

## Marine Resource Recovery Following the COVID-19 Event in Southern Thailand

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### Abstract

This study investigated coral and reef fish recovery following the COVID-19 event between low and high environmental disturbance reefs at Racha Yai Island, Southern Thailand. Three and four 50-m permanent line transects were set at low and high environmental reefs to collect the percent of live coral cover, fish diversity and abundance, and fish trophic-functional groups based on diet and habitat use. Our results showed a significant rise in the percentage of live coral cover, the number of individual fish, the number of fish species, and species richness at both bays following the COVID-19 lockdown due to a crucial reduction in human activities on the reef. In addition, there were increases in the number of corallivore fishes belonging to Chaetodontidae and Pomacentridae families and a reduction of omnivorous fish at the fish-feeding tourist attraction reefs due during the COVID-19 lockdown due to reducing fish-feeding tourism. This indicated that restricted human activities and reduced anthropogenic stress on a coral reef may have substantial short-term impacts on reef fish diversity. Our insights could help designate guidelines to manage tourist impacts on coral reefs and aid in their prolonged persistence.

**Keywords:** Coral Reefs; Fish; Shannon Diversity; Species Richness; Human Activity.

### 1. Introduction

The ongoing COVID-19 pandemic has imposed strict lockdowns in many countries around the world at various stages. These lockdowns have restricted human activities and reduced anthropogenic stress on nature [1-3]. Many studies have reported that the effect of COVID-19 lockdowns promoted clean air [4], clean water [5], and healthy coral reefs [6]. Coral reefs provide food and livelihood for more than 850 million people, yet they have been overexploited by overfishing, tourism, pollution, and physical devastation [7-10]. Reef-based tourism comes in various forms, such as boating, fishing, fish feeding, diving, and snorkeling. Overfishing can be reduced by helping fishermen with finances [11, 12]. The health of coral reefs can be improved by removing human pressure. The COVID-19 event provides a great opportunity to look at how restricted human activities promote reef fish recovery.

COVID-19 lockdowns have been reported to cause a significant reduction in human activities at coral reef sites around the world. Reef fish behavior has been precluded from becoming more diurnal [13-15]. Recreational activities have resulted in a decreased evenness of fish assemblages (*Abudefduf saxatilis*), reduced cleaning by cleaners [16], shorter latency periods and escape distances [17], and increased use of refuge during the presence of divers and snorkelers [18]. Fish-taking care is part of human-actuated changes that have been reported to support fish variety, grow trophic specialties, and have flow impacts on other fish species [19-22]. It is still not apparent, nevertheless, whether the effects of COVID-19 lockdowns causing the reduction of recreational exercise are short-term or long-term.

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Thailand had a countrywide lockdown since April 2020, which strictly limits the number of people entering and leaving the country. Complete lockdown and curfew measures were also implemented for the whole country during the disease outbreak. COVID-19 lockdowns and travel restrictions have significantly reduced human activities, resulting in no activities with regard to fishing, reef-based tourism, and hotel occupancy; these were the major source of human stress on the coral reef ecosystem. This study investigated the first-time temporary changes in fish diversity and fish communities in response to the COVID-19 lockdowns. This study addressed the following question: (1) How do lower human activities on the reef due to the COVID-19 lockdown affect coral cover recovery, reef fish diversity, and fish community changes at Racha Yai Island? To investigate this, we compared: (1) the percentage of live coral cover, (2) fish diversity, and (3) fish feeding habits between low and high environmental disturbance sites during 2018 (as the pre- COVID-19 lockdown period to 2019–2021) as (post- COVID-19 lockdown period) at Racha Yai Island. We expected to find an increase in the percentage of live coral cover, fish diversity, fish abundance, and changes in fish communities based on feeding habits that rely directly or indirectly on live corals for their diet after the COVID-19 lockdown.

## 2. Materials and Methods

### 2.1. Study Site

The study was carried out at two locations: Khonkhae Bay ( $07^{\circ}36'17''\text{N}$ ,  $98^{\circ}22'35''\text{E}$ ) and Patok Bay ( $07^{\circ}36'34''\text{N}$ ,  $98^{\circ}21'56''\text{E}$ ) at Racha Yai Island, Southern Thailand. A fringing reef at Khonkhae Bay was at 1–12 m deep and located on the eastern side of Racha Yai Island, and a fringing reef at Patok Bay was 5–18 m deep and located on the western side of Racha Yai Island. The reef at Khonkhae Bay was heavily damaged by the 2010 mass bleaching, with a 90% loss of live coral, but the reef at Patok Bay was affected less by the bleaching event, with a 10% loss of live coral [23]. Further details of the study sites can be found in Jaroensutasinee et al. [23].

### 2.2. Data Collection

The fish surveys from both Khonkhae Bay and Patok Bay were collected in November–December 2018–2019 (before COVID-19), in June 2020 (after COVID-19), and in February 2021 using the fish visual census method along 50-m transect lines (Figures 1-a, and 1-b) [24–27]. In this study, we used the fish survey data from 2018–2019, which had been published in our previous study [23], as it was collected before the COVID-19 lockdown, and collected more fish survey data in 2020–2021, as it was collected after the COVID-19 lockdown. We set three permanent transect lines parallel to the reef slope at 8–12 m depth at Patok Bay and four permanent transect lines at 10 m depth at Khonkhae Bay. Each census area covered  $250\text{ m}^2$  and extended by 2.5 m at both the right- and left-hand sides of a 50-m transect line, and the total coverage census area with three replicates for Patok Bay and four replicates for Khonkhae Bay was  $750$  and  $1,000\text{ m}^2$ . Each transect line was 10-m apart from each other. We identified and counted all reef fish in each transect line at both bays based on several fish identification books [28, 29]. Each fish species was categorized into one of seven trophic-functional groups based on diet and habitat use (i.e., carnivore, corallivore, herbivore, invertebrate consumer, omnivore, piscivore, and planktivore [30–33] (Figure 2).

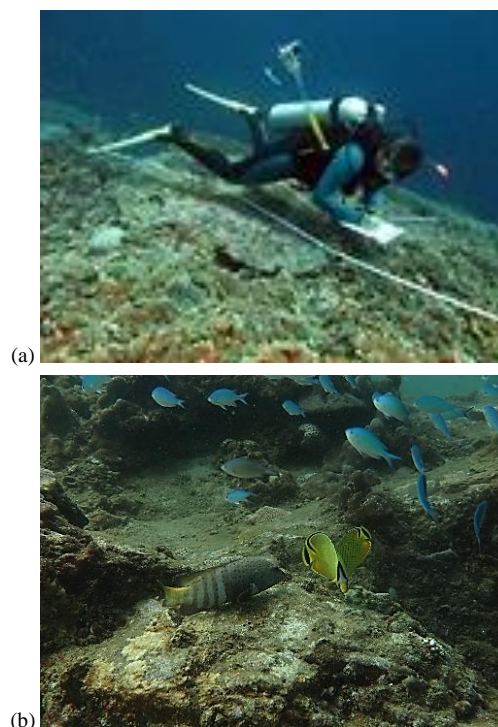
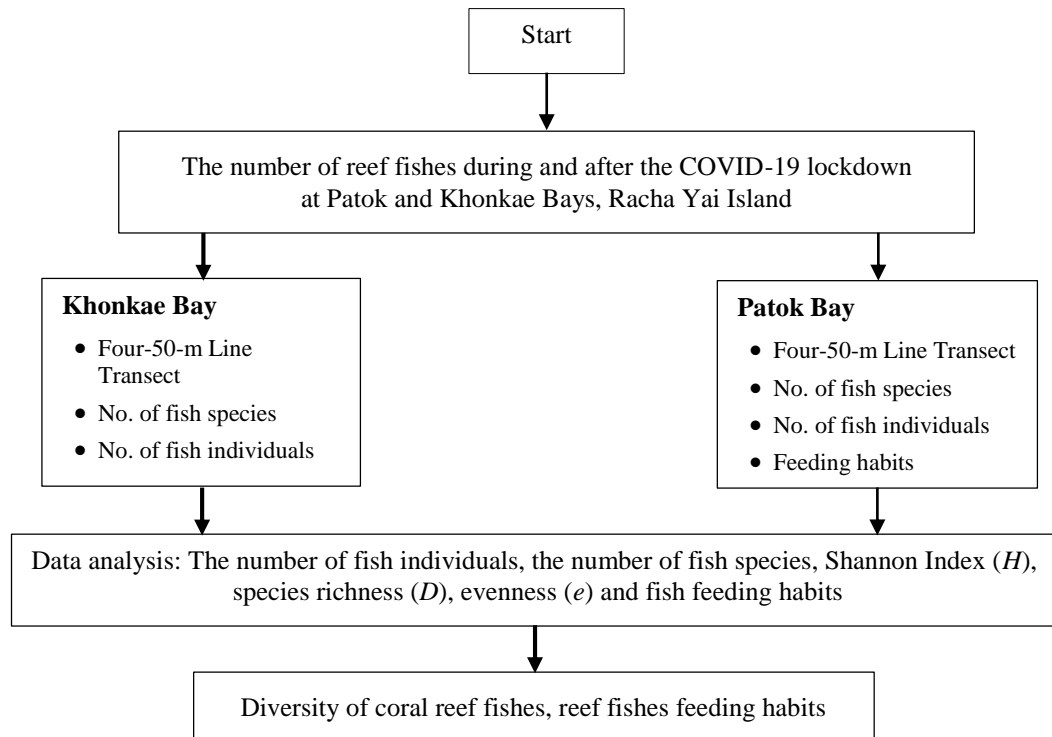


