Fig. 1).

2.2. Data analysis

The data were divided into two groups according to the size of the farm – small-scale (less than 2 ha) and large-scale (more than 2.01 ha). The size categorisation was based on the small-scale farm definition by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security (HLPE, 2013). There are no clear cut-offs for small-, medium- and large-scale agriculture and aquaculture farms. For example, with regards to agriculture, 73% of smallholders worldwide have access to less than 1 hectare of land (HLPE, 2013), meanwhile, a 10 acre (4 ha) cut off to define small-scale aquaculture in Myanmar was used by Filipski and Belton (2018).

2.2.1. Stakeholder perception analysis

The questionnaire was based on the themes identified through a literature search on the drivers and limitations of the aquaculture sector. These largely coincide with challenges and opportunities reported by Naylor et al. (2000, 2001). The themes are land and water resources, seed (initial stock), feed, disease, financial and legislative support, market demand and conditions and climate change. Although our output was quantitative, the results were analysed acknowledging the theme they cover. The statistical analysis was conducted using the Statistical Package for Social Scientists (IBM SPSS Statistics 24). The Chi-Square test of independence was used to determine whether there was a significant relationship between the variables.

2.2.2. Financial analysis – a snapshot

As long-term financial data are difficult to obtain, a snapshot analysis of one harvest (year), was conducted to obtain indicative financial information to inform a scenario analysis. Cost and revenue data gathered were used to calculate the profitability of mud crab aquaculture for one year (2019). The following indicators were calculated from the survey

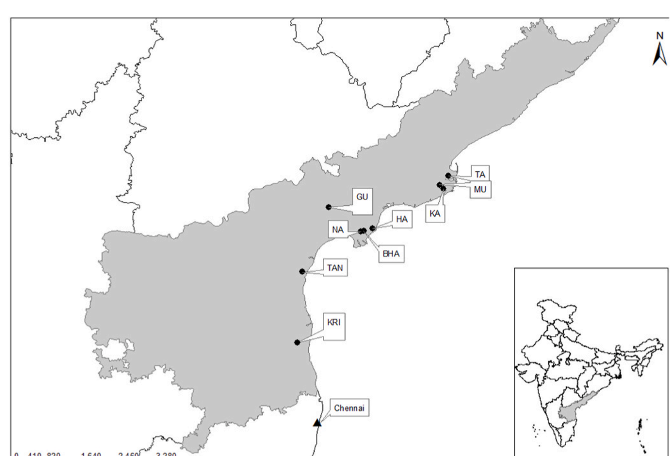

Fig. 1. Study sites across Andhra Pradesh – Krishnapatnam (KRI) (n = 7), Tangaturu (TAN) (n = 1), Guntur (GU) (n = 1), Nagaylanka (NA) (n = 5), Bhavadevarapalle (BHA) (n = 5), Hamsaladeevi (HA) (n = 1), Tallarevu (TA) (n = 7), Mummidivaram (MU) (n = 7) and Katrenikona (KA) (n = 3).

data: total costs (TC), total revenue (TR), net profit (NP), benefit-cost ratio (BCR) and return on an investment expressed as a percentage (ROI%). Total revenue was calculated from the amount of the harvested production and the selling price at the time. Six respondents were yet to harvest their mud crabs at the time of the survey, and thus were unable to provide information on revenue, and were therefore excluded from further analysis on profit.

2.2.3. Scenario analysis of potential economic outcomes

Crab aquaculture is very dynamic and harvest successes depend on various factors, including cannibalism, climate change and disease. Therefore, to determine the potential economic outcomes for aquaculture in SE India various scenarios were developed to represent a range of financial, biological and ecological conditions. The financial data from stakeholder surveys were used to guide the values of costs and prices applied in these scenarios. The five scenarios (high, medium, low, high/low and medium/low) represented three harvest rates based on the literature and our empirical findings. The maximum harvest is set to be 45% (high scenario) (Moksnes et al., 2015b; Islam et al., 2018; Mwaluma and Kaunda-Arara, 2021) and the mean harvest is set to be 23% (medium scenario) based on the mean survival rate seen in this study and also on findings by Mirera and Moksnes (2014). The survival rate for the low scenario is 10% (Mirera and Moksnes, 2014). The high/low and medium/low scenarios were included to show the high variability of harvest successes.

The Net present value (NPV) of costs and benefits was calculated over 5, 10, and 15 years with different harvest successes (Table 1). Such timeframes were chosen as fishers and aquaculture practitioners respond to changes and might switch to species with higher market prices or species that are easier to maintain. To account for variable market conditions, NPV was estimated by using three discount rates – low 5%, medium 10% and a higher discount rate of 15% (Bag et al., 2014; Anokyewaa and Asiedu, 2019; Namonje-Kapembwa and Samboko, 2020). Mean total fixed and variable costs and profits were calculated based on the values given by the respondents. Total revenue was calculated using the mean number of crablets stocked per culture. Crablets were restocked every year as they were fully harvested at the end of the season.

For all the scenarios initially it was assumed that: i) Crabs were 1st quality class size (big); ii) The selling price was the mean price reported by respondents in October 2019 for the 1st quality class size (big); iii) The initial stock was the mean number of crabs stocked for small-scale and large-scale farms; iv) Mud crab farmers have one crop per year and the growth period is between 5 and 6 months.

A sensitivity analysis was carried out to account for changes in input variables such as the selling price and size of the crab. Two selling prices were tested - the highest reported selling price and the lowest reported selling price). Two crab sizes were applied – a high weight of 700 g each and a low weight of 300 g each. Each change in input variable was tested independently and applied for all the scenarios with a 10% discount rate for 10 years.

