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RESEARCH

Temporal variation in the incidence of seaweed health problems affecting farmed *Kappaphycus striatus* in relation to environmental conditions in shallow waters

Joseph P. Faisan Jr.[1,2] · **Rema C. Sibonga**[2,4] · **Jonalyn P. Mateo**[3] · **Maria Rovilla J. Luhan**[2] · **Victor Marco Emmanuel N. Ferriols**[2] · **Vicente T. Balinas**[5] · **Janina Brakel**[6,7,8] · **David Bass**[10,11,9] · **Stuart Ross**[10] · **Grant D. Stentiford**[10,11] · **Juliet Brodie**[9] · **Georgia M. Ward**[10,9] · **Anicia Q. Hurtado**[2]

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Abstract

A fixed off-bottom *Kappaphycus striatus* var. *sacol* farm was monitored for 12 months (June 2019 to May 2020) and the monthly incidence of disease and pests was recorded. Meteorological information *in situ,* from the nearest synoptic station and online data were collected to determine the relationships between temporal environmental changes and the incidence of seaweed health problems. The results showed that “ice-ice” disease (IID) was observed in dry months (i.e., from February to April 2020) and was significantly influenced by increased irradiance, salinity, sea surface temperature, and wind speed (p=0.004−0.030). Also, the IID incidence was positively affected by reduced precipitation, storm surface run-off, water current speed, and inorganic nutrient (nitrite and ammonia) levels (p=0.002−0.019). In comparison, epiphytic filamentous algae (EFA) were observed in wet months (i.e., from September to December 2019), with incidence varying from low to very high (≤25–100%) as the culture progressed. EFA incidence was significantly influenced by reduced salinity and increased storm surface run-off and inorganic nutrient (nitrate and ammonia) levels (p=0.006−0.040). An intense tropical cyclone struck the farming area in December 2019, resulting in partial die-offs of farmed seaweed. Such seaweed health problems are expected to become more prevalent in the coming years as weather disturbances brought about by changing weather patterns become more frequent and intense. Hence, mitigation and preventative approaches must be fully considered to sustain the industry’s growth while protecting the livelihoods of many coastal communities dependent on seaweed farming.

Keywords Climate change · Disease · Pest · Rhodophyta · Seaweed farming · Seaweed health problems

✉ Joseph P. Faisan Jr.
jfaisan@seafdec.org.ph

✉ Anicia Q. Hurtado
anicia.hurtado@gmail.com

[1] Aquaculture Department, Southeast Asian Fisheries Development Center, 5021 Tigbauan, Iloilo, Philippines

[2] Institute of Aquaculture, College of Fisheries and Ocean Sciences, University of the Philippines Visayas, 5023 Miagao, Iloilo, Philippines

[3] Institute of Marine Fisheries and Oceanology, College of Fisheries and Ocean Sciences, University of the Philippines Visayas, 5023 Miagao, Iloilo, Philippines

[4] Center for Chemical Biology and Biotechnology, University of San Agustin, 5000 Iloilo City, Philippines

[5] Division of Physical Sciences, College of Arts and Sciences, University of the Philippines Visayas, 5023 Miagao, Iloilo, Philippines

[6] Scottish Association for Marine Science, Scottish Marine Institute, Dunbeg, Oban, Argyll PA37, UK

[7] Helmholtz Institute for Functional Marine Biodiversity at the University of Oldenburg (HIFMB), Ammerländer Heerstrasse 231, 26129 Oldenburg, Germany

[8] Alfred-Wegener-Institute, Helmholtz Center for Polar and Marine Research, Am Handelshafen 12, 27570 Bremerhaven, Germany

[9] Natural History Museum, Science, Cromwell Road, London SW7 5BD, UK

[10] Centre for Environment, Fisheries and Aquaculture Science (Cefas), Weymouth Laboratory, Weymouth, Dorset DT4 8UB, UK

[11] Biosciences, University of Exeter, Stocker Road, Exeter EX4 4QY, UK

Introduction

Eucheumatoid (*Kappaphycus* and *Eucheuma*) red seaweed farming has been an important and expanding aquaculture industry from tropical to subtropical countries since the 1970s (Sulu et al. 2004; Pickering 2006; Hurtado et al. 2014; Msuya et al. 2014; Hayashi et al. 2017; Shanmugam et al. 2017; Alemañ et al. 2019). In Southeast Asia, where the majority of eucheumatoid seaweeds are produced, biomass yields increased by almost 200% between 2010 and 2019, with 5.95 million tonnes (Mt) wet weight and 11.60 Mt, respectively (FAO 2021). In 2019, eucheumatoid red seaweeds constituted 33.5% of the world's total seaweed production (Cai et al. 2021). The increase in the production of these seaweeds can be attributed to the widespread economic demand for carrageenan, a hydrocolloid polysaccharide sought after for its many uses in the food, pharmaceutical, cosmetics, and nutraceutical industries (Bixler and Porse 2011; Porse and Rudolph 2017).

However, seaweed health problems, particularly "ice-ice" disease (IID) and epiphytic pests, significantly affect eucheumatoid seaweed farms. IID-infected seaweed shows depigmentation or whitening of the thallus and, in severe cases, necrosis, leading to the disintegration of the affected tissues from the culture line (Ward et al. 2020, 2022). The epiphytic pests observed on farms include macroepiphytes such as other seaweeds (i.e., *Sargassum, Ulva,* and *Gracilaria*) and epiphytic filamentous algae (EFA) (Faisan et al. 2021). EFA are common epiphytic pests affecting farmed seaweeds and are mainly assigned to the red algal genus *Melanothamnus* (previously known as *Neosiphonia*) (Critchley et al. 2004; Hurtado et al. 2006; Vairappan 2006; 2008). EFA tetraspores attach to the surface of host seaweeds and penetrate through the cortex to the medullary layers of the thallus, causing mechanical damage to the host plant (Ask 1999; Vairappan 2006; Pang et al. 2011; Tsiresy et al. 2016; Ingle et al. 2018). EFA outbreaks on seaweed farms often result in decreased biomass yield and compromised carrageenan quality (Hurtado et al. 2006; Vairappan et al. 2008; Ali et al. 2020).

The occurrence of disease and pests on eucheumatoid red seaweeds is often influenced by fluctuating environmental conditions (Hurtado and Critchley 2006; Msuya and Porter 2014; Largo et al. 2017, 2020; Arasamuthu and Edward 2018; Pang and Liu 2019). Changing environmental conditions can greatly influence seaweed cultivation. Many of the farms are located near intertidal areas that are most vulnerable to destruction during extreme weather events such as typhoons and storm surges. However, information about the changing environmental factors affecting eucheumatoid cultivation on shallow water farms has yet to be fully explored. Here, we monitored a fixed off-bottom *Kappaphycus striatus* seaweed farm for one year (12 months), encompassing wet and dry seasons, and observed the incidence and severity of disease and epiphytic pests. We also collected temporal environmental data *in situ* from online sources and the nearest climatological synoptic station to determine the interactive effects of this environmental information on the incidence of seaweed health problems. Moreover, as a result of this study we have made recommendations for reduction or potential mitigation strategies for the impact of fluctuating environmental conditions on eucheumatoid farms, particularly in shallow water areas.

