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RESEARCH ARTICLE

Unbaited Light-Emitting Diode Traps Performance for Catching Orange Mud Crabs

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Abstract

Mud crabs (*Scylla* spp.) are a vital fishery resource and targeted for a valuable source of income for coastal communities throughout the Indo-Pacific region. Baited traps are a considerable expense in crustacean fishing. Hence, the present study was performed to investigate the catchability of *Scylla olivacea* in response to light-emitting diodes (LEDs) in captivity and field conditions. We used a new experimental setup in the captivity condition that revealed most *S. olivacea* were attracted to green, blue, and white LED lights and no attractive effect by red LED lights similar to the controls. Field studies have shown that the catch per unit of effort (CPUE) of *S. olivacea* and other organisms, including bycatch species, is significantly higher when conventional mackerel and chicken head baits are used. However, unbaited traps equipped with green LED lights produced low CPUE of *S. olivacea*. Moreover, baited trap with chicken head, mackerel and green LED caught 4.52%, 7.28% and 2.18% more CPUE of *S. olivacea* compare to empty trap, respectively. Besides, both the mackerel and chicken head treatments resulted in the higher average CPUE of *S. olivacea* than did the green LED treatments; 0.66, 0.38 and 0.13 per trap. No significant differences were detected in the average carapace width of *S. olivacea* across all treatments. Our findings demonstrated that mud crabs can be captured using artificial lights, like other aquatic species but further in-depth studies and specific modifications to improve the performance of LED lights are warranted.

Keywords: Light preference, Crab vision, Mangrove, LED light

1. Introduction

Mud crabs (*Scylla* spp.) are some of the most highly valued crustacean species in the commercial fisheries and aquaculture industries in Australia and subtropical and tropical Asia, particularly southeast Asia [1,2]. Mud crabs are euryhaline species, mainly found near intertidal mangrove forests and along river banks [2,3]. High demand and economic value of mud crab is due to its appealing taste and rapid growth [3,4].

Scylla olivacea, commonly known as the orange mud crab (Herbst 1796), is an important commercial species [5] that is distributed throughout the South China Sea, Indian Ocean, and western Pacific Ocean [2]. *S. olivacea*, *Scylla paramamosain*, and *Scylla tranquebarica* are the most common mud-crab species caught in the waters of Malaysian mangrove forests [2]. Small-scale coastal fishing communities throughout the Indo-Pacific region depend on mud crab fishing as a primary source of income [1,2]. Mud crab fishing involves various methods (e.g.,

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hand fishing) and gear [6], including gillnets, trawls, and traps, in shallow waters [7]. However, to our knowledge, fishermen most commonly use traps with fresh bait. Fishermen leave the traps in the water for several hours, overnight, or even for several days or longer (personal observation and communication).

Fresh bait is a considerable expense related to the fishing of crustaceans such as mud crab and can account for up to 50% of total operating costs [8,9]. Most fishermen use high-quality bait—fish of the same quality as those people consume daily [10,11]. To our knowledge, no studies of natural bait preferences for mud crab trap fishing have been conducted. However, several experiments have indicated that using mackerel, *Scomber* spp. enables the catching of more portunids than using other types of bait [10]. Furthermore, research has been conducted on byproducts of various animal industries, such as agricultural waste and the heads, viscera, blood, bones, and skin of fish and livestock, to develop formulated crab bait [10,12]. In Malaysia, crab traps are typically baited with bigeyes (*Priacanthus* spp.) [13], catfish (*Arius* spp.) [14], chicken heads [15], *mackerel* (personal observation and communication), and other bony fish [16].

The high operating costs of using fresh bait are primarily attributable to the fact that it can only be used once. In Malaysia, mackerel is harvested and sold locally for human consumption, it usually costs ~RM10-15 (USD2.40–3.60) per kg (i.e., depending on the season, monsoon seasons higher price). Other poultry by-products such as chicken heads do not have any cost but limited, due to use in agriculture as livestock feed (personal observation and communication). Therefore, more durable and cheaper alternatives, such as the use of light to attract crabs, might be introduced to reduce these costs. The application of light as a method for attracting fish has ranged from basic flares to purse seines, squid jigging, light stick–holding devices, lift nets, and drop nets [17–19].

In other fishing methods, including traps [20,21], pots [22], trawls [23,24], long lines [25,26], and gill nets [27,28], light is used as a stimulus to improve the catchability of target species and reduce bycatch. With the advancement of engineering technology, light-emitting diodes (LEDs) are increasingly used in the fishing industry because they conserve more energy, are more effective in improving catchability, and have better chromatic performance than other types of lighting [17–22]. To our knowledge, the only published study related to mud crabs was on the vertical movement of *Scylla serrata* (i.e., mud crab megalopae) larvae toward the light [29]. However, that study did not test any crab fishing equipment to capture mud crabs.

The high economic value and market demand for mud crabs [16] as well as the high operating costs of crab fishing have increased the demand for research on new alternatives to attract mud crabs into traps. Moreover, with the development of fishing technologies such as the use of LEDs, exceptional contributions to the fishery sector have been made to reduce harvesting costs and exert less strain on the environment. However, preferences for light as an aggregating device to attract orange mud crabs have not been examined. In the present study, we determined the behavior and commercial catchability of *S. olivacea* in response to LED lights under captivity and field conditions. For the captivity experiments, which were conducted in a controlled tank environment, we created conditions that allowed *S. olivacea* to choose to approach or move away from LED lights of different colors. Five field trials were then performed to compare the catchability of *S. olivacea* between the control baited trap (i.e., using mackerel and chicken heads as natural bait) and the use of LED lights with unbaited traps.

2. Material and methods

2.1. LED lights

Waterproof, flashing LED light bulbs (60 mm long and 19 mm wide) were used for both the captivity and field experiments, were purchased locally (Fig. 2a). Each LED light was powered by a non-rechargeable disposable CR927 battery with a longevity of more than 100 consecutive hours and cost from RM6.00–8.00 (USD1.40–1.90) per piece. We evaluated the distribution of spectral wavelengths emitted from each LED light using a FluoroMax® spectrofluorometer with wavelength selection provided by a Czerny-Turner grating monochromator. Luminescence was detected by an Emission: R928P photon counting PMT (185–850 nm) and reference photodiode for monitoring lamp output. Lights of four colors, namely blue, green, red, and white with peak wavelengths of 458, 526, 630, and 460 nm, respectively (Fig. 1).