Table 1
Scenarios for benefit-cost analysis. Survival rates differ significantly depending on husbandry practices, quality of stock, stocking density and growth period.

Scenario	Harvest
Scenario 1 – High scenario	45% of stocked crabs harvested every year
Scenario 2 – High/low variable scenario	45% of stocked crabs harvested the first year, 10% stocked crabs harvested next year with the recurring pattern of 45% and 10% every year
Scenario 3 – Medium scenario	23% of stocked crabs harvested every year
Scenario 4 – Medium/low scenario	23% of stocked crabs harvested the first year, 10% stocked crabs harvested next year with the recurring pattern of 23% and 10% every year
Scenario 5 – Low scenario	10% of stocked crabs harvested every year

3. Results

3.1. Demographics and characteristics of mud crab farms

All respondents were male, aged from 26 to 81 years with an average age of 43 years and with Telugu as their native language. Over half (57.6%) of the crab farmers interviewed have been undertaking mud crab aquaculture for less than five years. Of those who have been involved in crab farming for six or more years, five respondents have been farming crabs for 15 years. The aquaculture ponds varied in size from 0.405 ha to 16 ha, yet the majority of respondents (64.9%, $n = 24$) had small-scale mud crab farms, ranging in size from 0.405 ha (1 acre) to 2 ha (Table S1). The two largest large-scale farms covered 16 and 12 ha farms, while the majority of the large-scale farms were between 2.01 and 4.9 ha in size. The majority of large-scale farmers (53.8%) owned the land, the farms were located on or leased additional land, while small-scale farmers tend to lease the land or used common resources. All respondents from Krishnapatnam (KRI) were undertaking crab farming in a natural water body – a large lake-like water basin that has been created after building a thermal power station in the area. The majority of respondents had one or three one-acre ponds, yet one respondent had five ponds (5 acres or 2.03 ha), which placed him into the large-scale farming group. Furthermore, five respondents, formerly fishers, from Tallarevu (TA) and Mummidivaram (MU) had acquired 1 ha in the mid-1980s from the District Rural Development Agency (DRDA) after being trained in aquaculture. One respondent had a cage culture, where crabs were kept in individual boxes partially submerged in the water. All of the respondents were mainly involved in 'grow out' aquaculture which means acquiring and farming early juvenile stage crabs to reach their adult stage in the aquaculture system. The juvenile stage crabs could be purchased from a commercial mud crab hatchery, but at the time of the study, there was only one such hatchery providing for crab farmers across the whole of India. The majority of respondents stocked around 800 to 1200 instars (small early-stage juvenile crabs 0.5 cm in carapace width) and 400 to 500 crablets (slightly larger juvenile crabs from 2 cm carapace width) per acre. Small-scale farmers on average stocked 2043 crablets at the beginning of the season, while the mean number for large-scale farmers was 5846 crablets. Instars and crablets are terms used in the aquaculture sector in India to refer to different sizes of not yet sexually mature juvenile crabs (Rajiv Gandhi Centre for Aquaculture, 2013). Therefore, due to the high competition to obtain seeds, the majority of respondents also relied on wild stock collected by local fishers or procured from crab dealers in Chennai. The majority described access to crab seed to be very difficult (51.4%) or somewhat difficult (27%) (Fig. 2). The crabs were kept in the ponds for 3–8 months, with 5.3 months being the average duration. The survival rate varied significantly from as low as 2% to as high as 60%, with a mean survival rate of 23% (including mass mortalities).

Respondents did not face any issues with water availability as the farms were located near rivers, man-made canals or seaside (Fig. 2). The majority of large-scale farmers (69.2%) regularly checked water salinity, temperature, pH and bacterial load or treated water chemically. The chemicals applied, such as fertiliser dolomite lime to balance pH, fertiliser diammonium phosphate (DAP), urea and superphosphate, are commonly used in more intensive aquaculture setups such as shrimp aquaculture (Gräslund and Bengtsson, 2001). The Chi-Square test of independence indicated that there is a statistically significant difference between the type of water quality maintenance and the main source of income ($p = 0.019$). Chemicals are used mainly by those involved both in shrimp and crab farming.

Access to feed was assessed as easy by 54.1% of large-scale farmers, yet 47.4% and 5.3% of small-scale farmers identified access to feed as somewhat difficult and very difficult, respectively. Thus, a correlation between the perception of access to feed and the scale of crab farms was found ($p = 0.042$). Small-scale crab farmers mainly used chopped fresh fish as feed, while the majority of large-scale farmers used dried fish. The

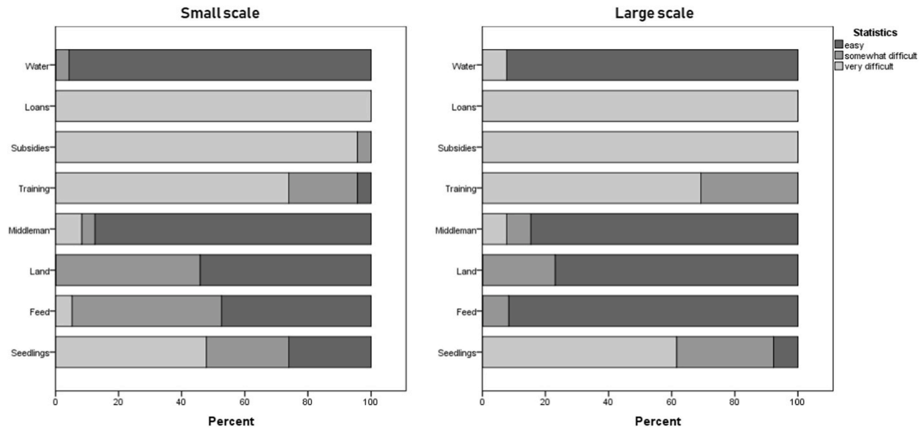

Fig. 2. Perception (%) of mud crab farmers of access to essential items for mud crab farming.