Figure 1. (a) Fish visual census method along 50-m transect lines; and (b) Reef fish and coral at Patok Bay, Southern Thailand



**Figure 2. A proposed method for investigating reef fish diversity at Racha Island, Southern Thailand during and after the COVID-19 lockdown**

In this study, we used the same three permanent transect lines at Patok Bay, and four permanent transect lines at Khonkae Bay to monitor changes in the percent of live coral cover with the permanent quadrat method. We took underwater photographs of 50×50 cm<sup>2</sup> quadrat at 2 m intervals, for a total of 25 photographs per 50 m transect line, to estimate the percentage of live coral cover in each transect line. The photographs were analyzed using CPCe software developed by the National Coral Reef Institute. Percent benthic cover in each quadrat was estimated from 200 randomly distributed points using CPCe software, with quadrat data pooled for each transect and averaged across transects at each measurement period. We categorized the benthic cover into four main groups: (1) live coral, (2) dead coral, (3) pavement, rubble, and sand, and (4) macro-algae and others.

### 2.3. Data Analysis

The Shannon index,  $H = -\sum P_i \ln P_i$  [12], Margalef's richness index,  $D = (s - 1)/\ln N$  [12], and Pielou's evenness index,  $e = H/\ln S$  [34, 35] were used to measure the fish diversity.  $H$  was the diversity index.  $P_i$  was the relative abundance ( $S/N$ ).  $D$  was the richness index.  $S$  was the number of individuals for each species.  $N$  was the total number of fish per transect line.  $e$  was the evenness index. It was the natural logarithm.  $S$  was the total number of species. Parametric statistics were used when normality or other assumptions of parametric tests were met. Two-way ANOVA tests with post-hoc Bonferroni adjustment were used to test bays, fish trophic functional groups and their interactions during the spans of COVID-19 events during 2018-2021. Linear regression analyses between the number of coral reef fish, number of fish species, Shannon diversity ( $H$ ), species richness ( $D$ ), evenness ( $e$ ), and fish feeding habits and years were tested. All tests were two-tailed with a significance level of  $P < 0.05$ .

## 3. Results

### 3.1. Coral Cover Changes during 2018-2021

The percentage of live coral cover at both Khonkae Bay and Patok Bay was positively associated with the years during 2018-2021, (Linear regression: Khonkae Bay:  $R^2 = 0.992$ ,  $F_{1,2} = 239.403$ ,  $Y_{KK} = 0.393x + 2010.182$ ,  $P < 0.05$ ; Patok Bay:  $R^2 = 0.953$ ,  $F_{1,2} = 40.993$ ,  $Y_{PT} = 0.473x + 2005.639$ ,  $P < 0.05$ , Figures 3-a and 3-b). The percentage of dead coral cover at both Khonkae Bay and Patok Bay was negatively associated with the years during 2018-2021, (Linear regression: Khonkae Bay:  $R^2 = 0.970$ ,  $F_{1,2} = 64.380$ ,  $Y_{KK} = -0.450x + 2040.751$ ,  $P < 0.05$ ; Patok Bay:  $R^2 = 0.963$ ,  $F_{1,2} = 52.424$ ,  $Y_{PT} = -0.810x + 2046.253$ ,  $P < 0.05$ , Figures 3-c and 3-d).

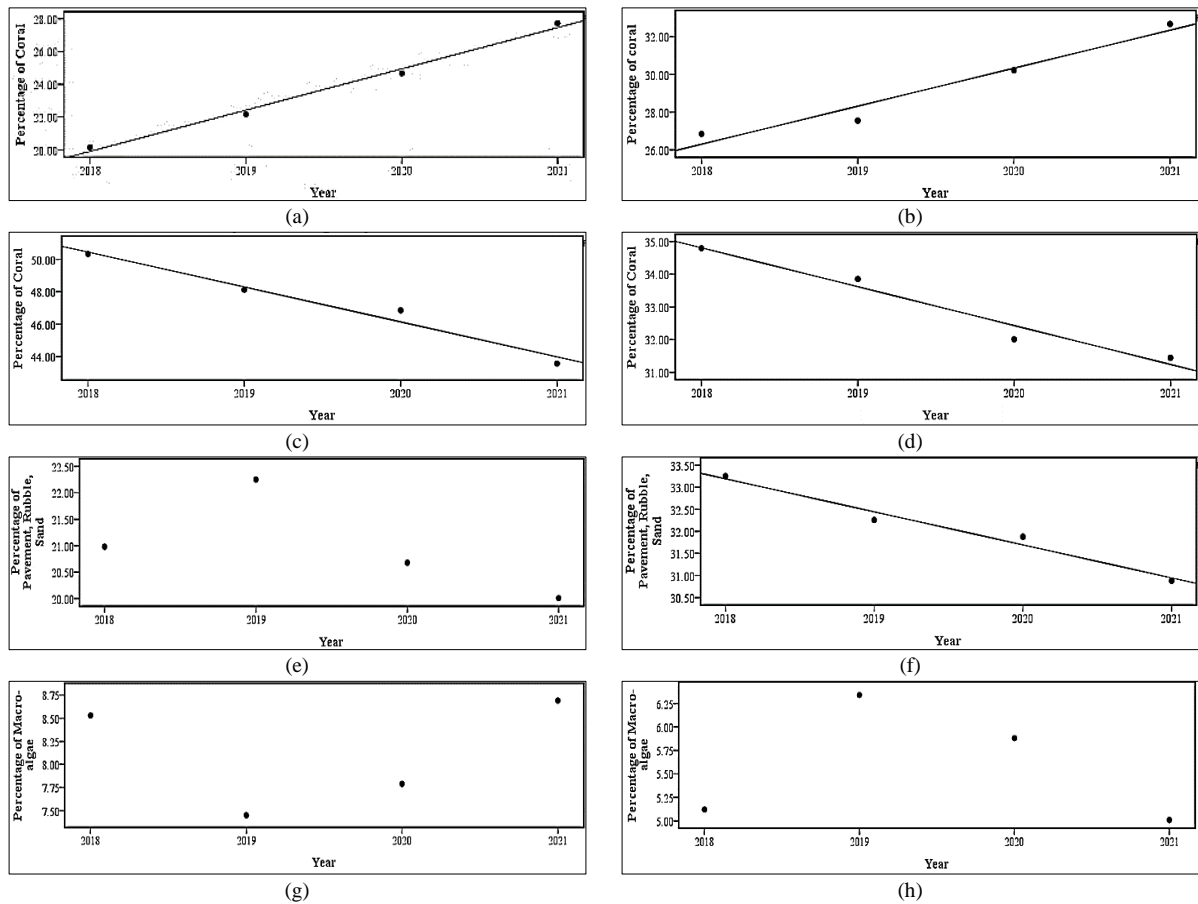


Figure 3. Percentage of live coral cover at two study sites at Khonkhae Bay and Patok Bay at, Racha Yai Island, Southern Thailand during 2018-2021. (a, b) Percentage of live coral; (c, d) Percentage of dead coral; (e, f) Percentage of pavement, rubble, sand, and (g, h) Percentage of macro algae.

### 3.2. Fish Diversity Changes during 2018-2021

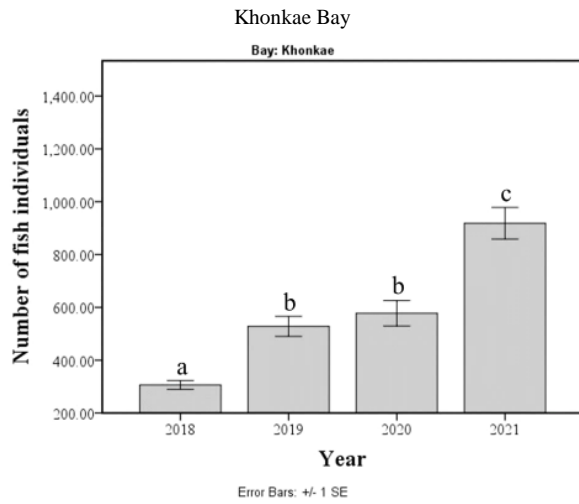
At Khonkhae Bay during 2018-2021, there were 69 reef fish species and 9,320 individual fish belonging to 7 orders, with 26 families and 57 genera observed. There were reef fish from seven orders: Perciformes (90.88%), Tetraodontiformes (6.04%), Syngnathiformes (1.12%), Beloniformes (0.30%), Beryciformes (1.25%), Scorpaeniformes (0.25%), and Aulopiformes (0.16%). The top three reef fish families were Pomacentridae, Labridae, and Serranidae (Table 1).