2.2. Mud crabs

S. olivacea were captured from the Setiu Wetlands, located in northeast Terengganu, Malaysia, in June 2017 by using a baited rectangular collapsible trap deployed at the mangroves at a depth of 3–5 m. The *S. olivacea* were measured for carapace width (CW) and held under continuous aeration in two

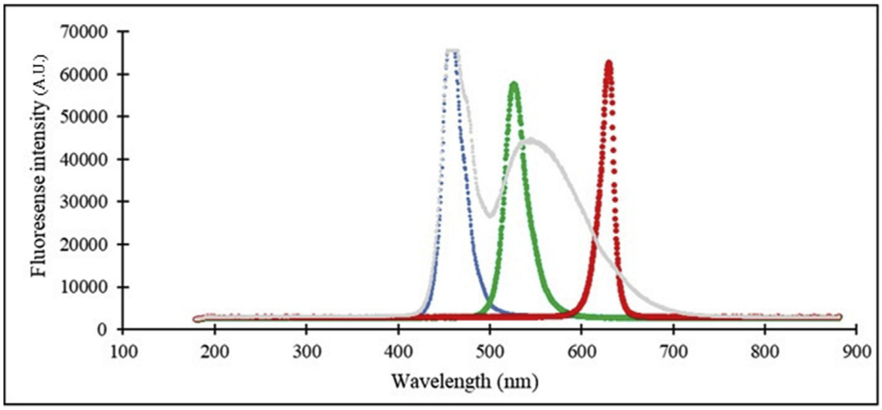

Fig. 1. Fluorescence of LED lights. Peak wavelengths were 458 nm for blue LED lights, 526 nm for green LED lights, 630 nm for red LED lights, and 460 nm for white LED lights.

rectangular holding tanks (with a length, width, and height of 5, 1, and 1m) containing water with salinity approaching 20 ppt. The mud crabs were separated according to sex (male and female) in different holding tanks. To mimic the natural habitat of mud crabs, sand was placed at the bottom of each tank, and shelters were constructed from cylindrical polyvinyl chloride pipes. The crabs were fed with chopped mackerel (10% of body weight) once a day and were quarantined for two days without feed before the start of the captivity experiments.

2.3. Captivity experiment setup

The captivity experiment setup consisted of an enclosed 10-ton fiberglass tank with a length, width, and height of 4, 2, and 2 m, respectively (Fig. 2). The interior walls of the tanks were light blue. The water was 1.5 m deep, and black agricultural nets covered most of the light penetration at the top of the tanks (Fig. 2b, d). The water salinity was maintained at 20 ppt, and continuous aeration was ensured (Fig. 2c). The experiment was conducted during night time in an enclosed area and the tanks contained no odors or food sources. To determine the crabs' locations when the lights were placed in the center of the tanks, we divided the bottom of the tanks into two areas: near light (NL) and far from light (FL; Fig. 2I, II). The NL area had a length, width, and height of 0.6, 0.3, and 0.25 m, respectively, the same dimensions as those of the collapsible crab traps often used by local fishermen. A 100% fluorocarbon fishing line linked the LED lights to one end of the middle of the crab trap structure in the NL area. The light was submerged in the tank using a vertical lever that reached the base of the tank.

2.4. Captivity experiment data collection

A total of 120 untrained mud crabs, divided into two groups of 60 males and 60 females, were examined. Five treatments—one control (without LED lights) and four with LED lights of different colors—were employed. The control treatment was performed before the LED treatments to ensure that crab movements were randomized in the experimental tanks (Table 1). To prevent the crabs from being tested twice for each color, the crabs were separated into two standby tanks of the same size and with the same setup with experiment tanks after each trial.

The 120 mud crabs were divided into 12 subgroups of 10 (5 males and 5 females). Each trial began with the random transfer a group of five crabs, starting with the males, from the holding tanks to the experimental tanks. The crabs were given 30 min of acclimation, and then the LED light colors were randomly selected and the lights were lowered into the center of the experimental tanks, each of which was completely covered with a black nylon net to prevent bias toward other stimuli. After 1 h, the crab locations were recorded as either NL or FL. All five crabs were transferred to the standby tanks after data were recorded. This process was repeated until all the crabs had been tested. The average number of crabs in the NL area for each group and treatment was calculated as follows:

$$\text{Average number of crabs in the NL area} = \frac{\Sigma \text{ number of crabs in the NL areas}}{\Sigma \text{ number of subgroups}} \quad (1)$$

where the average number of crabs in the FL calculated with a similar formula.

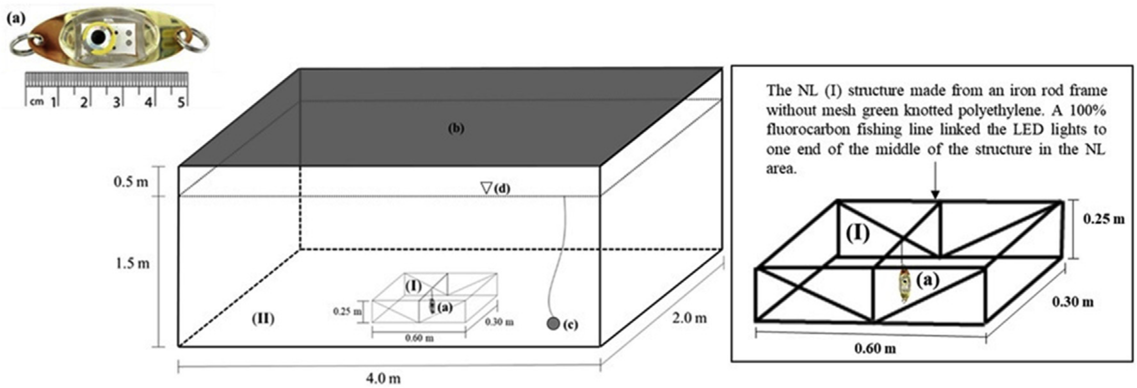

Fig. 2. The captivity experiment tank. (a) The waterproof flashing LED lights; (b) the black agriculture nets; (c) tank aeration; (d) tank water level; (I) the NL area; (II) the FL area.

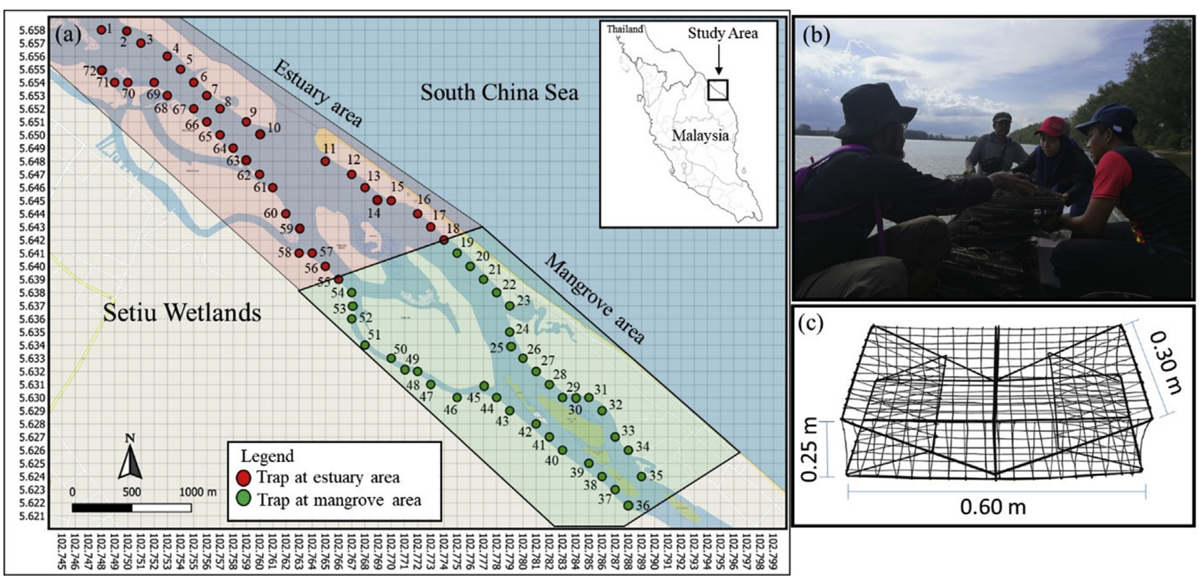

Fig. 3. (a) Field experiment location in the mangrove estuary area of the Setiu Wetlands; (b) the crab fisherman guide aboard a fiberglass boat; (c) collapsible traps used in the field experiments.