Materials and methods

Site selection

The experimental seaweed farm was chosen based on a prior survey among the different eucheumatoid farming areas in Panay Island and located in San Dionisio in northern Iloilo, Western Visayas, Philippines (11.2890 N°, 123.0930 E°) (Fig. 1). The farm site was located in an area where commercial seaweed aquaculture is located, employing a fixed

Fig. 1 Location of *Kappaphycus striatus* farm using a fixed off-bottom culture method in San Dionisio, Iloilo, Western Visayas, Philippines (11.2890 N°, 123.0930 E°). Photo showing farmed seaweed and a parallel ridge (uppermost right) to distinguish farm boundaries and ownership. Photo credits: Google Maps and JP Faisan, Jr

off-bottom method with a minimal water depth of 20–30 cm during low tide, sandy-muddy substrate, and abundant seagrasses and seaweeds (*Sargassum* and *Gracilaria*) growing in the surrounding areas and protected from direct wind and strong tidal actions due to the presence of adjacent islands. No rivers are found in the neighboring area indicating that there is no direct effect on salinity fluctuations in the farming site except during wet seasons when rainfall could affect the salinity level.

The area of the farm was 500 m^2 and separated from the other farms by a parallel ridge of stones and dead corals to distinguish the boundaries and ownership of other seaweed farms (i.e., with different farm operators/farmers), which also functioned as a breakwater, protecting the farmed seaweeds from strong wave actions and washing away.

Cultivation system

The seaweed species farmed was *Kappaphycus striatus* var. *sacol*. The culture method employed was the fixed off-bottom method, which is the typical method of culturing seaweeds used in the near-shore area of the locality (CARE Philippines 2021). It is the simplest to construct with low investment capital and minimal skill requirements. The materials used were wooden stakes as anchors, flat binders or polyethylene ropes (PER#7) as culture lines, and plastic strips (i.e., soft plastic 'tie-tie') to tie the seaweed seedlings (Hurtado et al. 2014; Hayashi et al. 2017).

Farm management

The seedlings used in the study were taken from the same farm cultured in the previous cropping. Initially, ten 10 m long lines were planted with seaweed seedlings. A total of 50 bunches of seedlings were planted per line (i.e., 5 seedlings m^{-2} line^{-1}). The mean weight of each seedling bunch planted was 25 g. Only those seedlings with no apparent signs of infection/infestation from disease or pests were used (i.e., healthy with smooth thalli). All the materials (i.e., polyethylene rope and soft plastic tie-tie) used in the experiment were newly purchased, except during the subsequent expansion (i.e., the addition of cultivation lines to increase the area), when the old planting materials were also used but were thoroughly washed in fresh water and dried completely in the sun for 3–4 days before use.

The seaweeds were cut or pruned following a lunar cycle (i.e., an interval of 30 days) by cutting the younger branches and leaving behind the older thallus tied on the culture line. The younger pruned branches (seedlings) were planted on new culture lines and the pruning process was repeated 3−4 times (~4 months) until the total area of 500 m^2 of the farm was fully occupied (i.e., 100 lines). Once the area was fully planted, the earliest planted seaweeds were partially harvested, followed by the second earliest seaweed planted until all lines were harvested regularly at an interval of 45 days. No external intervention (i.e., biosecurity protocol) was implemented during the study except for the regular manual cleaning of the seaweed lines (e.g., shaking of cultivation lines to remove attached debris and sediments), which is a common farming practice on farms.

Assessment of seaweed health status

Sampling activities were conducted twice a month (approximately every 15 calendar days) to assess the health status of the farmed *K. striatus*. A total of 14 seaweed plants were randomly collected monthly (seven per sampling activity) until the termination of the study. Visual assessments of seaweed health problems, including IID, EFA, the presence of entangled macroepiphytes, and grazing were conducted for each collected seaweed plant. For IID and EFA, seaweeds were assessed as "no abnormalities detected" − no observed signs of disease or pests, and "visually diseased or EFA-infested." The incidence of seaweed health problems was calculated using a modified formula (Faisan et al. 2021):

$$\text{Incidence}(\%) = \frac{\text{number of affected seaweeds}}{\text{total number of seaweeds assessed}} \times 100$$

The incidence levels of EFA and IID were then differentiated into low (≤25%), moderate (26–50%), high (51–75%), and very high (76–100%) (Faisan et al. 2021). The observations of individual seaweed plants (the apical tissue, secondary branch, and primary branch) were classified according to severity cover (%) using a semiquantitative scale of 1–5 (1=1–10%, 2=11–25%, 3=26–50%, 4=51–75%, and 5=76–100%, respectively) (Borlongan et al. 2011). To obtain a per-plant severity score, the total score per region of tissue was divided by the number of seaweeds observed, and the severity cover was classified as low (≤25%), moderate (26–50%), high (51–75%), or very high (76–100%) (modified from Ateweberhan et al. 2015).

Monitoring of environmental parameters

In situ physico-chemical parameters, including salinity (psu) (digital refractometer MA886 sodium chloride refractometer, Milwaukee Instruments, Inc., USA), sea surface temperature (SST, °C) (hand-held thermometer), pH (pH meter PH-200 HM Digital, USA), and water current speed (m s^{-1}) (modified apparatus using a plastic floater and 5 m length polyethylene line), were measured thrice weekly (i.e., Monday, Wednesday and Friday). The water parameters were monitored once during high tide in the daytime (i.e., 6 AM−4 PM). Additionally, environmental data from the nearest synoptic station (Roxas City, Capiz; 11.600265° N, 122.749621° E; elevation: 2.495 m) of the Philippine

Atmospheric, Geophysical and Astronomical Services Administration (PAGASA), including the mean near-surface air temperature ($T_{air,}$ °C) and wind speed (m s^{-1}), were collected daily. The information for collecting the environmental data from the synoptic station was described by Villafuerte et al. (2021). The area in northern Panay Island, which covers the farm site and the nearest synoptic station locations, belongs to the same climate type, the Type III climate, wherein there is no very pronounced maximum rain period, with short dry months for two to three months (e.g., from December to February or from March to May) (http://bagong.pagasa.dost.gov.ph/information/climate-philippines). Furthermore, daily irradiance (μmol photons m^{-2} s^{-1}), precipitation (mm), and storm surface run-off (kg $m^{-2}s^{-1}$) data were taken from the online source Giovanni (https://giovanni.gsfc.nasa.gov/giovanni/), which covers the area of the farm in San Dionisio, Iloilo, Philippines (123.5°E, 11.5°N, 123.5°E, 11.5°N) (Table 1).

Inorganic nutrient determination

Inorganic nutrients (nitrite, nitrate, ammonia, and phosphate; ppm) were monitored twice a month (LaMotte test kits, USA). Triplicate seawater samples were randomly collected within the farm using 200 mL sterile polyethylene plastic bottles, and immediately stored in a cold container under dark conditions (i.e., with an ice pack) and processed immediately upon return to the Algal Production Laboratory, SEAFDEC/AQD or stored directly in a freezer upon arrival and completely thawed before analysis.

Duration and limitations of the study

The *K. striatus* farm was monitored for one year (June 2019 to May 2020), encompassing the rainy (June−November) and dry (December−May) seasons in the Philippines (PAGASA, https://www.pagasa.dost.gov.ph/information/climate-philippines). However, seaweed assessment on farm was not performed, as the farm is mostly underwater or, if exposed during spring tides, occurred only in a limited time or during the night or early morning. In addition, due to COVID-19 travel restrictions, bi-monthly farm visits and the collection of seaweed samples were not conducted in March and April 2020. Instead, visual observations by the farmer/owner were considered (i.e., disease and pest observations).

