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Socio-economic opportunities and challenges of seaweed (*Gracilaria* sp.) farming in polyculture systems in Brebes regency, Indonesia

Olivia Azhari [a,*], Sinne van der Veer [a], Katell G. Hamon [a], Ingvild H.T. Harkes [b], Restiana W. Ariyati [c], Lestari Lakhsmi [c], Harxylen Kinanti Purnomo [a,d], Sri Rejeki [c], Lailatul Rokhmah [b,e], W.K. van den Burg Sander [a]

[a] *Wageningen Social and Economic Research, Wageningen University & Research, the Netherlands*
[b] *Wageningen Marine Research, Wageningen University & Research, the Netherlands*
[c] *Department of Aquaculture, Faculty of Fisheries and Marine Sciences, Universitas Diponegoro, Indonesia*
[d] *Indonesia Ocean Program, Yayasan Konservasi Alam Nusantara, Indonesia*
[e] *Yayasan Masyarakat dan Perikanan, Indonesia*

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ABSTRACT

Indonesia accounts for nearly 30 % of seaweed production worldwide and is one of the primary global producers. Part of Indonesian production is done in polyculture, defined as the joint cultivation of two or more species. This can improve pond productivity and increase environmental quality in the pond. Despite the potential benefits of polyculture, the socio-economic elements of the polyculture practices remain largely understudied. Investigated by means of literature review, interviews and survey of 101 farmers, this article aims to better understand the socio-economic aspects of polyculture seaweed (*Gracilaria* sp.) farming in Brebes regency, Central Java Province, Indonesia. The results presented illustrate that – from a financial perspective – there is no obvious incentive for farmers to switch to polyculture as there is no significant impact on operating profit. Two key considerations that influence adoption of polyculture practices are the relationship to other household productive activities and the benefits of polyculture. From societal perspective, polyculture is an alternative supporting farmers food resilience and offering the possibility to generate higher revenues per m^2. Farmers and farmer organizations need support for adopting polyculture practices. This can be done by increasing their bargaining power vis-à-vis the middlemen and/or financial support that enables farmers to do upfront investments in polyculture practices.

1. Introduction

Indonesia accounts for nearly 30 % of seaweed production worldwide and thereby is one of the primary global producers (Cai, 2021). The average annual production of Indonesian seaweed accounted for approximately 9.4 million tons between 2021 and 2023 (KKP, 2025a). During the same period, the average annual export value of Indonesian seaweed was approximately USD 460 thousand (KKP, 2025b). Seaweed farming has brought positive impact in improving household benefits and women's well-being of Indonesian coastal communities (Larson et al., 2021). Seaweed cultivation in Indonesia is mainly carried out by low income smallholder farmers (Langford et al., 2021).

One of the main seaweed genera produced in Indonesia, representing about 20 % of the weight produced and 18 % of the value, is *Gracilaria* sp. Between 2021 and 2023, national *Gracilaria* sp. production was about 1.6 million tons in average, worth around USD 185 million (KKP, 2025a, 2025b). *Gracilaria* sp. is used in agar production worldwide which gives it a high economic value (Mantri et al., 2023). Agar has a function as an emulsifying, stabilizing and gelling property (Selby and Whistler, 2012). Agar is used for food applications and culture medium to cultivate micro-organisms (Samanthi, 2020). Moreover, it can be used in food products (e.g. cookies, icings, cheese and bread) and cosmetic products (e.g. ointment, bath soap, face cleanser and lotion) (Selby and Whistler, 2012; Susilawati et al., 2022).

Earlier studies sought to evaluate the potential of seaweed farming to contribute to improved and more resilient livelihoods for people in Indonesia. Neish (2013) found that the cash earnings from seaweed farming generally led to higher income and better economic status of the seaweed-farming families. Moreover, this also caused multiplier effect on improving local village economies. Rimmer et al. (2021) showed that

* Corresponding author.
E-mail address: olivia1.azhari@wur.nl (O. Azhari).

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seaweed farming can, but does not always, lift rural households above the Indonesian poverty line.

Polyculture is defined as the joint cultivation of two or more species where ponds used for polyculture combine a range of species with dense dispersion and little cultivation care (Hendrajat and Ratnawati, 2021). Polyculture is credited for a range of positive environmental effects (Zhou et al., 2006). Those have been, for example, observed in the coastal open water cultivation of *Kappaphycus* for which polyculture has been shown to improve their growth (Qian et al., 1996), the environmental sustainability (Hayashi et al., 2024) and provide economic benefits to the farmers (da Silva et al., 2022). In pond polyculture, the presence of milkfish in the ponds would, for example, enhance the seaweed production by increasing the water nutrients and eliminate parasites in the water. In return, seaweed would provide shelter for the fish. Additionally, seaweed provides oxygen and acts as carbon dioxide absorbent to support milkfish survival (Hendrajat and Ratnawati, 2021). An and Anh (2020) further proved that integrating seaweed with fish in polyculture systems enhances water quality, as evidenced by notably lower concentrations of TAN, NO_2^-, NO_3^- and PO_4^{3-} compared to monoculture, while providing 80 % of the feed ration, which led to a 28.9 % reduction in feed costs. Hence, the quality of the pond environment, which has recently tended to decline, may be enhanced by utilizing the polyculture cultivation which increase the efficiency of pond cultivation, pond sustainability and farmers' income (Widyastuti and Setiadi, 2021). Despite the potentials of polyculture mentioned above, the socio-economic elements of the polyculture practices remain largely understudied, particularly in relation to seaweed pond aquaculture.

Using a case study of *Gracilaria* sp. farming in Brebes Regency, Central Java Province, Indonesia, this paper aims to contribute to a better understanding of the current situation, opportunities and challenges, specifically on seaweed (*Gracilaria* sp.), milkfish and shrimp polyculture. To ensure clarity and readability throughout this paper, the term 'seaweed' will hereafter refer specifically to *Gracilaria* sp., unless otherwise stated. Investigated with means of literature review, interviews and a survey, we aim to better understand the socio-economic aspects of polyculture seaweed farming and answer the following research question: What are the socio-economic opportunities and challenges of polyculture seaweed farming in Indonesia?

A number of sub-questions are formulated and addressed to answer the main research question:

- What are the characteristics of polyculture seaweed farming in Brebes Regency?
- How does polyculture farming perform compared to monoculture from a financial perspective?
- What are the perceived challenges to adoption of polyculture practices?

The study covers the polyculture of *Gracilaria* sp., milkfish and/or shrimp ponds found in four villages (Randusanga Wetan, Randusanga Kulon, Prapag Lor and Prapag Kidul) of the Brebes Regency, Central Java Province, Indonesia. Lessons learned from this region can be used for further discussion on the future of polyculture, also in different geographic settings.

1.1. System description

Brebes Regency is located on the north shore of Java Island between 6° 44′ and 7° 21' South Latitude and 108° 41′ and 109° 11′ East Longitude and depicted in Fig. 1. The survey was filled in by a total of 101 farmers who use one or more of the following three different production systems: (1) seaweed monoculture, (2) seaweed and milkfish and (3) seaweed, milkfish and shrimp. The location of the farmers is shown in Fig. 1 below.

