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RESEARCH

Yield determinants of *Kappaphycus alvarezii* seaweed in South Sulawesi, Indonesia

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Abstract

There has been limited systematic monitoring of seaweed growth with simultaneous measurement of important yield determinants. This study reports on *Kappaphycus alvarezii* (Cottonii) seaweed experiments in South Sulawesi, Indonesia. The first (June – Oct 2023) experiment showed lower yields for the lowest seedling weight and similar yields for the medium/high seedling weight. During this period, seaweed losses from lines (empty ties), ice-ice disease and fouling by epiphytes increased. The second experiment (March – July 2024) showed high yields for the traditional longline and low yields with tube-nets and cages, due to fouling by epiphytes and mud. Yields did not differ systematically between villages and did not differ systematically between nearshore and further offshore. Yields were highest for planting in March and lowest for planting in August. Stronger winds and rougher sea towards October were shown to be an important yield determinant, but not the only one. During the March-October period losses from lines increased, pressure from the ice-ice disease increased, fouling by mud and epiphytes increased, temperatures decreased and windspeed increased. Yields in the March-October cultivation cycles were determined by a combination of the effects of these five yield determinants. To our best knowledge the current study is the first to study this full range of possible yield determinants and to simultaneously monitor for longer period (five cycles, with bi-weekly sampling) both seaweed biomass and yield determinants.

Keywords Seaweed · *Kappaphycus alvarezii* · Rhodophyta · Planting date · Initial weight · Tube-net and cage method

Introduction

Seaweed farming is an important livelihood for coastal communities in a number of tropical countries such as India, Indonesia and the Philippines (McHugh 2003; FAO 2018; Waldron et al. 2023). In those countries seaweed species *Gracilaria* spp., *Kappaphycus alvarezii* (Cottonii) and *Eucheuma denticulatum* (Spinosum) are amongst the most commonly commercially cultivated tropical seaweeds (Santelices and Doty 1989; Dawes et al. 1994; McHugh

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2003; Neish 2013; Hurtado et al. 2014; Periyasamy et al. 2019). Seaweed farming is a major source of income for many coastal communities in Indonesia, especially in South Sulawesi Province. Based on that, the Government of Indonesia has made plans and strategies to expand seaweed cultivation and its downstream industry.

The predominant method in commercial cultivation involves the vegetative propagation of seedlings, which are secured to long lines through a process known as the tie–tie technique (TT technique) (Ask and Azanza 2002; McHugh 2003). These lines can be anchored in one of three ways: off-bottom, floating long line, or rafts. However, this approach is regarded as labour-intensive and requires significant time. Alternatives that eliminate the need for tying include the tubular net (TN technique) and cage. The tube-net requires less time for seeding when compared to traditional approaches like the 'tie-tie' or 'loop attachment' techniques typically used for carrageenophyte cultivation in open water. Furthermore, the placement of the tube nets in relation to water flow minimizes resistance, allowing them to endure strong currents, thereby offering a benefit over other floating cultivation methods (Mantri et al. 2017). In 2013, a group of farmers in eastern Indonesia, particularly in South Sulawesi, began adopting a new cultivation method that utilizes floating cages. This approach is an alternative strategy to safeguard seaweed from various herbivores (Kasim et al. 2016). The floating cage is an innovative structure designed specifically for cultivating seaweed. Different sizes and configurations have been created to enhance seaweed farming. Floating cages are primarily composed of PVC pipes, nets with buoy markers, and weights to secure the raft in the desired location.

One of the most basic decisions farmers make is on the weight of the seedlings tied to the longlines. In previous research we hypothesised a higher initial weight would lead to stronger growth and thus higher yields (van Oort et al. 2022, 2024). The relation between initial weight, and daily growth rate has been studied before in Indonesia (Kasim et al. 2018; Aslan et al. 2019a; Embi et al. 2019; Isroni et al. 2020; Irfan et al. 2021; Rasnijal et al. 2021). From the Philippines, Hurtado et al. (2008) reported highest daily growth rate at lowest initial density (500 vs 1000 g m^{-1} line) and highest daily growth rate earlier in the growth cycle (30 vs 45/60 days after planting). All previous studies report a higher daily relative growth rate (RGR, % day^{-1}) for the lower initial seedling weight. These results are in line with the sigmoid growth model which predicts highest *RGR* for lowest initial weight and predicts lower RGR for higher initial weight and later on in the cultivation cycle (van Oort et al. 2022, 2024). This focus on daily relative growth rate might lead to the misconception that lower initial seedling weights are better, because of their higher RGR. We believe this is not the right conclusion. It is important to consider here the difference between relative growth and absolute growth. *RGR* is a measure of relative growth. A seedling of 50 g with *RGR* 4.0% day^{-1} will after t days have a weight of $W(t) = W_0 * \exp(RGR * t)$, thus after $t = 1$ day the new weight $W(1) = 50 * \exp(0.04 * 1) = 52.04$ and so the absolute growth in this example is 52.04 – 50 = 2.04 g day^{-1}. For a seedling of 150 g with RGR 3.0% day^{-1}, $W(1) = 150 * \exp(0.03 * 1) = 154.57$ and the absolute growth is 154.57 – 150 = 4.57 g day^{-1}. Thus in this example for the 50g seed the relative growth rate is higher (4% vs 3%) but the daily absolute growth rate is lower (2.04 vs 4.57 g day^{-1}). Absolute growth rate is more relevant to farmers as they earn their income from selling kilograms and not percentages. In this example we would expect the farmer to prefer the larger initial seed of 150 because that one in this example gives highest absolute growth (AG). In the current paper we therefore focussed on absolute growth and final yield in relation to initial seedling weight and cultivation method.

As we will show in this paper, losses from lines were experienced in all cultivation cycles, the most visible effects being empty ties (Fig. 1). To the best of our knowledge, such losses have not been systematically measured before. Here, we systematically quantified losses from lines by counting

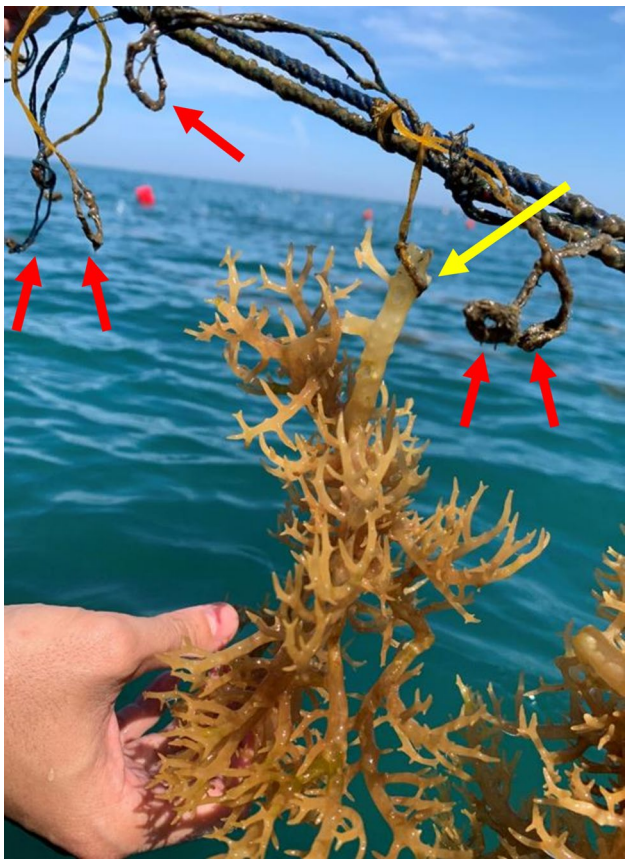


Fig. 1 Photo of empty ties. Red arrows indicate ties from which seaweed has been lost, yellow arrow shows a seaweed almost falling off

filled and empty ties per meter. There have been several studies suggesting cages and tube-nets might prevent losses from lines caused by fish predation, sea turtle predation or waves (Hurtado-Ponce 1992; Kasim et al. 2016; Shanmugam et al. 2017; Ask and Azanza 2002; Mantri et al. 2017; Periyasamy and Rao 2017; Johnson et al. 2020; Ma'ruf et al. 2020; Kavale et al. 2021; Prasad Behera et al. 2022). At the same time, we observe in these studies quite a bit of wishful thinking and limited experimentation with side-by-side comparisons of the three cultivation methods (longline, tube-net, cage). There is therefore a need for further experimentation to investigate if seaweed losses are less (and production higher) from tube-nets and cages versus the traditional longline cultivation method.