At Patok Bay during 2018-2021, there were 77 reef fish species and 12,003 individual fish belonging to 6 orders, with 25 families and 54 genera observed. There were reef fish from six orders: Perciformes (91.95%), Tetraodontiformes (5.92%), Beryciformes (1.09%), Anguilliformes (0.55%), Aulopiformes (0.55%), and Scorpaeniformes (0.55%). The list of families that had the top three species composition in the coral reef areas included Pomacentridae, Labridae, and Chaetodontidae (Table 1).

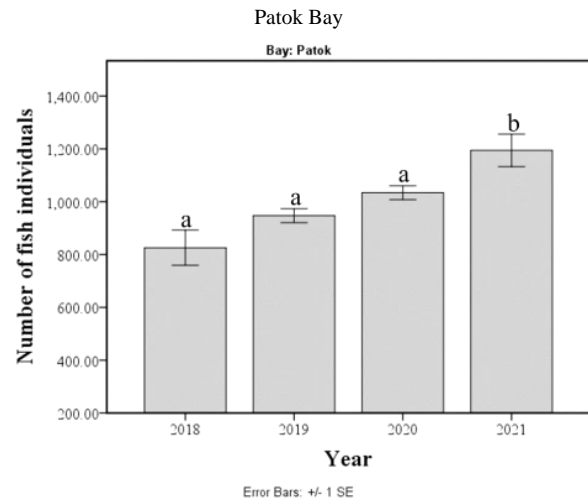
Table 1. Percentage of fish orders at Khonkhae Bay and Patok Bay, Southern Thailand during 2018-2021

Fish Order	Khonkhae Bay				Patok Bay			
	2018	2019	2020	2021	2018	2019	2020	2021
Perciformes	91.15	90.70	91.50	91.70	94.85	94.90	92.89	94.31
Tetraodontiformes	6.19	6.70	6.70	4.20	5.15	2.00	2.00	2.00
Syngnathiformes	0.88	1.00	0.70	1.70	-	3.10	-	2.10
Beloniformes	0.88	-	-	1.50	-	-	-	-
Beryciformes	-	0.90	0.50	-	-	-	1.15	-
Scorpaeniformes	0.88	0.40	0.40	0.40	-	-	1.48	-
Anguilliformes	-	-	-	-	-	-	1.59	1.59
Aulopiformes	-	0.40	0.20	0.50	-	-	0.89	-

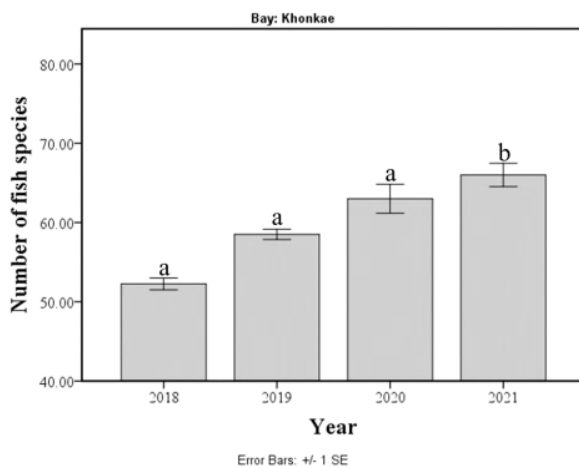
Comparing the number of fish observed at both bays, Patok Bay ( $\bar{x} \pm \text{SD}$ :  $1028.58 \pm 49.22$ ) had a higher number of fishes than Khonkae Bay; the number of fish in 2018 was lower than in 2021 at both bays with no interaction between bays and years ( $\bar{x} \pm \text{SD}$ :  $582.50 \pm 59.84$ ) (Two-way ANOVA: bays:  $F_{1,20} = 143.584$ ,  $P < 0.001$ ; years:  $F_{3,20} = 29.001$ ,  $P < 0.001$ , interaction:  $F_{3,20} = 2.953$ ,  $ns$ ; Figures 4-a and 4-b). Bonferroni's posthoc tests showed that at Khonkae Bay, the number of individual fish was the lowest in 2018, followed by 2019 and 2020, and the highest was in 2021 (Figure 4-a). At Patok Bay, the number of individual fish in 2018-2020 was lower than in 2021 (Figure 4-b)



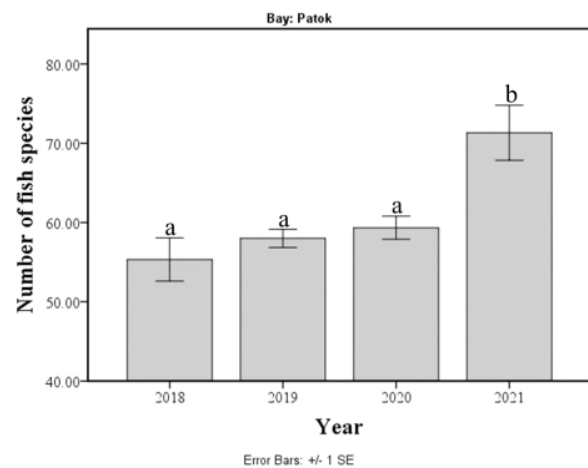
(a)



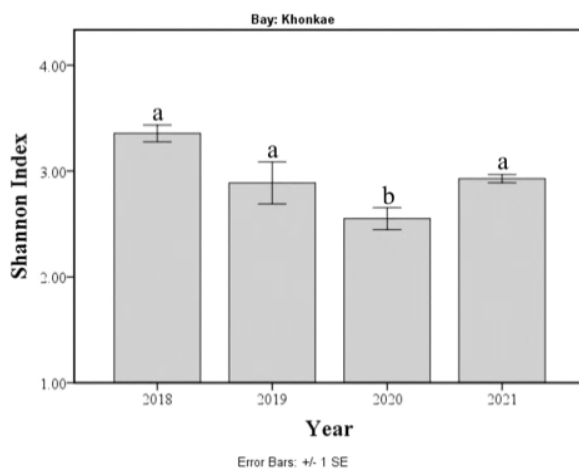
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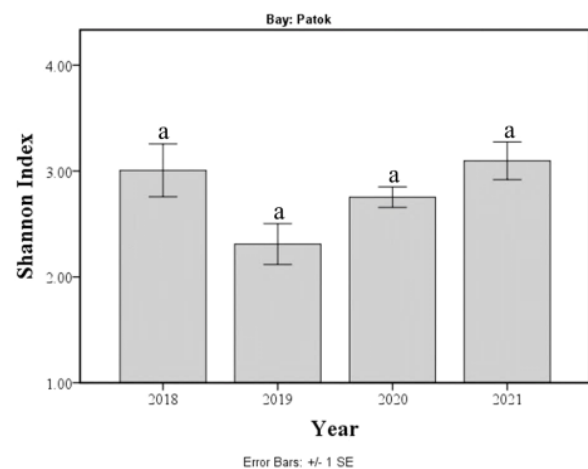
(c)