Table 1. Summary of S. olivacea responses to the different treatments in the captivity experiments.

Treatments	Total numbers of crabs	Number of crabs at NL	Average number of crabs at NL (crab/trial)	Number of crabs at FL	Average number of crab at FL (crab/trial)	*p*-value
Male						
Green	60	41	3.417	19	1.583	<0.001
Red	60	10	0.833	50	4.167	<0.001
Blue	60	39	3.250	21	1.750	0.002
White	60	33	2.750	27	2.250	0.275
Control	60	7	0.583	53	4.417	<0.001
Female						
Green	60	37	3.083	23	1.917	0.027
Red	60	14	1.166	46	3.833	0.002
Blue	60	33	2.750	27	2.250	0.274
White	60	34	2.833	26	2.167	0.136
Control	60	10	0.833	40	4.167	<0.001

2.5. Field experiments

Field experiments were conducted between August 9 and 22, 2017 in the mangrove estuary of Setiu Wetlands (Fig. 3a) aboard a 6-m fiberglass boat with a 15-horsepower engine and under the guidance of a local crab fisherman, respectively (Fig. 3b). The sampling site was divided into two areas; an estuary area—an area that does not have a mangrove tree, near to river estuary, and a mangrove area—an area that consists of mangrove and nipa tree (Fig. 3a). The water depth at the sampling site ranged from 1.5 to 3 m depending on the tide. Collapsible traps composed of an iron rod frame (0.6, 0.3, and 0.25 m in length, width, and height, respectively) and 5-cm mesh green knotted polyethylene were used (Fig. 3c). Each trap had two slit openings consisting of two netting panels forming a horizontal V shape. The animals expanded these openings when entering the trap. Four experimental treatments were investigated: a trap baited with 100 g of mackerel (trap 1), a trap baited with approximately 70–100 g of the chicken head (trap 2), an unbaited trap equipped with a green LED light (green light trap), and without any bait or LED light (empty trap) (Fig. 4a). The bait was tied to the wire between the doors, and the green LED light was tied to the top of the trap using a cable to prevent it from becoming stuck in the sand and mud.

On every fishing trip, all traps was set up at 4 pm and left overnight for 12 h in accordance with conventional fishing practices. Moon phases during the study were obtained from www.timeanddate.com (full moon; 100% illuminated, new moon; 0% illuminated, first-quarter moon; 50% illuminated, and third-quarter moon; 50% illuminated). However, no first-quarter moon phases were recorded during the study periods and have been remove from the analysis. Each trap was tied up with rope and floated to assist in tracking its location. The four trap treatments were randomly assigned, and the distance between each trap at the sampling location was approximately 20 m (Fig. 4b). On each fishing trial, the 72 numbered replicate traps were conducted (baited trap 1: 24 replicates; baited trap 2: 24 replicates; green light trap: 12 replicates; empty trap: 12 replicates). A total of 360 trap hauls (120, 120, 60, and 60 for baited trap 1, baited trap 2, green LED light trap, and empty trap) were successfully made over five fishing trials, with the same route and trap location used each time. All captures were counted except for those of Mollusca, which were released. The species, sex, and CW of the crabs were measured and recorded (Table 3). The catch per unit effort (CPUE) was defined as the number of each species captured per trap haul. For each species, sex, and treatment, the average CPUE was calculated as follows:

Table 2. Model output from GLMM: Number of crabs at NL or FL versus treatments and sex, relative to control treatment and female crab.

(a) Parameter	Estimate	Std. Error	Z value	*P*-value
(Intercept)	−1.81836	0.2777	−6.548	<0.001
Treatments				
Blue LED	2.20711	0.3213	6.868	<0.001
White LED	2.03603	0.3199	6.365	<0.001
Green LED	2.42070	0.3243	7.464	<0.001
Red LED	0.41523	0.3473	1.196	0.232
Sex				
Male	0.03348	0.1830	0.183	0.855

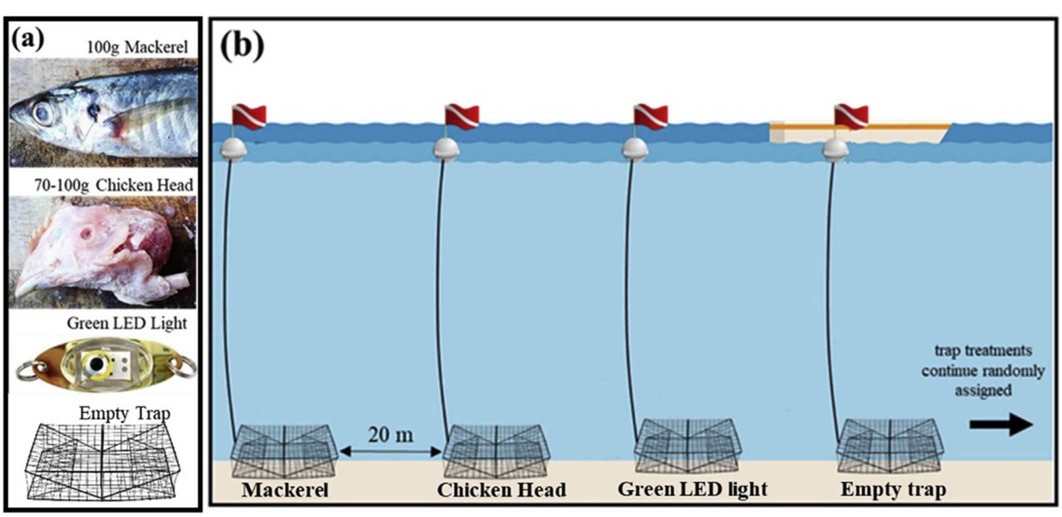

Fig. 4. (a) The four treatments in the field experiments; (b) random assignment of the treatments. The distance between each trap at the sampling location was approximately 20 m.

Table 3. Number of swimming crabs and bycatch organisms caught using the mackerel, chicken head, green LED, and empty trap treatments in Setiu Wetlands.