Together our experiments contained five cultivation cycles of 6 weeks each, covering planting dates from mid-March to late-August. The final harvest for the late August planting was 6 weeks later, in early October. Together this timespan from month 3 to 10 allowed us to investigate how yields depend on planting date. We conducted our experiments near the coast of South Sulawesi, near two villages called Aeng Batu-Batu and Ujung Baji. Together these data allow for investigating if possible spatial or temporal patterns in seaweed yields can be understood from spatial or temporal patterns in environmental variables collected for the same locations and timespan.

The objectives of this research were to test effects of environmental variables, planting date, initial seedling weight, and cultivation method (longline, tube-net and cage) on seaweed growth in South Sulawesi.

Materials and methods

Study sites & farmer involvement

The research was conducted in two villages in Takalar Regency: Aeng Batu-Batu and Ujung Baji village (Fig. 2). Takalar has been known as one of the most productive seaweed cultivation regencies for decades. In this study, four farmers from each village were recruited to participate. They deployed their seaweed longline in close and shallow areas and in outer and deeper farming plots from the shore (Table 1). Before the research started, researchers visited the farmers (May 2023), discussed with farmers their possible issues for which research might help and discussed the researchers' idea to experiment with different initial seedling weights. The research protocol was developed after these meetings and benefited from close observation of how women tie seedlings to the lines, and the range of seedling weights and sizes used by them. Measurement of empty ties (losses from lines) was included in the protocol because farmers reported this to occur but did not know how big the problem was. While the growing season normally starts somewhere in February, our research started only late May 2023, because first months were used for research planning activities. Lines to be used for research were rented from the farmers. Farmers used their own local seedlings in the experiment. From scientific perspective it would have been interesting to use the same species seedling strain from a single common pool. A possible disadvantage to this more scientific approach is that it introduces the risk of a failed experiment if the externally provided strain happens to be poorly adapted to the site-specific environment. In a previous experiment we introduced externally sourced *Kappaphycus alvarezii* seedlings and locally grown *Gracilaria* (van Oort et al. 2022). In that experiment the growth of *K. alvarezii* completely failed hence we only reported on *Gracilaria* in van Oort et al. (2022). Thus the risk of a failed experiment with externally sourced strains is a genuine risk and the use of local strains avoids this risk. We used previously used lines, the same lines as farmers always use in their daily practice. Women prepared the lines with guidance of the researchers to ensure initial seedling weights were as planned. Researchers showed with mass balances the intended sizes of the different initial seedling weights. While the women were busy preparing the lines with small, medium and large seedlings, researchers were present randomly checking prepared seedlings to check if they had the intended weights. Researchers working with the farmers had several years of experience working with the farmers.

Timeline

In total 5 cultivation cycles of 6 weeks (42 days) each were monitored covering the normal cultivation period from March to October. Table 2 shows the timeline of the two experiments. Earliest planting was in mid-March 2024 (month 3.5), the latest planting was in late August 2023 (month 8.7).

Results of the experiments were discussed in a workshop in December 2023, with farmers (men and women), UNHAS, JaSuDa, WUR and Dinas Kelautan dan Perikanan (Fisheries Agency of Takalar Regency). Next to the research reported on in the current paper, a documentary of the seaweed research project was produced, a first version was presented at the workshop in December 2023 and the final version was launched online in March 2024, at https://www.youtube.com/watch?v=yk8Y9fIilFI.



Fig. 2 Map of Indonesia, South Sulawesi and the two villages of the seaweed research

Table 1 Participating farmers, village and distance from shore

nr	Farmer name#	Cycles	Village	Meters from shore 2023	2024
1	Haris Dg. Lurang	1,2,3,4,5	Aeng Batu-Batu	420	640
2	Nawir Dg. Sila	1,2,3,4,5	Aeng Batu-Batu	250	400
3	Amir Dg. Tika	1,2,3,4,5	Ujung Baji	550	600
4	Kahar Dg. Tayang	1,4,5	Ujung Baji	1300	1320
4.2	Baharuddin Dg. Pasang	3	Ujung Baji	1300	
5	Azis Dg. Ngopo	1,2,3	Ujung Baji	1320	
6	Abd. Majid Dg. Bundu	1,2,3	Ujung Baji	1070	

farmers agreed to be mentioned by name in this research. Farmer 4 fell sick after cycle 1 hence did not participate in cycles 2 & 3. Farmer 4.2 replaced farmer 4 in cycle 3. Numbering 4 and 4.2 is for aesthetic reasons when presenting results per farmer and to more clearly indicate that per cycle 4–6 farmers participated.

Experiment 1: initial seedling weight

Figure 3 illustrates the traditional longline method with double long lines, ties and young seedlings hooked into each tie, one seedling per tie. Farmers in both villages planted with double lines (nylon; 20–25 m long; 3–4 mm thick). On such lines there are smaller nylon "ties", loops of approximately 10 cm long and 1–2 mm thick in which seedlings are hooked. Tying seedlings to the lines is done by the women. In one village, Aeng Batu-Batu, lines have 2 ties (double ties) together at ~ 13.2 cm intervals (100/13.2 = 7.6 points per meter), which for double lines gives 4 ties per point. In the other location, Ujung Baji, lines have single ties which results in two ties per point. A design was chosen with in the two villages the same weight per point in the three treatments: 20, 40 and 60 g fresh per point plus the farmer practice. An outline of the experiment is presented in the Supplementary Material 1.1. Initial seedling weights per seedling, per point and per meter are shown in Table 3.

Experiment 2: longline, tube-net and cage

In the second experiment we compared the traditional longline with the tube-net and cage. An outline of the experiment is presented in Supplementary Material 1.2. In all treatments, an initial weight of 60 g fresh/point was applied. This allowed for comparison between the 60 g/point treatment in experiment 1 with the longline treatment in experiment 2. It also allowed for fair comparison between the three treatments in experiment 2 (longline, tube-net and cage) with the same starting conditions. Tube-nets and cages were prepared on the beach of farmers with locally used fishing nets. Mesh sizes of ~ 1.5 inch (3–4 cm) used were similar to mesh sizes used in previous research as cited in the introduction section of this paper. As in experiment 1, bi-weekly samples were taken from 1 m of line, this year with three replicates per treatment. Locations in 2024 were very similar to those in 2023. The hypothesis was that seaweed losses experienced as empty ties in longlines would be less from tube-nets and from cages, resulting in higher production per meter of line in tube-nets and cages and lower yields from the traditional longline.

Measured seaweed variables

The main measurement was seaweed fresh biomass at 0, 2, 4 and 6 weeks after planting. Number of ties per point and number of ties per meter differed between villages and farmers (Table 3). We corrected for these differences and express all measured seaweed variables per meter of line, i.e., a standardised method of reporting. We measured the fraction filled and unfilled ties (%) by counting

Table 2 Timeline of the experiments

CycleNr	Planting Date	Planting Month	Period cultivation	Experiment
1	2023–05–24	5.8	May—July 2023	1. initial seedling weight
2	2023–07–10	7.3	July—Aug 2023	1. initial seedling weight
3	2023–08–22	8.7	Aug—Oct 2023	1. initial seedling weight
4	2024–03–15	3.5	Mar—Apr 2024	2. Longline, tube-net, cage
5	2024–05–06	5.2	May—June 2024	2. Longline, tube-net, cage