amount of feed given greatly varied between farms, but on average small-scale farmers used 1608 kg of live fish per culture, which takes around 5–6 months, and large-scale farmers used 7600 kg/culture. Feed was mainly procured from local fishers or landing sites. For 43.2% of respondents, mud crab farming was their primary source of income, followed by crab and shrimp farming (alternating between crabs and shrimps). Small-scale mud crab farmers had more diverse sources of income compared to large-scale farmers. For instance, a primary and secondary source of income for small-scale farmers was crab farming (42% and 12%, respectively), crab and shrimp farming (33% and 4%), small business (13% and 4%), shrimp farming (8% and 4%), and wage labour (4% and 17%). One small-scale farmer was also involved in fishing as a secondary activity. Meanwhile, large-scale farmers were involved in crab farming (43%), crab and shrimp farming (43%) and only shrimp farming (7%) as a primary income generating activity, and wage labour was only a secondary activity for one farmer and a tertiary activity for another farmer. No large-scale farmer was involved in small business ventures or fishing.

3.2. Perceptions of the market, access to support and environmental issues

Respondents were asked about access to the market, information and assistance. As expected for this species, the majority (83.8%) sold the live crabs to a middleman who in turn sold them to an exporter for shipment overseas (e.g. to Singapore). The remaining 16.2% sold their crabs in the local market. Very few respondents (5.4%) were not satisfied at all with the service of their middleman, while the majority (70.3%) were somewhat satisfied. The main reason for not being 'very satisfied' was the uncertainty of whether the prices set by the middlemen are fair. The price depends on the size and the quality of the crab, and it fluctuates depending on the international demand and season. The average price per kilogram reported by crab farmers in October 2019 for the 1st class (XL) crab (>800 g, intact) was £15.48/kg, £10.13/kg for big, 500–800 g crab, £5.79/kg for 300–500 g intact crab and £3.12/kg for 300–800 g crab with physical damage. The most common way to deliver harvested crabs was by transport organised by a middleman. All of the large-scale farmers used this option, while small-scale farmers also used their own transport (4.2%) or used public transport (12.5%).

Access to training in aquaculture practices was assessed as very difficult by the majority of the respondents along with almost impossible access to loans and subsidies (Fig. 2). More than half of mud crab farmers (75.7%) thus disagreed with the statement that they receive enough support from various organisations, yet 97.3% said that they would be willing to expand if they received support. Asked whether they perceive mud crab farming as a profitable activity, 70% responded positively. Yet at the same time, 70% said that mud crab farming is not a stable source of income. Although mud crab farming is not perceived as an unambiguously stable or profitable activity, all of the respondents unanimously agreed that they would encourage their friends and family to undertake mud crab farming.

The majority (48.6%) perceived that the wild mud crab population has slightly decreased since they have been involved (varying between 2 and 23 years) in mud crab farming, and 29.7% reported it to be significantly decreasing. The biggest environmental issues were reported to be increased water temperature and water pollution and saltwater intrusion. Consequently, these were mentioned as the reasons for disease and mortality of crabs as 78.4% of respondents had noticed sick or temperature-affected crabs in their ponds, thus highlighting the direct and indirect effects of climate change on mud crab aquaculture. Mangrove destruction harming their crab culture was only reported by small-scale crab farmers.

3.3. Assessing profitability of mud crab farming

Small-scale farmers invested the most in fencing, feed and crablets procured in kilograms, while large-scale farmers spent the most on crab instars and crablets sold per piece and digging and preparing ponds (Table 2). Besides, one of the biggest differences was the number of people involved in harvesting and thus its impact on costs, which was on average ~£139 (13,452 Indian rupees) per culture for a small-scale farm and ~£272 (26,192 Indian rupees) per culture for a large-scale farmer. Two large-scale farmers did not report any fixed costs. One of them owned the land, thus there were no land lease expenses and other fixed costs might have been accounted for in the variable costs reported. The other farmer only reported costs on crab seed and labour, although was leasing 3 acres of land beside the 7 acres he owned. The total cost of production was more than two times higher for large-scale farmers compared to small-scale farmers. Bigger investments, however, also can mean bigger losses in case of disease outbreaks. Four small-scale farmers and two large-scale farmers lost all of their crabs due to increased water temperature or white spot virus (WSV) outbreaks, resulting in a significant financial loss in the production year 2019. Yet even the farmers who did not lose all of their harvests faced a significant decrease in numbers compared to their previous harvests due to identical factors. The financial indicators varied significantly between mud crab farmers, yet the average net profit was only positive for the small-scale farms. However, it should be noted that it was largely because of the farms with ROI of 622% and 998%. These farmers owned their land, had minimal labour and transportation costs and the highest costs were associated with feed, but did not report any maintenance costs. They also reported high total harvest success, yet without detailed information on the crab weight they sold. This shows how mean values of indicators and ratios are not always indicative of individual feasibility. While the mean value

Table 2
Itemised fixed and variable costs per culture in British Pound (£) for small-scale and large-scale mud crab farmers. Values are expressed as mean ± standard deviation (SD).

