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Evaluating Surface Water Quality Using Indexes of Water Quality and Plankton Diversity

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Abstract

The study aimed to assess the relationship between surface water quality and the diversity of planktonic communities in An Giang province, Vietnam. The national technical regulations on surface water quality, the water quality index (WQI), and the Shannon-Wiener diversity index (H') were applied to evaluate water quality. The considerable influence of water quality parameters on the dominant plankton was determined by canonical correspondence analysis (CCA) and similarity percentage analysis (SIMPER). The results showed that water quality was contaminated by organic matter, total suspended solids (TSS), and microorganisms. WQI values classified water quality as ranging from bad to good. The species composition of phytoplankton was dominated by two phyla, Chlorophyta and Bacillariophyta, and that of zooplankton was the Rotifera group. SIMPER analysis identified phytoplankton species with dominant density, including *Melosira granulata*, *Pediastrum duplex*, *Anabaena sp.*, and *Lyngbya circumcreta*. *Microcyclops varicans*, *Filinia longiseta*, *Trichocerca pusilla*, *Copepoda nauplius*, *Brachionus caudatus*, and *Polyarthra vulgaris* dominated the density of zooplankton. Temperature, pH, TSS, ammonium, orthophosphate, and coliform considerably influence the dominant species composition of plankton. However, the indicators of diversity and composition of plankton were unable to completely reflect water quality. These findings could contribute to the indicator selection in developing the monitoring water quality programs.

Keywords: Phytoplankton; Water Quality; Zooplankton; An Giang Province; WQI.

1. Introduction

Water quality monitoring is deemed to be an important task in water resource management around the world [1]. In Vietnam, environmental quality monitoring is conducted under the guidance of the Environmental Protection Law [2]. The guidance covers different physicochemical and biological criteria to monitor surface water quality [3]. The monitoring parameters vary with the characteristics of surface water receiving various pollution sources. In general, the monitoring program should include certain parameters, such as pH, total suspended solids (TSS), dissolved oxygen (DO), chemical oxygen demand (COD), biological oxygen demand (BOD), ammonium ($N\text{-}NH_4^+$), total nitrogen or nitrate ($N\text{-}NO_3^-$), total phosphorus or orthophosphate ($P\text{-}PO_4^{3-}$), and total coliform [3]. Surface water quality is commonly evaluated using the national technical regulations on surface water quality (QCVN 08-MT: 2015/BTNMT) [4] and the water quality index (WQI) [5].

Surface water quality assessment based on WQI has been extensively applied in Vietnam, such as in coastal regions [6], Can Tho city [7], Ha Noi [8], and Ho Chi Minh City [9]. However, surface water quality assessment based on

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physicochemical parameters and WQI remains challenging in the context of the complex impacts of human activities [1]. A biological indicator is considered an alternative environmental monitoring parameter, and it is cost-effective because it is directly related to the physiochemical characteristics of a water body [10, 11].

Phytoplankton and zooplankton are two types of plankton. Phytoplankton is sensitive to changes in sunlight, water characteristics, and its consumers [10]. Similar to phytoplankton, zooplankton diversity also depends on water quality, hydrological conditions, phytoplankton diversity, and its consumers. Plankton is small in size, fast-growing, widely distributed, and sensitive to changes in the water environment [12–14]. Therefore, they are often used as indicator species to monitor river ecosystems [15, 16] and surface water quality [17, 18]. However, the relationship between planktonic communities and the physiochemical characteristics of the aquatic environment has not been well explained because their interactions are very complex [14].

Several studies have recognized the effects of temperature, water clarity, pH, DO, and electrical conductivity (EC) on plankton [14, 19–21]. In addition, this relationship is even more complex under seasonal impacts [14, 21]. Both plankton and physicochemical properties of the aquatic environment are strongly affected by anthropogenic activities, such as riverine activities, industry, agriculture, fisheries, and the construction of flood control irrigation works [14]. Due to the complexity of domestic interactions, similarity percentage analysis (SIMPER) and canonical correspondence analysis (CCA) have been studied and applied to obtain a more general and in-depth assessment. These methods are often used to assess species composition and dominance and the relationship between plankton and water quality [11, 22, 23].