Pond cultivation in Brebes Regency has a long history, going back to the early 1970s. The pond areas were initially cultivated with shrimp and milkfish. Over time, due to high production cost of shrimp, people started switching their pond cultivation to seaweed, which requires lower production costs and less maintenance. The seaweed species *Gracilaria* sp. was introduced to Brebes Regency at the beginning of the 2000s and since then has become the main income source for people (Nurhayati et al., 2021). Brebes Regency covers 166,296 ha of Java Island, where the whole farming area in Brebes Regency is 12,748 ha and seaweed aquaculture makes up about one-third of it, 4350 ha (Arina et al., 2019). The type of pond is brackish water, locally known as

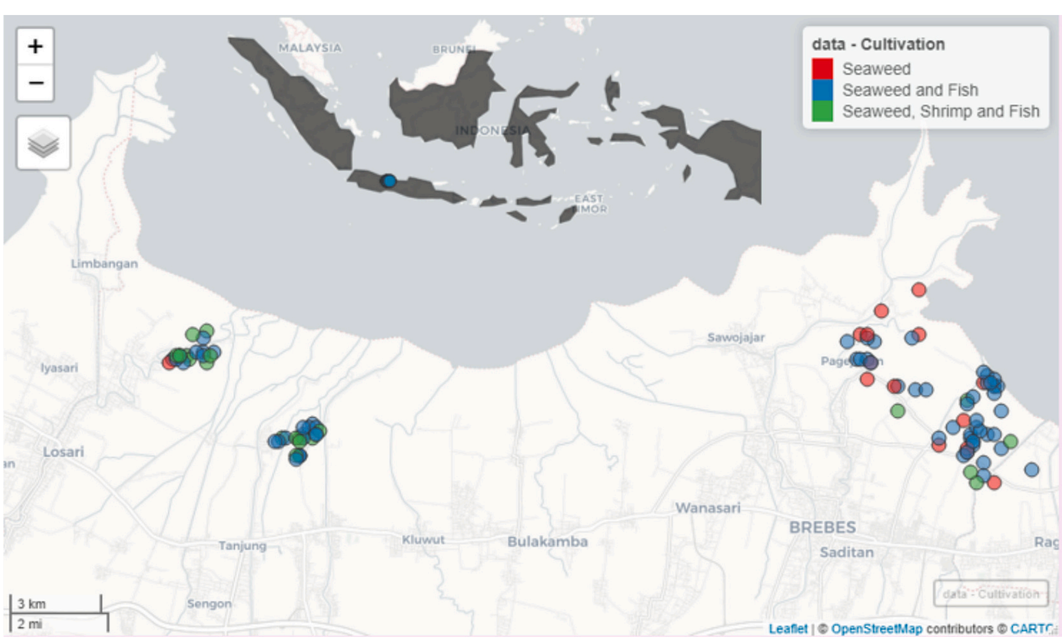

Fig. 1. Map of seaweed cultivation areas in Brebes Regency (see blue dot on the map of Indonesia, at the top of the map). The coloured dots correspond to the position of the farms of the surveyed farmers; each cultivation system type being represented by a different colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tambak, with the inlet water from the river and outlet to the ocean (Arina et al., 2019).

The cultivated *Gracilaria* sp. in polyculture ponds in Brebes Regency is mainly used for the agar powder production. A further description and visualisation of the production steps and supply chain of *Gracilaria* sp. is presented in the Supplementary Material, (see: Supplementary Fig. S1).

2. Method

2.1. Data collection

Three different methods were used to collect the data needed to answer the research questions: literature review, qualitative interviews and a survey. Table 1 shows which methods were used per sub-question.

2.2. Literature review

The literature study was performed using a snowballing approach, searching for peer-reviewed articles related to seaweed in Brebes Regency in English and Indonesian language (Bahasa Indonesia). The articles were retrieved from Web of Science, Scopus and Google Scholar. Additionally, a number of references on seaweed aquaculture such as research reports were also included in this literature review. This provided preliminary background information for the study, and it was also used in preparing the list of questions for the qualitative interviews.

2.3. Survey

The survey questionnaire was developed in collaboration between social scientists, anthropologists and economists participating in the project team. The questionnaire was aimed at the seaweed farmers in the Brebes Regency and contained a consent form followed by six parts:

1. Farmer information: demographic information about the respondents, the location of the seaweed farm, the economic importance of seaweed farming for the farmer
2. Cultivation system: description of the cultivated area and ponds, description of the species composition of the cultivated ponds, risk perception
3. Cost and revenue structure: description of fixed and variable costs, revenue and personal consumption
4. Knowledge of multi-species aquaculture systems
5. Capabilities to adopt multi-species aquaculture
6. Perceived challenges to polyculture

The data was collected locally in the fall of 2021 during interviews by Indonesian scientists in Bahasa Indonesia from 101 seaweed farmers of the Brebes Regency, and all of the farmers are men. Seaweed cultivation in Brebes is done only by men as it is a cultural tradition in this area.

2.4. Qualitative interviews

Qualitative interviews were used to clarify the processes in the production chain of agar powder in the Brebes Regency, with emphasis on the role played by the different actors at the different steps. Semi-structured interviews were done with local stakeholders during a fieldwork trip to Brebes Regency, Central Java Province, Indonesia, from 30 May 2022 to 12 June 2022. The fieldwork was conducted in several villages in Brebes Regency (Randusanga Kulon, Randusanga Wetan, Prapag Lor and Prapag Kidul). In total, eight interviews were held: three middlemen, three local researchers from Semarang (Diponegoro University), one representative of the Local Government of Dinas Perikanan Brebes (Fisheries Agency of Brebes) and the company owner of a local seaweed processing company. Additionally, three Focus Group interviews were held with farmers in the three villages. Before the interview, a list of questions was made for each stakeholder. All interviews were recorded using mobile phone. These were used as additional source of knowledge on how the seaweed production systems fit in the agar powder production chain. Information from those interviews are cited as “Interview, 2022”.

Table 1
link between research questions and methods for data collection.

	Literature review	Survey	Interviews
What are the characteristics of polyculture seaweed farming in Brebes Regency?		x	
How does polyculture farming perform compared to monoculture from a financial perspective?		x	x
What are the perceived challenges to adoption of polyculture practices?	x	x	x

2.5. Analysis of the survey data

The survey data underwent a cleaning and analysis process. The data of the 101 questionnaires was translated into English, stored in a table and later processed using R programming language. To ensure data validity, simple calculation rules were applied to check for any inconsistencies in the economic performance data. The inconsistencies were flagged, and the researchers who conducted the surveys checked and corrected them when needed.

After the data was cleaned and validated, it was transformed to prepare it for further analysis. Categorical variables with multiple possible outcomes were converted using the one-hot-encoding technique, which transformed them into vectors of binary data. This method allowed for a more straightforward analysis of categorical data. Subsequently, insight into the economic performance was given by calculating total economic revenue (summation of revenue from all aquaculture activities) and their corresponding operational costs (summation of all variable costs[1]). We emphasize that the operational costs exclude costs of unpaid labour.