Treatment	Mackerel	Chicken Head	Green LED	Empty Trap
Price	RM10.00/kg	No value	RM6.00/pcs	No value
No. of trap hauls	120	120	60	60
Mean soaking time (hour)	12	12	12	12
Scylla olivacea				
Total no. caught [a]	79	45	8	–
Total weight (kg) [a]	10.89	5.42	0.96	–
Mean carapace width (mm) [b]	90.35	86.57	86.35	–
Sex ratio (F:M) [a]	1:2.6	1:1.14	1:3	–
Bycatch no.				
Scylla Paramamosain [b]	9	10	1	–
Scylla tranquebarica [c]	2	4	–	–
Portunus pelagicus [c]	11	4	–	–
Thalamita crenata [a]	56	66	5	–
Menippe mercenaria [b]	38	34	6	–
Epinephelus coioides [c]	14	8	–	–
Scatophagus argus [c]	2	–	–	–
Lutjanus rivulatus [c]	2	–	–	–
Total catch[a]	213	171	20	0

[a] Indicates where a significant between-treatment difference was observed.
[b] Indicates where no significant between-treatment difference was observed.
[c] Indicates where term not applicable for analysis.

$$\text{Average CPUE} = \frac{\Sigma\text{Catch number for each species}}{\Sigma\text{Trap number for every treatment}} \quad (2)$$

2.6. Statistical analysis

For the captivity and field experiments, we used three Generalized Linear Mixed Models (GLMMs) [30] to assess the effect of different treatments on the *S. olivacea* movement, how bait type affected the number of *S. olivacea* caught per trial, and the carapace width of *S. olivacea* caught across bait types. We ran GLMM's using the glmmTMB package [31] and used the tidyverse package [32] to conduct data manipulation and visualization.

In our first model, a binomial GLMMs was employed (Eq. (3)). We modeled the locations of *S. olivacea* either NL or FL as the response variable, with fixed effects are treatments (control, blue LED, white LED, green LED, red LED), and sex (male and female). We incorporated the random effects of trials (i.e. first trials of the field experiment = 1) to account for the temporal dependency structure of the data. Our first model is presented (Eq. (3)), where crablocation$_{ij}$ is the jth observation in captivity trials i. The crablocation$_{ij}$ is modeled as

$$\mu_{ij} = \beta_0 + \text{Treatment}_{ij} + \text{Sex}_{ij} + \text{Trials}_i \quad (3)$$

For our second model, we used a Poisson GLMMs (Eq. (4)). We modeled the number of *S. olivacea* caught per trap as the response variable, with fixed effects are bait type (mackerel, chicken head, green LED), sampling site (estuary area, mangrove area), and moon phase (full moon, new moon, third-quarter moon). We incorporated the random effects of fishing trials (i.e. first fishing trials of the field experiment = 1) and trap numbers used for every fishing trials to account for the temporal dependency structure of the data. In second model, both male and female *S. olivacea* catch were combined as a total catch. Our second model is presented (Eq. (4)), where totalcatch$_{ij}$ is the jth observation in sampling trials i. The totalcatch$_{ij}$ is modeled as

$$\mu_{ij} = \beta_0 + \text{Bait}_{ij} + \text{Moon}_{ij} + \text{Site}_{ij} + \text{Trials}_i + \text{TrapNumber}_i \quad (4)$$

In our last model (a Gaussian GLMMs), CW (mm) was the response variable, and fixed effects are bait type, sampling site, moon phase and sex (male, female), with sampling trials as random effects. Our last model is presented (Eq. (5)), where total carapacewidth$_{ijk}$ is the kth observation in the jth trap, which is nested within the ith trials. The carapacewidth$_{ijk}$ is modeled as

$$\mu_{ij} = \beta_0 + \text{Bait}_{ij} + \text{Site}_{ij} + \text{Moon}_{ij} + \text{Sex}_{ij} + \text{Trials}_i \quad (5)$$

The statistical significance of all fixed terms for the field experiment was calculated using chi-squared tests to determine if categorical variables have a significant correlation between them. GLMMs models were tested for outliers, homogeneity,

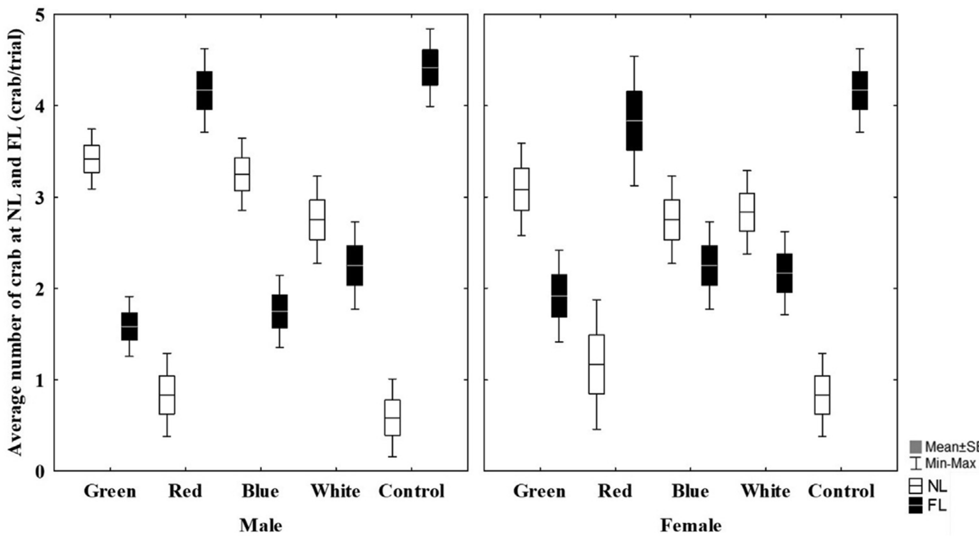

Fig. 5. Boxplots of average number of male and female S. olivacea in the captivity experiments that moved toward the near light and far from light area.

normality, collinearity, interactions, and independence (for each model) according to the method in supplementary data by [11]. We conducted GLMMs analysis for data preparation, and visualization using R Statistical Software 3.6 [33].

3. Results

3.1. Captivity experiments

Figure 5 showed the average number of crabs in the captivity experiments that moved toward the NL or FL area. In the control, most crabs were recorded in the FL area (Table 1, Fig. 5), and significant differences between crabs in the NL and FL areas were observed. The number of crabs in the NL area was highest for the green, blue and white LED treatment but not differed significantly between these three treatments (Table 1). For green LED light, no significant sex differences were noted with males and females (3.417 and 3.083 per trial, respectively; Table 1). In the blue and white LED treatments, more crabs were observed in the NL area than in the FL area. In the blue LED treatment, this difference was only significant for the males. In the white LED treatment, no significant sex differences were noted (Table 1). The red LED treatment had no attractive effect; similar to the controls, all crabs, both male and female remained in the FL area (Table 1, Fig. 5).

Chi-square analysis showed that the type of treatments greatly influenced the locations of *S. olivacea* ($P < 0.05$) in the captivity experiment, whereas the sex did not show significant differences between the five treatments ($P > 0.05$). For GLMMs, significant differences were noted in relation to different LED lights with control treatment (which we treated as “control” as this experiment not consist any LED light), for which blue, white and green LED had a positive significant with the number of *S. olivacea* to NL area compare to red LED and control treatment (Table 2, Fig. 6). Male *S. olivacea* had a positive significant with the treatments but does not differ from the female *S. olivacea* (Table 2).