The combination of physicochemical characteristics and plankton diversity will provide better information and interpretation of the current state of the aquatic environment. In An Giang province, Vietnam, surface water has been assessed based on physicochemical indicators [24–26], and plankton diversity and water quality have only been observed in some regions [27–29]. However, the research on the relationship between water quality, phytoplankton, and zooplankton in water bodies in An Giang province using SIMPER and CCA methods is limited. Therefore, this study was conducted to (1) assess surface water quality, (2) calculate the biodiversity index of phytoplankton and zooplankton, and (3) identify the relationship between plankton diversity and water quality. These approaches can provide important information in water quality monitoring and assist in predicting biological changes in changing environmental conditions.

2. Methodology

2.1. Study Area and Sampling Sites

The study was conducted in An Giang province, where rivers directly receive water from the Mekong River. The total area of the province is 353,668.02 ha, with two main terrain types, including one per three of the area is hills and mountains in the west two per three of the area is plain. The elevation gradually lowers from the northeast to the southwest, with a height difference of 0.5–1 cm/km. The hydrological regime depends on the water source of the Mekong River and four other factors (tidal regime, flow regime, rainfall regime, and topographical and canal characteristics). The system of rivers, canals, and irrigation canals has a total length of 5,500 km (density 1.6 km/km^2).

The system of tributaries, canals, and canals throughout the province depends entirely on the water source of the Hau and Tien rivers. The average annual discharge of this river system is 13,800 m^3/s; the flow in the flood season is up to 24,000 m^3/s; and the flow in the dry season is down to 5,020 m^3/s [30]. The water source is mainly for domestic use and production, especially agriculture and aquaculture. Moreover, the quantity and quality of surface water also depend on exploitation and discharges from upstream countries. Surface water is affected by many pollution sources, such as mining, agricultural production, and aquaculture [31]. This contributes to increasing pressure on demand and pollution of surface water resources, leading to adverse effects on ecosystems and reducing the biodiversity of species, especially aquatic organisms.

Water samples, phytoplankton, and zooplankton samples were collected simultaneously at 7 locations in the rainy season (May–November) and dry season (December–April). Two locations, T1 and H1, were located in the upstream area of the Tien and Hau rivers to control the quality of water flowing from Cambodia into Vietnam. FC1 and FC2 were recorded in the Bac Vam Nao flood control area. Locations AQ1, AQ2, and AQ3 were collected in an area affected by aquaculture due to raft culture, pond fish culture, cellar farming, and shrimp farming in rice fields. The map of the sampling location is shown in Figure 1.