To gain insight into the data, a graphical analysis of the variables of interest was conducted by creating distributional plots. This method visually represented the data distribution and helped to identify any outliers or patterns. Correlations between the variables were explored through the use of hypothetical correlation plots, which aided in detecting patterns and relationships within the data. Graphs that could support or reject the hypotheses presented in the paper were kept. This approach helped to illustrate the findings and aided in drawing conclusions from the data analysis.

Additionally, statistical tests were used to compare operating profit across cultivation types. Operating profit is total revenue per m^2 subtracted by total cost per m^2. In order to compare the average profitability of the different cultivation type, the Welch two sample *t*-test (Welch, 1947) is used. This test assumes normally distributed data. This assumption can be tested using the Shapiro-Wilk’s W test using the procedure of Royston (1982). In case the normality assumption is violated, a non-parametric Wilcoxon rank sum test as described in Bauer (1972) is used to compare the distributions of profitability per cultivation type. The Wilcoxon coefficient used to obtain a probability and is calculated by summing all the ranks of the values in one of the samples. As will become clear in the results section, both tests are used to analyse the survey data.

[1] This includes the costs of paid labour, shrimp larvae, seaweed seed, other seed, lime, fertilizer, bamboo, rope, feed, probiotics, seraponin, electricity, natural gas, diesel, materials for pond maintenance, land lease, rent of equipment, tax, insurance and interest.

3. Results

3.1. Characteristics of the farmers

The first interesting result is that, while the farmers were selected randomly, a large majority is involved in polyculture (67 in seaweed and milkfish and 20 in seaweed, milkfish and shrimp, see Table 2) while only 14 farmers practice seaweed monoculture.

The farmers who practice monoculture are on average older. Meanwhile, younger farmers tend to be more active in polyculture, especially on seaweed, milkfish and shrimp polyculture. Table 2 also shows how the production system used are distributed within four levels of education. It is noticeable that the share of monoculture farmers increases as education level goes up. This might suggest that younger seaweed farmers with lower education level are, to some extent, more willing to adopt polyculture farming practices. In addition, the monoculture farmers are more likely to be member of a farmer group compared to polyculture farmers. In terms of seaweed farming scale, the farmers engaged in seaweed and milkfish polyculture exhibit the highest seaweed production volume among all farming types, whereas the highest revenue is generated by those practicing polyculture of seaweed, milkfish, and shrimp.

This section analyses the finances of *Gracilaria* sp. cultivation, with special interest in the differences between monoculture and polyculture. We emphasize that this is a farm-level analysis – results presented do not reflect total household income. Fig. 2 presents one of the main insights from the quantitative analysis. It shows that polyculture farmers – both seaweed and milkfish as well as seaweed, milkfish and shrimp farmers have higher revenues (red bars) and operating costs per m^2 production area (green bars) compared to monoculture farmers.

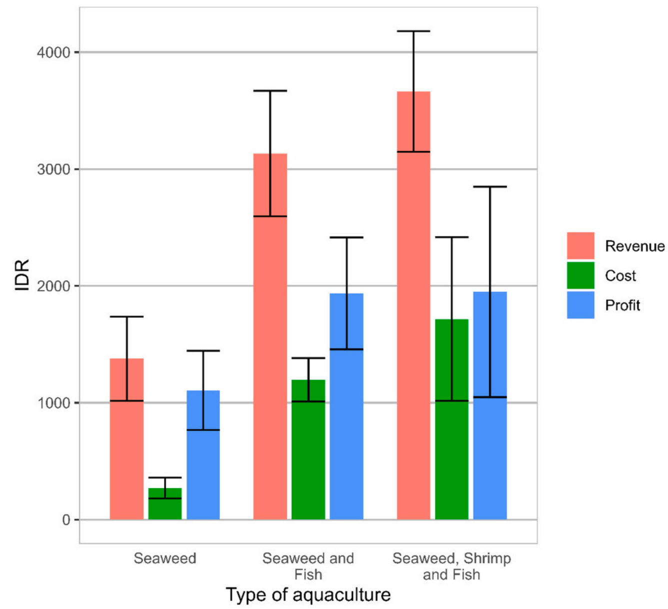

Fig. 2. Average revenue, operational costs and operating profit in IDR per m^2 for the different types of cultivation. Error bars represent the standard error.

The average operating profit per m^2 for polyculture (blue bars) is higher than for monoculture and we tested with a Welch two-sample *t*-test (see Table 4 in Appendix A for the outcomes of the *t*-tests). While the tests do not show significant differences in average operating profit when comparing any two cultivation types, we have to be careful not stating: 'there is no difference'. The probability of falsely assuming the null hypothesis is large when we have few observations as is the case for monoculture of seaweed and the polyculture with the three species (see Table 5 in Appendix A for the results of a statistical power analysis). Here we simply cannot firmly conclude that the difference is significant. Subsequently, the normality assumption of the Welch two-sample t-test is further tested using the Shapiro-Wilk test and shows that the normality of the data cannot be assumed (see Table 6 in Appendix A for the outcomes of the Shapiro-Wilk tests). Therefore, the non-parametric Wilcoxon rank sum test is used to compare the distributions of operating profit across cultivation types. The results of which are shown in Table 3.

The Wilcoxon rank sum exact test shows only statistically significant differences in the distribution of operating profit when comparing seaweed, milkfish and shrimp with monoculture at $p < 0.1$, but not $p < 0.05$. This confirms the results of the two-sample *t*-tests. From these results, the following conclusion can be drawn: Visually inspecting the operating profit and comparing it across cultivation types suggests that polyculture yields higher operating profit than monoculture. However, no statistically significant differences can be found.

Table 2
Characteristics of interviewed seaweed farmers and their cultivation systems: monoculture of seaweed, polyculture of seaweed and milkfish, also polyculture of seaweed, milkfish and shrimp. The characteristics of each group include age of the farmer (in years), education as proportion of the farmers at each level of education, percentage of farmers being a member of a farmer group, the average own consumption in percentage of production, total revenue, and total production volume per species. Note: in Brebes there are very few seaweed and shrimp farmers because of the experience needed to add shrimps in the seaweed pond with a high survival rate.

		Monoculture	Polyculture	
		Seaweed	Seaweed and Milkfish	Seaweed, Milkfish and Shrimp
Number in our sample		14	67	20
Age	Min	29	19	24
	Max	66	71	64
	Average	52	47	43
Education	Primary education	21 %	52 %	55 %
	Secondary education	21 %	15 %	20 %
	Higher education	21 %	7 %	5 %
	Senior high education	36 %	24 %	20 %
Farmer group membership		100 %	81 %	63 %
Average own consumption	Seaweed	1 %	0 %	0 %
	Milkfish		9 %	4 %
	Shrimp			4 %
Total revenue (million IDR)	Min	6	7	6
	Max	45	194	169
	Average	20	39	49
Total seaweed production volume (kg)	Min	2000	1000	1000
	Max	10,000	36,000	24,000
	Average	4057	6902	5250
Total milkfish production volume (kg)	Min		40	50
	Max		3000	1200
	Average		407	488
Total shrimp production volume (kg)	Min			2
	Max			2000
	Average			331

Table 3
Output of Wilcoxon rank sum exact test comparing operating profit across cultivation types.