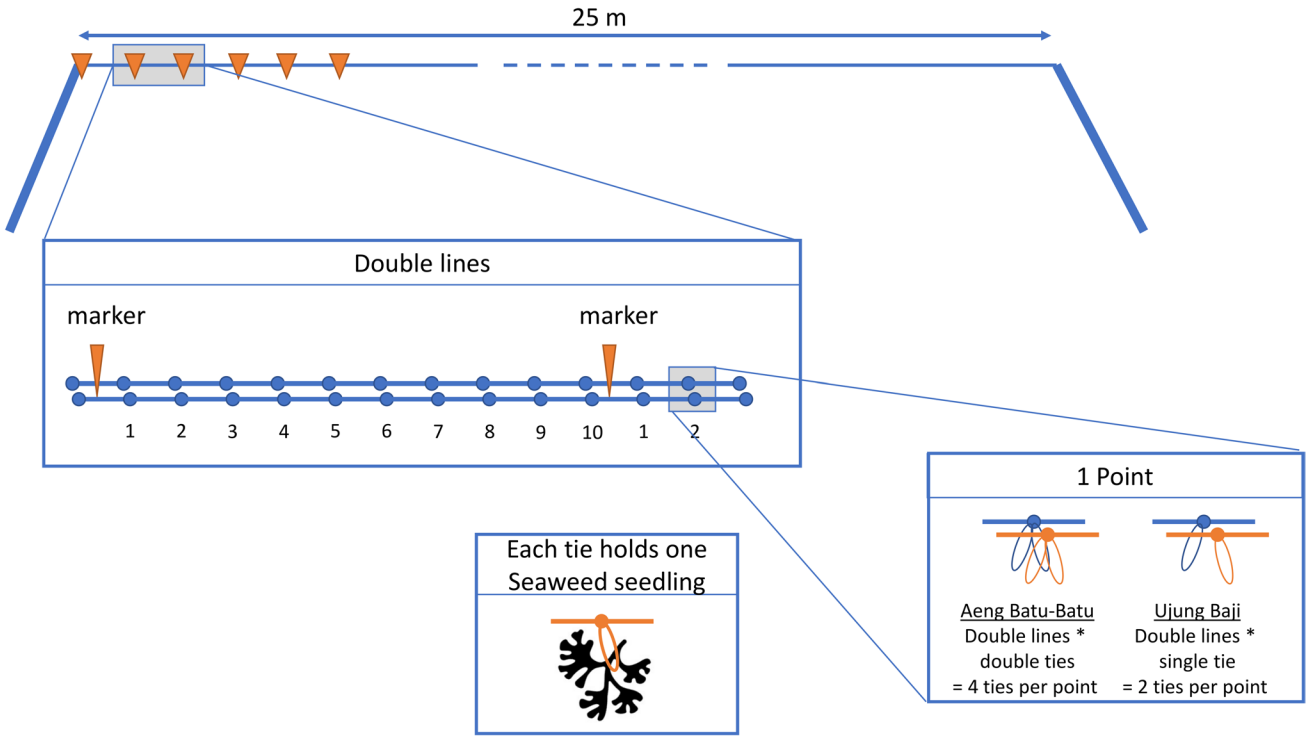


Fig. 3 Schematic illustration of the longline method with double lines and 2 or 4 ties per point

all filled and unfilled ties per meter of line sampled. Visual observations were made of incidence of the ice-ice disease and of fouling by mud and epiphytes. The observations were all visually ranked by one field researcher per experiment on a scale from 1 (none), 2 (some), 3 (bad), 4 (very bad). Two fouling scores were visually observed: fouling of the seaweed was observed in all experiments and in all treatments. Additionally in 2024 for the tube-net and cage, fouling of the net was observed. In some cases we observed strong fouling of the nets with relatively clean seaweed inside. Here in this paper we report fouling as a single score as the maximum of fouling of the seaweed and fouling of the net. Thus if for example in a tube net the fouling score of the seaweed was 2 and the fouling score of the net was 3, then the combined fouling score became Max(2,3) = 3. The method of scoring ice-ice or fouling severity requires further refinement and would be good to develop more objective methods of observation. At the time of writing no such more objective standardised methods existed for measuring ice-ice or fouling severity, hence the approach followed here.

Environmental data

Environmental data (turbidity, salinity, pH, nitrate and phosphate) were measured in cycles 4 and 5 in 2024, at the laboratory of UNHAS, using the same methods as described before in (van Oort et al. 2022). Environmental data were obtained from water samples taken at sites of the experimental lines of the four farmers participating in cycles 4 and 5 (Table 1). Per site per sampling date 3 replicates were taken, resulting in a total of 96 samples (4 sites * 2 cycles * 4 dates * 3 replicates) for each of the five environmental variables. As differences between replicates were small we report only averages. Temperature loggers were installed in the 4 sites taking continuously hourly readings during the two cycles.

Monthly average 0.25° (28 × 28 km) ERA5 weather data were retrieved in August 2024 from (Hersbach 2023). From the ERA5 netcdf files we extracted timeseries for the two pixels near the coast of the two villages in this study. We downloaded sea surface temperature, precipitation and wind (at 10 m above surface), with windspeed in two directions, east–west (u) and north–south (v). Absolute windspeed (ws) was calculated using the standard Eq. (1):

$$ws = \sqrt{u^2 + v^2} \tag{1}$$

To investigate correlations between environmental variables and seaweed yield, we averaged environmental data over the period of each cultivation cycle, separately for the two villages.

Statistical analysis

Table 4 lists the total number of observations made. The number of replicates per treatment was too small (2023: 1; 2024: 3) to allow for statistical testing. Therefore we rely mainly on visual interpretation to identify systematic patterns in the data. Nonetheless, the dataset is large, covering two villages over a timespan of five cycles in which 560 datapoints were collected. For ease of interpretation we sometimes fitted parabolic functions through the data.

Results

Raw data of growth curves split out per farmer, cycle and treatment are presented in Supplementary Material 2, Figure S2.1–5.

Table 3 Experiment 1. Average initial seedling weights

Village	Variable	Seedling weight			
		Low	Medium	High	Farmer practice average
Aeng Batu-Batu	Ties per point	4	4	4	4
	Seedling weight (g/tie)	5	10	15	11.6
	Seedling weight (g/point)	20	40	60	46
	Avg points per meter	7.6	7.6	7.6	7.6
	Seedling weight (g m^{-1})	152	304	456	350
Ujung Baji	Ties per point	2	2	2	2
	Seedling weight (g/tie)	10	20	30	16.5
	Seedling weight (gram/point)	20	40	60	33
	Avg points per meter	6.8	6.8	6.8	6.8
	Seedling weight (g m^{-1})	136	272	408	224

Planting date, empty ties, ice-ice disease and fouling

Figure 4 shows final biomass at 6 weeks after planting for the longline treatment with 60 g/point which was the treatment used in both experiments of 2023 and 2024. For all seaweed variables and for all planting dates, we can observe large variation between yields on lines of the different farmers. There is no consistent ranking between the farmers: a farmer with the highest yield in one cycle may well have the lowest yield in another cycle. Further on in this paper we will explore whether differences can be explained from location (village and distance from shore).

Figure 4 shows a significant influence of planting date on seaweed yields. Seaweeds planted earlier in March consistently yielded higher than those planted later in August. Variation in yields was attributed to several factors, including the presence of empty ties, ice-ice disease and fouling. For the earliest planting in March, farmers 1 & 2 had higher yields and less empty ties and farmers 3 & 4 had lower yields with more empty ties. This suggests a negative effect of empty ties from these 4 data points. Comparing the yields and percentage of empty ties, we observe similar % empty ties of 40–70% in March and in August. Farmers 3 & 4 in March obtained much higher yields of 900—1500 g m^{-1} while for the August planting farmers 1, 2, 5 & 6 obtained low yields of less than 500 g m^{-1}. This large yield difference at similar percentage empty ties must therefore be caused by other factors. Our results suggest that the increased pressure of fouling and ice-ice disease are additional yield determinants, both of which were higher in August compared with March (Fig. 4). Another indication that empty ties is not the only important yield determinant can be seen from a simple calculation example. Final yield in August from a line is approximately 150 g m^{-1} and around 50% of ties is unfilled. Imagine all ties had remained filled, then imaginary potential yield is 150/50% = 300 g m^{-1}, still substantially lower than the yields of 1000–2000 g m^{-1} obtained for the other planting dates. All three yield determinants (empty ties, fouling, ice-ice) increase over time, which means these explanatory variables are correlated with each other. With such correlation between explanatory variables, it is impossible to separately quantify their individual effects. What is clear though from the current analysis is that yields are determined by a combination of at least these three interconnected factors: empty ties, ice-ice and fouling.

Treatments

Figure 5 shows mean yields (averaged over lines of 4–6 farmers) for the different treatments, in interaction with the five planting dates. Our results confirm to some extent the hypothesis of experiment 1. Yields are consistently higher for the medium and large initial weight (40/60 g / point) than for the low initial weight (20 g / point). Thus it is better to avoid these really small seedlings. But between the medium and large initial weight (40/60) results are less consistent: in cycle 1 (planting May 2023, month 5.8) 40 g / point gave highest yields, whereas in cycle 2 (planting July 2023, month 7.3), 60 g/point gave highest yields. In practice it is also more relevant to suggest to farmers a range of weights and not an exact weight, because there is inevitably a variation in the size of seedlings attached to lines. We would thus recommend a range of 40–60 g /point, which implies in Aeng Batu-Batu seedling weights of 10–15 g (with 4 ties/point) and in Ujung Baji 20–30 g (with 2 ties/point).

The hypothesis of experiment 2 was that seaweed losses would be less from tube-net and from cage rather than from the standard longline, which would lead to higher yields from tube-net and cage. This hypothesis was strongly rejected. In both cycles 4 and 5, biomass production was highest for the longline, lower for the tube-net and lowest for the cages. Visually observed problems with the tube-net and cages were fouling by mud and epiphytes (Supplementary Material 3, Table S3.1 & Table S3.2), which is also seen in the high and very high scores for fouling in Fig. 5. Additionally in some cases nets of the cages got torn, possibly by fish or accidentally by the seaweed farmers' boats (Supplementary Material 3).