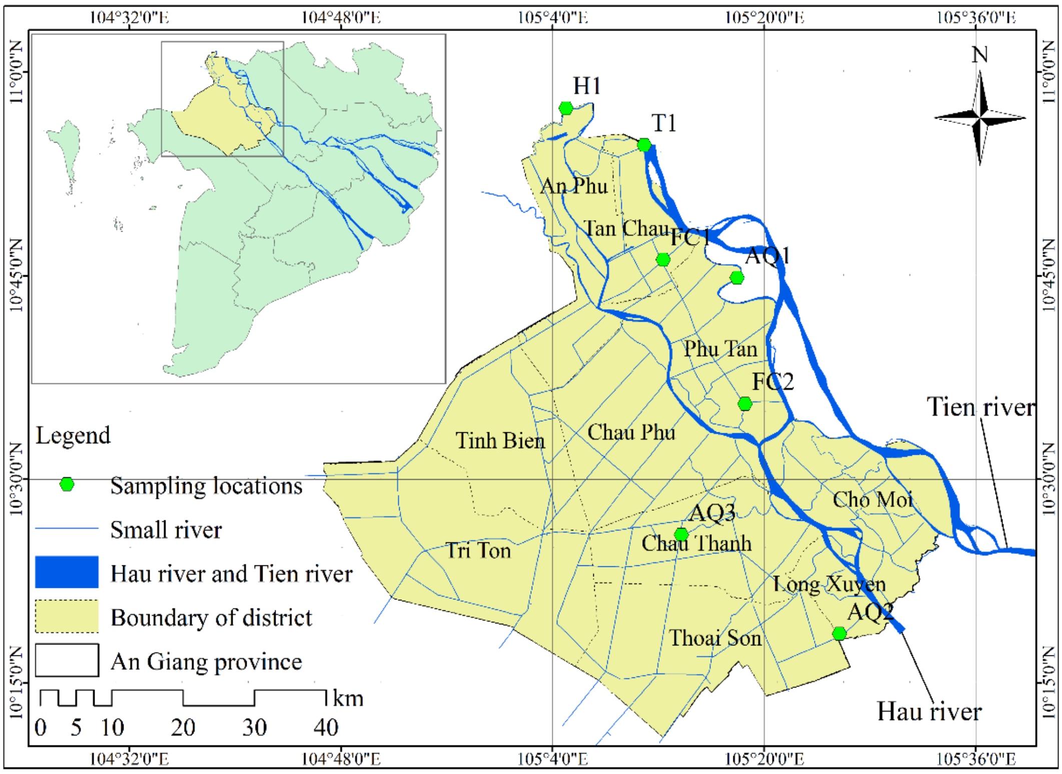


Figure 1. Map of sampling locations

2.2. Sample Collection and Analytical Methodology

The flowchart of the methodology of this study is illustrated in Figure 2. Details of each method are presented in the following sections.

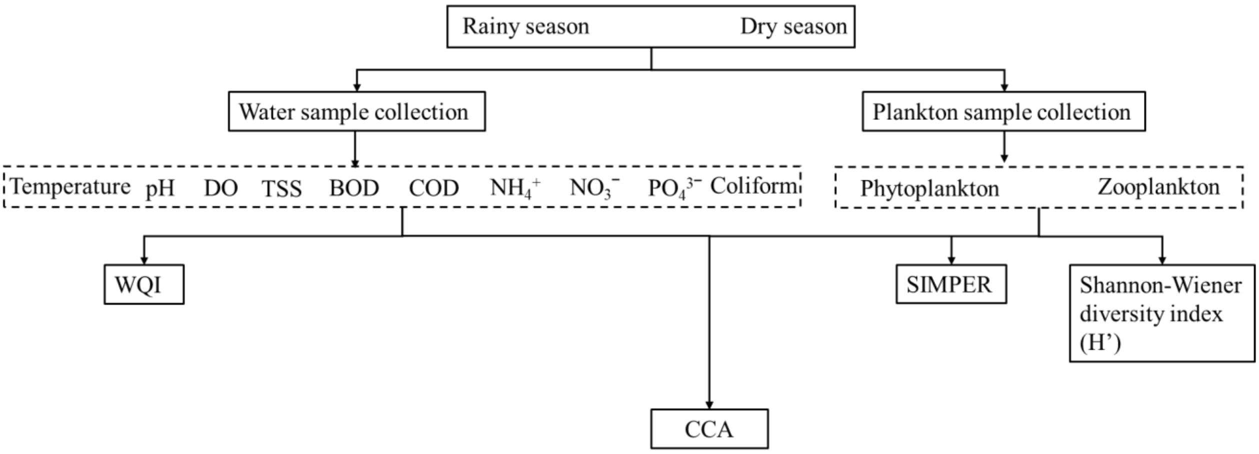


Figure 2. Flowchart for research methodology

2.2.1. Water Sampling

Water samples were collected and preserved according to the guidance of the Ministry of Science and Technology, Vietnam, including TCVN 6663-6:2018 (ISO 5667-6:2014) [32], TCVN 8880:2011 (ISO 19458:2006) [33], and TCVN 6663-3:2016 (ISO 5667-3:2012) [34]. Plastic bottles were prepared to collect water samples. These bottles were placed about 30 cm below the water surface to completely submerge the sampling vessel. Especially glass containers used for coliform samples must be handled aseptically and under vacuum conditions. The criteria for assessing water quality include temperature (T, °C), pH, DO (mg/L), TSS (mg/L), BOD (mg/L), COD (mg/L), N-NH_4^+ (mg/L), N-NO_3^- (mg/L), P-PO_4^{3-} (mg/L), and coliform (MPN/100mL). Parameters were selected based on the characteristics of the region and national technical regulations for surface water quality assessment. Temperature, pH, and DO were measured directly in the field by hand-held devices (AL20pH, Aqualytic; Thermometer, Vietnam; AL20Oxi, Aqualytic). Other parameters were analyzed in the laboratory by standard methods [35], and the specific methods are presented in Table 1.