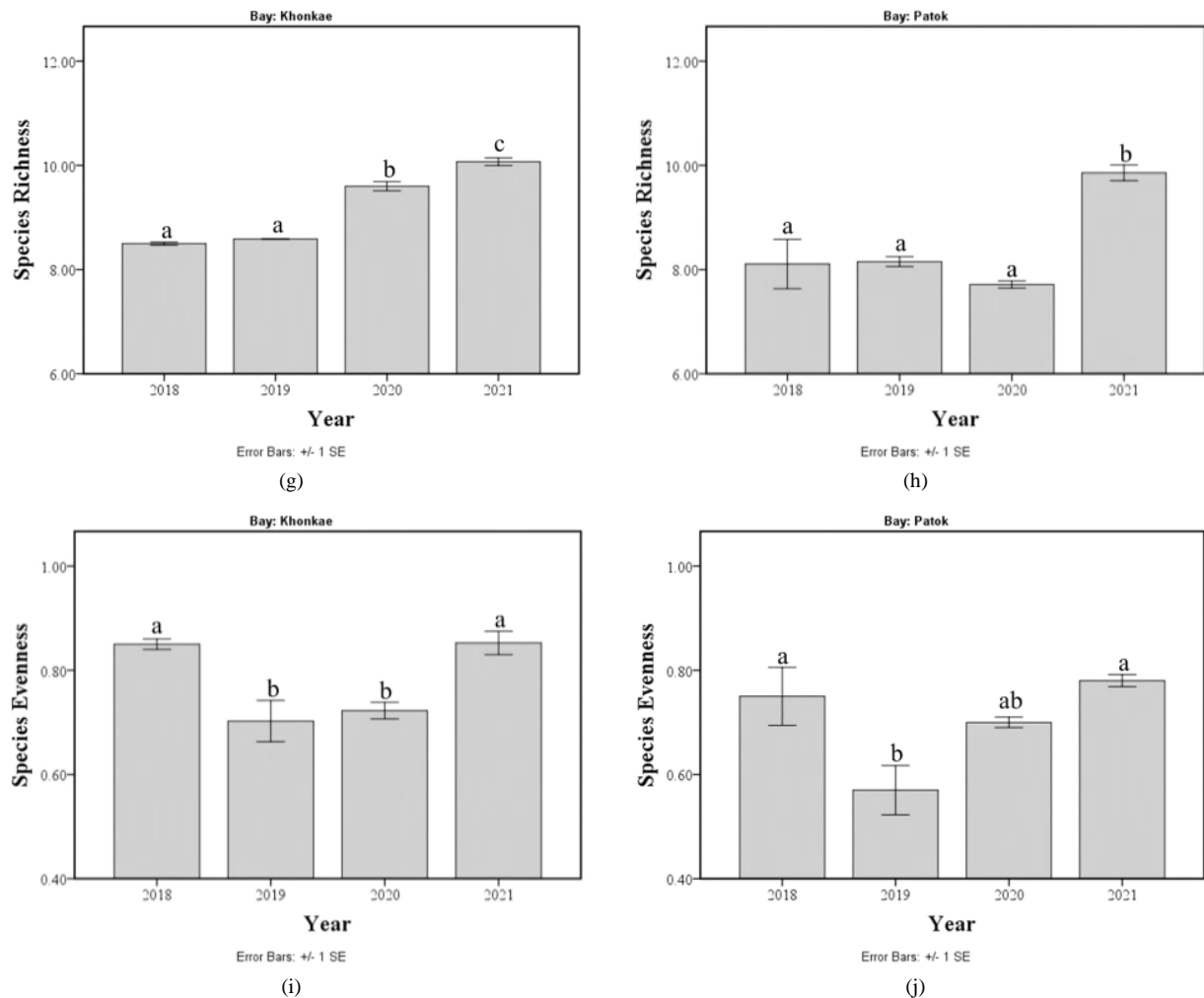
(d)



(e)



(f)



**Figure 4. Fish species, diversity, species richness, and evenness at Khonkai Bay and Patok Bay during 2018-2021 following the COVID-19 event. (a, b) Number of individual fish, (c, d) Number of fish species, (e, f) Shannon index, (g, h) Species richness, and (i, j) Species evenness.**

The number of fish species did not differ between bays but the number of fish species in 2018 was lower than in 2021 at both bays with no interaction between bays and years (Two-way ANOVA: bays:  $F_{1,20} = 0.343$ ,  $ns$ ; year:  $F_{3,20} = 10.228$ ,  $P < 0.001$ , interaction:  $F_{3,20} = 0.889$ ,  $ns$ ; Figures 4-c, and 4-d). Bonferroni's posthoc tests showed that the number of fish species at both bays in 2018-2020 was lower than in 2021 (Figures 4-c and 4-d).

The Shannon index did not differ between bays but the Shannon index in 2018 was higher than in 2021 at both bays and there was an interaction between bays and years (Two-way ANOVA: bays:  $F_{1,20} = 1.701$ ,  $ns$ ; years:  $F_{3,20} = 7.044$ ,  $P < 0.05$ , interaction:  $F_{3,20} = 3.321$ ,  $P < 0.05$ ; Figures 4-e and 4-f). Bonferroni's posthoc tests showed that the Shannon index at Khonkai Bay in 2020 was lower than in other years (Figure 4-e); the Shannon index at Patok Bay in 2019 was lower than in other years (Figure 4-f).

The species richness at Khonkai Bay was higher than at Patok Bay, and the species richness during 2018-2020 was lower than in 2021 at both bays and there was an interaction between bays and years (Two-way ANOVA: bays:  $F_{1,20} = 49.415$ ,  $P < 0.001$ ; year:  $F_{3,20} = 12.541$ ,  $P < 0.001$ , interaction:  $F_{3,20} = 4.257$ ,  $P < 0.05$ ; Figure 4-g and 4-h). Bonferroni's posthoc tests showed that the species richness at Khonkai Bay was lowest in 2018-2019, higher in 2020, and highest in 2021 (Figure 4-g); the species richness at Patok Bay in 2021 was higher than in other years (Figure 4-h).

The species evenness at Khonkai Bay was higher than at Patok Bay, and the species evenness in 2018 and 2021 was higher than in 2019-2020 at both bays with no interaction between bays and years (Two-way ANOVA: bays:  $F_{1,20} = 14.680$ ,  $P < 0.001$ ; years:  $F_{3,20} = 15.330$ ,  $P < 0.001$ , interaction:  $F_{3,20} = 1.187$ ,  $ns$ ; Figures 4-i and 4-j). Bonferroni's posthoc tests showed that the species evenness at Khonkai Bay in 2018 and 2021 was higher than in 2019-2020 (Figure 4-i); the species evenness at Patok Bay in 2019 was lower than in 2018 and 2021 (Figure 4-j).

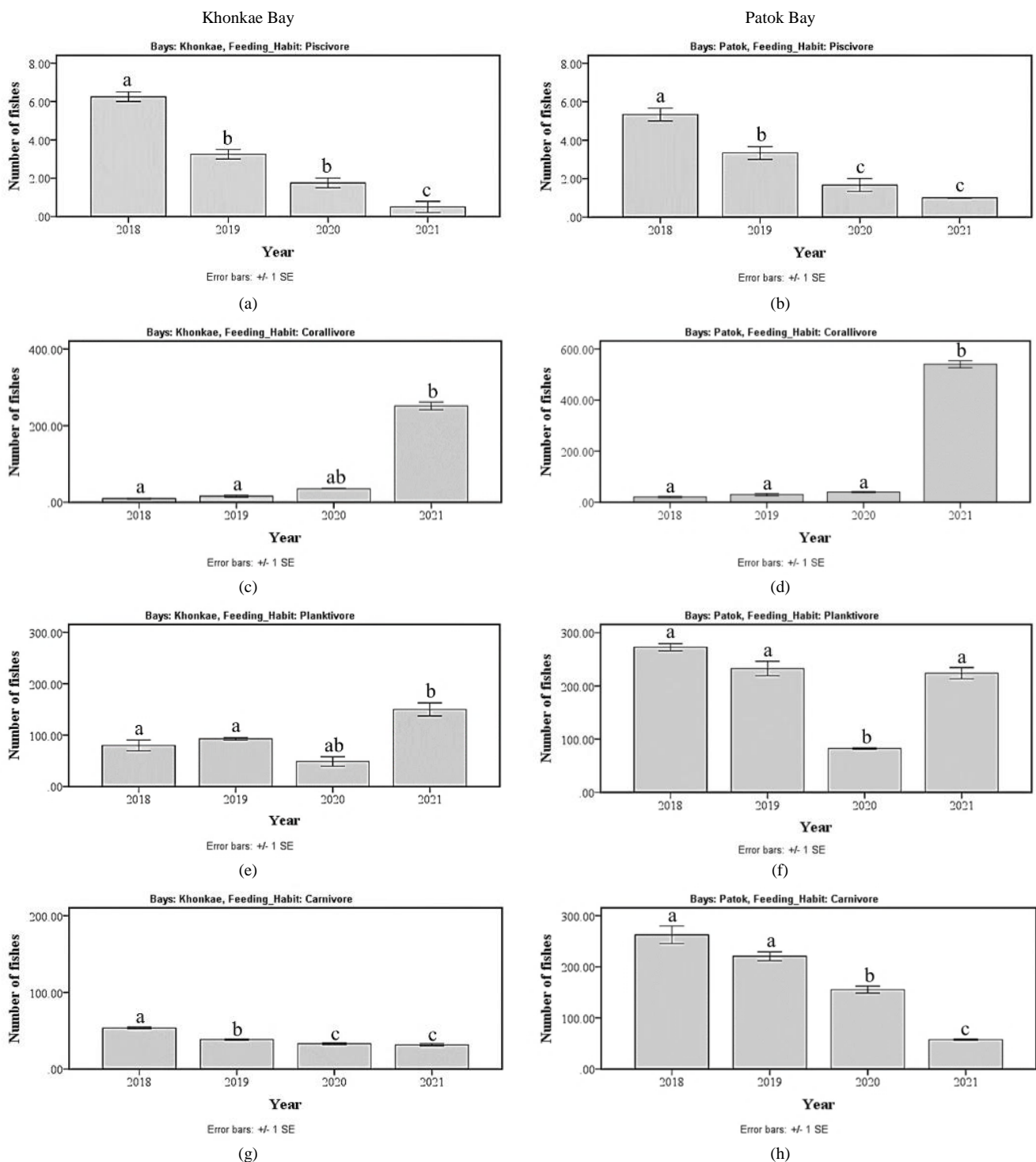
### 3.3. Fish Feeding Habit Changes during 2018-2021