	Item	Total costs per culture (£) [a]	
		Small-scale	Large-scale
Fixed costs			
	Land lease (n = 7, n = 5) [b]	366 ± 207	1974 ± 1704
	Digging and preparing the pond (n = 9, n = 5)	218 ± 123	588 ± 557
	Fencing (n = 12, n = 10)	695 ± 384	1500 ± 1843
Variable costs			
	Crabs (instars and crablets) (n = 24, n = 13)	668 ± 654	1213 ± 1000
	Feed (n = 19, n = 12)	765 ± 490	3168 ± 4214
	Transportation (n = 12, n = 4)	209 ± 170	174.±97
	Labour (n = 23, n = 13)	139 ± 117	272 ± 192
	Water/electricity (n = 8, n = 6)	295 ± 103	117 ± 77
	Maintenance [c] (n = 12, n = 8)	195 ± 178	1479 ± 2786
Total costs [d, e] as a sum of above indicated individual items		**3550**	**10485**
Total costs [d, f] indicated by the respondents (n = 24, n = 13)		**2395 ± 928**	**7568 ± 6645**

[a] Indian rupee is equivalent to 0.01039 GBP (10.06.2020).
[b] Indicates sample size for small-scale and large-scale farms, respectively.
[c] Includes watch and ward costs, which is a fixed variable, however was reported as variable maintenance costs. The proportion was not disclosed.
[d] Total cost = Capital costs + Operational costs.
[e] This is the sum of all the items indicated in the table.
[f] These total costs were reported by the respondents as their final total costs.

is positive (1.4), more than half (n = 13) of the small-scale farmers included in this analysis had a low BCR indicator (value above 1 indicates profit) and a negative ROI% (Table 3). Only two large-scale farms had positive ROI% and beneficial BCR. Overall, it can be concluded that this year's harvest brought financial losses to the majority of the mud crab farmers regardless of the scale of the farm. Other authors have reported the mean BCR of *Scylla* sp. aquaculture to range from as low as 0.39 (Moksnes et al., 2015a) to as high as 1.97 (Petersen et al., 2013) (Table 4).

3.4. Future feasibility assessment of mud crab farming

Analysis of the costs and benefits of one isolated year gives a static picture of a business that is influenced by many various factors affecting the success of the harvest. To investigate the longer-term feasibility of the mud crab enterprise the net present value of costs and benefits was calculated based on the mean costs and benefits in five different harvest scenarios, with three different discount rates and over three different time periods. The mean total fixed costs, calculated from the survey data, were £601 (57,863 Indian Rupees) for small-scale farmers and £2139 (205,923 Indian Rupees) for large-scale farmers. Mean total variable costs were significantly higher – £1709 (164,530 Indian Rupees) and £5828 (560,938 Indian Rupees) for small and large-scale farmers, respectively. Scenario analysis outcomes show that if the crab survival rate each year is 23% (medium scenario, mean survival rate recorded by the respondents), both small- and large-scale mud crab farmers gain moderate profit in the long term (Fig. 3, Table S2). The two most profitable scenarios are the high and the high/low scenarios, the latter indicating that for long term profit, the effects of mass mortalities can be reduced by obtaining higher survival rates in the following year. The low scenario unsurprisingly showed that all farmers would suffer significant losses, yet while the medium/low scenario would bring losses to large-scale mud crab farmers, small-scale farmers would still obtain a positive net present value (NPV), albeit low.

The sensitivity analysis showed that the NPV in the case of the high scenario would increase by 38% for small-scale farmers and by 43% for large-scale farmers if the price was to increase to £12.46/kg. If the crab size was 700 g, the NPV in the case of the high scenario would increase by 65% for small-scale farmers and by 75% for large-scale farmers. (Fig. 4, Table S3, Table S4). At the same time if the price decreased to £6.23/kg and the size of each harvested crab was 300 g, both small- and

Table 3
Individual profitability indicators– total revenue (TR), net profit (NP), benefit-cost ratio (BCR) and return on investment (ROI%) for all small and large-scale mud crab farms (excluding six crab farmers, who had not harvested at the time of interviews and one small scale mud crab farmer that had not provided information on total profit). The Indian rupee is equivalent to 0.01039 GBP (10.06.2020).

Small-scale (n = 20)					Large-scale (n = 10)				
ID	TR (£)	NP (£)	BCR	ROI%	ID	TR (£)	NP (£)	BCR	ROI%
S1	909	−1429	0.389	−61	L1	3637	−1559	0.700	−30
S2	0	−3324	0	−100	L2	5610	−15432	0.266	−73
S3	327	−1751	0.158	−84	L3	1559	−364	0.811	−19
S4	1455	−810	0.642	−36	**L4**	**2598**	**1397**	**2.165**	**116**
S5	468	−425	0.524	−48	L5	1559	−7550	0.171	−83
S6	2057	−2629	0.439	−56	L6	1299	−3398	0.277	−72
S7	0	−2187	0	−100	L7	0	−6368	0	−100
S8	**2286**	**327**	**1.167**	**17**	L8	312	−13351	0.023	−98
S9	1766	−1901	0.482	−52	L9	0	−446	0	−100
S10	1766	−499	0.780	−22	**L10**	**17922**	**12223**	**3.144**	**214**
S11	1766	−499	0.780	−22					
S12	**4738**	**3069**	**2.839**	**184**					
S13	**4738**	**3304**	**3.304**	**230**					
S14	**4738**	**3069**	**2.839**	**184**					
S15	**17922**	**16290**	**10.983**	**998**					
S16	**21507**	**18530**	**7.225**	**622**					
S17	0	−4000	0	−100					
S18	1039	−758	0.578	−42					
S19	**2857**	**754**	**1.359**	**36**					
S20	312	−2390	0.115	−88					

Table 4
Net revenue (NR) and benefit-cost ratio (BCR) for Scylla sp. Aquaculture in Bangladesh, Vietnam, Kenya and Tanzania.