Table 1. Analytical methods and limit values of water quality parameters

Variables	Unit	Analytical methods	Limit values (A1)*
pH	-	TCVN 6492:2011	6.5 - 8.5
DO	mg/L	ASTM D 888-12	≥ 6
TSS	mg/L	TCVN 6625:2000	20
BOD	mg/L	TCVN 6001-1:2008	4
COD	mg/L	SMEWW 5220C:2012	10
$N\text{-}NH_4^+$	mg/L	SMEWW 4500NH$_3$, F:2012	0.3
$N\text{-}NO_3^-$	mg/L	SMEWW 4500-NO$_3$ $^-$.E:2017	2
$P\text{-}PO_4^{3-}$	mg/L	SMEWW 4500-P,E:2012	0.1
Coliform	MPN/100 mL	TCVN 6187-2:2009	2,500

** Limit values in column A1 of National Technical Regulation on Surface Water Quality (QCVN 08-MT: 2015/BTNMT).*

2.2.2. Plankton Sampling and Analysis

Qualitative phytoplankton samples were collected by using plankton nets (25 µm mesh size). The nets were turned in circles at least 20 times on surface water. Meanwhile, the quantitative phytoplankton samples were collected by filtering 100L of water through a mesh. Qualitative zooplankton sampling was conducted with the same method as phytoplankton but using a Juday plankton net with a mesh size of 45 µm. These concentrated samples were placed in 110 mL vials and fixed with 2-4% formaldehyde. The collected samples were labeled and noted the date, time, and location of the collection.

Qualitative analysis was performed using 10X-40X objective microscopy and plankton photography to determine morphological and structural features. The identification and classification of phytoplankton were done based on the documents of previous studies [36-38]. Moreover, the studies of Dang et al. (2002) and Fernando (2002) were used for morphological identification and identification of zooplankton species [39, 40]. The quantitative samples were analyzed by counting the number of individuals of each species present in the sample and calculating the density of individuals per liter for phytoplankton and individuals per cubic meter for zooplankton.

2.3. Data Analyses

The average values of the water quality parameters in the rainy and dry seasons were calculated for each region. According to the guidance of Decision 1460/QD-TCMT dated November 12, 2019 of the Vietnam Environment Administration on the issuance of a manual to guide the calculation of the water quality index [5], the WQI was calculated based on nine parameters (i.e., temperature, pH, DO, BOD, COD, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, $P\text{-}PO_4^{3-}$, and coliform). Water quality is classified into 5 levels depending on WQI values: very good (WQI = 91–100), good (WQI = 76–90), moderate (WQI = 51–75), bad (WQI = 26–50), and very bad (WQI = 10–25). WQI is calculated using the general Equation 1. Other calculation components are detailed in the guidelines of VEA (2019) [5].

$$\mathrm{WQI} = \frac{\mathrm{WQI_{pH}}}{100} \times \left[\frac{1}{6}\sum_{i=1}^{6} \mathrm{WQI_{organic\ and\ nutritional\ parameters}} \times \mathrm{WQI_{coliform}}\right]^{\frac{1}{2}} \tag{1}$$

The group of organic and nutrient parameters includes DO, BOD, COD, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, and $P\text{-}PO_4^{3-}$. The Shannon-Wiener diversity index (H') was applied to test the diversity of organisms [41]:

$$\mathrm{H'} = -\sum_{i=1}^{S} \mathrm{P_i} . \ln \mathrm{P_i} \tag{2}$$

$$\mathrm{P_i} = \frac{\mathrm{N_i}}{\mathrm{N}} \tag{3}$$

where, P_i is the ratio of the number of individuals of species i to the total number of individuals, N_i is the number of individuals of species i, N is the total number of individuals and S is the total number of species.

Water quality ranking according to biodiversity index (H’) is divided into 5 levels: very polluted (H’ < 1), pollution (1 < H’ ≤ 2), mildly polluted (2 < H’ ≤ 3), clean (3 < H’ ≤ 4.5), and very clean (H’ > 4.5).

The uniformity index (J’) is calculated according to Equation 4:

$$\mathrm{J'} = \frac{\mathrm{H'}}{\ln \mathrm{S}} \tag{4}$$

S is the number of plankton species. For any number of species (> 1), the uniformity index ranges from 0 to 1. If the value gets closer and closer to 1, individuals will have more and more evenly distributed numbers of individuals [42].