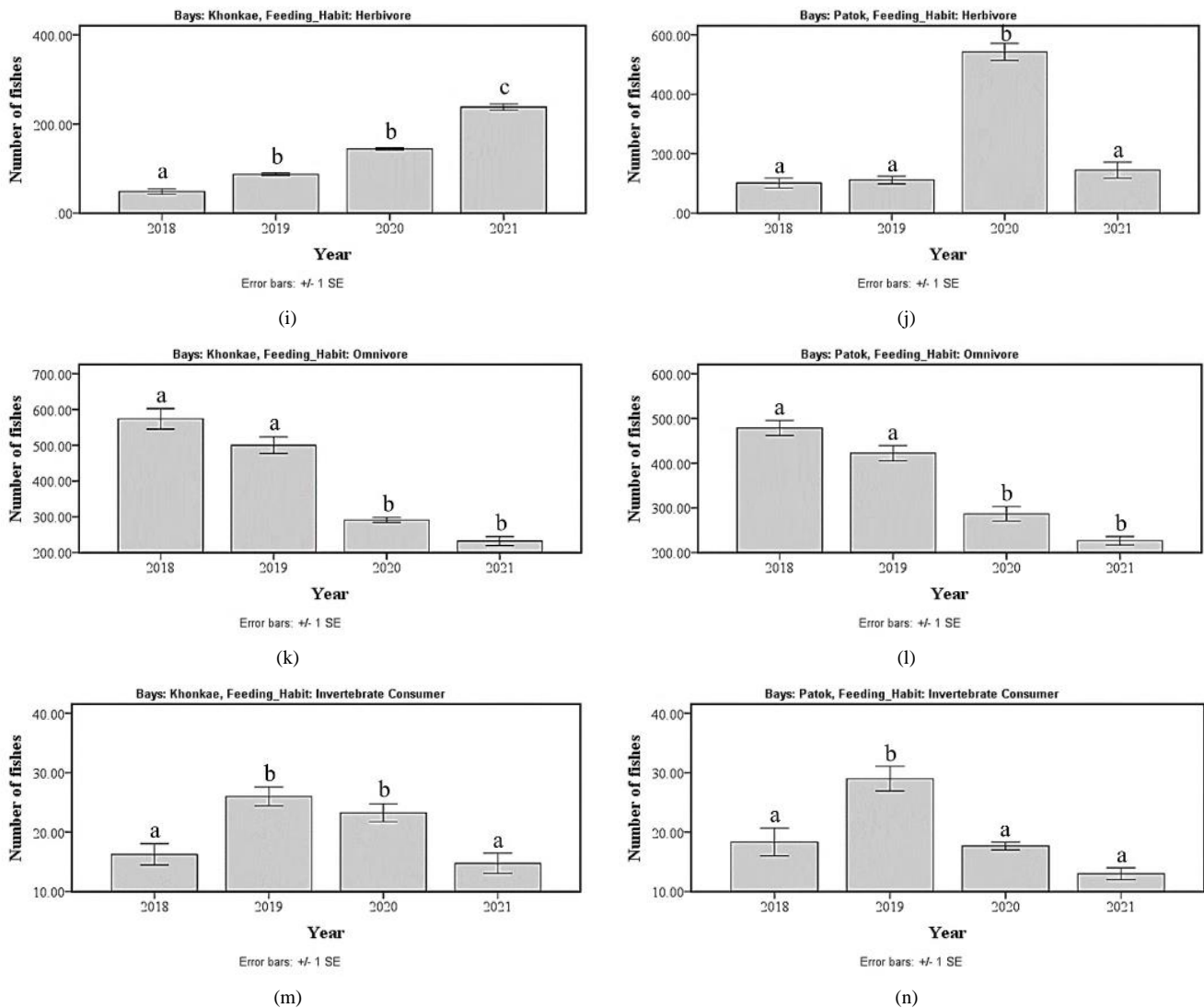
From the seven trophic functional groups, Patok Bay had higher numbers of planktivore and carnivore fish than Khonkai Bay and the other five trophic functional groups did not differ between both bays: piscivore ( $\bar{x} \pm SD_{KK}$ :



$2.94 \pm 2.26$ ;  $\bar{x} \pm \text{SD}_{\text{PT}}: 2.83 \pm 1.80$ ;  $t_{26} = -0.131$ ; *ns*), corallivore ( $\bar{x} \pm \text{SD}_{\text{KK}}: 77.88 \pm 104.41$ ;  $\bar{x} \pm \text{SD}_{\text{PT}}: 157.503 \pm 231.23$ ;  $t_{14.375} = 1.111$ ; *ns*), planktivore ( $\bar{x} \pm \text{SD}_{\text{KK}}: 92.88 \pm 41.53$ ;  $\bar{x} \pm \text{SD}_{\text{PT}}: 203.00 \pm 76.29$ ;  $t_{15.858} = 4.523$ ;  $P < 0.001$ ), carnivore ( $\bar{x} \pm \text{SD}_{\text{KK}}: 39.13 \pm 9.27$ ;  $\bar{x} \pm \text{SD}_{\text{PT}}: 174.00 \pm 82.29$ ;  $t_{11.210} = 5.651$ ;  $P < 0.001$ ), herbivore ( $\bar{x} \pm \text{SD}_{\text{KK}}: 129.38 \pm 74.26$ ;  $\bar{x} \pm \text{SD}_{\text{PT}}: 224.92 \pm 108.22$ ;  $t_{13.404} = 1.611$ ; *ns*), omnivore ( $\bar{x} \pm \text{SD}_{\text{KK}}: 399.25 \pm 150.61$ ;  $\bar{x} \pm \text{SD}_{\text{PT}}: 353.42 \pm 108.22$ ;  $t_{25.975} = -0.937$ ; *ns*), and invertebrate consumer ( $\bar{x} \pm \text{SD}_{\text{KK}}: 20.06 \pm 5.67$ ;  $\bar{x} \pm \text{SD}_{\text{PT}}: 19.50 \pm 6.60$ ;  $t_{21.691} = -0.237$ ; *ns*).

The number of piscivore ( $\bar{x} \pm \text{SE}_{\text{KK}}: 2.94 \pm 0.13$ ;  $\bar{x} \pm \text{SE}_{\text{PT}}: 2.83 \pm 0.15$ ) and invertebrate consumer ( $\bar{x} \pm \text{SE}_{\text{KK}}: 20.06 \pm 0.79$ ;  $\bar{x} \pm \text{SE}_{\text{PT}}: 19.50 \pm 0.91$ ) fish did not differ between bays but the number of piscivore fish differed among years with no interaction between bays and years (Two-way ANOVA for piscivore fish: bays:  $F_{1,20} = 0.283$ , *ns*; years:  $F_{3,20} = 126.754$ ,  $P < 0.001$ , interaction:  $F_{3,20} = 2.309$ , *ns*; Figure 5a,b; Two-way ANOVA for invertebrate consumer fish: bays:  $F_{1,20} = 0.220$ , *ns*; year:  $F_{3,20} = 23.396$ ,  $P < 0.001$ , interaction:  $F_{3,20} = 2.679$ , *ns*; Figures 5-m, and 5-n). Bonferroni's posthoc tests showed that the number of piscivore fish was highest in 2018, followed by 2019-2020; and the lowest was in 2021 at both bays (Figures 5-a, and 5-b). The number of invertebrate consumer fish in 2019 was higher than in other years at both bays (Figures 5-m, and 5-n).