Reference	Country	Species	Type of culture	Number of farms	NR US $	BCR
Khatun et al (2009)	Bangladesh	*Scylla olivacea*	Bamboo pens	6 trial blocks	651.28[a]/ha^{-1}	1.71
Ferdoushi and Guo (2010)	Bangladesh	*Scylla* sp.	Fattening in ponds	50	7900.93/ha^{-1}	1.94
Basu and Roy (2018)	Bangladesh	*Scylla serrata*	Grow out in ponds	40	1371.57/ha^{-1}	1.64
Sujan et al (2021)	Bangladesh	*Scylla serrata*	Fattening in ponds	75	4418/ha^{-1}	1.72
Petersen et al (2013)	Vietnam	*Scylla paramamosain*	Grow out	80	4700 central Vietnam and 1000 southern Vietnam/ per crop	3.55 and 1.97
Moksnes et al (2015a)	Kenya	*Scylla serrata*	Grow out and cage culture	Trials	226 and −816/crop	1.22 and 0.61
Moksnes et al (2015a)	Tanzania	*Scylla serrata*	Grow out and cage culture	Trials	−211 and −970/crop	0.72 and 0.39

[a] Average of all trials, NR ranged from −26 US $ for all male crab culture to 1346.27 for all female culture and 1018.79 kept in high water level and 330.62 in low water level.

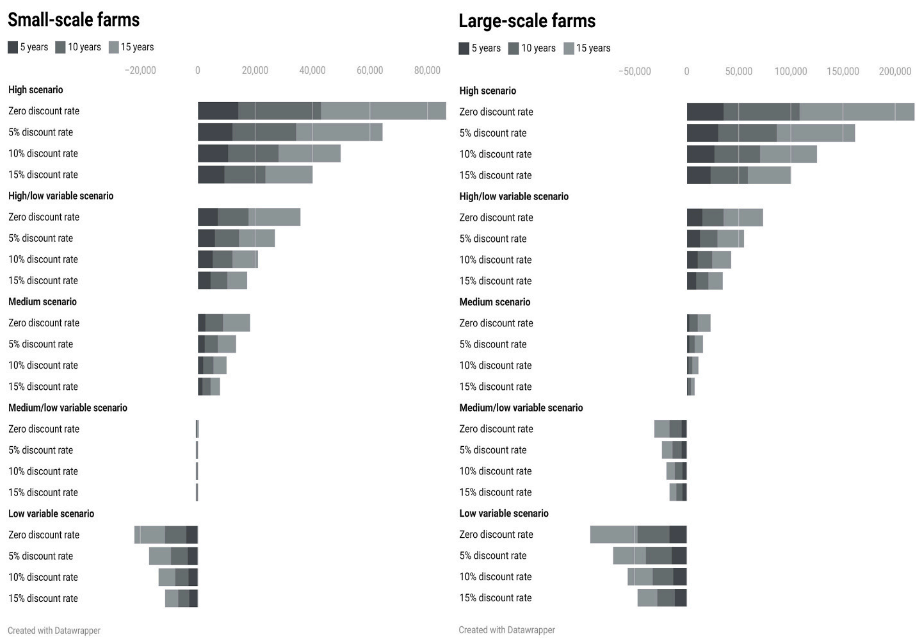

Fig. 3. Net present value (NPV) in British Pound (£) for small- and large-scale farms in five different scenarios with three different discount rates. Indian rupee is equivalent to 0.01039 GBP (10.06.2020).

large-scale mud crab farms would experience a decrease in profit in the high scenario case and experience loss of income in the high/low variable scenario. The highest losses and gains are seen in the medium/low scenario and in the case of the low scenario, indicating that the survival rate is a dominant factor.

4. Discussion

4.1. Perceived resource opportunities and limitations

A number of resources are required for crab aquaculture and while the availability of water resources in coastal India is a significant advantage compared to other countries such as Tanzania (e.g., Mulokozi et al., 2020) and Cambodia (e.g. Richardson and Suvedi, 2018), access to land for establishing earthen ponds can be limited. Andhra Pradesh is well known for its intensive inland aquaculture sector for which earthen ponds and canal systems have been built (Belton et al., 2017), thus it is common to undertake intensive crab culture with higher stocking densities. Yet, such farming can exclude certain communities that would benefit from livelihood diversification such as artisanal fishers who often do not possess more than their homestead land and suffer from social inequality (Bakshi, 2008). Land costs can contribute as high as 70% of total expenses (Sathiadhas and Najmudeen, 2004). Land in an agrarian society such as India, where agriculture provides a livelihood for 58% of India's population (IBEF, 2020), is a valuable commodity. The average size of the land owned by a rural household in Andhra Pradesh is 0.471 ha and 47% of all operational holdings in the state can be described as marginal, owning 0.002–1.00 ha of land (NSSO, 2016). The majority of the respondents of this study, however, had access to more than 0.6 ha of land for crab farming and did not consider access to land to be a barrier. A significant proportion of these crab farmers were also involved in shrimp farming, thus potentially having had access to training or other support. Thus, it highlighted that mud crab farming in Andhra Pradesh was perceived as a large-scale business opportunity rather than as a small-scale sustainable diversification enterprise. While the land is not a ubiquitous limitation for the crab farmers recruited in this study, the lack of access can act as a barrier for those needing livelihood diversification due to low income (Belton et al., 2014; Little et al., 2010). This was shown to be the case in an earlier study, investigating the limitations of undertaking crab farming among fisher communities in southwest India (Apine et al., 2019). Furthermore, differences in land lease costs per hectare indicate that communities could be affected by economies of scale. Unit costs decrease with the increase of scale, thus unit costs for smallholders are higher compared to