Table 1 Summary of meteorological and nutrient data taken from *Kappaphycus striatus* farm in San Dionisio, Iloilo, Western Visayas, Philippines

Variable		Data description	Source
Irradiance	*Irra*	10−13-day area-average of daily solar irradiance at 380 nm (mW m^{-2} converted to μmol photons m^{-2} s^{-1})	OMUVBd (Giovanni)
Precipitation	*Prec*	15-day area-average of daily accumulated precipitation (mm)	GPM_31MERDE (Giovanni)
Storm surface run-off	*Rnoff*	15-day area-average of daily storm surface run-off (kg m^{-2} s^{-1})	GLDAS (Giovanni)
Salinity	*Sal*	6-day average of thrice weekly sampling for water salinity taken during high tide (psu)	This study
Sea surface temperature (SST)	*Temp*	6-day average of thrice weekly sampling for water temperature taken during high tide (˚C)	This study
pH	*pH*	6-day average of thrice weekly sampling for water pH taken during high tide	This study
Water current speed	*Vel*	6-day average of thrice weekly sampling for water current speed (m s^{-1}) taken during high tide	This study
Inorganic phosphate	*Phos*	Twice monthly sampling taken during high tide, phosphate (ppm)	This study
Inorganic nitrite	*Nrite*	Twice monthly sampling taken during high tide, nitrite (ppm)	This study
Inorganic nitrate	*Nrate*	Twice monthly sampling taken during high tide, nitrate (ppm)	This study
Inorganic ammonia	*NH3*	Twice monthly sampling taken during high tide, ammonia (ppm)	This study
Wind speed	*Wind*	15-day area-average of daily mean wind speed (m s^{-1})	Nearest synoptic station (PAGASA)
Near-surface air temperature (T_{air})	*SurfT*	15-day area-average of daily mean near-surface air temperature (˚C)	Nearest synoptic station (PAGASA)
“Ice-ice” disease	*IID*	Twice monthly observation of “ice-ice” disease- infected seaweed (incidence)	This study
Epiphytic filamentous algae	*EFA*	Twice monthly sampling of epiphytic filamentous algae-infested seaweed (incidence)	This study

Statistical analysis

Mean values with standard error (mean±SE) were calculated for the seaweed health status (incidence and severity per individual) and the environmental parameters were computed as twice monthly data points (i.e., approximately every 15 days) for 12 months. The data were tested for normality and homogeneity using the Shapiro−Wilk test. Bi-monthly data were first log-transformed and normalized using PRIMER7 to determine the relationship between the incidence of "ice-ice" disease (IID) and epiphytic filamentous algae (EFA) and the environmental parameters collected. Relationships between the 24 data sets generated using Euclidian distances were analyzed through constrained ordination by canonical analysis of principal coordinates (CAP) (Anderson and Robinson 2003). Additionally, a non-parametric Mann−Whitney U test was used to determine the relationship between environmental parameters in relation to IID and EFA incidence after the results showed non-normal and non-homogeneous data. Moreover, a contingency correlation coefficient analysis was conducted to determine the associations between the test variables. A correlation closer to +1 or -1 denotes a strong association. A significance level of $p \leq 0.05$ was used as the threshold for significant differences. All the statistical tests were performed using SPSS ver. 23 (SPSS Inc., USA).

Results

Seaweed health problem observations

"Ice-ice" disease (IID)

Healthy seaweed plants were defined as those with no abnormalities detected and with a smooth and even surface on all thallus regions (Fig. 2a). IID-infected seaweeds exhibited bleaching and softening of the affected thallus regions and, in most cases, necrotic tissues (Fig. 2b). IID was first observed in February 2020 in this study, with a

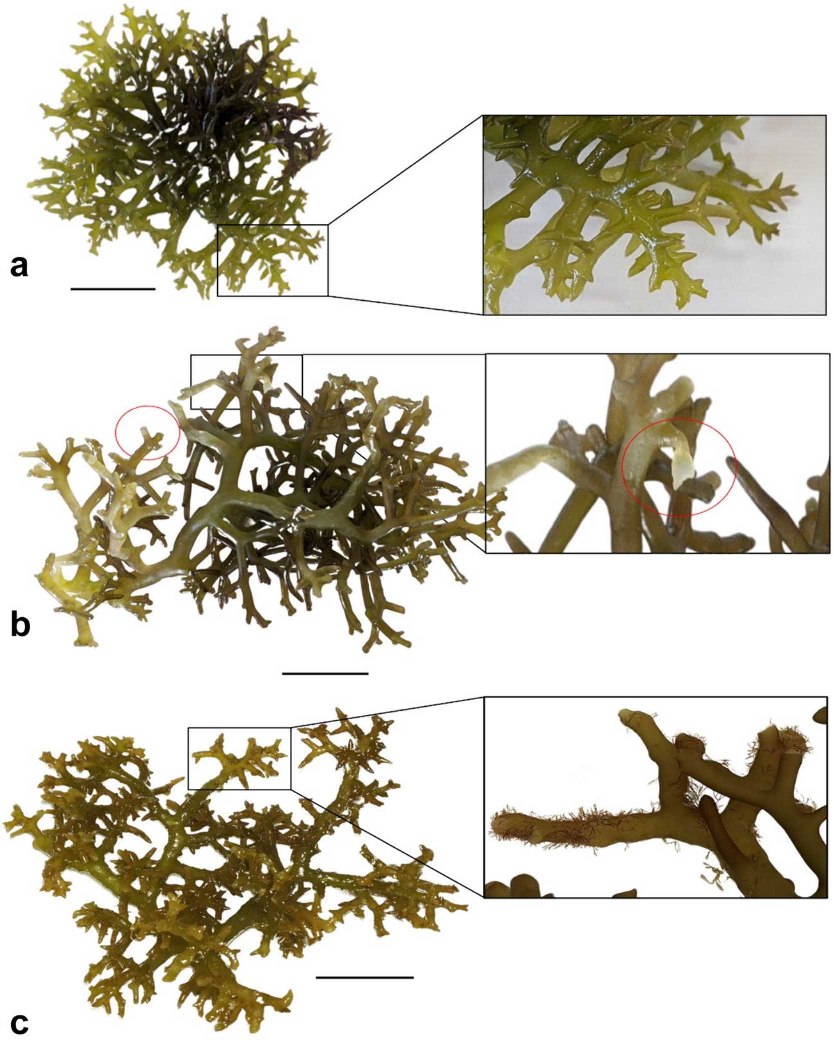

Fig. 2 Farmed *Kappaphycus striatus* var. *sacol* with **(a)** apparently healthy, **(b)** "ice-ice" diseased (IID) (circle), and **(c)** epiphytic filamentous algae (EFA)-infested thalli. Scale bar = 3 cm. Photos: JP Faisan, Jr

low incidence (21.4±1.4%) (Table 2). The seaweed thalli, including the apex (16.7±8.3%), secondary (16.7±8.3%), and primary (8.0±8.3%) branches, were affected by IID but with low severity (≤25%) (Fig. 3). IID was also observed in March and April 2020; however, no seaweed assessment was conducted due to COVID-19 travel restrictions (R. Arbigoso, pers. comm.)