**Figure 5. Feeding habits of fish at Khonkhae Bay and Patok Bay during 2018-2021 following the COVID-19 event: (a-b) Piscivore, (c-d) Corallivore, (e-f) Planktivore, (g-h) Carnivore, (i-j) Herbivore, (k-l) Omnivore, and (m-n) Invertebrate consumer.**

The number of corallivore, planktivore, carnivore, herbivore and omnivore fish differed between bays, years, and its interaction (Two-way ANOVA for corallivore fish: bays:  $F_{1,20} = 328.963$ ,  $P < 0.001$ ; years:  $F_{3,20} = 1,789.660$ ,  $P < 0.001$ , interaction:  $F_{3,20} = 252.521$ ,  $P < 0.001$ ; Figures 5c and 5-d; Two-way ANOVA for planktivore fish: bays:  $F_{1,20} = 259.005$ ,  $P < 0.001$ ; years:  $F_{3,20} = 66.292$ ,  $P < 0.001$ , interaction:  $F_{3,20} = 26.364$ ,  $P < 0.001$ ; Figures 5e and 5-f; Two-way ANOVA for carnivore fish: bays:  $F_{1,20} = 970.866$ ,  $P < 0.001$ ; years:  $F_{3,20} = 128.090$ ,  $P < 0.001$ , interaction:  $F_{3,20} = 88.074$ ,  $P < 0.001$ ; Figures 5-g and 5-h; Two-way ANOVA for herbivore fish: bays:  $F_{1,20} = 95.839$ ,  $P < 0.001$ ; years:  $F_{3,20} = 155.436$ ,  $P < 0.001$ , interaction:  $F_{3,20} = 117.597$ ,  $P < 0.001$ ; Figures 5-i and 5-j; Two-way ANOVA for omnivore fish: bays:  $F_{1,20} = 11.849$ ,  $P < 0.001$ ; years:  $F_{3,20} = 111.002$ ,  $P < 0.001$ , interaction:  $F_{3,20} = 3.183$ ,  $P < 0.05$ ; Figures 5-k and 5-l). Bonferroni's posthoc tests showed that the number of corallivore ( $\bar{x} \pm SE_{KK}$ :  $77.88 \pm 2.87$ ;  $\bar{x} \pm SE_{PT}$ :  $157.50 \pm 3.32$ ), planktivore ( $\bar{x} \pm SE_{KK}$ :  $92.88 \pm 4.48$ ;  $\bar{x} \pm SE_{PT}$ :  $203.00 \pm 5.17$ ), carnivore ( $\bar{x} \pm SE_{KK}$ :  $39.13 \pm 2.83$ ;  $\bar{x} \pm SE_{PT}$ :  $174.00 \pm 3.27$ ), and herbivore ( $\bar{x} \pm SE_{KK}$ :  $129.38 \pm 6.39$ ;  $\bar{x} \pm SE_{PT}$ :  $224.92 \pm 7.38$ ) fish at Khonkhae Bay was lower than at Patok Bay; but the number of omnivore fish ( $\bar{x} \pm SE_{KK}$ :  $399.25 \pm 8.72$ ;  $\bar{x} \pm SE_{PT}$ :  $353.42 \pm 10.07$ ) at Khonkhae Bay was higher than at Patok Bay. The number of corallivore and planktivore fish in 2021 at Khonkhae Bay was higher than in other years but the number of planktivore fish in 2020 at Patok Bay was lower than in other years (Figures 5-c and 5-f). The number of carnivore fish was highest in 2018, followed by 2019-2020; and the lowest was in 2021 at both bays (Figures 5-g and 5-h). The number of herbivore fish was lowest in 2018, followed by 2019-2020; and the highest was in 2021 at Khonkhae Bay but the number of herbivore fish was higher than in other years in 2020 (Figures 5-i and 5-j).

There were 12 corallivore species found at Khonkhae Bay, and 21 corallivore species found at Patok Bay, with a total of 24 corallivore species. There were 11 corallivore species found at both bays belonging to the Chaetodontidae and Pomacentridae families (i.e., *Chaetodon andamanensis*, *C. lunula*, *C. rafflesii*, *C. auriga*, *C. collare*, *C. lineolatus*,



*C. triangulum*, *C. trifasciatus*, *C. vagabundus*, *Heniochus singularius*, and *Pomacanthus imperator*). Of all 11 corallivore species found at both bays, there were four species that were found to have a greater increase in numbers (i.e. *C. collare*, *C. rafflesi*, *C. trifasciatus* and *Chrysiptera rollandi*) (Table 2). There were nine corallivore species that were only found at Patok Bays where the percentage of live coral cover was higher with less human activities (i.e., *Anampses meleagrides*, *Cephalopholis formosa*, *Cetoscarus bicolor*, *C. decussatus*, *C. meyeri*, *C. trifascialis*, *Cheilinus trilobatus*, *Heniochus acuminatus*, and *Labrichthys unilineatus*).

**Table 2. Fish feeding habits and the number of individual fish changed between pre-COVID (in 2018) and post-COVID (in 2021) at Khonkhae Bay and Patok Bay. +/- represents the number of individual fish that increased and decreased between 2018 and 2021.**

Fish Feeding Habit	Fish species	Numbers of fish individuals at Khonkhae Bay		Numbers of fish individuals at Patok Bay	
		2018	2021	2018	2021
Corallivore	(+) <i>Chaetodon collare</i>	4	27	15	22
	(+) <i>Chaetodon rafflesi</i>	0	2	0	6
	(+) <i>Chaetodon trifasciatus</i>	2	14	0	41
Planktivore	(+) <i>Caesio caeruleaurea</i>	30	73	10	53
	(+) <i>Dascyllus carneus</i>	0	18	0	40
	(+) <i>Pempheris schwenkii</i>	85	175	0	20
Herbivore	(+) <i>Chromis weberi</i>	0	100	0	200
	(+) <i>Plectroglyphidodon lacrymatus</i>	4	16	0	60
	(+) <i>Scarus niger</i>	4	12	25	30
	(+) <i>Scarus quoyi</i>	1	4	1	13
Piscivore	(-) <i>Epibulus insidiator</i>	2	0	6	0
	(-) <i>Epinephelus fuscoguttatus</i>	1	0	6	0
	(-) <i>Epinephelus malabaricus</i>	2	0	2	0
	(-) <i>Synodus variegatus</i>	1	0	1	0
Carnivore	(-) <i>Lutjanus fulviflamma</i>	2	1	10	0
	(-) <i>Scolopsis ciliatus</i>	22	3	40	3
Omnivore	(-) <i>Abudefduf sordidus</i>	51	0	20	0
	(-) <i>Abudefduf vaigiensis</i>	84	21	27	13
	(-) <i>Amblyglyphidodon indicus</i>	30	0	6	0
Invertebrate Consumer	(-) <i>Balistapus undulatus</i>	20	1	2	0
	(-) <i>Parupeneus pleurostigma</i>	2	0	2	0

There were 17 planktivore species found at Khonkhae Bay, and 20 planktivore species found at Patok Bay with a total of 29 planktivore species. There were eight planktivore species that were found at both bays belonging to the Acanthuridae, Blenniidae, Pempheridae and Pomacentridae families (i.e., *Dascyllus carneus*, *D.s trimaculatus*, *Ecsenius bicolor*, *Meiacanthus smithi*, *Naso brevirostris*, *N. thynnoides*, *Pempheris schwenkii*, *P. vanicolensis*). Of all nine planktivore species, there were four species that were found to have a greater increase in numbers (i.e. *Caesio caeruleaurea*, *Dascyllus carneus*, *Pempheris schwenkii* and *Pomacentrus lepidogenys*) (Table 2). There were eight planktivore species that were only found at Patok Bay (i.e., *Caesio caeruleaurea*, *C. cuning*, *C. lunaris*, *Chromis xanthochira*, *Naso Rachycentron*, *Pomacentrus lepidogenys*, *Pterocaesio chrysozona*, and *Scarus rubroviolaceus*).

There were 34 herbivore species found at Khonkhae Bay, and 32 herbivore species found at Patok Bay with a total of 41 herbivore species. There were 19 herbivore species that were found at both bays belonging to the Acanthuridae, Labridae, Pomacentridae, Scaridae and Siganidae families (i.e., *Acanthurus leacosternon*, *A. lineatus*, *A. nigricauda*, *A. tristis*, *Bodianus mesothorax*, *Chlorurus capistratoides*, *C. sordidus*, *C. troschellii*, *Chromis dimidiatus*, *C. flavipectoralis*, *C. opercularis*, *C. weberi*, *Ctenochaetus binotatus*, *C. striatus*, *Plectroglyphidodon lacrymatus*, *Scarus ghobbon*, *S. niger*, *S. quoyi*, *S. scaber* and *S. prasiognathos*). Of all 19 herbivore species, there were four species that were found to have a greater increase in numbers (i.e. *Chromis weberi*, *Plectroglyphidodon lacrymatus*, *Scarus niger* and *S. quoyi*) (Table 2). There were seven herbivore species that were only found at Patok Bays (i.e., *Bodianus diana*, *B. nielli*, *Chromis viridis*, *C. ternatensis*, *Dischistodus perspicillatus*, *Pomacentrus chrysurus* and *Stegastes obrepus*).