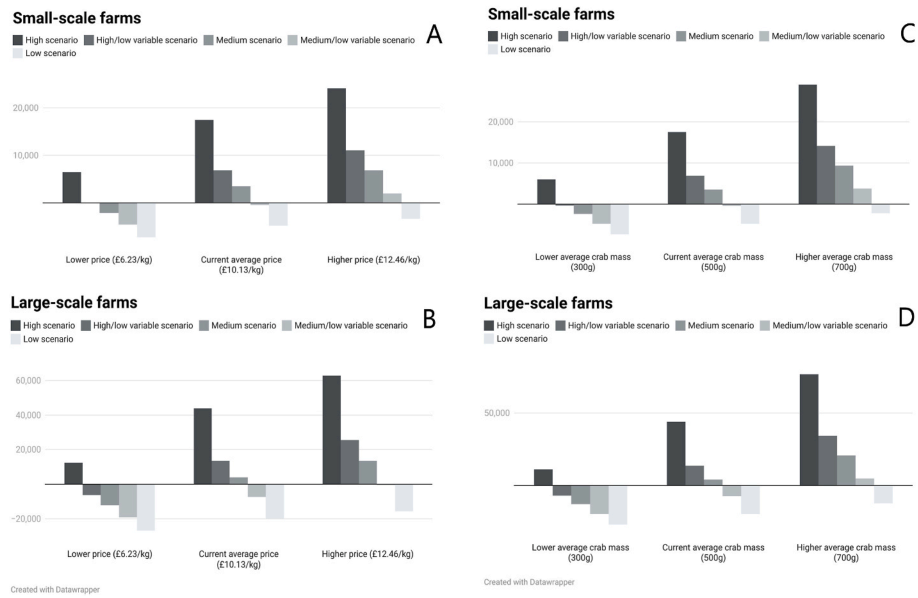

Fig. 4. Sensitivity analysis to changes in market price per kilogram for small-scale farms (A_ and large-scale farms (B) and changes to crab body mass for small-scale farms (C) and large-scale farms (D). Calculated for NPV (British Pound £) with a 10% discount rate after 10 years.

large-scale farm owners (OECD, 1993). Thus, incoherent property rights systems have the potential to limit community members interested in small-scale mud crab farming. Meanwhile, limited access to private land could stimulate undertaking sustainable farming practices in existing water bodies, such as mangroves and common water bodies. This could potentially create other issues such as environmental degradation if not managed properly and sustainably (Taskov et al., 2021). Coastal areas of Andhra Pradesh have undergone significant land use changes since 1977 and a high proportion of agricultural land as well as 3.8% of mangroves have been converted to aquaculture farms (Bagaria et al., 2021; Jayanthi et al., 2022). Simultaneously it is experiencing a high rate of aquaculture farm abandonment (Jayanthi et al., 2019). Transforming earthen ponds back to agricultural land or mangroves could be difficult (e.g. de Lacerda et al., 2021), thus repurposing them for other types of aquaculture, such as mud crab farming, could be an efficient way of managing these coastal resources. However, the above-mentioned statistics also indicate that reusing old shrimp farms should be a priority over creating new aquaculture farms.

Another fundamental resource required for aquaculture is seed. A technological breakthrough in the early 2000s (Quinitio et al., 2001) made it possible to obtain hatchery-reared mud crab juveniles. However, capacity and facilities differ greatly in the Indo-Pacific region. In India, to date, there is only one working commercial mud crab hatchery providing for all the farmers in the country, although plans of establishing a second mud crab hatchery have been made since the year 2017 (Sengupta, 2017). At the same time, the East African region still relies heavily on wild seeds (Moksnes et al., 2015a). Limited seed supply can be a potential source of further inequality as large-scale farmers are more likely to be able to purchase seeds from hatcheries that are not nearby and cover travel costs. Furthermore, small-scale fishers and fish farmers often tend to be marginalised and not accounted for (Song et al., 2018). Results of this study confirmed that limited access to seeds currently is a barrier for the majority of mud crab farmers and the unpredictability has a significant economic impact.

One of the most controversial aspects of the whole aquaculture sector, including mud crab farming, is the use of so-called “trash fish/low-value fish” as feed. Trash fish and bycatch are also used to produce fishmeal, a commercial product widely used in aquaculture/mariculture, land animal farming and pharmaceuticals (Shepherd and Jackson, 2013). As the aquaculture sector expands, the demand for fishmeal increases creating a ‘fishmeal trap’ – aquaculture is seen as an alternative to wild fish resources but at the same time is dependent on these resources (Wijkstrom and New, 1989; Ankamah-Yeboah et al., 2018). This study showed that mud crab farms heavily rely on “trash fish” – either as bycatch or as a targeted catch and based on observation most of these fish were sardines and tilapia - widely consumed nutritious fish. As it requires potentially thousands of kilograms of fish to feed one mud crab culture with a greater than 70% mortality rate for some farmers, it is important to question how sustainable the current practice of mud crab farming is and how it can be improved. Basu and Roy (2018) found that the high cost of crab feed was one of the major constraints to mud crab farming in Bangladesh. Poor communities are not able to afford farmed fish and crabs for their own nutrition and widely rely on more affordable wild-caught fish, often those deemed “low value” (Joffre et al., 2021). Yet, tilapia is considered to be an invasive species in India that has escaped from the aquaculture farms into the wild (Singh, 2021), thus it could be argued that using tilapia as feed could help maintain the balance in wild fisheries. However, before this could happen, further and more complex research is necessary firstly, to assess the commercial value of the fish used as feed, secondly, to investigate people’s preferences and thirdly, to conduct the stock assessment and future stock modelling.