Seaweed and milkfish	Seaweed, milkfish and shrimp	
316	81*	Monoculture seaweed
	546.5	Seaweed and milkfish

H_0: Distributions are not systematically higher or lower. H_1: Distributions are systematically higher or lower. The cells show the Wilcoxon test statistic (W). Only comparing seaweed, milkfish and shrimp with monoculture seaweed shows significant differences ($p < 0.1$, but not $P < 0.05$). Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

The analysis presented in Fig. 3 examines the impact of scale of revenues and costs. It suggests that the larger total cultivated area (ha) and the more species added within the cultivation, the higher revenue could be received by farmers. This is especially true for polyculture methods. For instance, for seaweed and milkfish polyculture, the maximum revenue of IDR 75 million is derived from 6 ha cultivation area. Meanwhile, when 1 more species is included (e.g. shrimp), such as on seaweed, milkfish and shrimp polyculture, such revenue could be gained from less than 2 ha cultivation area. It appears that seaweed, milkfish and shrimp polyculture is a beneficial method in terms of revenue optimization and land efficiency, compared to other cultivation types.

Furthermore, it is studied whether polyculture affects the prices paid for the produce. Fig. 4 shows that the price paid for seaweed and fish is not different for mono- or polyculture farming, meaning that the species can be cultivated together without damaging each other's price earning potential. Data suggests prices for seaweed (IDR 5000) and milkfish (IDR 20,000). Prices for milkfish produced are not affected by the presence of shrimp in the ponds.

The farmers in the survey harvest between 100 kg and 80,000 kg annually, which is sold for between IDR 4500 and IDR 5000 per kg. Additionally, farmers with polyculture ponds harvest between 2 kg and 2000 kg of shrimp and between 40 kg and 2000 kg of milkfish in a year. The farmers sell their products to different middlemen based on the commodity, hence, affecting the prices. As an instance, in case of seaweed, high shipping costs and quality downgrades might reduce middlemen's margins, forcing them to lower prices for farmers, who bear the impact despite extra processing efforts (see also Nurhayati et al. (2021)). Besides that, the farmer's income is also influenced by the number of hired workers and the total yield of harvested seaweed. If the seaweed farmers hire more workers to harvest their ponds, their income will be divided among more people, decreasing farmer's total income. For example, in Randusanga, the income is shared in two equal parts of 50 % each, between the farmer and the hired workers, while in Prapag the farmer keeps only 40 % and the hired workers receive the remaining 60 % (Interview, 2022), see also Arina et al. (2019).

Observing the result on the financial performance of polyculture, it is noticeable that monoculture and polyculture practices are rather comparable. Polyculture does not lead to significantly higher operating profit nor does it lead to lower operating profit. It is found that polyculture comes with higher costs but these are offset by higher revenues. While there is direct benefit for a farmer to adopt polyculture practices, the fact that it creates more revenues per m^2 points to a regional economic benefit. These higher costs might stem from needed materials, seeding and labour, the purchase of those means, an increased turnover and employment in the region.

3.2. The price-setting process

Both the seaweed processing company and the middleman determine the farm-gate seaweed prices (as noted in Interview, 2022 and confirmed in literature, e.g. Rimmer et al., 2021 and Langford et al., 2022). According to the interview with the middleman and the seaweed processing company, the seaweed prices are influenced by the seaweed quality and the market demands. If both quality and demand are high, the seaweed prices should also increase. However, seaweed prices paid to the farmers have been stable for the last ten years. It is unclear how the seaweed prices are determined and better insight into the price-setting process could benefit farmers vis-à-vis middlemen.

In interviews (2022), it was also observed that there is a relationship

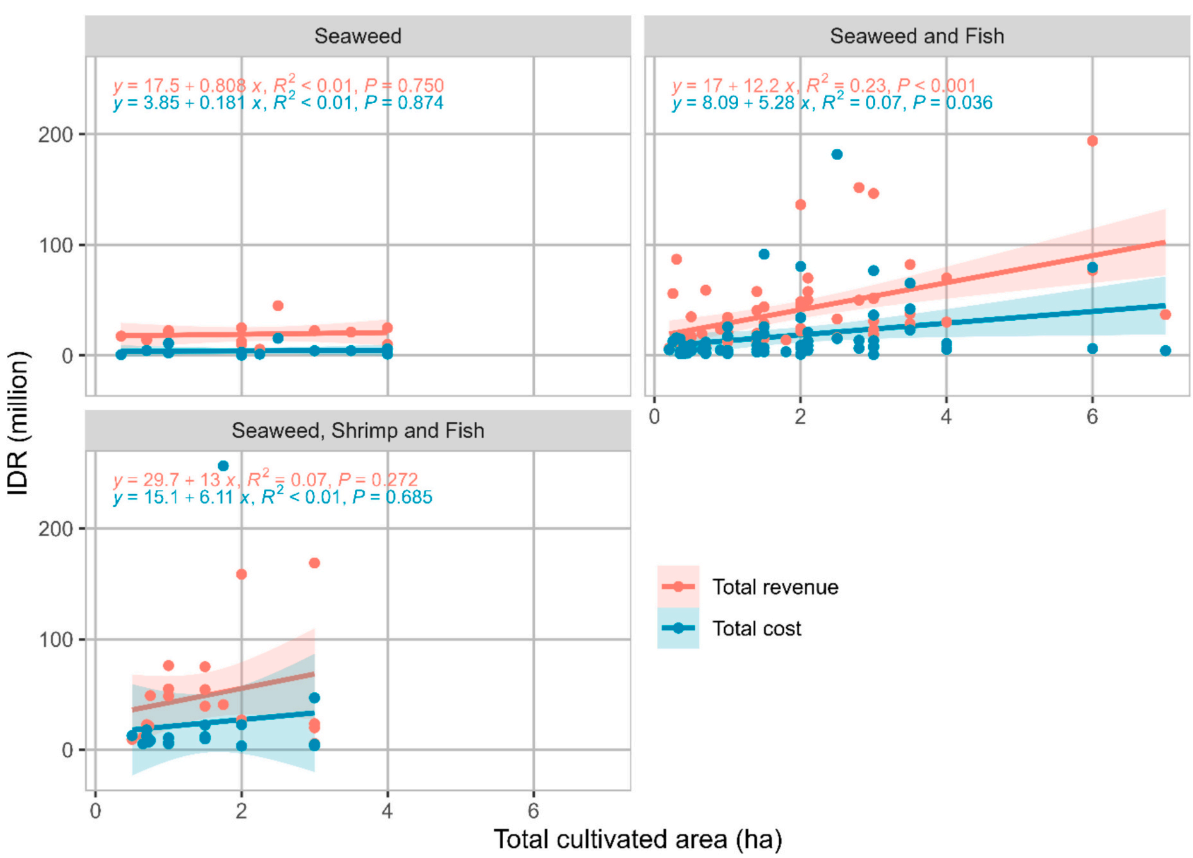

Fig. 3. Revenue and cost in million IDR per ha across cultivation types relative to the cultivated area of each farm. Each dot corresponds to one of the surveyed farmers, the lines show trends and the shaded areas represent the corresponding standard errors. The top-left of each plot shows the regression equation, R-squared and *p*-value corresponding to the fitted lines.