Table 4 Number of observations in the experiment

CycleNr	Period	Farmers	Treatments	Sampling weeks	Replicates	N
1	May—July 2023	6	4	4	1	96
2	July—Aug 2023	5	4	4	1	80
3	Aug—Oct 2023	6	4	4	1	96
4	Mar—Apr 2024	4	3	4	3	144
5	May—June 2024	4	3	4	3	144
Total						560

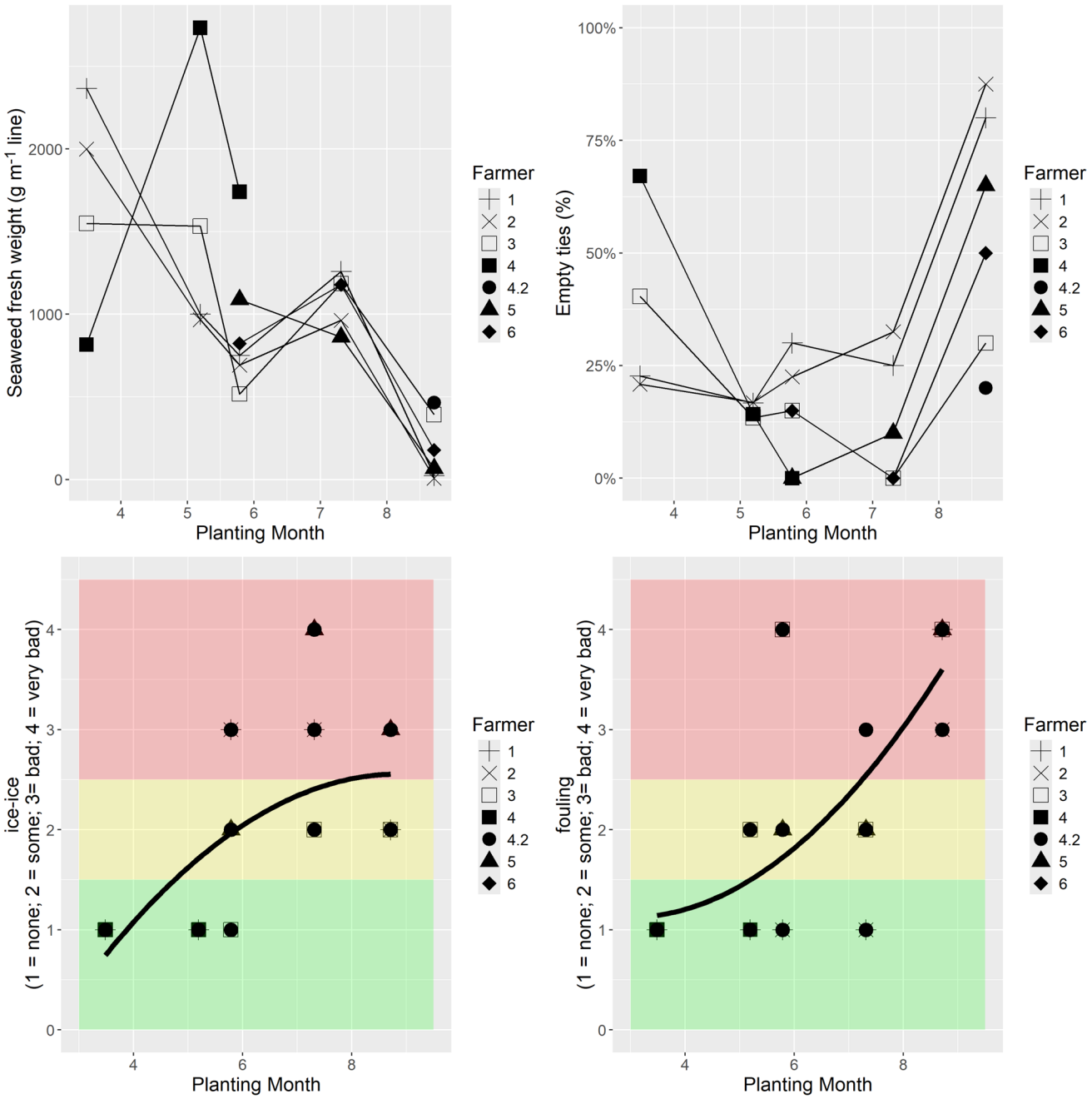


Fig. 4 Seaweed fresh weight at harvest (6 weeks) and three yield determinants: empty ties, ice-ice disease and fouling for five different planting dates from month 3 (March) to 8 (August). Comparison between Farmers (symbols). Results for the "60 g/point longline" treatment. The fat line is a polynomial fitted through all data points. Location of lines of Farmers (Table 1): 1(+) and 2(x) are from Aeng Batu-Batu, farmers 3–6 are from Ujung Baji. Seaweed lines from farmers 1–3 were near shore, lines from farmers 4–6 were offshore

Site differences

Figure 6 shows effects of location, in interaction with planting date on seaweed biomass at 4 and 6 weeks after planting. Like the previous figures it shows yields decrease with planting date and this reduction occurs in all three classes of locations (Aeng Batu-Batu nearshore, Ujung Baji nearshore, Ujung Baji offshore). Comparing the first two columns we can see the effect of village. There is no consistent effect: sometimes yields are higher in one village, sometimes in the other and sometimes they are very similar. Comparing the last two columns we can see the effect of distance from

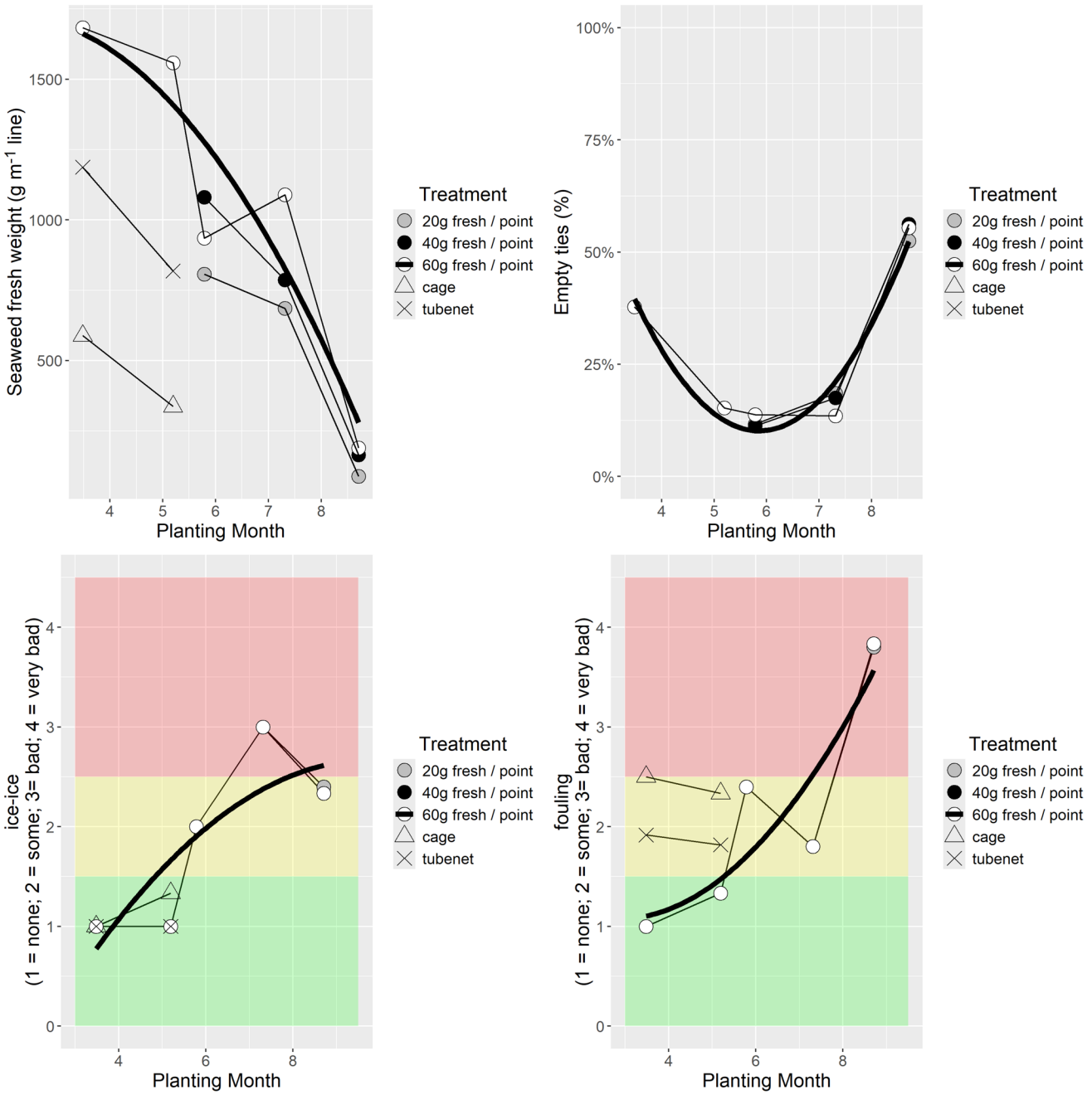


Fig. 5 Seaweed fresh weight at harvest (6 weeks) and three yield determinants: empty ties, ice-ice disease and fouling for 5 different planting dates from month 3 (March) to 8 (August). Comparison between Treatments (symbols). The fat line is a polynomial fitted through the "60 g/point longline". Data points shown are averages over data collected from 4–6 farmers and 1–3 replicates

shore. There is no consistent effect: sometimes yields are higher closer to the shore, sometimes yields are higher further away from the shore.