There were eight piscivore species found at Khonkhae Bay, and five piscivore species found at Patok Bay with a total of nine piscivore species. There were nine piscivore species that were found at both bays belonging to the Echeneidae, Labridae, Lethrinidae, Serranidae and Synodontidae families (i.e., *Diploprion bifasciatum*, *Echeneis naucratis*, *Epibulus insidiator*, *Epinephelus caeruleopunctatus*, *E. fuscoguttatus*, *E. malabaricus*, *Gomphosus caeruleus*, *Gnathodentex aurolineatus* and *Synodus variegatus*). Of all four piscivore species, there were four species that were found to have a decrease in number (i.e. *Epibulus insidiator*, *Epinephelus fuscoguttatus*, *E. malabaricus* and *Synodus variegatus*) (Table 2). One piscivore species was only found at Patok Bay (i.e., *Gomphosus caeruleus*).

There were 53 carnivore species found at Khonkhae Bay, and 44 carnivore species found at Patok Bay with a total of 66 carnivore species. There were 31 carnivore species that were found at both bays belonging to the Apogonidae, Balistidae, Carangidae, Kyphosidae, Labridae, Lethrinidae, Monacanthidae, Muraenidae, Pomacentridae, Serranidae and Tetraodontidae families (i.e., *Aethaloperca rogaa*, *Arothron nigropunctatus*, *A. stellatus*, *Balistoides viridescens*, *Caranx heberi*, *Cantherhines pardalis*, *Cephalopholis miniatum*, *C. argus*, *C. formosa*, *C. polyspila*, *Cheilodipterus macrodon*, *C. quinquelineatus*, *Coris cuvieri*, *C. batuensis*, *Gymnothorax javanicus*, *Halichoeres argus*, *H. scapularis*, *H. timorensis*, *H. vrolikii*, *Hemiglyphidodon plagiometopon*, *Hemigymnus melapterus*, *H. fasciatus*, *Kyphosus vaigiensis*, *Labroides bicolor*, *L. dimidiatus*, *Lethrinus croceus*, *L. lentjan*, *L. ornatus*, *Lutjanus biguttatus*, *L. decussatus*, *L. fulviflamma*, *L. fulvus*, *L. quinquelineatus*, *Ostorhinchus cyanosoma*, *Oxycheilinus digrammus*, *Parapercis hexophthalma*, *P. clathrata*, *Parupeneus barberinus*, *Parupeneus cyclostomus*, *Parupeneus macronema*, *Plectorhinchus vittatus*, *Pteocaesio chrysozona*, *Pterois antennata*, *Scolopsis ciliatus*, *S. monogramma*, *S. xenochroa*, *Scorpaenopsis diabolus*, *Stethojulis interrupta*, *S. trilineata*, *Sufflamen chrysopteron*, *Thalassoma lunare*, *Tylosurus acus*, and *Upeneus tragula*). Of all 31 carnivore species, there were two species that were found to have a greater decrease in numbers (i.e. *Lutjanus fulviflamma* and *Scolopsis ciliatus*) (Table 2). There were 13 carnivore species that were only found at Patok Bay (i.e., *Aulostomus chinensis*, *Bodianus axillaris*, *Cheilodipterus macrodon*, *Cirrhitilabrus cyanopleura*, *Kyphosus incisor*, *Lethrinus olivaceus*, *Ostracion meleagris*, *Parupeneus indicus*, *Pseudocheilinus evanidus*, *P. hexataenia*, *Scolopsis bilineatus*, *S. lineata*, and *Sphyrna obtusata*).

There were 27 omnivore species found at Khonkhae Bay, and 19 omnivore species found at Patok Bay, with a total of 30 omnivore species. There were 16 omnivore species found at both bays belonging to Acanthuridae, Gobiidae, Holocentridae, Labridae, Ostraciidae, Pomacanthidae and Pomacentridae families (i.e., *Abudefduf sordidus*, *A. notatus*, *A. vaigiensis*, *Acanthurus xanthopterus*, *Amblyglyphidodon indicus*, *A. leucogaster*, *Amblygobius hectori*, *Canthigaster solandri*, *Calotomus carolinus*, *Centropyge eibli*, *C. multispinus*, *Dischistodus perspicillatus*, *Macropharyngodon ornatus*, *Myripristis murdjan*, *Neoglyphidodon nigroris*, *Neopomacentrus cyanomos*, *N. sororius*, *Ostracion cubicus*, *O. meleagris*, *Pomacentrus amboinensis*, *P. chrysurus*, *P. lepidogenys*, *P. pavo*, *P. philippinus*, *P. similis*, *P. adelus* and *P. moluccensis*). Of all 16 omnivore species, there were three species that were found to have a decrease in number (i.e. *Abudefduf sordidus*, *A. vaigiensis*, and *Amblyglyphidodon indicus*) (Table 2). There were three omnivore species that were only found at Patok Bay (i.e., *Melichthys indicus*, *Ostorhinchus cyanosoma* and *Plectorhinchus vittatus*).

There were 22 invertebrate consumer species found at Khonkhae Bay, and 21 invertebrate consumer species found at Patok Bay with a total of 30 invertebrate consumer species. There were eight invertebrate consumer species that were found at both bays belonging to the Balistidae, Labridae, Mullidae, Siganidae and Zanclidae families (i.e., *Balistapus undulatus*, *Cheilinus chlorourus*, *Halichoeres hortulanus*, *H. marginatus*, *Mulloidichthys vanicolensis*, *Parupeneus pleurostigma*, *Siganus puelloides*, and *Zanclus cornutus*). Of all eight invertebrate consumer species, there were two species that were found to have a greater decrease in numbers (i.e. *Balistapus undulatus* and *Parupeneus pleurostigma*) (Table 2). There were eight invertebrate consumer species that were only found at Patok Bay (i.e., *Cheilinus fasciatus*, *Coris cuvieri*, *Halichoeres scapularis*, *H. timorensis*, *Ostracion cubicus*, *Pseudodax moluccanus*, *Pterois antennata* and *P. miles*).

## 4. Discussion

### 4.1. Coral Cover Changes at Two Bays during 2018-2021

Many studies have reported that human activities cause long-term damage to the habitat leading to local reductions in fish density and species and resulting in lower species richness [36, 37]. Our results clearly showed that the COVID-19 lockdown causing a crucial reduction in human activities on the reef was associated with a significant rise in the percentage of live coral cover at both bays. The majority of coral reef loss or recovery studies has focused on the percentage of live coral cover of key reef species, such as *Acropora* spp. and *Montipora* spp. Examples of coral reef loss and recovery studies include *Acropora palmata* and *Acropora cervicornis* in the Caribbean [38]; *Acropora aspera*, *Acropora cerealis*, *Acropora humilis*, and *Montipora* spp. in the South Andaman Islands [39]; *Acropora* spp. in the Maldives [40]; *Acropora* spp. and *Montipora* spp. in Samoa [41]; *Acropora* spp. in the Great Barrier Reef [42]; and *Acropora* spp. and *Montipora* spp. in Thailand. In addition, our study also showed that the key coral species with a high percentage of live coral recovery after the COVID-19 lockdown at both bays were also *Acropora* spp. and *Montipora* spp. The COVID-19 lockdowns, causing a reduction of human activities on coral reefs, resulted in coral

reef recovery [43].

#### 4.2. Fish Diversity Changes at Two Bays during 2018-2021

Our results showed that the number of individual fish, the number of fish species, and species richness was at their highest in 2021 after three years of the COVID-19 outbreak period at both bays. This is the first published record of the effects of the COVID-19 lockdown on fish diversity in Thailand, and it provides useful baseline information for further studies on the impact of human activities and tourism. This suggests that the sudden removal of human activities related to marine tourism, and fishing had a positive effect on the density and behavior of associated fish populations. Restricting human activities at coral reef sites can minimize the total effects of human disturbances on reef fish. Many studies have also reported that human disturbances may drive some fish species to nearby habitats, and may shift activity times to periods with less human disturbance [44-46].