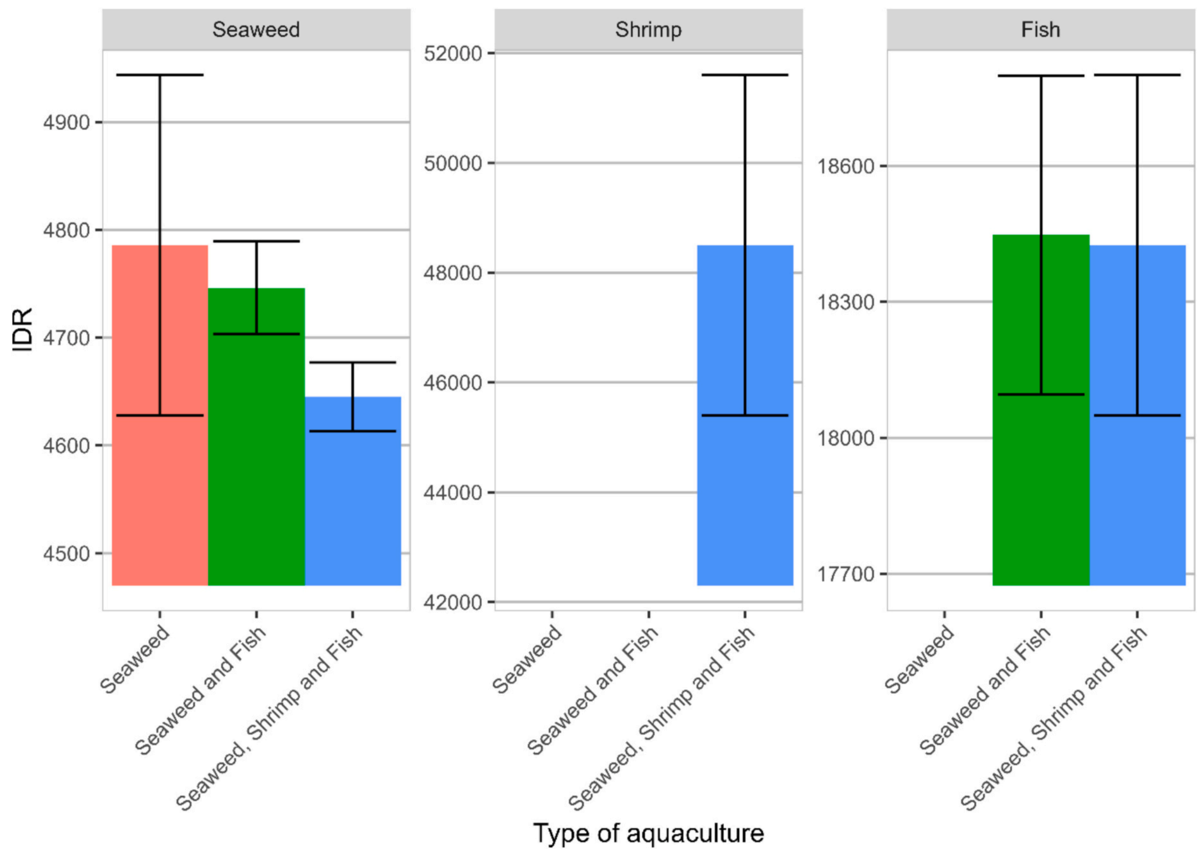

Fig. 4. Farm gate prices in IDR per kg of product paid per species (seaweed, shrimp and milkfish) in the different production systems shown by the different colours. Error bars represent the standard errors. Note the different y-axis scales for the three species and that the y-axis is truncated for a better comparison of the different systems.

dependency between the middlemen and seaweed farmers (see also Langford et al. (2022)). Usually, the middleman would give the seaweed seeds or capital to the farmers for the first trial, and due to their culture of relationship dependence, the seaweed farmers always sell their harvest to this middleman, despite considering the prices given to them.

3.3. *Other type of productive activities*

Furthermore, we explored other type of productive activities conducted by seaweed-farming households, of which the results are visualized in Fig. 5.

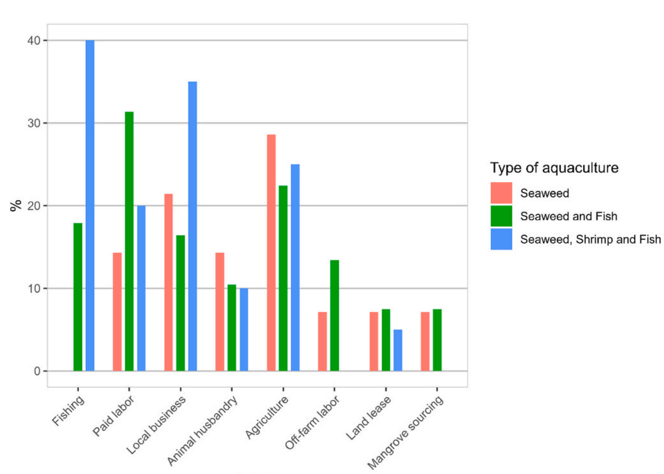

Fig. 5. Percentage of seaweed-farming households participating in other types of productive activities by cultivation types.

Fishing, a less capital-intensive job, is the most frequent other productive household activity among seaweed, milkfish and shrimp farmers. One of the activities most often done is agriculture, irrespective of the type of aquaculture. Paid labour is the most popular side-job for seaweed and milkfish farmers, making up about 32 %. Meanwhile, for monoculture farmers, side work in agriculture is the most prevalent, at around 27 %. In contrast, more capital-intensive type of jobs, such as land lease and mangrove sourcing appear to be the least popular side-jobs, with less than 10 % among the polyculture and monoculture farmers, respectively. However, it appears that there is no systematic pattern between different types of cultivation and other income-generating activities done by the seaweed-farming households.

3.4. *Non-financial advantages of polyculture*

The increased nutrient from seaweed growth also promotes the growth of *Chaetomorpha*, locally called *lumut sutera*. Accordingly, seaweed farmers added milkfish to prevent the *Chaetomorpha* blooming, by which the epiphytes of *Chaetomorpha* serve as feed for the fish (Interview, 2022), see also Widyastuti and Setiadi (2021). Moreover, the pond production in Brebes Regency is declining due to environmental issues (coastal flooding and land subsidence) which lead to a reduced number of ponds. Hence, due to less ponds remaining, the farmers try to find a way to maximize their production or income by applying polyculture practice (Interview, 2022), see also Susilo et al. (2019).

In polyculture systems, the milkfish and shrimp also seem to contribute to the farmers' food security as a source of protein for the seaweed-farming family. The pond production is utilized for farmers' own-consumption. As shown in Table 2, on average 9 % of the milkfish production in a seaweed and milkfish polyculture system, also 4 % of milkfish and 4 % of the shrimp produced in the seaweed, milkfish and shrimp polyculture system are being consumed by the farmers. In comparison, only 1 % of seaweed production is used for farmers' self-consumption in monoculture system.