Growth flattening off at 4 weeks after planting

In all experiments biomass increased from week 0 to week 4. After week 4 in a number of cases biomass growth stopped (i.e. same biomass in week 4 and 6) or even decreased (biomass in week 6 lower than in week 4). Such effects are seen in Fig. 6 with the most notable case biomass in the earliest cycle for Ujung Baji, where biomass on the line dropped from 3100 g m^{-1} in week 4 to 817 g m^{-1} offshore and from 2017 to 1550 g m^{-1} nearshore. According to the farmers at this location, there were in between week 4 and 6 "strong waves for about 2–3 consecutive days".

Overall in Fig. 6 in 6 out of 15 combinations (40%) biomass was higher in week 4 than in week 6. Overall average biomass is slightly higher in week 4 (1321 g m^{-1}) than in week 6 (1246 g m^{-1}). Figures S2.1 to S2.5 in the Supplementary Material 2 present the raw data of growth curves showing in several cases growth flattening off at 4 weeks after planting, or even decreasing from week 4 to 6.

Environmental data

Local measurements

Figure 7 shows correlations between seaweed biomass and water quality variables, with water quality variables averaged over the growing period of each location and cultivation cycle. In the Supplementary material, Figure S4.1 and Figure S4.2, we show progression of environmental variables over time. Figure 7 shows yields are not correlated with turbidity (b), nitrate (c), phosphate (d) or pH (e). Possibly the range of these the environmental variables, for example nitrate from 1.3 to 1.6 µmol L^{-1}, was too small to show an effect. Or possibly other factors such as empty ties were stronger yield determinants in these two cycles. Surprisingly Fig. 7a and f show a parabola with branches facing upwards and lowest yields at around 29 g kg^{-1} salinity and lowest yields at around 30 °C sea surface temperature. Normally the relation between environmental data and yield is opposite with branches facing downwards and highest yields in the middle for some optimum value of an environmental variable. For example (Hayashi et al. 2011) reported highest *Kappaphycus* yields at 38 g kg^{-1} salinity and lower yields below 35 and above 45 salinity. (Borlongan et al. 2017) reported highest *Kappaphycus* growth at water temperatures of 28.6 °C and lower growth at both lower and higher temperatures. The unlikely parabolas in Fig. 7a, f indicate the dataset with only 8 data points (two cycles * four farmers) is too small to allow for meaningful interpretations. This is an important finding for future research and indicates a need for future studies to conduct longer lasting simultaneous monitoring of water quality and seaweed production, for example during a period of five cycles in one year or better still, two years of five cycles.

Meteorological data

Figure 8 shows monthly average meteorological variables for the two years 2023 (blue) and 2024 (red; up to July) for the two villages. The green shaded area is the cultivation period of the experiment, from March (3) to early October (10). During the cultivation period we observe:

1. Sea surface temperatures decrease from 30 °C in March to 27–28 °C in September.
2. Sea surface temperatures increase from 27–28 °C in September to 28.5–29 °C in October
3. Wet season is December to April. Dry season is May to November. Cultivation starts at the end of the wet season and is mostly in the dry season
4. Almost no wind (0 m s^{-1}) in March—April to stronger winds (2–5 m s^{-1}) in May–August. During the cultivation period winds blow towards the West (away from the shore) and in Northern direction (parallel to shore). Stronger winds in Ujung Baji.
5. Wind direction is different during the dry season (months 5–11) and wet season (months 12 – 4). During the dry season winds blow mostly towards the West (Fig. 8c, negative values), which means winds come from the island in which case air will be relatively dry. During the wet (Monsoon) season winds blow mostly towards the East (Fig. 8c, positive values), which means winds come from sea towards the land in which case air will be relatively moist. Winds also change direction along the north–south axis, blowing during the dry season towards the North (Fig. 8d, ' + ' values) and during the wet season towards the South (Fig. 8d, '-' values).

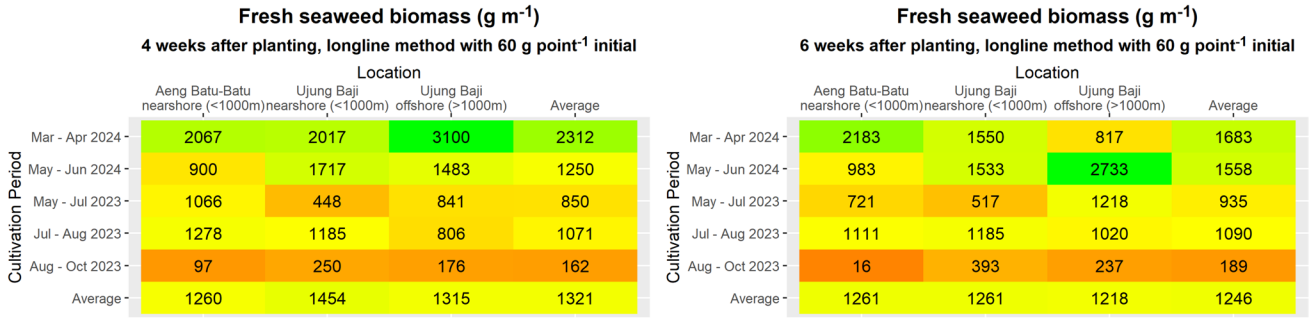


Fig. 6 Effects of location, in interaction with planting date on seaweed biomass at 4 weeks after planting (left panel) and 6 weeks after planting (right panel). Results of treatment with initial seedling weight "60 g/point", longline method. Colouring: green = high, medium = yellow, orange = low