3.2. Field experiments

In total, 360 trap hauls were successfully completed after a mean soaking time of 12 h (Table 3). The bait price (in Ringgit Malaysia per kg) was based on the local prices and discussions with local fisherman in the Setiu Wetlands area except for chicken head that got free at a local chicken farm due to poultry byproducts waste. Table 3 presents the differences in catch composition, namely those in catch number, total weight (in kg), mean carapace width (in mm), and sex ratio (female: male) for the mackerel, chicken head, green LED and empty trap treatments, as well as the number of species bycaught in each treatment and trap. However, zero catch of any organisms for the empty trap treatment during the 5-day field experiment. A total of 404 *S. olivacea* and bycatch organisms were caught over the 5-day experiment (Table 3).

Significant differences in the catch number of *S. olivacea* between the baited trap treatments and the green LED treatments were observed ($P < 0.05$; Table 3). The mackerel-baited traps caught the

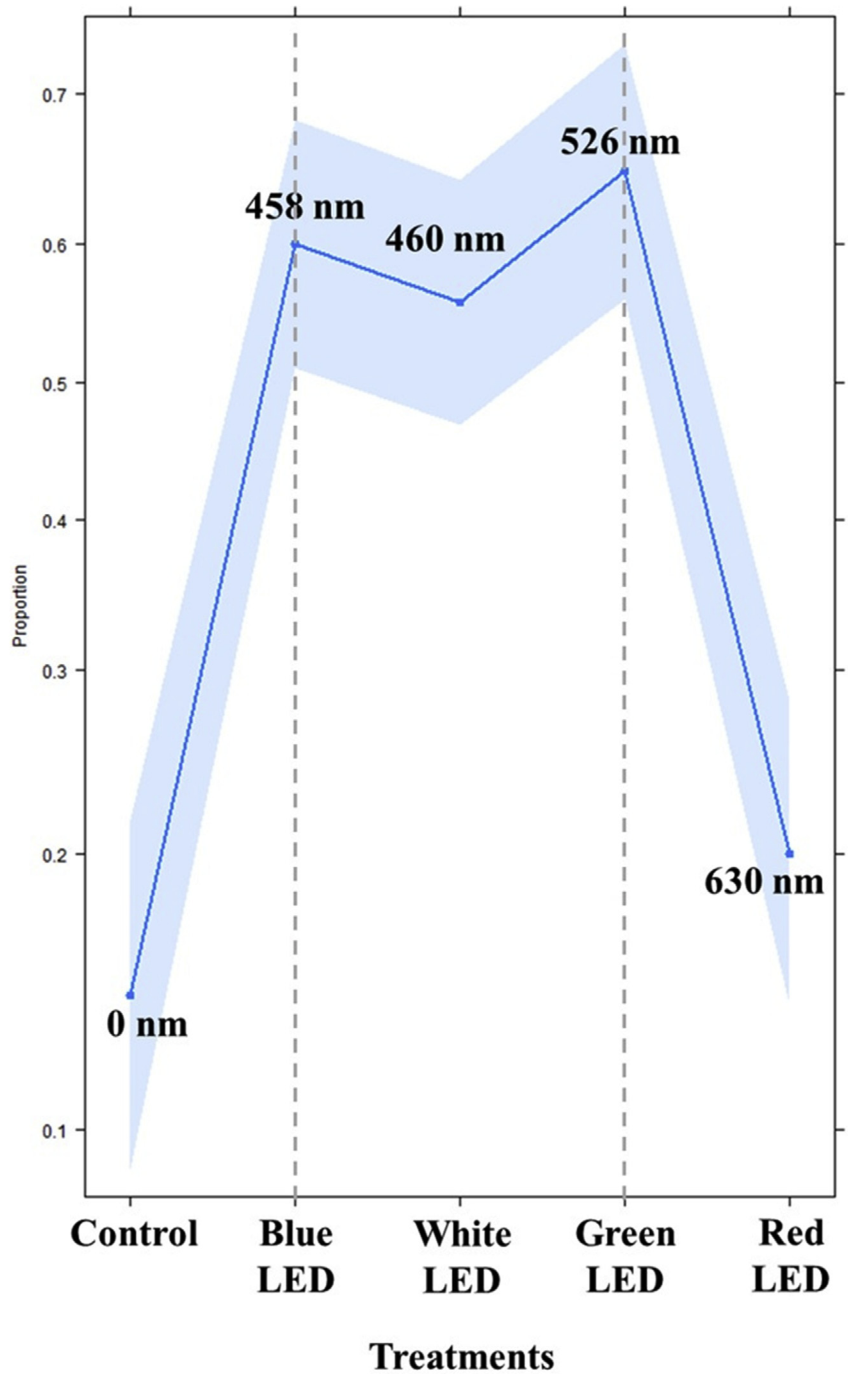

Fig. 6. The relationship between each treatment and the number of S. olivacea to NL area during captivity experiment. The value in the treatments represents the peak wavelengths for blue LED: 458 nm, white LED: 460 nm, green LED: 526 nm, and red LED: 630 nm. The dashed vertical gray line indicates the optimal range of light wavelength for S. olivacea.

highest numbers of *S. olivacea*, with a total weight of 10.89 kg crabs and a mean of carapace width of 90.35 mm, accounted for 59.8% of the total *S. olivacea* catch (Table 3). Across the entire field experiment, 65.9% of crabs were male and 34.1% were female of *S. olivacea* caught. Significant differences in the total catch were noted among all three treatments ($P < 0.001$). Both the mackerel and chicken head treatments resulted in the capture of higher numbers of organisms than did the green LED treatments (213, 171, and 20, respectively).

There were eight bycatch species recorded in the present study. In total, we found 20 *Scylla Paramamosain*, six *S. tranquebarica,* 15 *Portunus pelagicus*,

Table 4. Model output from GLMM: (a) total catch versus bait type, moon phases and sampling site, relative to empty trap, full moon phases and estuary area; (b) model output from GLMM of carapace width versus bait type, sampling site, moon phase and sex, relative to green LED, estuary area, full moon and female crab.

(a) Parameter	Estimate	Std. Error	Z value	*P*-value
(Intercept)	−2.36147	0.45066	−5.240	<0.001
Bait				
Chicken Head	1.50864	0.43288	3.485	<0.001
Green LED	0.78119	0.49480	1.579	0.114
Mackerel	1.98515	0.42451	4.676	<0.001
Moon				
New Moon	0.07569	0.23950	0.316	0.752
Third Quarter	−0.11744	0.20449	−0.574	0.566
Site				
Mangrove	0.19400	0.16254	1.194	0.233
(b)				
(Intercept)	86.4000	4.3208	19.997	<0.001
Bait				
Chicken Head	0.6484	3.4800	0.186	0.8522
Mackerel	3.4192	3.3445	1.022	0.3066
Site				
Mangrove	−3.2148	1.5646	−2.055	<0.05
Moon				
New Moon	3.3370	2.7545	1.212	0.2257
Third Quarter	1.4743	2.3657	0.623	0.5332
Sex				
Male	0.2268	1.8438	0.123	0.9021

127 *Thalamita crenata*, 78 *Menippe mercenaria*, 22 *Epinephelus coioides*, two *Scatophagus argus,* and two *Lutjanus rivulatus*. The CPUE values for *T. crenata* and *M. mercenaria* were also higher when the baited traps were used. The green LED treatment also attracted these two-crab species, but at very low numbers compared to the baited traps (Table 3). Significant differences were observed for *T. crenata* between the baited trap and green LED treatments ($P < 0.05$), but none were noted for *M. mercenaria* ($P > 0.05$). By contrast, no between-treatment differences between the other bycatch species were observed ($P > 0.05$).