3.5. Challenges to *Gracilaria* sp. cultivation

The results presented above suggest that polyculture of *Gracilaria* sp. with shrimp and/or milkfish results in higher aquaculture revenues in Brebes Regency but not in statistically significant different operating profit for the farmers. From a regional economic perspective, polyculture could be an interesting alternative to monoculture. To better understand if and how polyculture could be an alternative to farmers, the study looked further into the challenges *Gracilaria* sp. farmers are confronted with, identified in the survey.

As shown in Fig. 6, the top three perceived challenges of seaweed aquaculture are low sales prices, floods and disease, each of them cited by more than 70 % of the respondents. The current sales prices are defined by the middlemen who do not consider the quality level of the seaweed but merely the quantity despite the fact that the two primary processing factories of *Gracilaria* sp. in Java offer higher prices for good-grade seaweed (Purnomo et al., 2021). The middlemen do not pass on the higher prices to the farmers as they estimate that they are the one taking risks. Indeed, the agar content (and thus the price paid by the factories) remains unknown until after the processing which delays the payment to the middlemen by the processing factories. In addition, the farmers have no bargaining power as they depend on the middlemen to buy their seaweed and often take loans from them to buy good seeds and other materials. This dependency increases the middlemen's decisive role. Reducing the dependency of the farmers to the middlemen would provide an opportunity to improve the sales price when farmers can produce good quality seaweed.

The second challenge is flooding, as it can damage ponds and lead to a harvest loss. The maintenance of mangrove around the ponds has been proved to improve their resilience to coastal inundation (Gijsman et al., 2021). Yields are negatively affected by environmental conditions that negatively affect the cultivation process. This includes heavy precipitation, land subsidence and coastal abrasion. These processes degrade the ponds' embarkment and area, causing the area to decrease dramatically. Mangrove degradation, coastal development, sea level rise and global warming contribute to coastal abrasion (Cerlyawati et al., 2017).

Low revenues are a major disincentive in developing *Gracilaria* sp. production. Low revenues force farmers to keep using poor seed quality and invest little effort in maintaining the ponds, and post-harvest processing to reduce production and labour costs. This has consequences, such as poor sediment quality, which can lead to the third perceived challenge, disease and pest outbreaks. This traps the farmers in a vicious cycle: farmers lack the means to invest in good seed, maintenance and proper post-harvest processing methods, leading to low-quality seaweed and low prices. Consequently, efforts and investments reduce the yields even further, making the farmers more vulnerable to the effects of climate change and dependency on middlemen.

The provision of good seeds crucially determines the success of cultivation. Instead of using new seeds, farmers frequently leave some thalli in ponds to allow new thallus to thrive even though they know that the seed is poor in quality. This occurs due to the scarcity and high price of good-quality seeds, which now impedes *Gracilaria* sp. cultivation (Zamroni et al., 2011; Thahir et al., 2018; Purnomo et al., 2020a, 2020b). Poor seed quality can inhibit seaweed growth (Parenrengi et al., 2020), interfere with production and result in less optimal yields (Thahir et al., 2018). In 2019, the Brackish Water Aquaculture Center (BBPBAP) Jepara supplied around 10,000 kg of *Gracilaria* sp. seaweed seeds to Brebes Regency *Gracilaria* sp. farmers through the Farmer Groups of Kali Crucuk and Seaweed Lestari. However, as this is merely a program, it does not guarantee the long-term availability of good seeds. Therefore, farmers need to purchase the seeds from the middlemen, increasing their dependency on the middlemen.

4. Discussion

The results presented above illustrate that the majority of the seaweed farmers surveyed for this study operate in a polyculture system. While polyculture systems seem to yield a higher operating profit, the difference with seaweed monoculture was not found to be significant in our sample. We could not demonstrate an obvious financial incentive for the remaining monoculture farmers to switch to polyculture. It is difficult to pinpoint the reason why some have chosen monoculture of *Gracilaria* sp. instead of integrating it in a polyculture system, and it is likely that several factors play a role. In fact, as stated in the Road Map for the Development of the National Seaweed Industry 2018–2021, the polyculture practice of shrimp, milkfish and seaweed (*Gracilaria* sp.) is one of the suggested methods for seaweed cultivation in Indonesia (Presidential Decree No. 33, 2019, p.13). However, the uncertainty about the prices paid and the yields (due to environmental factors such

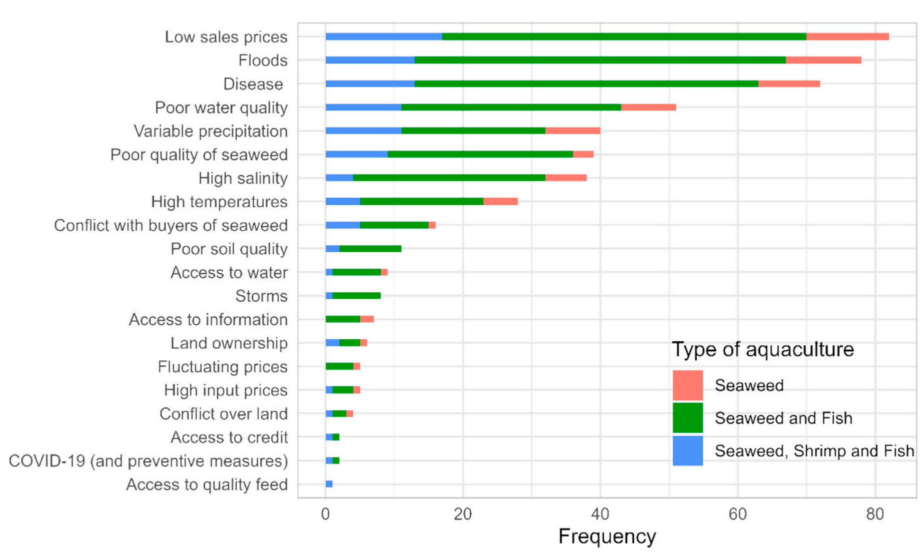

Fig. 6. Frequency of the different challenges perceived by farmers in Gracilaria sp. production in Brebes expressed in number of respondents, coloured by cultivation type of the respondents. The challenges are then ordered from the most frequently cited challenge on top to the least frequently mentioned challenges at the bottom.

as floods and diseases) were identified as the most important challenges by farmers and could make them reluctant to invest in improving their production process by adopting polyculture. Similarly, another study in Brebes Regency found that poor ecological condition (e.g. damaged pond dikes and abrasion) could reduce the land suitability for milkfish production, thereby increasing costs in polyculture practices (Widowati et al., 2020). Overall, there are two key considerations that influence the adoption of polyculture practices, namely the relationship to other household productive activities and the benefits of polyculture. Accordingly, societal incentive and measures to stimulate seaweed (*Gracilaria* sp.) farming, particularly in polyculture, will be discussed.