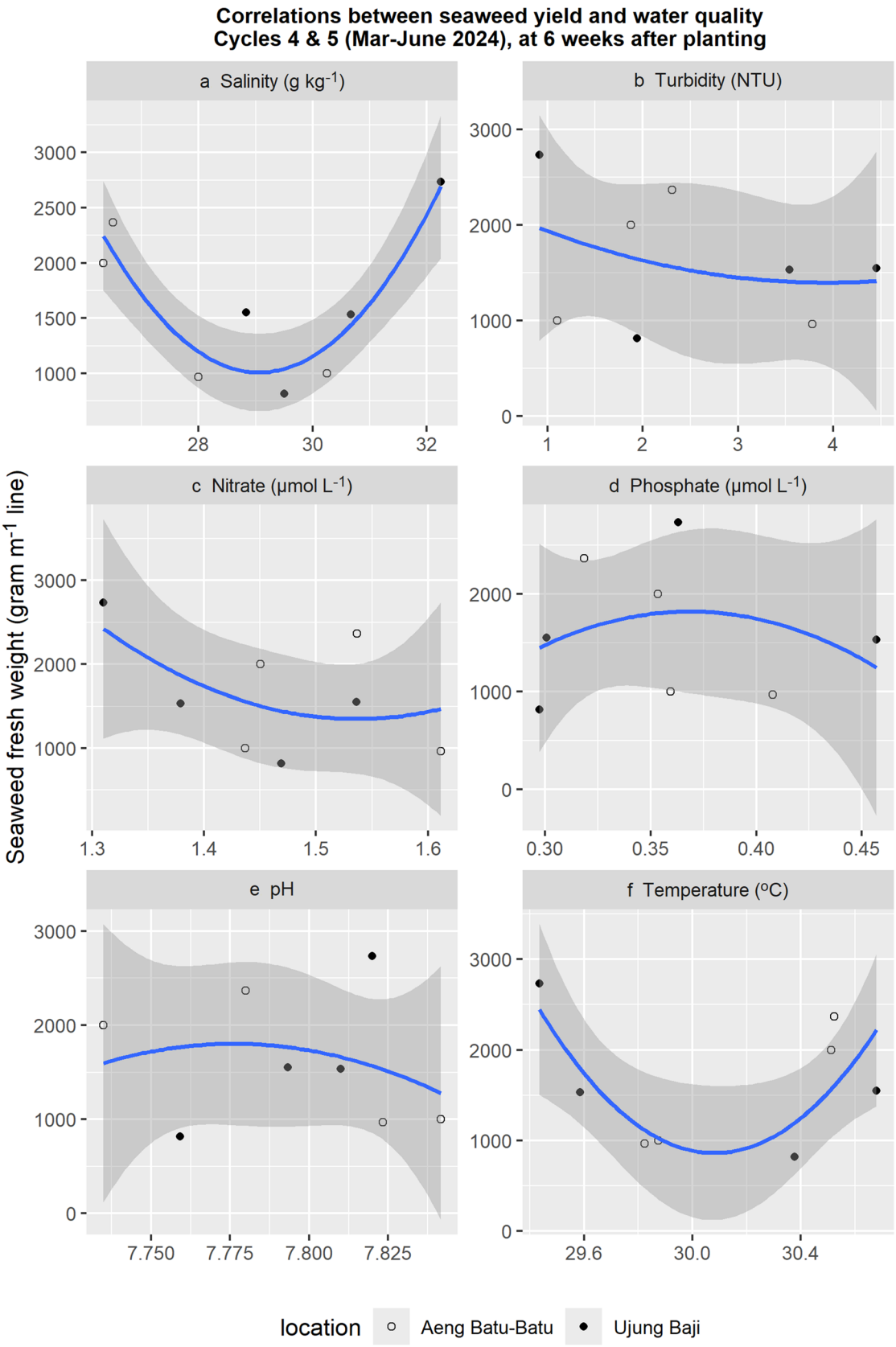


Fig. 7 Correlation between Seaweed fresh weight at harvest (6 weeks) and water quality in cycles 4 & 5. "60 g/point longline" data only. Blue line = fitted polynomial, grey area = 95% confidence level. Panels: (**a**) Salinity; (**b**) Turbidity; (**c**) Nitrate; (**d**) Phosphate; (**e**) pH; (**f**) Temperature

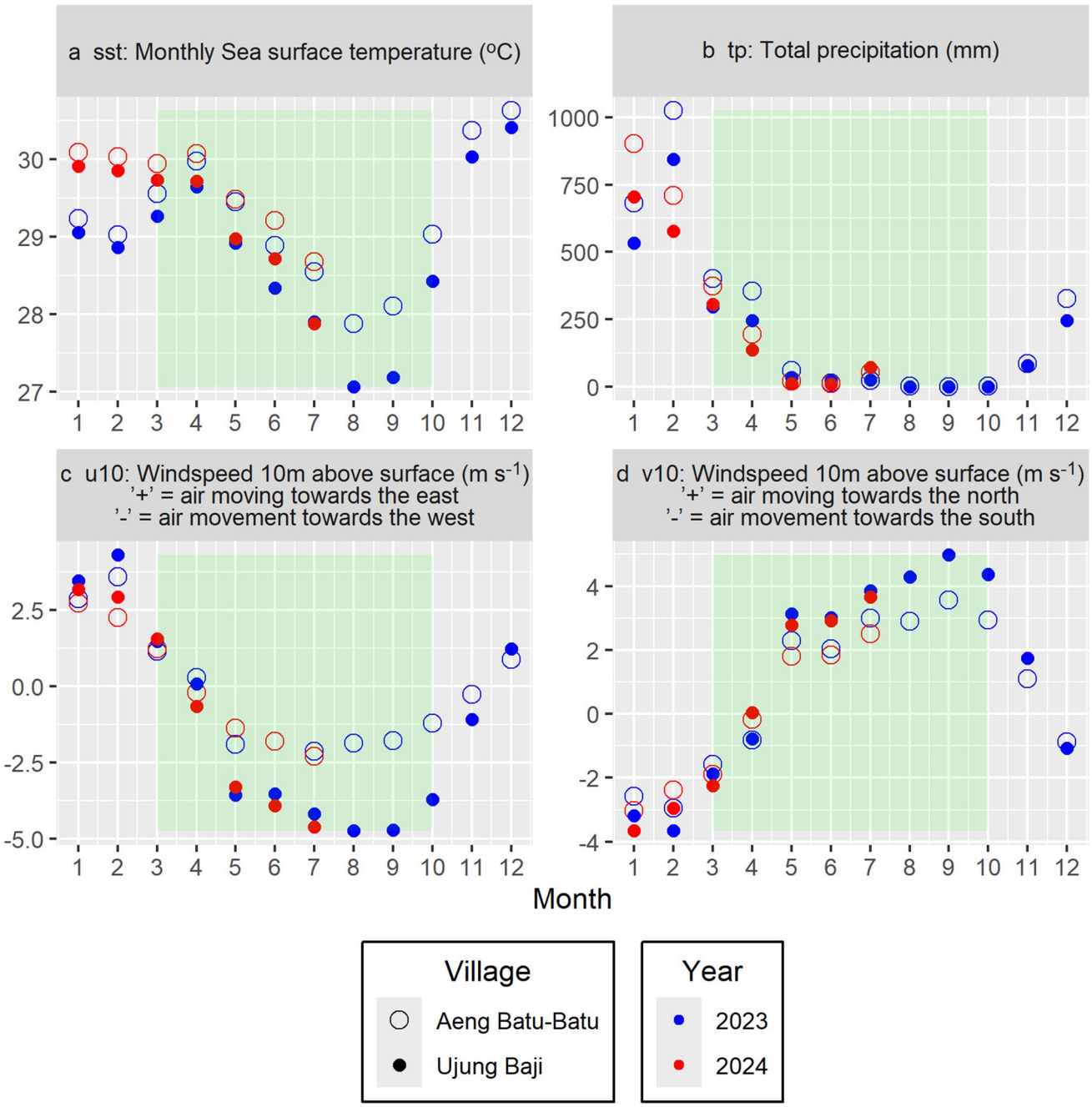


Fig. 8 Meteorological data. Green rectangle shows our experiments were from month 3 (March) to month 10 (October). Panels: (**a**) sst: Monthly Sea surface temperature; (**b**) tp: Total precipiration; (**c**) u10: Windspeed in East-West dimension; (**d**) u10: Windspeed in North-South dimension. Explanation windspeed data in panel (**c**): in month 1 (January), + 2.5 m s^{-1} indicates windspeed 2.5 m s^{-1} blowing towards the east; in month 4 (April), 0.0 indicates no winds; In month 8 (August), −2.5 to −5.0 m s^{-1} indicates windspeed 2.5 −5.0 m s^{-1} blowing towards the west

Figure 9 shows correlation between meteorological data for all five cycles and all farmers, for the treatment with 60 g fresh weight/point. The figure shows:

1. Higher yields at higher temperatures of 30 °C
2. Higher yields at lowest windspeeds close to 0 m s^{-1}

Also here, caution in interpretation is called for. ERA5 meteorological variables are spatial average values over large 28 × 28 km pixels, which may not exactly represent true conditions at ~ 1 km from the shore. The ERA5 meteorological data are monthly averages, which means they are not suitable for investigating the effects of a few days with strong winds during the month. Also, as Fig. 10 shows, meteorological variables are correlated with each other. Windspeed (*ws10*) is correlated with temperature (*sst*), with low windspeeds and high temperatures in March and high windspeed and low temperature in August. With such correlation between environmental variables, we cannot tell if high seaweed yields in March are caused by low windspeed in March, high temperatures in March or caused by a combination of these two environmental variables.

Discussion

Main findings

The highest yields were obtained for planting in March and the lowest for planting in August (with harvest early October). During this same period we observed (1) increasing number of empty ties; (2) increasing pressure of the ice-ice disease (3) increasing fouling by mud and epiphytes; (4) increasing windspeed and (5) decreasing temperatures. We showed the combination of these 5 co-occurring yield determinants together causes yield differences between the planting dates. We found lower yields for the low initial weight and higher yields for the medium/high initial weight. We found higher yields for the longline treatment and lower yields for the tube-net and cage treatment. These lower yields from tube-nets and cages were attributed to fouling of nets by mud and epiphytes. To our best knowledge the current study is the first to study this full range of possible yield determinants and to simultaneously monitor for longer period (five cycles, with bi-weekly sampling) both seaweed biomass and yield determinants. Much further research is needed into yield determinants and possible contributions of such research to help farmers improve their cultivation methods and livelihoods. We discuss our research outcomes in more detail below.