Our results showed a positive effect of the COVID-19 lockdown on the number of individual fish and species richness during 2018-2021 at both bays. Our data can currently differentiate the impact of the COVID-19 effect between low and high human disturbance reefs; at Patok Bay, the number of individual fish increased from 935 in 2018 to 1,299 in 2021, and at Khonkhae Bay, the number of individual fish increased from 279 in 2018 to 1,033 in 2021. At Patok Bay, the fish species richness increased from 8.11 in 2018 to 9.86 in 2021, and at Khonkhae Bay, the fish species richness increased from 8.50 in 2018 to 10.07 in 2021. In the deeper habitat (i.e. Patok Bay), accessible mostly to scuba divers, we did not find an effect from the COVID-19 lockdown on the number of species, Shannon index, and species evenness. Interestingly, at Khonkhae Bay (a high human disturbance reef with snorkeling, and scuba diving), we did find an effect from the COVID-19 lockdown by observing an increase in the number of individual fish and species richness since 2019. Impacts on the reefs with high human activities are mostly associated with physical breakage of the coral [47-50], causing long-term habitat degradation. In addition, at Patok Bay (a low human disturbance reef), the number of individual fish and species richness did not show any significant increase during 2018-2020. The significant increase in number of individual fish and species richness had significantly increased in 2021. This clearly demonstrated that the COVID-19 lockdown was associated with a significant rise in reef fish diversity in the habitat that received high human activities. The short-term temporal cessation in human activity has similar effects to spatial restrictions. As the COVID-19 lockdown effect was short-term, we have demonstrated that at least some of the human impacts on the reef are reversible and are likely related to fish behavior and an increase in live coral cover [51].

#### 4.3. Fish Feeding Habits Changes at Two Bays during 2018-2021

Our results strongly showed that the COVID-19 lockdown had a positive effect on corallivore fish and coral at both bays as supported by the increase in the number of corallivore fish and the percent of live coral cover since 2018. The majority of the reef fish associated with the live coral was corallivores belonging to Chaetodontidae and Pomacentridae families. At both bays, the majority of corallivore feeding habit groups belonging to the Chaetodontidae family were *Chaetodon collare*, *C. trifasciatus*, and *Chrysiptera rollandi*. Corallivore fish's main diet is centered on live coral [52, 53]. In addition, not all corallivores forage on coral, some are coral-associated fish using coral as shelter. In this study, we found that *Chrysiptera rollandi* belonging to the Pomacentridae family and a coral-associated species also increased in numbers after the COVID-19 lockdown. A majority of the Pomacentridae family are small and territorial, using corals as shelter than as a food resource, and feeding mainly on zooplankton in the water column above branching corals [54-56]. When they are threatened, they retreat within the coral branches for protection.

In this study, we found a high herbivore richness with a total of 42 herbivore species. Herbivores provide resilience to reefs by removing upright macroalgae, keeping macroalgae at low levels and allowing corals to recover [57-59]. Corals have to compete with algae for space and sunlight on the reefs, and herbivorous fish help corals by grazing on the encroaching macroalgae [60-62]. Many studies have indicated that high herbivore richness strongly reduced the cover, biomass, and diversity of algal prey due to species differences in diet selection, spatial impact, and contribution to grazing and bioerosion rates of herbivorous fish [56, 63-67]. For example, redband parrotfish (*Sparisoma aurofrenatum*) forages on upright macroalgae and all common algal species, except for *Kallymenia westii*; princess parrotfish (*Scarus taeniopterus*) forage on turf algae and ocean surgeonfish (*Acanthurus bahianus*) forage on upright macroalgae and on *Dictyota* spp., *Codium* spp., *Haloplegma duperryi*, and *K. westii* [68]. When human activities had been reduced by the COVID-19 lockdown, we found four herbivore species that increased in numbers (i.e. *Chromis weberi*, *Plectroglyphidodon lacrymatus*, *Scarus niger* and *S. quoyi*) at both bays. When we compared between low and high human-disturbed sites, we found seven herbivore species (i.e., *Bodianus diana*, *B. nielli*, *Chromis viridis*, *C. ternatensis*, *Dischistodus perspicillatus*, *Pomacentrus chrysurus* and *Stegastes obreptus*) that were only present at the low human-disturbed site (Patok Bay). This indicated that at the less human-disturbed site, the coral reef would become more resilient due to high herbivore species richness resulting in greater health and higher survival of coral reefs. The COVID-19 lockdown is one of the examples of decreasing human activities on the reef. The decrease in

human activities on the coral reef can cause some changes in fish diversity and its composition. This suggests that limiting recreational activity on the coral reefs is an effective management policy to minimize the total recreational human impacts on coral reefs.

Coral reef-based tourism has risen sharply, especially with a fish feeding at tourist attraction sites [69-72]. Fish feeding is used by tourism operations around the world causing disruptions to distribution patterns, abundances, fish community structure, and fish health [73-77]. Our study is among the first to show that the COVID-19 lockdown in reducing the presence of humans and fish-feeding tourism can cause a reduction of omnivorous fish (e.g. *Abudefduf sordidus*, *A. vaigiensis*, and *Amblyglyphidodon indicus*) at the fish-feeding tourist attraction reefs. The results suggest that decreasing fish feeding tourism promotes a decrease in the abundance of *A. sordidus* and *A. vaigiensis*. Both species are abundant in tropical reefs and are considered to be omnivorous generalists employing opportunistic feeding strategies, making them specifically vulnerable to fish feeding effects. Previous studies have reported that omnivorous *Abudefduf* fish species can change in behavior and spatial distribution, e.g. *A. saxatili*, *A. sexfasciatus*, and *A. sparoides* [78]. *A. sordidus* and *A. vaigiensis* have been reported to be the most abundant species in tourist-feeding reefs in the Indo-Pacific and Thai reefs, and feeding was the primary cause of the increased abundance of these species [45]. Other species of the *Abudefduf* genus also are reported to be the most abundant species in reef feeding areas e.g. *A. sexfasciatus* and *A. sparoides* in the Malindi, Watamu, and Mombasa MPAs in Southeastern Kenya [43]. The COVID-19 lockdown has had an impact on the tourism industry economy by forcing small fishermen to sell their catch at low prices to continue their home life while facing economic downturn. Groupers and snappers are reef fish that have great market value both nationally and internationally. This might force small fishermen to catch more groupers and snappers in order to maintain their reasonable income to sustain their home life. Our results showed that three species of groupers (i.e. *Epinephelus caeruleopunctatus*, *E. fuscoguttatus*, and *E. malabaricus*) and one species of snappers (i.e. *Lutjanus fulviflamma*) decreased in numbers at both bays.

The short-term temporal cessation in human activities has had similar effects to long-term spatial restrictions. As the COVID-19 lockdown effect was short-term, our results indicated that restricted human activities and reduced anthropogenic stress are reversible connections with fish abundance, species richness, and evenness [37]. For example, human disturbances may drive some species to nearby habitats, shift activity times to periods with less human disturbance, or cause some species to hide or inhibit their movement. However, short-term behavioral shifts between high- and low-disturbance sites may not be enough to mitigate the effects of human disturbance. The COVID-19 lockdown may help elucidate the short- and long-term impacts of humans on coral reefs. For example, if human activities cause long-term damage to the habitat, we can expect local reductions in fish density within impacted sites, which is likely to result in lower richness. This reduction in diversity will remain during the short-term cessation of human activities, such as during COVID-19 lockdowns.

## 5. Conclusion

This work aimed to assess coral and reef fish recovery at reefs around Racha Yai Island after the COVID-19 event. The fish surveys from both Khonkhae Bay and Patok Bay were collected in November-December 2018-2019 (before COVID-19), in June 2020 and in February 2021 (after COVID-19), using the fish visual census method along 50-m transect lines. Our study observed excellent live coral recovery after the COVID-19 event in Southern Thailand from both environmental disturbance sites during 2018-2021. The key coral species with a high percentage of live coral recovery after the COVID-19 lockdown in both bays were *Acropora* spp. and *Montipora* spp. This strongly indicated that the COVID-19 lockdown, which caused a crucial reduction in human activities on the reef, was associated with a significant rise in the percentage of live coral cover at both bays. We have found a positive effect of the COVID-19 lockdown on the number of individual fish and species richness during 2018–2021 at both bays. Our results strongly showed that the COVID-19 lockdown had a positive effect on corallivore fish and coral at both bays, as supported by the increase in the number of corallivore fish and the percent of live coral cover since 2018. At both bays, the majority of corallivore feeding habit groups belonging to the Chaetodontidae family were *Chaetodon collare*, *C. trifasciatus*, and *Chrysiptera rollandi*. Corallivore fish's main diet is centered on live coral. Our work is the first published record of the effects of the COVID-19 lockdown on fish diversity in Thailand, with all tourism activities ceased, but have gradually restarted in stages with the subsequent return of first domestic and then international tourists.

## 6. Declarations

### 6.1. Author Contributions

Conceptualization, K.J. and M.J.; methodology, K.J.; software, K.J.; validation, K.J., M.J., and S.S.; formal analysis, S.S.; investigation, S.S.; resources, K.J.; data curation, K.J.; writing—original draft preparation, S.S.; writing—review and editing, M.J.; visualization, S.S.; supervision, K.J.; project administration, K.J.; funding acquisition, K.J. All authors have read and agreed to the published version of the manuscript.

### 6.2. Data Availability Statement

Data sharing is not applicable to this article.

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### 6.5. Conflicts of Interest

The authors declare no conflict of interest.

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