Epiphytic filamentous algae (EFA)

EFA-infested seaweeds were observed to have a distorted thallus surface, making them uneven and bumpy in appearance and rough upon contact or touch (Fig. 2c). EFA were firmly attached to the host seaweed and emerged on the thallus surface with bumpy mound-like or "goosebump" structures. The EFA incidence varied from low (≤25%) to very high (75−100%) and was observed during the wet months, including September (0% and 42.9±20.2%), October (0% and 28.6±18.4%), November (100±0% and 100±0%), and December 2019 (100±0.0% and 42.9±20.2%) (Table 2). The severity of the EFA cover mainly increased between September and December (Fig. 3). EFA severity in the apical region (A) increased from 15.0±5.0% in September to 32.0±8.3% in December. While the secondary branch (SB) ranged from 3.3±3.3% in September to 19.0±9.4% in December. On the other hand, the severity in the primary branch (PB) increased from 0% in September to 15.7±4.8% in November but declined in December to 8.0±3.2%. Overall, the EFA severity was low (≤25%) in all regions of the thalli except for the apical area, with moderate severity (26–50%) observed in December 2019.

Macroepiphytes and grazing

Macroepiphytes, including *Gracilaria* sp. and *Sargassum* sp., were not present or found entangled on the farmed *K. striatus* during the sampling activities. However, these seaweeds were observed at the periphery of the farm site during the wet months (June to December 2019). Mechanical damage to the thallus due to grazing by herbivorous fishes was also not observed (Table 2).

Results of monitoring of environmental parameters

Seaweed health observations in relation to temporal environmental parameters

Two independent analyses (canonical coordinate analysis, CCA, and the Mann-Whitney U test) were performed to determine the relationship or variability between the incidence of seaweed health problems (i.e., IID and EFA) and environmental factors. IID was observed during the dry months between February and April 2020, and the variability

Table 2 Twice monthly observation of seaweed health problems incidence observed in a fixed off-bottom *Kappaphycus striatus* farm from June 2019 to May 2020 (n=7). Means are expressed as ±SE. †= with observed IID; no data collected, ⁑= no health problems observed; no data collected

		Month																							
		Jun		Jul		Aug		Sep		Oct		Nov		Dec		Jan		Feb		Mar		Apr		May	
		1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2
Incidence (%)	IID	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21.4±1.4	†	†	†	†	0	0
	EFA	0	0	0	0	0	0	0	42.9±20.2	0	28.6±18.4	100±0	100±0	100±0	42.9±20.2	0	0	0	0	⁑	⁑	⁑	⁑	0	0
	Macroepiphytes	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	⁑	⁑	⁑	⁑	0	0
	Grazing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	⁑	⁑	⁑	⁑	0	0

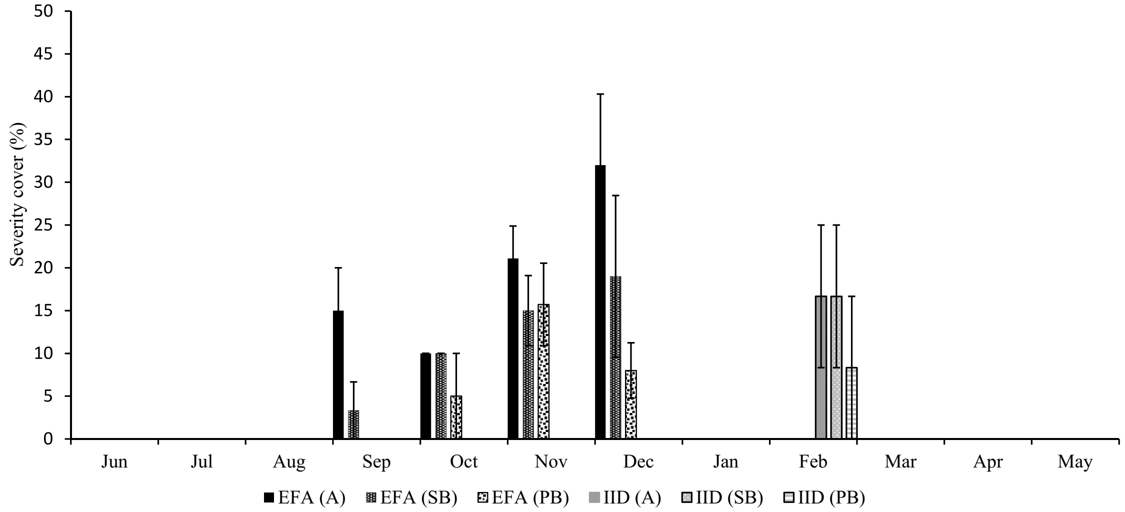

Fig. 3 Monthly severity cover (%) of "ice-ice" disease (IID) and epiphytic filamentous algae (EFA) observed in a fixed off-bottom *Kappaphycus striatus* farm from June 2019 to May 2020 affecting the apical (A), secondary branch (SB), and primary branch (PB) of the seaweed thalli (n=2−14). Error bars signify ±SEM. (No seaweed collection was conducted in March and April 2020)

was positively affected by wind speed (75%), pH (61%), and inorganic phosphate (48%), ammonia (41%), and nitrite (36%). However, the variability was negatively affected by T_{air} (-82%), irradiance (-55%), and inorganic nitrate (-55%) (CAP 1, 98.7%) (Fig. 4; Table 3). Further analysis revealed that an elevated irradiance level was found to significantly influence the incidence of IID on seaweeds (3.6±0.1 μmol photons m^{-2} s^{-1}) compared with no IID observance (3.2±0.1 μmol photons m^{-2} s^{-1}) (U=82.0, p=0.012). Also, an increase in salinity was observed in months with IID (36.9±0.4 psu) compared with months without IID (34.0±0.9 psu) (U=77.5, p=0.030). In addition, a higher wind speed significantly influenced the incidence of IID (3.9±0.1 m s^{-1}) compared with no recorded IID (3.3±0.1 m s^{-1}) (U=80.5, p=0.015). Moreover, an elevated SST (30.0±0.3 °C) was observed in months with an increased incidence of IID compared with no observed IID (28.8±0.2 °C) (U=86.0, p=0.004). Decreases in precipitation, storm surface run-off, water current speed, and inorganic nutrients, including nitrite and ammonia, significantly influenced the incidence of IID (p=0.002–0.019) (Table 4).

In contrast to IID, EFA was observed during the wet months, i.e., the northeast (NE) monsoon, which occurred between September and December 2019. EFA incidence variability was positively affected by precipitation (78%), storm surface run-off (73%), inorganic nitrate (50%), pH (31%), and water current speed (31%). However, the contribution to variability was negatively affected by irradiance (-55%) (CAP2, 93.6%) (Fig. 4; Table 3). A high storm surface run-off level was found to significantly influence the EFA incidence (3.5E-05±1.3E-05 kg $m^{-2}s^{-1}$) compared with no EFA (1.2E-05±3.2E-06 kg

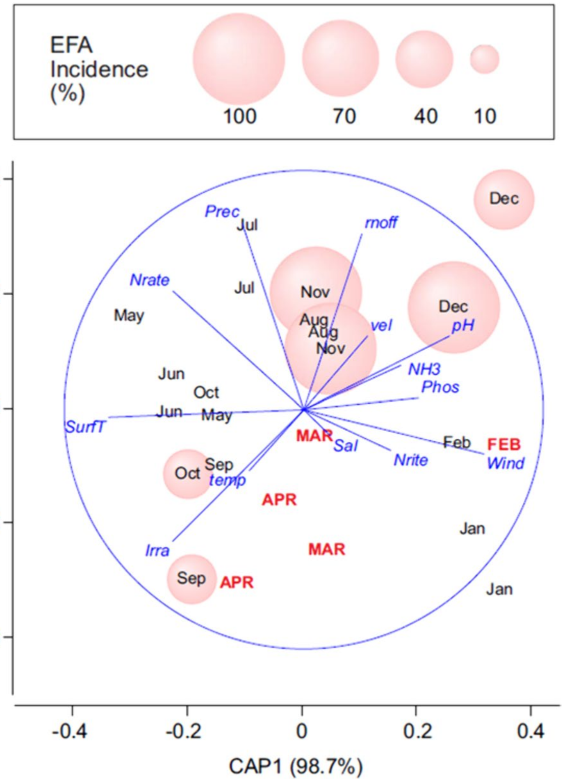

Fig. 4 Canonical analysis of principal coordinates (CAP) based on environmental parameters. Overlay bubbles are EFA incidence (%). Months in red font indicate IID incidence. *Irra*= irradiance; *Prec*= precipitation; *rnoff*= storm surface run-off; *Sal*= salinity; *temp*= sea surface temperature (SST); *pH*= pH; *vel*= water current speed; *Phos*= inorganic phosphate; *Nrite*= inorganic nitrite; *Nrate*= inorganic nitrate; *NH3*= inorganic ammonia; *Wind*= wind speed; *SurfT*= near-surface air temperature (T_{air})