4.1. Relation to other household productive activities

All responding seaweed farmers in our study are involved in other productive activities. These are in line with prior studies which found that agriculture, fisheries and employed worker are common types of livelihood diversification for seaweed farmers in Indonesia (Aslan et al., 2018; Mariño et al., 2019). The suggestion that farmers choose monoculture method because of lower cost, lower risk and the fact that it is less time consuming, making it easier to combine with their other businesses (e.g. running a local business and animal husbandry), cannot be substantiated with our data. Based on our result, it is interesting to see the diversity of other productive activities taken by different type of seaweed farmers. It appears that the most common additional activity of monoculture seaweed farmers is in agricultural sector. A probable reason why these farmers only do monoculture due to the nature of agricultural farms which also require intensive capital and high risk (e.g. climate-dependent and time-bound maintenance). Meanwhile, seaweed and milkfish farmers mostly work as paid labour on the side which is more flexible in terms of time and do not require capital investment in advance. Similarly, the seaweed, milkfish and shrimp farmers majorly work as fishermen and do fishing during the night, which is easier to combine with polyculture practice during the day. It is observed that there has been a livelihood development in Brebes Regency, where monoculture seaweed farmers at one point started to combine milkfish and/or shrimp into their ponds. These occurred due to the decline in ponds availability and the need to support farmers' living income.

4.2. Benefits of polyculture

Seaweed also provides many ecosystem services, even more, if cultivated using a polyculture system that allows two or more species to grow in the mutualistic symbiosis condition. The oxygen generated by seaweed, through photosynthesis, will increase the water dissolved oxygen and can enhance the respiration of other cultivated species (Yang et al., 2015). As stated by Hendrajat and Ratnawati (2021), seaweed has an important role in improving milkfish survival, as oxygen provider and CO_2-absorbing agent in ponds. Seaweed can efficiently convert the nutrients released by fish and shrimp into biomass (Chopin and Sawhney, 2009; Ihsan et al., 2019), hence, fertilizer is not required to stimulate the seaweed growth (García-Poza et al., 2020). And in turn, milkfish eat *Chaetomorpha,* which compete with *Gracilaria* sp. for nutrients. The presence of seaweed in polyculture can increase the shrimps' survival rate by 20 % (Ihsan et al., 2019), where seaweed could provide shelter and healthy environment for the shrimps.

Based on our survey, 58 % of polyculture farmers reported using the milkfish partly for their own consumption. On average, the farmers who cultivate milkfish use approximately 8 %, out of their total milkfish production, for own consumption. Milkfish has been well-known to be an affordable, easily available and nutritious source of protein for the Indonesian population. According to Priono (2019), the protein content of milkfish is about the same with salmon which is 40 %. Moreover, the variety of milkfish products (e.g. *pindang cue* milkfish (a preserving method (usually for fish or meat) with salting and boiling techniques (without drying)), *presto* milkfish (a processed soft thorn milkfish with pressure-cooking method)) has influenced the consumption behaviour of Indonesians. For example, in the traditional market, where the majority of buyers are middle to lower class, people tend to buy *pindang cue* (milkfish) when there is a shortage of fresh marine fish. Meanwhile, middle to upper class people tend to opt for *presto* milkfish or milkfish fillet (Priono, 2019). Similarly, it has been noted that milkfish farming significantly improves, among others, food and nutritional status in Kenya, Sri Lanka and Tanzania (Mirera, 2019; Dissanayake, 2019; Shalli et al., 2024). Furthermore, Shadrack et al. (2021) observed that milkfish has an important role in ensuring the food security of smallholder aquaculture farmers in Vanuatu.

4.3. A societal incentive to stimulate polyculture

Despite the higher cost incurred from polyculture practices compared to monoculture, the analysis shows that there are benefits that can make polyculture an interesting alternative to monoculture. Environmental benefits of polyculture are described by Nauta et al. (2024). Polyculture method generates significantly higher revenue compared to monoculture and likely higher profit. These differences in operating profit are not explained by prices paid for the products sold. The analysis also shows that operating profit is dependent on the scale of production. This implies that higher operating profits are made at larger scale, but also that, to generate a certain income, polyculture farmers need less area than monoculture farmers. Polyculture farmers have a range of products at their disposal, making them more resilient to fluctuations in supply and market demand.

The question that arises is then what can convince individual farmers to adopt polyculture practices, with higher costs but no significant higher profits. If societal, environmental and regional economic benefits are the main incentive for polyculture, governmental support could be instrumental for farmers to change their practices. This can include income support but can also risk reduction through, for example, natural farmer insurance or government guarantees.

4.4. Measures to stimulate Gracilaria sp. farming and polyculture in particular

In order to increase the *Gracilaria* sp. production, the first practical step for farmers is to improve the farmer organization, for instance by establishing a farmer cooperative. It is observed that the current membership of a farmer organization does not result in higher prices for the products sold. A cooperative (or similar structure) can provide a platform for information and knowledge exchange and is expected to lead to a better market position by improving production methods and lower dependency on middlemen. Accordingly, some earlier studies suggested the socio-economic benefits of cooperatives for seaweed farmers in Indonesia, such as by tackling the financing issue, empowering local communities and building resource-based industries in the village (Nuryadi et al., 2019; Busthanul et al., 2020; Pratama et al., 2021). It will also enable farmers to address larger issues such as upstream pollutants. For this to happen, obtaining government assistance and/or support by other external parties in providing knowledge, training and high-quality seeds is essential. Furthermore, setting up an organization that is able to deal with the challenges currently faced by the farmers, breaking the negative spiral and improving their livelihoods are the next pivotal steps to take. The help from government and external parties will dominate in the beginning of the uniting process. After that, the farmer cooperative is expected to be able to manage and solve the challenges in *Gracilaria* sp. production by utilizing their knowledge and skills. It is essential to make the farmer cooperative less dependent on external parties and more resistant to external disturbances.

It is critical to enhance several aspects to increase *Gracilaria* sp. polyculture in the Brebes Regency. First, to grow high-quality seaweed, the quality and availability of seeds must be enhanced. Second, constructing a common storage facility using advanced technology will assist in maintaining good seaweed quality and increase the bargaining power of seaweed producers, resulting in higher pricing. Third, farmers' knowledge and skills must be improved. Controlling disease and insect outbreaks and producing high-quality crops that earn significant revenue require knowledge. These interventions are all beyond what an individual farmer can do and require the establishment of influential private or public institutions dedicated to the further development of *Gracilaria* sp. production. Last, the variance in revenues, costs and profits needs to be understood better in order to formulate interventions tailored to farmers.

Post-harvest practices are proven to be a strong factor influencing seaweed quality. One of the examples is that some South Sulawesi's seaweeds have higher quality than those from other seaweed-producing locations, particularly Java. This is partly because of the Warehouse Receipt System (WRS), which permits farmers to put off sales by temporarily storing their goods in warehouses until they can sell them for the maximum price (Purnomo et al., 2020a, 2020b). Hence, farmers' bargaining power must be strengthened to alter the market structure and earn higher revenue, leading to further cultivation maintenance and improved harvesting techniques.