SIMPER analysis was used to analyze and identify the dominant plankton species (accounting for > 5% of the total density) in the study area. Furthermore, the results of the SIMPER analysis were combined with the CCA analysis to identify which environmental parameters significantly influenced the diversity of the dominant species. Specifically, CCA was used to analyze the relationship between dominant species composition and water quality parameters (10 physicochemical parameters, including temperature, pH, TSS, DO, BOD, COD, N-NH_4^+ , N-NO_3^-, P-PO_4^{3-} and coliform) in both dry and rainy seasons. In addition, the CCA histogram also shows the importance of environmental variables for dominant species through the lengths of the arrows [23, 43]. SIMPER was performed using PRIMER V5.2.9 software [22]. CCA in this study was determined by PAST (Paleontological Statistics) Version 3.06.

3. Results and Discussion

3.1. Characteristics of Water Quality in Water Bodies

The seasonal variation in surface water quality in different regions of An Giang province is presented in Table 2. The water temperature An Giang province ranged from 29.34±0.97 to 32.47±1.43℃. It is noticeable that the temperature value in the aquaculture regions tends to be higher than in other places throughout the year. However, these differences between locations and water bodies were insignificantly due to water's thermoregulatory function. Temperatures in the water bodies of An Giang province are similar to those of previous studies [25, 26]. The measured temperatures are within the normal growth limit of aquatic organisms [44]. The pH values fell in the neutral range and had little seasonal variation in the study area. pH ranged from 6.91±0.02-7.39±0.05 in the rainy season and from 7.09±0.02-7.22±0.11 in the dry season. pH in water bodies of the Mekong Delta has little spatiotemporal variation [45-47]. In addition, this pH fluctuation is also suitable for the development of aquatic organisms.

Table 2. Temporal changes of physiochemical water quality parameters in different regions

Parameter	Baseline (T1, H1)		Flood control (FC1-FC2)		Aquaculture (AQ1-AQ3)		A1
	Dry	Rainy	Dry	Rainy	Dry	Rainy	
Temperature	29.34±0.97	30.08±0.51	30.3±0.85	29.35±0.07	30.37±1.5	32.47±1.43	-
pH	7.09±0.02	7.2±0.02	7.22±0.11	6.91±0.02	7.18±0.31	7.39±0.05	**6.5-8.5**
DO	5.71±0.03	4.97±0.59	4.07±0.25	4.21±0.03	4.27±0.7	3.62±0.85	**≥ 6**
TSS	44.88±1.24	55.3±2.69	56.5±0.71	61.5±10.61	84±30.81	60.67±3.06	**20**
BOD	10±0.35	9.8±0.57	13.5±0.71	15.5±2.12	15±5.29	18.33±2.52	**4**
COD	16.13±0.18	15.6±0.57	22.0±0.00	24.5±3.54	23.33±7.77	29±3	**10**
N-NH_4^+	0.25±0.05	0.21±0	0.45±0.11	0.37±0.1	1.86±1.26	1.68±1.15	**0.3**
N-NO_3^-	0.07±0	0.14±0.06	0.07±0.01	0.06±0.01	0.07±0.03	0.17±0.05	**2**
P-PO_4^{3-}	0.05±0	0.05±0	0.03±0	0.07±0.05	0.08±0.1	0.15±0.12	**0.1**
Coliform	7200±565	11050±3295	4300±0	25150±29486	14433±9862	55100±50963	**2,500**
WQI	**68**	**43**	**77**	**53**	**26**	**31**	

Measured DO at all sampling locations ranging from 3.62±0.85 to 5.71±0.03 mg/L was lower than the permissible value of QCVN 08-MT: 2015/BTNMT, column A1 (≥ 6 mg/L). The lowest value of DO was recorded in the aquaculture area because of the high demand for oxygen from organisms to degrade high loads of organic matter. Low DO content has also been reported in other water bodies [29, 46–48]. The main causes of low DO are slow diffusion [25], consumption by aquatic organisms [49], and the presence of organic matter [50]. Low DO implies that the surface water is organically contaminated. The findings of BOD were recorded from 10±0.35-15±5.29 mg/L in the dry season and 9.8±0.57-18.33±2.52 mg/L in the rainy season. These concentrations were above the allowable limit of QCVN 08-MT: 2015/BTNMT column A1 (4 mg/L). In addition, the BOD concentration in the rainy season tends to be higher than in the dry season in two areas of flood control and fisheries. However, the opposite trend was observed in the baseline area. This is explained by the large amount of water from upstream that dilutes the organic matter during the rainy season. In addition, the flood control and aquaculture areas have higher BOD levels than the upstream Tien and Hau rivers, which is consistent with the DO results in the water bodies. Economic and social activities have impacted water quality in the study area. Specifically, the high BOD concentration in the aquaculture area can be explained by the pollution level from farming areas, wastewater, and other non-point source pollution [25].