Chi-square analysis showed that the type of bait greatly influenced the CPUE of *S. olivacea* ($P < 0.05$), whereas the phase of the moon and the location of sampling did not show significant differences between the three treatments ($P > 0.05$). For GLMMs, significant differences were noted in relation to traps baited with empty trap (which we treated as "control" as this trap not consist any bait or LED light), for which baited with chicken head, mackerel and green LED caught 4.52%, 7.28% and 2.18% more CPUE of *S. olivacea* compare to empty trap, respectively (Table 4a, Fig. 7). Besides, both the mackerel and chicken head treatments resulted in the higher average CPUE of *S. olivacea* than did the green LED treatments; 0.66, 0.38 and 0.13 per trap (Fig. 8). The new moon and full moon phases produced higher CPUE of *S. olivacea* than the third-quarter moon but were not significantly different (Table 4a, Fig. 7). Mangrove area catches higher *S. olivacea* but does not differ from the estuary area (Table 4a, Fig. 7).

For the carapace size, chi-square analysis showed that the sampling site had significant differences in CW ($P < 0.05$), but the bait type, moon phase and sex did not have a significant effect on the CW of *S. olivacea* caught ($P > 0.05$). Mackerel and chicken traps caught on average 24.50 mm and 1.21 mm wider of *S. olivacea* than those baited with green LED, respectively (Table 4b, Fig. 9). No significant change in body size was observed in all three-treatment traps and

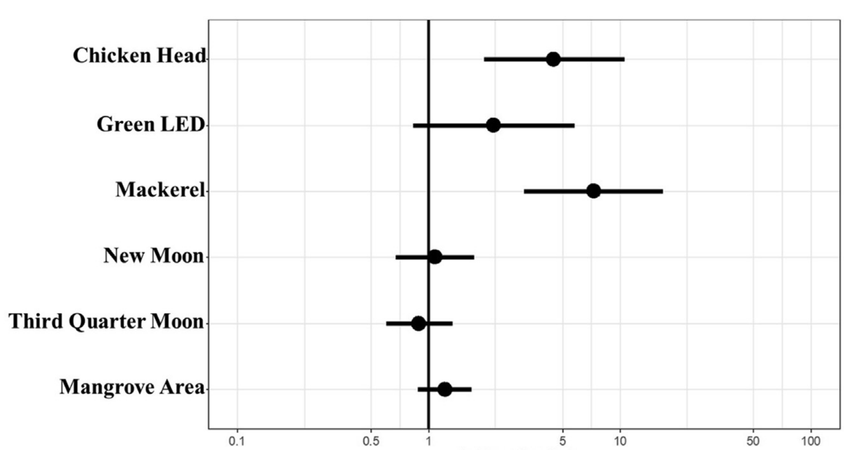

Fig. 7. Visualization of parameter estimates from GLMM's comparing S. olivacea catch versus bait type, moon phase and sampling site. The comparisons are relative to traps baited with empty trap (vertical solid black bar which we treated as "control") in full moon and estuary area. The solid vertical bar indicates no statistically significant effect of that covariate level on the response variable.

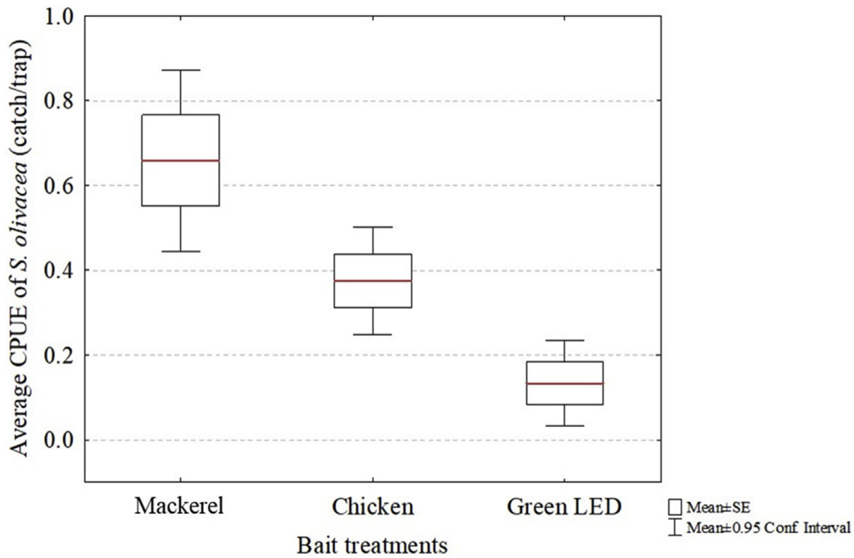

Fig. 8. Boxplots showing the average CPUE of S. olivacea for different baited trap treatments during the field experiment.

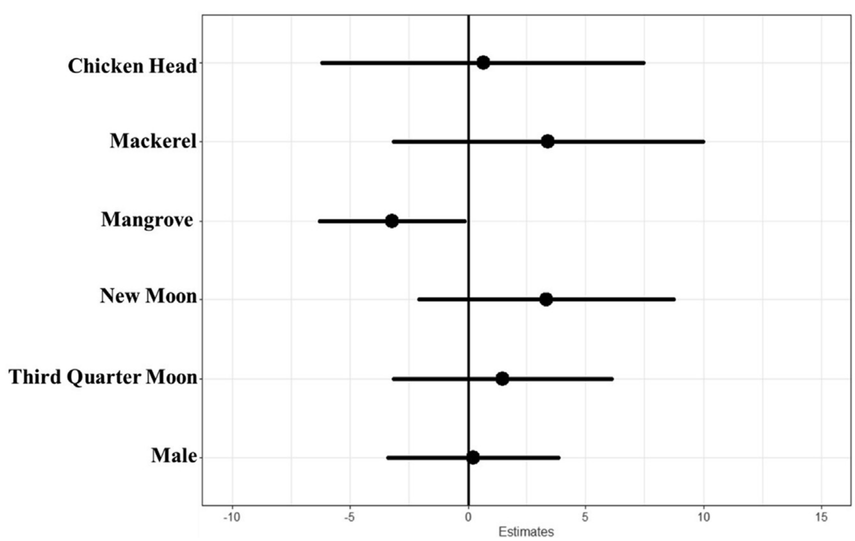

Fig. 9. Visualization of parameter estimates from GLMM's comparing S. olivacea carapace width versus bait type, sampling site, moon phase and sex. The comparisons are relative to traps baited with green LED (vertical solid black bar which we treated as "control") in estuary area, full moon and female. The solid vertical bar indicates no statistically significant effect of that covariate level on the response variable.

different moon phase. However, crabs caught in the estuary were larger than in the mangrove area and show a significance among the sampling site (Table 4b, Fig. 9). The largest average CW recorded in the estuary was baited by green LED, yet recorded the smallest average CW in the mangrove area (Fig. 10). In contrast, there were no sex differences between the CW (Table 4b, Fig. 9).