Table 3 Canonical coordinate scores of each parameter vector in relation to "ice-ice" disease (IID) and epiphytic filamentous algae (EFA) incidence

	Irra	*Prec*	*rnoff*	*Sal*	*temp*	*pH*	*Vel*	*Phos*	*Nrite*	*Nrate*	*NH3*	*Wind*	*SurfT*
CAP1	-0.55	-0.22	0.24	0.11	-0.23	0.61	0.27	0.48	0.36	-0.55	0.41	0.75	-0.82
CAP2	-0.55	0.78	0.73	-0.11	-.025	0.31	0.31	0.05	-0.17	0.50	0.19	-0.18	-0.03

Note: *Irra*= solar irradiance; *Prec*= precipitation; *rnoff*= storm surface run-off; *Sal*= salinity; *temp*= sea surface temperature (SST); *pH*= pH; *vel*= water current speed; *Phos*= inorganic phosphate; *Nrite*= inorganic nitrite; *Nrate*= inorganic nitrate; *NH3*= inorganic ammonia; *Wind*= wind speed; *SurfT*= near-surface air surface temperature (T_{air})

Table 4 Relationship between the incidence of "ice-ice" disease (IID) and environmental parameters in a fixed off-bottom *K. striatus* farm (mean ±SE); *-denotes a significant relationship at $p<0.05$

Parameter	IID		Mann-Whitney U	*p*-value
	0 (*n*=19)	1 (*n*=5)		
Irradiance (μmol photons m^{-2} s^{-1})	3.2±0.1	3.6±0.1	82.0	0.012*
Precipitation (mm)	5.6±0.9	0.5±0.3	7.0	0.002*
Storm surface run-off (kg $m^{-2}s^{-1}$)	2.2E-5±5.1E-6	3.2E-6±1.9E-6	9.0	0.004*
Salinity (psu)	34.0±0.9	36.9±0.4	77.5	0.030*
SST (°C)	28.8±0.2	30.0±0.3	86.0	0.004*
pH	8.0±0.1	8.1±0.2	56.0	0.581
Water current speed (m s^{-1})	0.12±0.0	0.10±0.0	10.0	0.005*
Phosphate (mg L^{-1})	0.06±0.01	0.08±0.01	61.5	0.331
Nitrite (mg L^{-1})	0.11±0.01	0.05±0.01	12.0	0.009*
Nitrate (mg L^{-1})	0.27±0.03	0.28±0.03	39.5	0.581
Ammonia (mg L^{-1})	0.03±0.01	0.00±0.0	15.0	0.019*
Wind speed (m s^{-1})	3.3±0.1	3.9±0.1	80.5	0.015*
T_{air} (°C)	28.7±0.2	28.9±0.5	53.0	0.731

Note: sea surface temperature (SST); near-surface air temperature (T_{air})

$m^{-2}s^{-1}$), U=85.0, p=0.040. Also, elevated inorganic nutrients, including nitrate and ammonia, were recorded in wet months with EFA incidence (Supplementary Fig. 1). Inorganic nitrate was greater in the EFA−recorded months (0.36±0.02 mg L^{-1}) than in those without EFA (0.25±0.03 mg L^{-1}), U=92.5, p=0.007. Inorganic ammonia was more elevated during EFA (0.10±0.02 mg L^{-1}) than without EFA (0.03±0.01 mg L^{-1}), U=94.0, p=0.006. On the other hand, a decrease in salinity level significantly influenced the occurrence of EFA (31.5±2.0 psu) compared with no EFA observation (35.6±0.6 psu), U=18.0, p=0.015 (Table 5).

Further analysis using the contingency correlation coefficient revealed a positive association between IID and salinity, SST, and wind speed (p= 0.012−0.034). However, IID was negatively associated with precipitation, storm surface run-off, and inorganic ammonia (p=0.012−0.027) (Table 6 and 7). Moreover, the season (dry) correlated with the occurrence of IID (p=0.012). On the other hand, EFA was positively associated with inorganic nutrients, particularly nitrite and ammonia (p=0.002−0.046) (Table 8 and 9).

Extreme weather disturbance observation

In late December 2019, an intense tropical cyclone (Typhoon Phanfone) hit the vicinity of the farming area (PAGASA 2021), bringing torrential rainfall and freshwater flooding to the cultivation site from surface run-off (Supplementary Fig. 2). Also, strong winds and decreased salinity were observed (Supplementary Fig. 3) resulting in partial seaweed die-offs.

Discussion

Health and disease issues are key barriers to the sustainability of aquaculture commodities, including seaweeds. These problems could be further exacerbated by changing climatic conditions. Among the major farmed red eucheumatoid carrageenophytes, *K. striatus* is the preferred seaweed species for cultivation in near-shore areas because of its wide tolerance to changes in environmental conditions (Pang et al. 2015). Additionally, the farming of *K. striatus* in intertidal areas is preferred because of its reported resistance to

Table 5 Relationship between the incidence of epiphytic filamentous algae (EFA) and environmental parameters in a fixed off-bottom *Kappaphycus striatus* farm (mean ±SE); *-denotes a significant relationship at $p<0.05$

Parameter	EFA		Mann-Whitney U	*p*-value
	0 (*n*=18)	1 (*n*=6)		
Irradiance (µmol photons m^{-2} s^{-1})	3.3±0.1	3.1±0.1	38.0	0.310
Precipitation (mm)	4.0±0.9	6.1±1.8	73.0	0.224
Storm surface run-off (kg $m^{-2}s^{-1}$)	1.2E-05±3.2E-06	3.5E-05±1.3E-05	85.0	0.040*
Salinity (psu)	35.6±0.6	31.5±2.0	18.0	0.015*
SST (˚C)	29.2±0.2	28.6±0.2	32.0	0.156
pH	8.1±0.1	7.9±0.3	48.0	0.721
Water current speed (m s^{-1})	0.11±0.0	0.12±0.0	74.0	0.199
Phosphate (mg L^{-1})	0.06±0.01	0.07±0.02	64.5	0.494
Nitrite (mg L^{-1})	0.09±0.02	0.11±0.01	81.0	0.077
Nitrate (mg L^{-1})	0.25±0.03	0.36±0.02	92.5	0.007*
Ammonia (mg L^{-1})	0.03±0.01	0.10±0.02	94.0	0.006*
Wind speed (m s^{-1})	3.4±0.1	3.6±0.2	69.0	0.343
T_{air} (˚C)	28.8±0.2	28.6±0.2	45.0	0.581

Note: sea surface temperature (SST); near-surface air temperature (T_{air})