4.2. Financial opportunities and limitations

The reason behind the potential economic success of the mud crab is clear – high market demand in both local and international markets. Foreign demand was also acknowledged to be the main driver for shifting from shrimp cultivation to mud crab farming in Bangladesh (Basu and Roy, 2018). A study based on FAO FishStat J Database showed that 85% of aquaculture production from the ten biggest aquaculture producer countries is consumed domestically and in India, this share is as high as 95% (Belton et al., 2018). However, it is difficult to trace where the production chain of the mud crab ends as there are no species-specific databases. Data sets on crabs might include marine crabs and data sets on crustaceans usually include shrimps and prawns which would account for the biggest share. The data from the International Trade Centre showed India is a net exporter of all types of crabs and crab products, with an annual growth of 18% and the main markets are China, Singapore, the United States of America, Taipei and Thailand

(ITC, 2019). Yet, there are no clear data on the total amount of produce and what share stays in the domestic market. There is enough anecdotal evidence to support the importance of the domestic market in the trade of mud crabs, yet the lack of official data sets can render identifying any signs of market failure that can have a significant adverse impact on mud crab farmers.

Mud crab farming is perceived as a profitable, yet unsteady income-generating activity due to the unpredictable crab survival rates. However, the prospect of profit outweighed the unpredictability and even a complete loss of stock did not discourage farmers to continue. Thus, similarly to shrimp aquaculture, crab farming is 'like gambling' as several factors can influence the outcome, shrimp farmers were found to be fully aware of risks and chose species, intensity and risk management plans accordingly (Joffre et al., 2018). Therefore, for mud crab farmers, flexibility regarding the type of culture (grow-out or fattening), stocking density and the length of culture and diverse source of income (especially for small-scale farmers) is their response to mitigate and/or adapt to risks.

The results of various scenarios suggest that mud crab farming can be a feasible income-generating activity, however, the level of success is highly dependent on various factors such as the discount rate applied, market price that mud crab farmers cannot affect, and the survival rate of crabs that can partially be managed by monitoring and maintaining ponds. The most critical factor in determining success (positive NPV), unsurprisingly, was found to be the survival rate of mud crabs.

The survival rate and physiological or morphological state of crabs can be affected by water quality (e.g.Botton and Itow, 2009), climate change effects such as heatwaves or droughts (e.g. Hamasaki, 2003; Ruscoe et al., 2004) and disease (e.g. Waiho et al., 2018; Sujan et al., 2021). Furthermore, cannibalism is a major issue and the main reason for low survival rates (Alberts-Hubatsch et al., 2016). Several factors can determine survival rates and growth performance such as stocking density (Mann et al., 2007), the use of shelter (Mirera and Moksnes, 2014) and the type of culture system (Islam et al., 2018; Mwaluma and Kaunda-Arara, 2021). For instance, cage culture is labour intensive as each animal is kept in an individual box, thus potentially having high labour costs. Monoculture using seeds has been reported to obtain the highest return on investment, followed by fattening (Marichamy and Rajapackiam, 2001). This, therefore, indicates how complex and unpredictable mud crab farming is and that a collaboration between fishers, crab farmers, researchers and the aquaculture industry is required to address these various challenges. Despite the assumptions and based on research studies that indicate white spot virus outbreaks might be rare, a major outbreak took place in *S. serrata* farms in Nagalayanka, Andhra Pradesh (CIBA, 2019), thus indicating that precautions must be taken to prevent the risks to infect crabs at their juvenile stage.

Other studies in Asia have shown that mud crab fishing and farming is a lucrative business (e.g. Ferdoushi and Guo, 2010; Jahan and Islam, 2016; Basu and Roy, 2018) if the highest possible survival rates are achieved. Meanwhile in East Africa, where selling prices are lower compared to Asia and the seed is limited as no commercial hatcheries have been established, profit is marginal and cage culture, in particular, can result in a significant loss (Moksnes et al., 2015a). Further research on mud crab aquaculture reports a wide range of BCR and net revenue depending on the species, type of culture and country (Table 4). Most studies had higher mean BCR than in this study, however only one study showed individual results. Basu and Roy (2018) reported a similarly wide range of net revenue among crab farmers in Bangladesh. Based on the individual values of total costs and total revenue reported by Basu and Roy (2018), it is possible that ROI% for their study varied significantly between 13% and 354%, while there were no negative values. This indicates that mean values can easily disguise any losses (or minimal success) individual farms have experienced.

As in the case of most studies only mean ROI% values are available. Sathiadhas and Najmudeen (2004) showed that return on investment varies depending on the type of culture, from 90% of composite mud crab/fish or shrimp culture to 185% of grow-out system and 244% of crab fattening. The ROIs% for *S. paramamosain* culture in Vietnam were 90% and 261% (Petersen et al., 2013). Return on investment from other coastal aquaculture types in India ranged between 71% and 146% for open and semi-enclosed mussel farms in Goa, respectively (Lekshmi et al., 2019), to 241%/m^3 for cage fish farming in Kerala (Aswathy and Joseph, 2019). This highlights the two highest ROIs% in our study as potentially exceptional. These two mud crab farmers were from the same location and had 15-year experience with aquaculture, they owned the land the farms were located on and one of them was applying chemicals that are commonly used in shrimp aquaculture (EDTA, urea, single superphosphate and lime). Thus, the success could be explained by advanced aquaculture practices and limited costs on maintenance and labour, yet to elucidate the main reason would require further investigation. Furthermore, to fully assess the sustainability and feasibility of mud crab farming, a longitudinal study is required, recording environmental parameters and external factors affecting the market price.