4. Discussion

There are two major limitations in this study that could be addressed in future research. First, the study on crab's behavior in captivity experiment. Mud crab is known as one of the high cannibalism species among them [34]. In the natural habitat, mud crabs will try to enter or approach the traps even if there are mud crabs or other organisms in them due to the strong natural bait attraction. In our captivity experiment, we decided to select groups of five crabs for each trial to observe the mud crab attraction to the LED light even in the high-density area. However, in the future, the treatment of individual single reactions of crab against differences treatment (i.e. different LED light colors) should be performed. This is to observe either the behavior of crab responses to treatment is not affected in the presence of other crabs. Besides, a control treatment with LED light switched off should be performed to know whether or not the presence of the plastic LED or battery had some effect on the movement of crabs.

Second, the limitations of the study on baits performance to improve catchability of crabs. In the present study, we found that the differences of CPUE with the use of three different treatments had significant differences. This supports that the hypothesis of using different baits to catch target species is not a problem. However, these results indicate that bait selection is very important. Given the relatively small sample size and the study conducted in a short time, we did not conclude that mackerel maximized CPUE and the size of the crabs caught. This unbalanced experiment increases the likelihood of type II errors and leads to a loss of statistical power in general. Instead, other LED light color (i.e., blue light, white light, red light) should also test as one of the treatments and the combination between natural baits with artificial baits (i.e., mackerel combined with green LED light in a trap) to observe the catchability of target species should be done for future study.

4.1. Captivity experiments

The captivity experiments indicate that *S. olivacea* can be attracted using artificial lights as other aquatic species are [17–19,21,22]. In the present study, *S. olivacea* responded differently to different LED light colors, and the results suggest that crab behavior, in general, depended on exposure to lights of different colors and wavelengths. These findings were consistent with those of Nguyen et al. [20] and Kawamura et al. [35].

This response to various wavelengths of light may vary depending on the eye anatomy, the biology of each crab species, and potentially the density of the crab as well. The receptors in almost all crustacean compound eyes belong to two anatomically distinct classes: seven retinal cells comprising the main rhabdom and a single eighth cell representing a smaller, typically distal portion [36,37]. Many of the eighth cells contain comparatively short-wavelength, ultraviolet-sensitive, or violet-sensitive visual pigments and the seven retinal cells typically contain visual pigments more sensitive to the blue–green regions of the spectrum [37]. Crustaceans such as certain crabs, *Uca mjoebergi,* and *Callinectes sapidus*are dichromatic or, like cephalopods, *Sepia* sp., are color blind, with a single spectral range of approximately 500 nm [38]. The giant mud crab *S. serrata* has a peak visual sensitivity in the blue–green wavelengths of 450–500 nm [39] and a single type of photoreceptor [40].

According to a study by Forward et al. [41], the overall visual pigment absorbance of 27 benthic crustacean species in semiterrestrial, estuarine, and coastal environments ranges from 483 to 516 nm. Cronin and Forward [42] in their study on five Portunidae species distributed across estuarine and coastal environments, reported that four species, namely *Arenaeus cribrarius*, *Callinectes sapidus*, *C. Ornatus*, and *Ovalipes stephensoni*, have similar visual pigment systems, with a peak of approximately 500 nm. Horch et al. [43] indicated a median absorbance between 473 and 515 nm in all crab species, with that of semiterrestrial crabs being between 487 and 508 nm. In the present study, the *S. olivacea* responded well to the green, blue, and white LEDs and poorly to the red LEDs is consistent with the fact that the main rhabdom in crabs has a maximum spectral sensitivity between 450 nm and 550 nm (Fig. 6). Besides, during the control treatment, our results showed that crab randomly moved in the experiments tank, and a few numbers of crabs were recorded in the NL area. Moreover, our finding discovers that *S. olivacea* was not attracted to red light is consistent with the result in the control treatment and those of previous studies that crustaceans only respond to particular wavelengths of light [20,21,37,42,43]. Taken together, these findings indicate that the visual system of *S. olivacea* is more sensitive to shorter wavelengths of light and less so to longer wavelengths.

4.2. Field experiments

The catchability performance of collapsible traps highly depends on factors such as the prey numbers; season; type of bait; the size, shape, entrance location, and levels of saturation of the traps; soaking duration; and oceanographic conditions [44,45]. Field studies have demonstrated that significantly higher CPUE values of *S. olivacea* and other organisms, including bycatch species, are obtained when mackerel and chicken head baits are used. However, unbaited green LED traps also attract *S. olivacea, T. crenata*, and *M. mercenaria* but at very low numbers compared to baited traps. Marine animals rely more on olfaction than vision when searching for food [46]. Besides, chemical cues are a more common mode of attraction than vision in aquatic environments because of attraction distance, light availability, and turbidity [47].

Nguyen et al. [20] found that unbaited traps equipped with LED lights caught equivalent

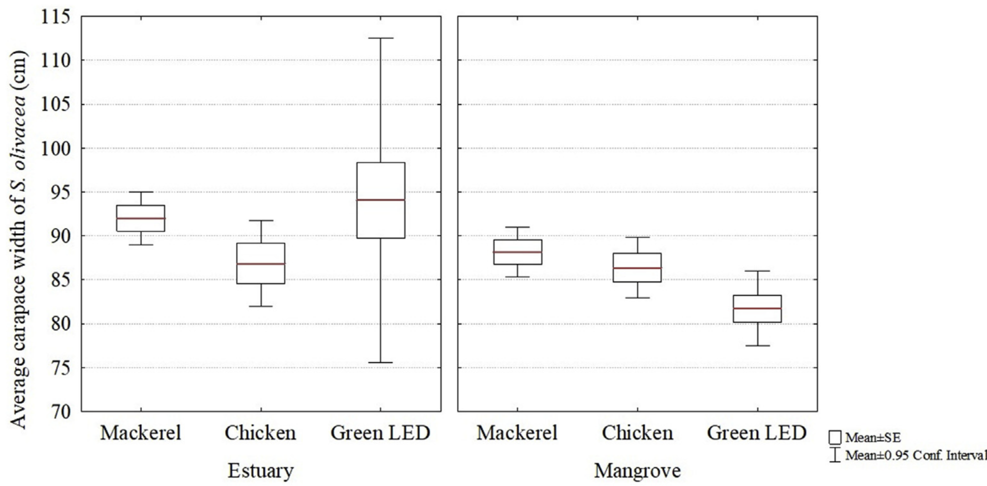

Fig. 10. Boxplots showing the average carapace width of S. olivacea for different baited trap treatments at the different sampling site during the field experiment.

numbers of snow crabs to conventional baited traps, with soaking time and water depth explaining some of the CPUE variations. The use of LED lights to replace the conventional baiting method is not new and is promising and readily applicable to the fishing industry. For example, with the introduction of underwater light–equipped fishing equipment, the CPUE values of large-scale fish traps and snow crab traps have increased by 200% and 77%, respectively [20,22]. Besides, Nguyen et al. [48] discover that luminescent netting increases the efficiency of the snow crab traps by 21.6% higher catch per unit effort of legal-sized crab than control traps, which provides economic and environmental benefits to the fisherman.