Table 6 Correlation of "ice-ice" disease (IID) with selected environmental factors in a fixed off-bottom *Kappaphycus striatus* farm. *-denotes a significant relationship at $p<0.05$

Factor	Contingency correlation coefficient	*p*-value
Irradiance (µmol photons m^{-2} s^{-1})	0.29	0.132
Precipitation (mm)	0.46	0.012*
Storm surface run-off (kg $m^{-2}s^{-1}$)	0.46	0.012*
Salinity (psu)	0.46	0.012*
SST (˚C)	0.49	0.012*
pH	0.29	0.132
Water current speed (m s^{-1})	0.37	0.051
Phosphate (mg L^{-1})	0.33	0.085
Nitrite (mg L^{-1})	0.37	0.052
Nitrate (mg L^{-1})	0.02	0.932
Ammonia (mg L^{-1})	0.43	0.027*
Wind speed (m s^{-1})	0.40	0.034*
T_{air} (˚C)	0.06	0.769
Season	0.46	0.012*

Note: sea surface temperature (SST); near-surface air temperature (T_{air})

Table 7 Incidence of IID (in percent) between low and high values of environmental factors

Factor	Low	High
Precipitation (mm)	41.7	0.0
Storm surface run-off (kg $m^{-2}s^{-1}$)	41.7	0.0
Salinity (psu)	0.0	41.7
SST (˚C)	0.0	45.5
Ammonia (mg L^{-1})	38.5	0.0
Wind speed (m s^{-1})	0.0	35.7
	Dry	**Wet**
Season	41.7	0.0

Notes: 1. sea surface temperature (SST); near-surface air temperature (T_{air})

2. The cut value for the 2 groups is the median value of a particular environmental factor

epiphytic pests (Pang et al. 2015; Ali et al. 2020). However, the results of the present study revealed that fluctuations in key environmental parameters could be a predisposing factor for the occurrence of seaweed disease and pests, particularly "ice-ice" disease (IID) and epiphytic filamentous algae (EFA). Also, any extreme changes in environmental parameters outside the optimal culture conditions caused by severe weather events (i.e., typhoons) have detrimental consequences on seaweed crops.

IID was first observed at the study site in February 2020 in a dry month, affecting all the thallus regions of the seaweed plant, albeit at a low severity (i.e., ≤ 25%), which may suggest that any part of the seaweed thallus could be susceptible to IID infection, and not limited to a particular thallus area. The IID observed in this study coincided with increasing salinity levels. The optimal salinity for eucheumatoid seaweeds ranges between 30 and 35 psu (Largo et al. 1995), while in this study, the salinity during IID reached 37 psu. A high salinity level could be attributed to a higher temperature during dry months, exacerbated by high evaporation rates in shallow water areas. At the same time, the low precipitation levels observed during dry months (i.e., February and March 2020) might have contributed to the high salinity levels observed on the farm. Also, increased irradiance or solar radiation during the dry season may affect the salinity level in shallow water farms by increasing evaporation rates and exposing seaweeds to high air and water temperatures

Table 8 Correlation of epiphytic filamentous algae (EFA)with selected environmental factors in a fixed off-bottom *Kappaphycus striatus* farm. *-denotes a significant relationship at $p<0.05$

Factor	Contingency correlation coefficient	*p*-value
Irradiance (μmol photons m^{-2} s^{-1})	0.19	0.346
Precipitation (mm)	0.19	0.346
Storm surface run-off (kg $m^{-2}s^{-1}$)	0.36	0.059
Salinity (psu)	0.36	0.059
SST (°C)	0.32	0.098
pH	0.00	1.00
Water current speed (m s^{-1})	0.28	0.151
Phosphate (mg L^{-1})	0.05	0.813
Nitrite (mg L^{-1})	0.38	0.046*
Nitrate (mg L^{-1})	0.28	0.151
Ammonia (mg L^{-1})	0.53	0.002*
Wind speed (m s^{-1})	0.28	0.151
T_{air} (°C)	0.05	0.813
Season	0.19	0.346

Note: sea surface temperature (SST); near-surface air temperature (T_{air})

Table 9 Incidence of IID (in percent) between low and high values of environmental factors

Factor	Low	High
Nitrite (mg L^{-1})	12.5	50.0
Ammonia (mg L^{-1})	0.0	54.5

Note: The cut value for the 2 groups is the median value of a particular environmental factor

during low tide, leading to crop desiccation. Red seaweeds in near-shore areas are periodically exposed to a wide variety of stressful environmental conditions (Collén and Davidson 1999). However, extreme fluctuations in abiotic factors may disrupt the normal physiological mechanisms of seaweed resulting in health problems. High salinity, water temperature, and pH have been previously linked to the high prevalence of IID (Msuya and Porter 2014; Arasamuthu and Edward 2018; Alibon et al. 2019; Kumar et al. 2020).

Previous studies have suggested that IID is associated with different microbes, either singly or in complex, including bacteria (*Vibrio* sp., *Cytophaga-Flavobacterium* complex, *Alteromonas, Pseudoalteromonas,* and *Aurantomonas*) and fungi (*Aspergillus ochraceus, A. terreus,* and *Phoma* sp.) (Largo et al. 1995; Solis et al. 2010; Syafitri et al. 2017), although few studies have investigated the association of these taxa (or any other) with healthy eucheumatoid tissue, resulting in a lack of baseline data (Ward et al. 2022). There is also a lack of studies related to other microbial taxa, including prokaryotes, protists, and viruses, and thus, the role of the seaweed holobiont in the development of IID disease signs has yet to be fully explored, with the possibility remaining that other microorganisms or combinations thereof could contribute to the incidence of IID.

Although it is not fully understood how microbial complexes cause IID, it is possible that consortia of microorganisms, particularly gram-negative bacteria (as mentioned above), have the ability to infect seaweed. Seaweeds have a natural defense mechanism against stressful conditions, which involves the release of volatile halogenated compounds (VHCs). These VHCs help prevent infections from harmful organisms, as observed in *Eucheuma denticulatum* (Mtolera et al. 1996). However, gram-negative bacteria have a distinctive component in their cell walls, known as lipopolysaccharide (LPS) (Anwar and Choi 2014). This component may aid in protecting the bacterial cell membrane from being disrupted when exposed to VHCs. As a result, complexes of opportunistic gram-negative bacteria can infiltrate the protective barrier of seaweed, resulting in infections.

Outbreaks of epiphytism in farmed seaweeds have resulted in decreased biomass yields and stoppage in production (Hurtado and Critchley 2006; Hurtado et al. 2006). In this study, EFA incidence was observed between September and December 2019, and EFA severity was highest in the apical thallus region and seemed to spread to different thallus regions as cultivation progressed. The toughness or maturity of the seaweed thallus may play a crucial role in the degree of EFA severity in farmed *K. striatus.* Compared to other thallus regions of the seaweed plant, the apical thallus region has softer tissues, possibly allowing the EFA spores to attach more easily and penetrate the epidermal layer. This observation parallels the study of Yamamoto et al. (2012) in *Sargassum patens*, which showed that the soft tissues of the apical thallus region are more susceptible to epiphyte colonization, further suggesting that the young thallus is the initial site of epiphyte infestation. As the seaweed plant grows, the attached EFA matures and releases more spores, possibly infecting the other thallus regions and contributing to the increasing severity in the primary and secondary branches. In the absence of biosecurity measures carried out on farms (i.e., collection, removal, and destruction of diseased plants), EFA-infested seaweed plants may accidentally be used as a source for new seedlings, thus inadvertently spreading the incidence of EFA on farms. Vegetative propagation for successive farm expansion may also indirectly contribute to the increased EFA observed on farmed seaweed. As the host seaweed grows, as does EFA, the infected apical thallus becomes mature and is used in farm expansion, contributing to the increasing severity of the other thallus regions. However, the detection of very early-stage infestations (i.e., before goosebumps are visible) and the transplantation of seemingly uninfected material into farms remain a major biosecurity challenge that need consideration.