Farmers are well aware of which period of the year is best for cultivation. Our results are consistent with a previous study on mapping seaweed cultivation with satellite data for a village along the same coast but further North. In that study, Langford et al. (2021) found peak cultivation from March to June, the period for which we here found highest yields. Our results are also consistent with (Aslan et al. 2019b) who report for a site in South Sulawesi lowest growth from August to October. What is new here is that the current study provides deeper understanding of why which part of the year are more or less suitable for cultivation. Langford et al. (2021) reported almost no seaweed cultivation during the monsoon period (approximately December – April). It is well known the monsoon period is not suitable for seaweed cultivation due to rough sea. What was less well known was why in the first part of the dry season there is more seaweed cultivation (Langford et al. 2021) and higher yields (this study) and why both are less during the later part of the dry season. The current study provides a glimpse of an answer to that question, indicating the later part of the dry season is less suitable due to increasing empty ties, ice-ice disease, fouling, increasing windspeed and (possibly) due to dropping temperatures.

Uncertainties and further research

It is important to keep in mind we are reporting correlations, which does not necessarily mean causal relations. For the empty ties, ice-ice and fouling the causal relation with seaweed yield is clear, but we still lack a clear understanding of *why* pressure of ice-ice and fouling increased during the season. One possible explanation is that incidence increases due to environmental changes in the same period. For example, one could imagine stronger winds associated with rougher sea, more turbulence, leading to more dissolved mud and ultimately more fouling. This seems a plausible connection but could not be explicitly tested because we did not continuously measure turbulence of the water during all five cycles. Much is yet unknown about if and how ice-ice is affected by environmental conditions (Mohammed Riyaz et al. 2021; Ward et al. 2022). Much is unknown about if and how growth of epiphytes is affected by environmental conditions. Alternatively, it is also possible that during the cultivation period there is a build-up of ice-ice and epiphytes, caused by the practice of replanting (possibly infected) seaweeds. Cultivation starts in March with clean seaweed. During the cycle the infection by ice-ice and epiphytes increases. Part of the harvested seaweed is set aside for replanting. Branches infected by ice-ice are thrown away, epiphytes are removed and then the cleaned seaweed is replanted. Yet human eye may not be able to detect all the ice-ice/epiphytes. Therefore it is possible that the initial degree of infection is higher in the second cycle, leading to stronger growth of ice-ice and epiphytes in the second cycle. These dynamics could theoretically lead to a natural increase of the disease ice-ice and epiphytes, independently of environmental conditions. Both the hypotheses of environmental conditions and of natural build-up due to replanting require

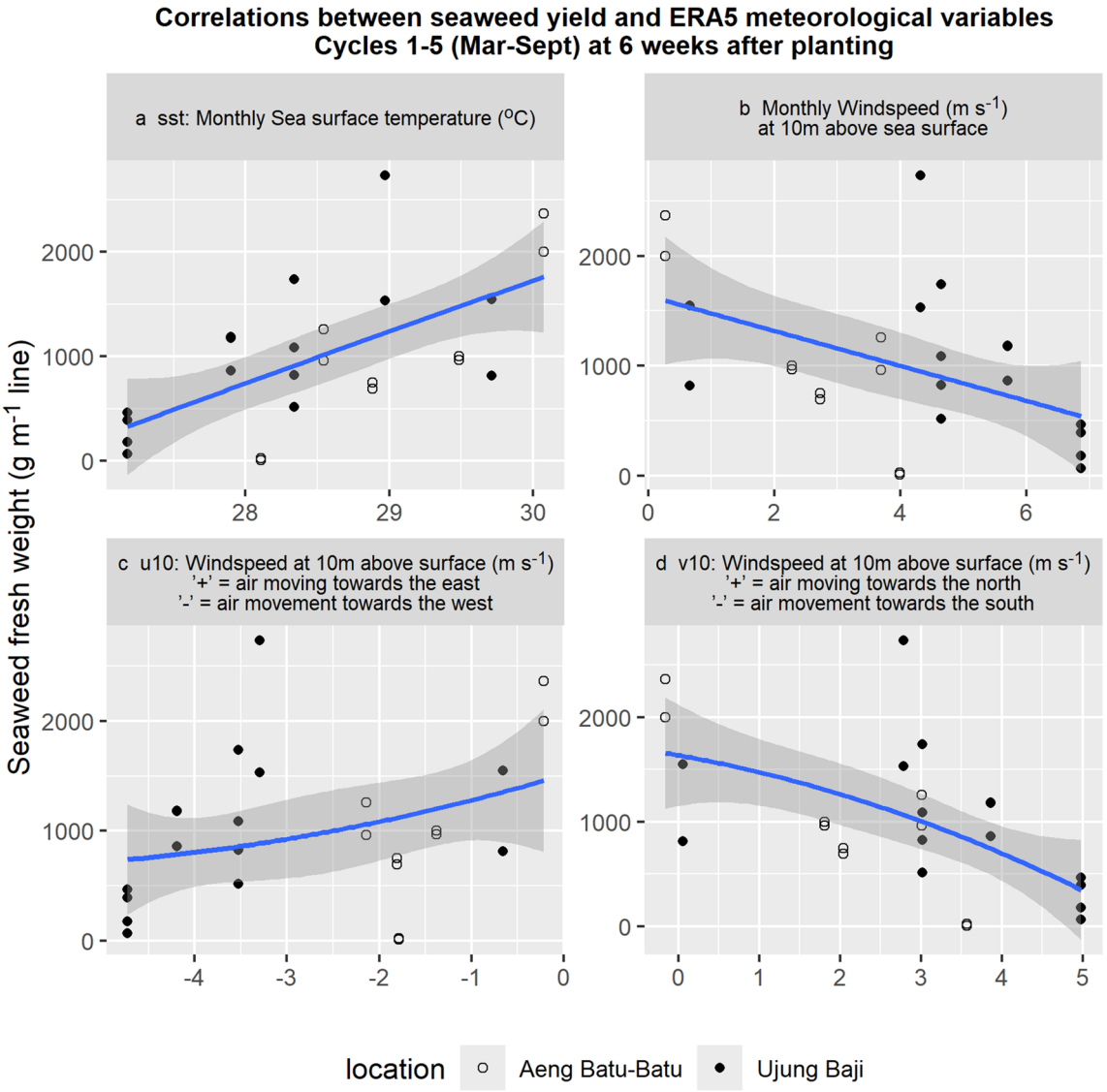


Fig. 9 Correlation between seaweed yield and monthly meteorological values in cycles 1 to 5. "60 g/point longline" data only. Data points for individual farmers. Blue line = fitted polynomial, grey area = 95% confidence level. Panels: (**a**) sst: Monthly Sea surface temperature; (**b**) Monthly windspeed; (**c**) u10: Windspeed in East-West dimension; (**d**) u10: Windspeed in North-South dimension

further testing. Clearly many of these processes are yet poorly understood. We have shown ice-ice and fouling by mud and epiphytes have a negative effect on yields. It is therefore important to further research possible causes and solutions for the build-up of ice-ice and fouling during the cultivation period.

We found higher yields at low windspeeds and higher temperatures of 30 °C. These three variables are correlated but the causal relations require further investigation. It seems plausible that stronger winds cause rough sea, resulting in seaweed falling off (resulting in empty ties) but also seaweed breaking off resulting in smaller seaweeds on remaining filled ties. Reporting by famers suggested that just a few days of rough sea or just a few days of high temperatures could already have detrimental effects, yet with our monthly averaged weather data such claims could not be explicitly tested. For further research it would be relevant to conduct frequent observations during the full cultivation period from March to October, measuring simultaneously on a daily basis weather and bi-weekly seaweed biomass. The relation between temperature and seaweed yields requires further investigation. Our results showed high yields and low to moderate ice-ice at temperatures of 30 °C for planting in March and low yields and moderate to high ice-ice at temperatures for planting in August, which may have experienced temperatures increasing from 27–28 °C in September to 28.5–29 °C in October. Thus, the relation between temperature, yields and ice-ice remains uncertain.