We hypothesized that light allows crabs to approach and detect trap entrances and specifics within them. Specifically, we hypothesized that LED light lacks the ability to attract crabs to approach the trap compared to natural baits that have an odor as well as produce enough amino acids to attract *S. olivacea* over a wide range. Archdale and Nakamura [49], have shown that, in the bioassay experiments, blue swimming crab *P. pelagicus* react to different amino acid and can detect minor changes in the chemical composition such as galactose and glucose in the water surrounding them. Besides, swimming crabs such as *S. olivacea* are scavengers that rely heavily on their chemoreceptive sense for locating their food.

LED light clearly has a significant disadvantage in that is not able to move in a wide radius compared to the smell of natural bait that is able to move according to the movement and change of water current. Estuaries are characterized by high concentrations of total suspended solids as well as high turbidity and fluctuations in salinity [50]. The elevated turbidity of estuarine waters at high tide may also explain why crabs are not more responsive to LED traps.

The results of our study show, during the use of LED light as a treatment bait, CPUE of *S. olivacea* showed a slight increase when carried out during the new moon and third quarter moon, however, the catch was lower when carried out on the full moon, but did not show a significant difference between these three moon phases. Some study also approves that, moon illumination are affected catches through an influence on the behavior and movements of fishes [51]. In addition, both water depth—between 0.5 and 3 m, depending on tide conditions [52]—and moonlight effects (moon phase) in the Setiu Wetlands may affect the output of LED lights that give the negative impacts on the catches of *S. olivacea* during the study.

4.3. Carapace size and sex differences in trap attraction

Scylla spp. populations are commonly associated with mangroves and can serve as useful indicators for mangrove habitat conditions [53]. Hill et al. [54] have described habitat use by several stages of life *Scylla* spp. in Australia, with mud crab species more concentrated in mangrove habitats. In the present study, the mangrove area catches higher *S. olivacea* but does not differ from the estuary area. Although the natural environment between the estuary and the mangrove area can be seen with the naked eye (i.e. the mangrove area covers more mangrove trees), the difference in terms of an environmental factor (i.e., salinity and water depth) is not very significant among them. Mostapa and Weston [55] reported that the same sampling location in our study recorded a high mean salinity value in the range of 27–30 ppt, indicating the main influence of seawater in this area which may not cause significant differences between catches of *S. olivacea* in Setiu Wetlands.

Regarding crab size, no significant effect of bait treatment on CW was detected. However, the field experiments showed that the baited traps caught more *S. olivacea* than did the green LED traps. Besides, the estuary area caught a bigger CW compare to the mangrove area. Larger juveniles and adult *S. serrata* reported migrating into mangroves habitat for shelter and foraging, whereas adult female mud crabs migrate towards offshore regions with oceanic conditions during the spawning season [56]. Also, Walton et al. [53] mention that larger *S. paramamosain* were caught offshore (mean CW: 125.0 mm) where females accounted for 60% of the catch compare to the mangrove area. In the present study, the field experiments showed no significant sex difference in CW of *S. olivacea* catch. Besides, no sex differences were observed for the movement of *S. olivacea* toward the light in captivity; however, significant between-treatment differences were noted. The results suggest that the visual receptor systems of all adult *S. olivacea* are similar. These results show a close relationship between estuary areas and specific niches in mangrove habitats, with the main population found living far from the mouth of the river i.e. areas with mangrove trees, while larger CW sizes inhabit the estuary area.

4.4. Future alternative baits

The present findings can inform conservation measures through the use of LED lamps as lures for mud crabs. However, the higher cost of LED lights with a lower number of catches per trap compared to natural baits may be one of the disadvantages of these artificial baits (Fig. 11). Meanwhile, in another perspective, the LED light advantage in this experiment is that they can be used repeatedly for up to 100 consecutive hours compared to natural baits that cannot be used after a single use. Although detailed economic analysis is not yet complete, our rough calculations show that LED light investment will result in high variable cost in short term for the fisherman, but over time it will recoup investment, and at that point they will profit due to the LED light can reusable. Two studies by Nguyen et al. [20,21] reported improved crustacean catchability with the use of artificial light rather than fresh bait. Moreover, artificial light use can reduce the consumption of fish food as bait. This benefit is particularly relevant because of the growing demand and substantial rise in prices of bait also used for human consumption, such as squid, mackerel, and herring, over the past decade [57]. Meanwhile, other by-products such as chicken heads should be considered to become alternative baits. However, the quantity of poultry by-product is usually limited because it is also used in the field of aquaculture as livestock feed [58]. Besides catchability, several other factors such as availability, storage logistics, and pricing need to be considered for the success of new bait in commercial trap fisheries [8]. Other solutions such as reducing the amount of natural bait needed by adding compounds consisting of wheat starch, garlic, and brown sugar, were found to

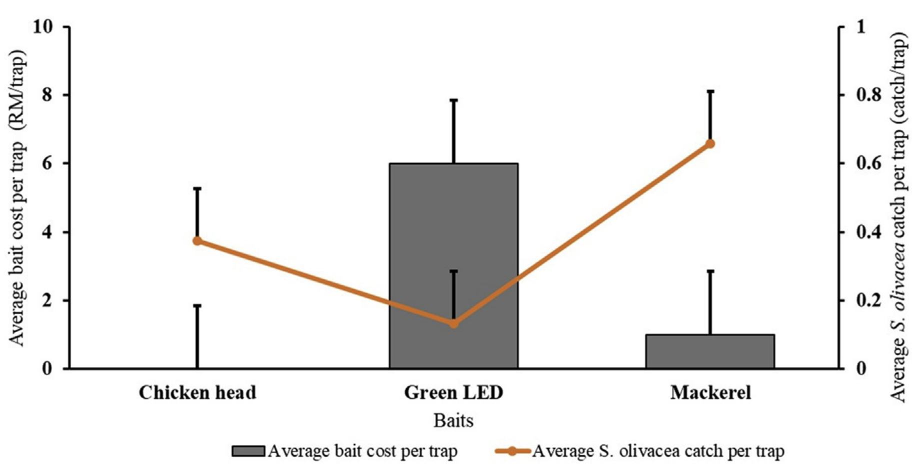

Fig. 11. The comparison between the average bait cost per trap with the average S. olivacea catch per trap for different baited trap treatments during the field experiment. The top of the box and circle indicate the standard error.

attract swimming crabs, as suggested by Archdale and Kawamura [12].

In conclusion, in the present study, LED lights attracted the orange mud crab *S. olivacea* but at very low numbers compared to natural baits. The captivity experiments revealed that green, blue, and white LED lights attracted the crabs more than did the red LED lights. In the field experiments, conventional baits (mackerel and chicken heads) achieved higher CPUE values for *S. olivacea* compared with the green LED lights. However, the performance of the LED lights may have been considerably affected by environmental factors such as the moon phase. Although the CPUE values of *S. olivacea* in the present study obtained using LED traps were lower than those achieved using baited traps, further in-depth studies, and specific modifications to improve the performance of LED lights are warranted. We recommend assessing the results for the capture of both crabs and non-target species to determine the effect of baited traps equipped with LED lights on crab catchability. Furthermore, in such studies, LED lights should be tested for a variety of colors, longer soaking duration, longevity, combination with baited trap, impact to the environment, and economic benefits.

Declaration of competing interest

There was no conflict of interest.

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