EFA penetrates the cortical and medullary layers as they grow (Ask 1999; Leonardi et al. 2006; Vairappan 2006; Arasamuthu and Edward 2018; Pang et al. 2011; Tsiresy et al. 2016). Following maturation and death, the EFA leaves an opening, exposing the internal tissues of the host seaweed to the outside environment and increasing the susceptibility of the host to opportunistic microbial infection. The identification and succession of EFA species, specifically those affecting farmed *K. striatus,* has been lacking and warrants further investigation. This study did not aim to establish the onset of EFA spore infestation on farmed seaweed. EFA was first observed in September; however, the EFA spores might already be embedded in the seaweed epidermis seedlings used in the initial planting but not observed visually and might proliferate only once prevailing factors are conducive to growth. The integration of molecular tools into protocols for screening crop plants for the presence of epiphytic pests before outplanting or translocating seaweed seedlings should be considered a priority, as this could be a helpful biosecurity measure for reducing the spread of EFA.

The incidence of other epiphytic pests, such as macroepiphytes (i.e., other larger seaweed species, including *Gracilaria* and *Sargassum*), has not been directly observed to affect farmed *K. striatus*. These macroepiphytes could be easily disentangled or removed from farmed seaweed or from cultivation lines during constant tidal fluctuations in the near-shore areas. Nevertheless, these seaweeds were abundant near the study farm site during the wet months. The high incidence of EFA coincided with the seasonal vegetative growth peaks of *Sargassum* from October to December (Trono and Largo 2019) and the involvement of other aquatic plants (e.g., seagrasses, wild and other farmed seaweeds) as environmental reservoirs for epiphytic pests cannot be ruled out. Although the monitoring of epiphytic pests in the surrounding *K. striatus* farms was not conducted, it could be that those seaweeds harbor this seaweed health problem and transfer and infect the farmed seaweed aided by water movement. Additionally, grazing activities (i.e., by herbivorous fish and other animals) were not recorded on the farm. The farming site is located within the seaweed farming community, wherein plots of seaweed farms are on the periphery and along the coastal area; hence, the presence of grazers was not captured.

The first EFA in the present study was recorded in September 2019, coinciding with a decrease in pH (i.e., pH 6.0). *Kappaphycus alvarezii* exposed to a lower pH at pH 6.0 exhibited a reduced daily growth rate (Tee et al. 2015), suggesting that a decrease in pH may have negative consequences on the overall physiological fitness of the seaweed plant, affecting its growth. Therefore, short- or long-term pH fluctuations may have a negative effect on seaweed health, suggesting increased susceptibility to epiphytic pest problems. No freshwater source (i.e., rivers) was found near the farming site that could affect the salinity and nutrient levels brought to the farm. However, lower salinity and an increase in inorganic nutrients were observed during the rainy months, suggesting that heavy rain could affect the salinity level and bring in excess nutrients from inland areas (i.e., fertilizers from crops). EFA incidence was significantly influenced by the increase in inorganic ammonia, further suggesting that inorganic nutrients provide nourishment for growth not only for farmed seaweed but also for other algal epiphytic pests such as EFA. The EFA incidence observed on the farm is in concordance with previous studies reported by Vairappan (2006) and Borlongan et al. (2011), where high epiphyte infestation emerges during rainy months.

The wet season in the Philippines typically experiences an increase in precipitation, coupled with the regular occurrence of tropical cyclones. Annually, an average of 20 tropical cyclones (typhoons) enter the Philippine area of responsibility (PAR), and approximately eight to nine typhoons cross the Philippines (Cinco et al. 2016). In late December 2019, a typhoon struck the farming area, bringing torrential rain and flooding. A typhoon (with a maximum wind speed of 118 to 220 km h^{-1}) can generate an excessively high amount of rainfall (i.e., 199.6 mm), strong winds (i.e., 8.0 m s^{-1}), and storm surges and reduced salinity (i.e., 11 psu) (PAGASA, https://www.pagasa.dost.gov.ph/climate/tropical-cyclone-information). No significant physical damage was observed on the experimental farm itself. However, the exceptionally high rainfall in the locality resulted in heavy surface run-off from the inland area, inundating the coastal site where the farm is located and diluting seawater to a very low salinity level. Also, the physical impact of storm surges in shallow water areas where the farms are situated further contributes to physiological stress, a factor that compromises the overall health status of seaweeds. In addition, high organic nutrient loads from upland areas were transported to the farm site, making the seawater in the intertidal area turbid. Moreover, silts and dirt may cover farmed crops, preventing the optimal photosynthetic activity needed by seaweed for growth. The combination of extreme environmental events (including the influence of multiple abiotic stressors) that bombarded the farmed *K. striatus* seaweeds resulted in partial die-offs a few days later. An emergency harvest was then conducted immediately to salvage the remaining seaweed (Supplementary Fig. 4). Seaweed die-offs on farms have reportedly affected production and livelihoods due to stoppage in cultivation (Msuya and Porter 2014).

Extreme weather events could be attributed to changing climate patterns. The strong tropical cyclone that affected the farming area in December 2019 was outside of the pronounced two seasons observed in the Philippines, where the rainy season occurred from June to November and the dry season from December to May. Additionally, the occurrence of strong tropical cyclone was outside of the peak of the typhoon season (July–October), when nearly 70% of all typhoons develop (PAGASA, https://www.pagasa.dost.gov.ph/information/climate-philippines). A shift in weather conditions may negatively impact farming activities in the country. The changes in extreme rainfall in the Philippines are linked to the global mean temperature and the El Niño Southern Oscillation (ENSO), and it is predicted that extreme rainfall will increase in the future, with increasing global temperature (Villafuerte et al. 2015). In China, IID and EFA outbreaks on eucheumatoid farms are directly related to El Niño and La Niña environmental anomalies, together with ENSO data (Pang and Liu 2019). In Tanzania, the recorded extreme increase in sea surface temperature is correlated with a high incidence of IID and EFA, leading to seaweed die-offs, which are mainly located on shallow water farms (Msuya and Porter 2014; Largo et al. 2020). Disease and pest outbreaks remain a significant limiting factor in increasing seaweed production and expanding farming areas if there are no definite preventive or mitigation strategies to address the problem of changing environmental conditions.

The impacts of global warming on seaweed aquaculture in the tropics have yet to be fully assessed. However, the increasing frequency and strength of weather anomalies have become more apparent in recent years, increasing the vulnerability of farmed seaweeds to reduced health status (Largo et al. 2017). The direct and indirect impacts of global climate change result not only in physical damage to farm crops but also in the overall physiological fitness of seaweed. According to Garcia-Sotto et al. (2021), the rate of ocean surface warming in the last decade (2010−2019) has accelerated to 4.5 times greater than the long-term mean. High ocean warming was recorded in 2020 (Cheng et al. 2021). At the same time, climate change is limited not only to increasing mean SSTs but also to variability and extremes (Alexander et al. 2018). An increase in sea surface temperature could be detrimental to many seaweed species, even in sub-tropical regions (Takao et al. 2015). *K. striatus* is predicted to lose habitat under increasing sea surface temperatures (Du et al. 2023).