Aquaculture at any scale involves various risks and having no access to subsidies and loans that could provide a safety cushion makes it even more difficult (Kleih et al., 2013). Thus, it hinders community members who could potentially be interested in undertaking mud crab farming and also existing crab farmers to continue or expand crab aquaculture. Poor access to loans was found to be the second main constraint to mud crab farming in Bangladesh (Basu and Roy. 2018). Fisheries and small-scale aquaculture always have been a sector with poor access to institutional financial help such as credit. It was assessed in 2008 that 51.4% of farmer households did not have access to institutional and non-institutional credit in India (Rangarajan, 2008). No clear official statistics can be found regarding the situation currently, but it is likely that access to institutional credits for agriculture, fisheries and aquaculture is still relatively poor. Thus, microfinance is an essential tool for many in rural areas. In India, microfinance services could be obtained from microfinance institutions that are regulated by the Reserve Bank of India and recently non-banking microfinance institutions have been recognised (Rangarajan, 2008; Ashaletha, 2018). Another important player in providing financial support for rural communities is the National Bank for Agriculture and Rural Development (NABARD) and especially linking bank services with self-help groups (SHGs).

This study was conducted before the COVID-19 pandemic, yet the pandemic has had a significant adverse effect on capture fisheries and aquaculture, leaving communities with no income and negatively affecting market prices (Manlosa et al., 2021; Kiruba-Sankar et al., 2022). In May 2020 it was announced that as part of the relief package to mitigate COVID-19 impacts, India's government will assign USD 2.6 billion to support the integrated, sustainable, inclusive development of marine and inland fisheries (Dao, 2020). More than half of these funds were dedicated to marine and inland fisheries, and aquaculture, and the rest of it will be used to improve infrastructure, including fishing harbours and market development. However, priority was given to marine fisheries and mariculture, thus again potentially excluding mud crab farmers, especially since, on a small-scale, mud crab farming, although relatively common and lucrative, is not perceived as being as important as shrimp or fish farming by the state. Although the contribution of small-scale aquaculture (FAO, 2009) and small-scale fisheries (Teh and Pauly, 2018) has been widely recognised, often it lacks evidence in the form of institutional support. Davis and Ruddle (2012) even argue that in the context of neoliberalism, support through co-management practices or other seemingly small-scale holder empowering approaches is not possible, as social and cultural values often in the core of smallholders are not esteemed by neoliberalism. Thus, this indicates that any financial and legislative governmental support will likely benefit large-scale practitioners and therefore the non-institutional sector (e.g. NGOs, SHGs) is left to play an essential role in supporting smallholders.

5. Conclusion

Aquaculture is the fastest growing food production sector worldwide (FAO, 2022), while some warn about over-optimism and potential decline due to environmental, technological and economic reasons as well as socio-economic implications to marginal communities (Sumaila et al., 2022). Therefore, understanding and assessing all pillars supporting the sustainability of aquaculture is increasingly important. Small-scale fish and crustacean farming, in particular, requires attention as it has the potential to generate greater economic spillovers and provide better employment opportunities than large-scale fish farms or agriculture (Allison, 2011; Phillips et al., 2016; Filipski and Belton, 2018; FAO, 2022). However, there are still challenges, such as lack of technological knowledge, lack of capital and limited involvement of women in decision making that hinder small-scale aquaculture success in tropical coastal regions (e.g. Mulokozi et al., 2020; Aung et al., 2021; Ragasa et al., 2022; Gwazani et al., 2022). Simultaneously small-scale fisheries and aquaculture are especially vulnerable to climate, environmental and economic shocks (Short et al., 2021). Mud crab aquaculture is an expanding sector and by using a case study approach, we investigated what challenges and opportunities crab farmers in southeast India face and how they correspond to a wider context.

The main challenges to achieving sustainable mud crab farming were found to be limited supply of mud crab seeds, high mortality rates and the lack of support from governmental or non-governmental organisations. There are no financial buffers, therefore in the case of a disease outbreak or extreme weather conditions, farmers will suffer a huge loss. Meanwhile, perceived as a delicacy with high nutritional value, mud crab has high demand in domestic and international markets, ensuring competitive prices compared to other aquaculture species.

Through various scenarios based on the empirical indicative financial data, we found that the development of small to medium-sized mud crab aquaculture in southeast India could be feasible under certain conditions. Innovative solutions are required to reduce mortality to ensure that this activity is profitable long term and reduce the uncertainty that farmers face. Especially as limited financial support or advanced training is available. Currently mud crab farming heavily relies on so-called trash fish, which often are juveniles, negatively affecting fish populations and potentially making nutritious, low-value fish less accessible for marginalised communities. This study indicates that there could be negative implications due to the high amounts of fish needed to feed one mud crab culture, yet further systems-based studies are needed to fully understand the impact on fish population structure and communities.

By comparing our findings with other studies and considering our case study within a broader context, we conclude that challenges and opportunities to small-scale aquaculture in tropical coastal regions are similar, but to varying degrees. Each country and type of mud crab culture system produce different outcomes in terms of feasibility and thus might mislead policy makers as limited studies are available. Furthermore, mean values might misrepresent the variability between individual farms. For support programmes and policy makers to recognise the contribution of mud crab farming, detailed information on production chains and market values is required. In Andhra Pradesh where the rate of abandonment of shrimp farms is high, mud crab farming could be a way of repurposing existing earthen ponds. In other areas before undertaking mud crab farming, especially if considering setting up new farms, it is important to assess all the risks (environmental, social and economic) and not solely rely on benefit-cost analyses. Further interdisciplinary research is necessary to assess the effects of direct and indirect climate change caused mortalities and their impact on the feasibility of crab aquaculture in southeast India and other tropical coastal regions.

Author contributions

EA – Writing-original draft preparation, Visualization, Investigation, Software, Validation. PR – Investigation, Writing-reviewing and editing. RB - Conceptualization, Methodology, Writing-reviewing and editing. LMT – Conceptualization, Funding acquisition, Writing-reviewing and editing. LDR - Conceptualization, Methodology, Writing-reviewing and editing, Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ocecoaman.2023.106711.

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