Furthermore, the campaign provided by government institutions to help farmers enhance their knowledge and solve their problems is considered to be unsuccessful due to ineffective communication and inaccuracy of purpose (Kustiari et al., 2012). Therefore, instead of a campaign, technical assistance should be performed. In technical assistance, there should be a group dialougue among the farmers and government agencies to discuss what challenges the farmers perceived related to *Gracilaria* sp. production and the most probable solution. For such group dialogue, Farmer Field Schools have proven to be successful in enhancing human, social, natural and financial capital of rural communities (Van Den Berg et al., 2020). The government should assist in the implementation of the solution and evaluate the progress.

4.5. Limitations of the study

This study provides valuable insights into the socio-economic aspects of polyculture farming, in comparison with monoculture farming of *Gracilaria* sp., drawing upon data collected in Brebes Regency, Indonesia. The following limitations of the study are acknowledged. The study is based on data collected in one area and species only and care should be taken when discussing polyculture farming of seaweed in general as each production area and each seaweed species comes with its own specificities. The results presented are based on farmer-reported data which leaves room for differing interpretations of the cost categories. The researchers have carefully drafted the questionnaire used and interviews were conducted by local researchers to avoid differing interpretations as much as possible. Lastly, it should be noted that the data was collected during the Covid-19 pandemic. Since then, global inflation rates have gone up and current prices of materials are likely higher. There is no known reason to assume inflation has impacted some cost categories more than others, and we believe the overall conclusion of the study are still valid.

5. Conclusions

This study aimed to answer the question what the potential socio-economic opportunities and challenges of seaweed polyculture in Indonesia are. To answer this question, three sub-questions were formulated.

What are characteristics of polyculture seaweed farming in Brebes Regency? The differences between mono- and polyculture farmers are minor when it comes to age but there are differences in education level; among the seaweed farmers, the monoculture farmers have higher education compare the polyculture ones. Also polyculture farmers are less often member of farmer groups.

How does polyculture farming perform compared to monoculture from a financial perspective? There is no significant difference in operating profit. Based on the results, we conclude that, despite the higher cost incurred from polyculture practices compared to monoculture practices, the analysis has proven that polyculture method also generates higher revenue compared to monoculture. There is no difference in prices paid for the products. Polyculture offers the opportunity to generate comparable revenues as for monoculture with smaller area in use. From a regional perspective, polyculture offers more opportunities for providing income. Higher revenues and higher costs are reflected in more money spent in labour (i.e. more job opportunities) also in the supply-chain. An important caveat is the costs of unpaid labour. Polyculture practices are less interesting if farmers then have less time for other income-generating household activities. As shown in our finding that monoculture and polyculture farmers are engaged in diverse types of other income-generating household activities.

What are the perceived challenges to adoption of polyculture practices? The main challenge perceived by farmers relates to the low price paid for seaweed. The low price of seaweed is set by middleman. So, the farmer gets low revenue from the pond. If they have other resources, they prefer to invest in other sectors rather than using them to invest in ponds and switch to polyculture. Environmental and climatological challenges are also constraining the adoption of polyculture practices.

Overall, this study concludes that polyculture - with higher costs and higher revenues – appears to be more demanding for farmers. Perceived challenges might make farmers reluctant to switch to polyculture practices. Polyculture is interesting from an economic perspective, offering the possibility to generate higher revenues per m^2. From societal perspective, polyculture seems to be a potential alternative for supporting farmers food security, such as providing source of protein for aquaculture households. Higher operating costs and revenues mean more local labour is sourced and other actors in the value chain benefits from farmers purchasing goods. Other research also points to the better environmental performance of polyculture. Institutional support, reducing risks for farmers, could motivate them to adopt polyculture practices.

Polyculture is credited for positive effects, including reduced environmental impacts, animal welfare and diversification of income. Yet farmer organization, education and political stimulation will not convince farmers, as economic agents, to be 'pushed' to a farming practice that is not profitable. Financial incentives are required to make farmers switch to polyculture practices, either from private and/or public institutions.

5.1. Recommendations

- Firstly, it is recommended to promote the establishment of farmer cooperatives to enhance *Gracilaria* sp. production. Such cooperatives could serve as platforms for knowledge sharing, improved production practices, and strengthened bargaining power.
- Secondly, it is recommended to implement coordinated institutional intervention to accelerate *Gracilaria* sp. polyculture with key focus on improving seed quality and availability, developing advanced post-harvest facilities, enhancing farmer technical knowledge, and analyzing economic variability to inform the targeted intervention.
- Thirdly, it is recommended to enhance post-harvest practices, as higher product quality and product value could contribute to a more favorable market position and increased revenues, which in turn support the advancement of *Gracilaria* sp. cultivation and harvesting techniques.
- Finally, it is recommended to prioritize technical assistance through initiatives such as Farmer Field Schools between farmers and government agencies to identify challenges and develop solutions, with government supports for implementation and ongoing evaluation.

CRediT authorship contribution statement

Olivia Azhari: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation. **Sinne van der Veer:** Writing – original draft, Investigation, Formal analysis, Data curation. **Katell G. Hamon:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Ingvild H.T. Harkes:** Supervision, Investigation. **Restiana W. Ariyati:** Data curation, Conceptualization. **Lestari Lakhsmi:** Investigation, Data curation. **Harxylen Kinanti Purnomo:** Writing – original draft, Investigation, Formal analysis, Data curation. **Sri Rejeki:** Supervision, Formal analysis, Data curation. **Lailatul Rokhmah:** Writing – original draft, Investigation, Formal analysis. **W.K. van den Burg Sander:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

None.

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Appendix A. Annexes

Table 4
Output of Welch two-sample t-tests comparing operating profit across cultivation types.

Seaweed and milkfish	Seaweed, milkfish and shrimp	
1.413	0.875	Mono culture seaweed
	0.012	Seaweed and milkfish

H0: Means are equal. H1: Means are different. The cells show the t-values for the Welch two-sample t-test. No statistically significant differences in means are found ($p < 0.1$, but not $P < 0.05$). Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Table 5
Statistical power (one minus the probability of falsely assuming the null hypothesis of equal means) for the Welch two-sample t-tests across different minimum detectable effect sizes of the operating profit at a 95 % significance level.

Cultivation type comparison	Minimum detectable effect size			Observed differences in means (IDR/m^2)
	IDR 200 per m^2	IDR 500 per m^2	IDR 800 per m^2	
Mono | seaweed and milkfish	0.094	0.208	0.380	802.9
Mono | seaweed, milkfish and shrimp	0.073	0.123	0.194	803.3
Seaweed and milkfish | seaweed milkfish and shrimp	0.072	0.119	0.184	0.4

Table 6
Output of Shapiro-Wilk test for normality of the operating profit across cultivation types.

Mono culture seaweed	Seaweed and milkfish	Seaweed, milkfish and shrimp
0.699***	0.608***	0.765***

H_0: Data are normally distributed. H_1: Data are not normally distributed. The cells show the values for the Shapiro-Wilk test statistic (W). Operating profits are not normally distributed for any of the cultivation types ($p < 0.1$, but not $P < 0.05$). Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2025.742944.

Data availability

Data will be made available on request.

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