Similar to BOD, the figure of COD in the flood control and agriculture areas was higher than in the upstream locations (Table 2). COD in the rainy season tends to be higher than in the dry season. COD values also exceeded the allowable limit of QCVN 08-MT: 2015/BTNMT column A1 (10 mg/L). The results of BOD and COD indicated that the water was organically contaminated. Previous studies also reported that organic pollution had been one of the common issues in the Mekong Delta region [26, 47]. The presence of organic matter increases water treatment costs and leads to the formation of harmful disinfection by-products in drinking water. It is necessary to have prompt solutions to eliminate and prevent organic pollution in the study area.

High TSS values were found in the study area, ranging from 44.88±1.24 to 84±30.81 mg/L. These figures also exceed the allowable limit QCVN 08-MT: 2015/BTNMT, column A1 (20 mg/L). TSS in the upstream and flood control areas in the rainy season were higher than in the dry season because the activities of the hydrological regime, river bank erosion and storm water runoff frequently occur in the rainy season [25]. However, TSS in the aquaculture area in the dry season (84±30.81 mg/L) was higher than in the rainy season (60.67±3.06 mg/L). Great values and seasonal variation in TSS found in the study area are the common points of the water bodies in the Mekong Delta [36, 47]. High TSS-containing water can cause potential risks to human health because it acts as a carrier of other pollutants [51] and microorganisms [52]. Moreover, reducing light penetration due to highly suspended solids also affects the biological productivity of water bodies [29]. High TSS is also costly for the water treatment process.

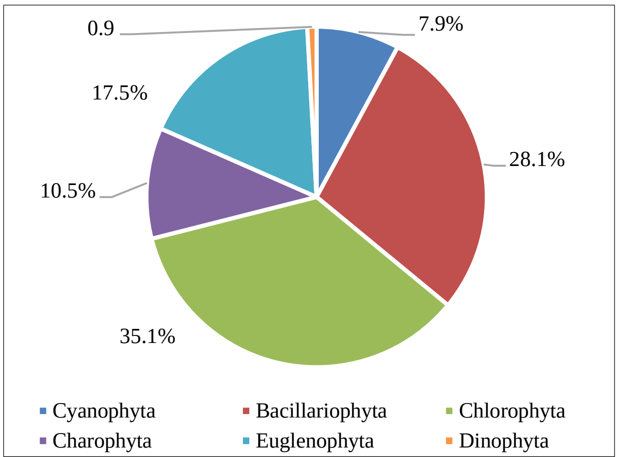
Ammonium concentrations in the flood control and aquaculture areas were higher than the allowable limit of QCVN 08-MT: 2015/BTNMT, column A1 (0.3 mg/L). These concentrations were also higher than in the upstream area all year round. Insignificant variation was found in nitrate concentrations in the dry. The highest concentration in the aquaculture area was recorded in the rainy season (0.17±0.05 mg/L). The figures for nitrate were generally lower than the allowable limit (2 mg/L). The concentration of P-PO_4^{3-} varied from 0.03±0 to 0.15±0.12 mg/L. Only the concentration of P-PO_4^{3-} in the aquaculture area exceeded the permissible limit of QCVN 08-MT: 2015/BTNMT, column A1 (0.1 mg/L). This is associated with the high level of TSS in the region [50, 51]. It is noted that the nutrient concentration in the aquaculture area was higher than in the flood control areas and the upstream areas of the Tien and Hau rivers. From the above results, it is indicated that aquaculture has such a great impact on water quality in the study area. The levels of coliform in the rainy season tend to be higher than in the dry season (Table 2). Coliform in the flood control and aquaculture areas was higher than in the upstream area of the Tien and Hau rivers. The presence of coliform indicates that the water has suffered from poor management of animal carcasses, livestock, and human wastes [47].