In the Philippines alone, more than 200,000 families are engaged in seaweed farming, and most of the farms are small-scale and family-owned, providing an alternative source of income to fishing to many rural coastal communities (Hurtado 2013; Pedrosa 2017). However, seaweed health problems, including outbreaks of disease and pests and poor weather conditions, have reportedly forced farmers in some areas to reduce cropping cycles (i.e., from six to four rounds) to avoid experiencing large-scale losses (Suyo et al. 2021). It was reported that the losses caused by these outbreaks reached $100 million a year in the Philippines (Cottier-Cook et al. 2016).

The use of seaweed-derived biostimulants (e.g., AMPEP) was found to promote growth and lessen the incidence of IID and epiphytic pests (e.g., macroalgae and EFA) in farmed seaweeds (Borlongan et al. 2011; Ali et al. 2020; Capacio et al. 2023). The lower incidence of these seaweed health problems could be attributed to the increased phenolic content, free-radical scavenging ability, and transition metal chelating ability of the seaweeds treated with this biostimulant (Hurtado et al. 2012). Treating farmed *K. striatus* during the period when fluctuations in environmental parameters occur (i.e., the rainy season) and during known months where the incidence of IID and epiphytic pests are high could help mitigate these problems and prevent potential outbreaks from occurring.

As with other aquaculture commodities (e.g., fish, mollusks, and crustaceans), farmed seaweeds are affected by health and disease issues, and a holistic approach should be considered to mitigate these problems. Stentiford et al. (2020, 2022) proposed adopting the One Health approach to increase the production of aquaculture species with efficient food production and sustainable environmental footprints — while supporting local socio-economic needs. Also, enhancing biosecurity measures could minimize seaweed health problems (Kambey et al. 2021; Ndawala et al. 2022). A recent report by Cottier-Cook et al. (2022) described a novel progressive pathway for improving seaweed biosecurity that will lead to a low incidence of infectious disease and pest outbreaks, thus increasing productivity and seaweed yields. Policies to enhance biosecurity initiatives at the local and international levels should be properly implemented to safeguard the industry from risks related to farming practices and threats from seaweed disease and pest outbreaks (Campbell et al. 2020; Mateo et al. 2020; Hurtado et al. 2021).

On the other hand, seaweed could help mitigate the effects of climate change (Sultana et al. 2022; Troell et al. 2022; UNDP 2023). Ross et al. (2023) presented four pathways: 1) protecting and restoring wild seaweed forests with potential climate change mitigation co-benefits; 2) expanding sustainable near-shore seaweed aquaculture with potential climate change mitigation co-benefits; 3) offsetting industrial CO_2 emissions using seaweed products for emission abatement; and 4) sinking seaweed into the deep sea to sequester CO_2. However, these pathways to mitigate the effects of climate change are yet to be fully realized, and consensus efforts from different stakeholders are needed to implement such huge tasks.

Conclusion and Recommendations

Fluctuations in the environmental parameters of shallow water farms are potential risk factors for the incidence of seaweed health problems affecting the farmed species *Kappaphycus striatus*, particularly “ice-ice” disease (IID) and epiphytic filamentous algae (EFA) (Fig. 5). Additionally,

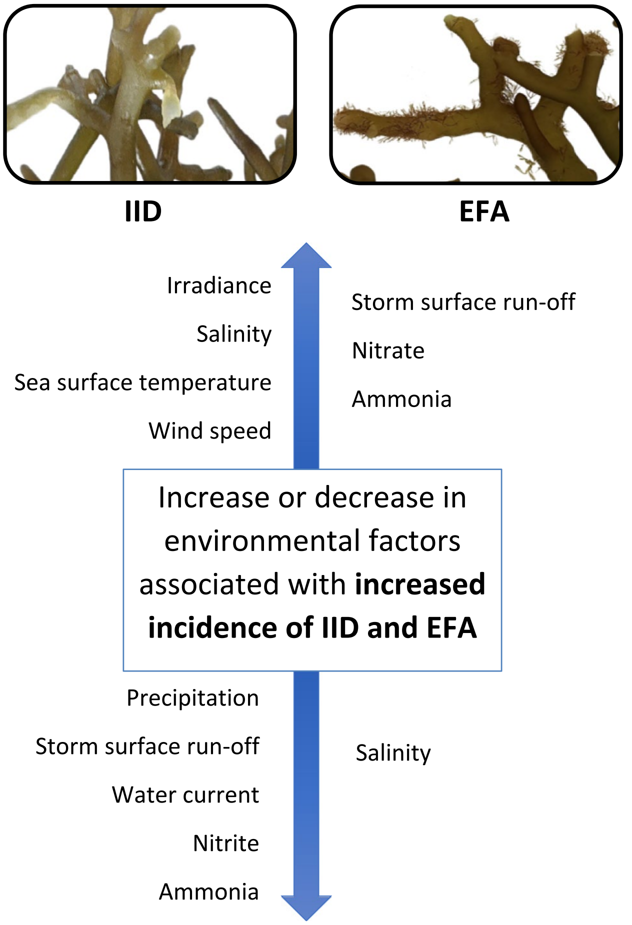

Fig. 5 Schematic summary of relationship between environmental parameters and seaweed health problems affecting farmed *Kappaphycus striatus* in shallow waters. Arrow indicates an increase or decrease in environmental factors associated with increased incidence of "ice-ice" disease (IID) and epiphytic filamentous algae (EFA) (Mann-Whitney U, $p \le 0.05$)

farms in shallow water areas are frequently more exposed to these environmental changes, making cultivated seaweed more prone to physiological stress, thus increasing susceptibility to disease and pest incidence. Extreme weather disturbances (in this case, a tropical cyclone) can lead to catastrophic damage on farms, resulting in massive seaweed die-offs and preventing farmers from earning profits due to the emergency harvesting of stocks with compromised yields and quality. This affects the cultivation for the next cropping season due to the unavailability of seaweed seedlings.

Disease and pest outbreaks are expected to become more pronounced and frequent as the shift in climatic conditions increases in amplitude, as has been the case in recent years. However, implementing changes in farming practices is likely a major challenge, particularly as the associated costs are perceived to be an added financial burden to farmers at a time when biomass yields are uncertain. Therefore, close coordination between farming communities/organizations, local and national government units, and research institutions is critical for improving farming practices. The following are mitigation and prevention strategies to be considered in sustaining the seaweed industry under changing environmental conditions:

- Introduction of new seaweed strains that are resilient to a wide range of environmental fluctuations,
- Strict implementation of biosecurity measures from seedling sourcing to farming (to include procurement of disease-free seedlings from reputable sources, monitoring and surveillance of seaweed health problems, and proper disposal of infected stocks),
- Proactive and timely seasonal weather forecasting, and
- Increased government support to farmers through low-interest loans and crop insurance protection and by providing enhanced technical support during farming up to postharvest and marketing.

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Authors' contributions All authors contributed to the conceptualization of the study; JPF, RCS, JPM, MRJL, VMENF, and AQH implemented the study; JPF, JaB, DB, SR, GDS, JuB, GMW, VTB and AQH analyzed the data, including the preparation of tables and figures; and all authors reviewed the manuscript. AQH is the Philippine project leader and spearheaded all activities undertaken in the country.

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Data Availability The data supporting the study's findings can be accessed from the corresponding author upon reasonable request.

Declarations

Competing interests The authors have no known competing interests, whether financial or personal, that could have appeared to influence the findings reported in this paper.

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