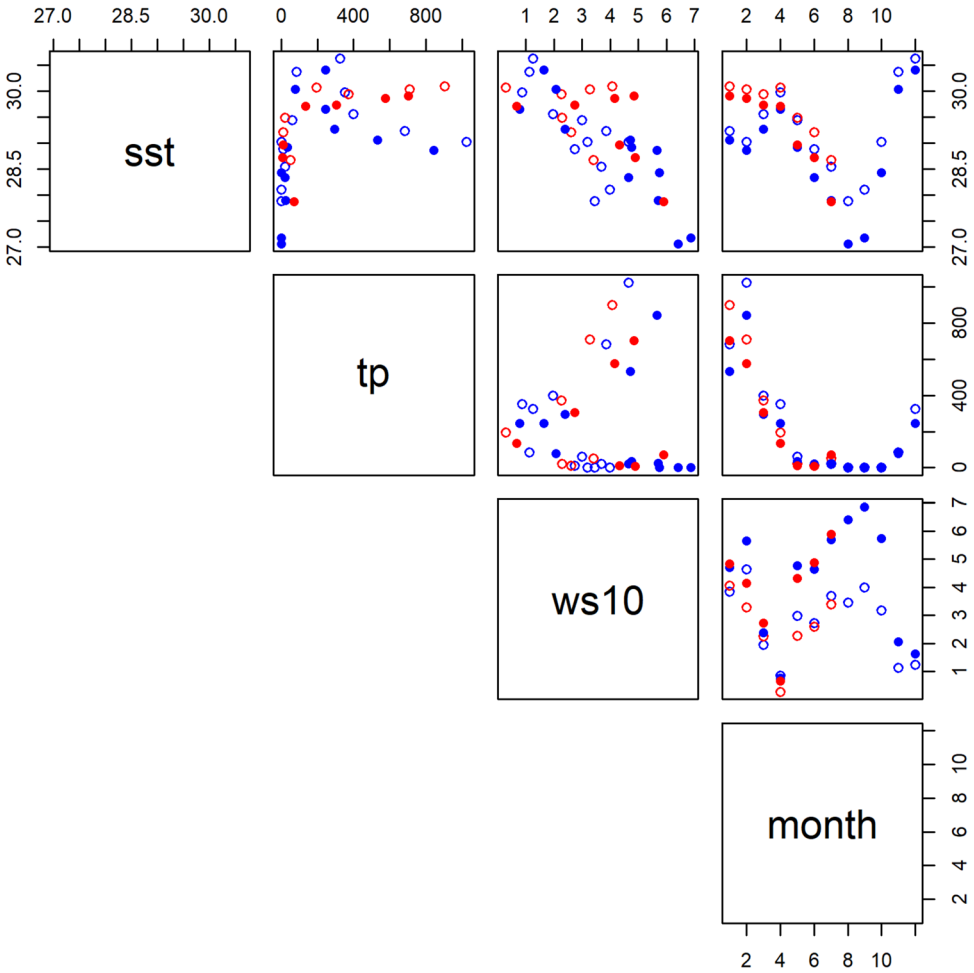


Fig. 10 Correlation between ERA5 environmental variables in the study area. 'sst' = Monthly Sea surface temperature (°C); 'tp' = Monthly precipitation sum (mm); 'ws10' = Monthly average windspeed at 10 m elevation (m s^{-1}); 'month' = month number (1 = Jan, …, 12 = Dec). Legend same as in Fig. 8. Note in the top row middle panel strong correlation between 'sst' and 'ws10': high temperatures and low windspeeds coincide

Interpretation from observations from open sea such as in the current study were hampered by the fact that in open sea temperature was correlated with windspeed. Therefore, it is theoretically possible that there is no temperature effect at all and that the relation of high yields at high temperatures was just because the real yield determinant, windspeed, also happened to be low at high temperatures. We found lowest seaweed yields at 27 °C and highest at 30 °C but note this is quite a narrow temperature range around the temperature optimum of 28.6 °C for brown *Kappaphycus* (Borlongan et al. 2017). Previously Borlongan et al. (2017) reported much lower growth rates at higher temperatures above 30 °C and lower temperatures below 27 °C. In Japan for *K. alvarezii*, Ohno et al. (1994) showed that the optimum temperature is 25–28 °C. In Mexico Muñoz et al. (2004) found stronger growth at temperatures of 25–28 °C. In Indonesia, a tropical area, the optimum temperature range for *Kappaphycus* spp. is 22–33 °C (Lideman et al. 2013). For further research to disentangle effects of temperature and windspeed it would be interesting to conduct controlled experiments with a larger range of temperatures and at controlled low current speed, for example in larger water basins in a laboratory.

Nutrients, like nitrate and phosphate, are essential for seaweed in photosynthesis processes and growth. In cycles 4 & 5 we found nitrate concentrations of on average 1.47 µmol L^{-1} (0.091 mg L^{-1}) and phosphate concentrations of on average 0.36 µmol L^{-1} (0.034 mg L^{-1}). The range of concentrations was small (1.3–1.6 µmol NO_3 L^{-1}, 0.3—0.45 µmol PO_4 L^{-1}), probably too small to detect a significant effect. There has been very little experimentation for determining optimum marine nutrient concentrations for tropical seaweeds (van Oort et al. 2023). It is difficult to tell from our results if nutrient concentrations were a limiting factor during the research. For tropical seaweeds it would be relevant to conduct laboratory research in otherwise constant conditions and at different nutrient concentrations, to determine the relation between seaweed growth and nutrient concentration. And when conducting research in the marine environment to collect data for longer period in time and from more contrasting sites with high and low nutrient concentrations. Also, in this study only nitrate and phosphate were analysed, and so we may have missed growth effects of other limiting macro- and or micro-nutrients.

Seaweed growth is often reported by reporting weight of individual seaweeds at different moments in time. A drawback

of such methods of reporting is that it ignores possible effects of seaweed planting density, i.e. how many seaweeds are there on a meter of line. We showed in our study density differed, with differences in distance between ties (Table 3: 7.6 or 6.8 points per meter) and number of ties per point (Table 3, Fig. 3: 2 or 4 ties per point). In the current study farmers in both locations planted with double lines, in other locations farmers are known to plant single lines. With such differences in densities between different seaweed cultivation locations, it becomes tricky to compare research outcomes when reporting in terms of weight of individual seaweeds. The method of reporting as presented here, where seaweed variables are reported per meter of line, allows for more standardised, more objective comparison of productivity between different sites with different cultivation methods. Reporting per unit meter of line is not new, for example some studies such as (Hurtado et al. 2008) also report yields per meter and investigated effects of stocking density. But this approach of reporting per unit meter is still far from being commonly applied and the wider applied phycology research community would benefit from more widespread adoption of this method of reporting.

In this study, we did not impose on farmers a single scientifically set cultivation method. Instead, we went along with farmers' practice in which in one village farmers planted double lines with 2 ties per point and in the other village farmers planted double lines with 4 ties per point. To our best knowledge the current study is the first to report on this detail of differences in farmers practices (in terms of number of ties per meter of line). For further research it would be interesting to explicitly investigate different longline cultivation methods such as single line or double line and single ties or double ties. And to learn from farmers why in their location they apply their specific cultivation methods.

Most studies report positively on potential benefits of cages and/or tube-nets (Hurtado-Ponce 1992; Ask and Azanza 2002; Kasim et al. 2016; Mantri et al. 2017; Periyasamy and Rao 2017; Shanmugam et al. 2017; Johnson et al. 2020; Ma'ruf et al. 2020; Kavale et al. 2021; Prasad Behera et al. 2022). However, many of these studies only discuss possible benefits and did not make actual side-by-side experimental comparisons such as we did here. Some of these studies for example introduce tube-nets as a possible solution and then quantify production from tube-nets, without a control treatment of the traditional longline. From such studies, we cannot quantify if the tube-net or cage really perform better than the traditional longline, or possibly even worse than the longline. Contrary to expectations we found lower yields for the cages and tube-nets in comparison with the traditional longline method. The most likely cause for this poorer performance was fouling of the nets by mud and epiphytes. Our experiment raises awareness of the possible risks of lower yields with cages and tube-nets but does not provide ultimate answers. We note that our experiment was quite small, conducted in only two locations between 250 to 1320 m from the coast and in only two growing cycles. Further research is needed to examine the potential benefits from cages and tube-nets in sites with more fish or turtle foraging. Additionally, it is important to determine whether fouling by mud or epiphytes decreases further offshore with clearer water.

Conclusions

Seaweed yields were determined by a combination of factors including empty ties, ice-ice disease, fouling, temperature and windspeed. All these factors were correlated with planting date, which resulted in highest yields for the earliest planting date (March) and lowest yields for the latest planting date (August). Cages and tube-nets had lower performance compared to the traditional longline method, most likely due to mud and epiphytes fouling the cages and tube-nets. Higher yields were observed for medium to large seedlings (15–30 g per seedling, 272–456 g m^{-1}) than for small seedlings (5–10 g per seedling, 136–152 g m^{-1}).

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10811-025-03446-8.

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Authors' contributions All authors conceived and designed the analysis.
B.J., G.L., I.S., N.R., Z.Z.W., and I.A.I. collected the data.
P.O. performed the analysis.
P.O. wrote the paper.
All authors reviewed the manuscript.

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Declarations

Competing interests Authors declare we have no competing interests.

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