The results show that surface water quality has been contaminated with organic matter, TSS, and microorganisms. In the rainy season, the concentrations of these indicators tend to be higher than in the dry season. The water quality index also shows that water quality in the upstream area was classified as moderate in the dry season (WQI = 68) and bad in the rainy season (WQI = 43). In the flood control area, water quality was good in the dry season (WQI = 77) and average in the rainy season (WQI = 53). Meanwhile, water quality in the rainy season and dry season in the aquaculture area was at bad level. The results of WQI again confirmed the negative impacts of aquaculture on water bodies. WQI ranged from 56 - 67 in Sai Gon River [9] and from 48.39 – 80.01 (dry season) and from 54.78 – 69.72 (rainy season) in Rach Gia [6].

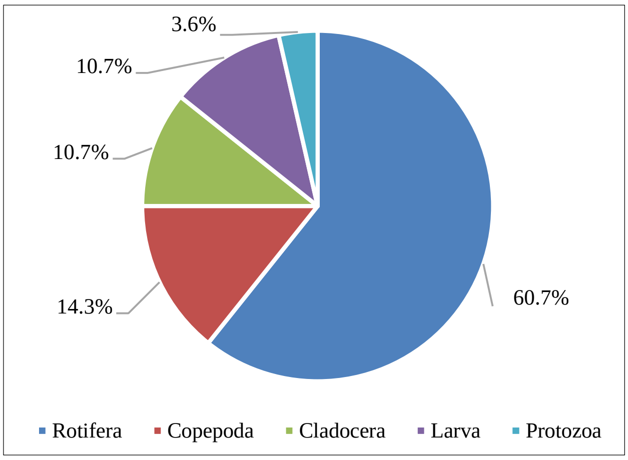
3.2. Composition and Diversity of Plankton

3.2.1. Composition of plankton

114 phytoplankton species belonging to 6 phyla were identified in the study area (Figure 3-a). The results showed that Chlorophyta was the most dominant species with a rate of 35.1% (40 species). The lowest species was Dinophyta (0.9%). The phyla include Bacillariophyta (32 species), Euglenophyta (20 species), Charophyta (12 species), and Cyanophyta (9 species), accounting for 28.1%, 17.5%, 10.5%, and 7.9%, respectively. The occurrence of these six phyla has been reported in water bodies in the Mekong Delta [46, 48, 53, 54]. These studies have found the predominance of Bacillariophyta phyla over the rest has been reported in these studies. This is in contrast to the results analyzed in the present study.



(a)



(b)

Figure 3. The composition of plankton in An Giang province

The percentage of the zooplankton composition is illustrated in Figure 3-b. There were 28 species belonging to 5 groups. The highest proportion was Rotifera, with 17 species (accounting for 60.7%), and the lowest proportion of species was Protozoa (1 species) (accounting for 3.6%). The species composition of Copepoda accounted for 14.3% (4 species), while Larva and Cladocera accounted for 10.7% (3 species). The presence of zooplankton species in the study area was recorded as much lower than that of the Hau river basin [29]. The diversity of the Rotifera group has also been reported in many previous studies in An Giang province [29], Hau River [55], and freshwater environments [56]. Rotifera is the most important group of zooplankton in eutrophic water bodies, and they often serve as better nutritional indicators than crustaceans because they are less affected by phytoplankton abundance.

3.2.2. Seasonal Variation of Plankton

The presence of phytoplankton species is strongly influenced by the season, in which the phytoplankton species composition in the dry season tends to be higher than in the rainy season (Figure 4-a). This is similar to the previous study by Le et al. [48] that reported the high presence of phytoplankton during the dry season. Chlorophyta was considerably reduced in the upstream watershed and flood control in the rainy season, while Chlorophyta in the aquatic area had less variation. According to Flura et al. [57], the presence of Chlorophyta tends to be higher due to low river flow [57]. This could be explained by the variation of Chlorophyta in the study area. According to a report by Jordan et al. [30], the water flow on the Mekong River in An Giang in the rainy and dry seasons is about 24,000 m^3/s and 5,020 m^3/s. In addition, Figure 4a also shows that the number of phytoplankton species in the aquaculture area is always higher than in the upstream and flood control areas. The presence of species belonging to the phylum Chlorophyta and Bacillariophyta always prevailed in all study areas. It can be inferred that water quality in the agriculture area was more nutrient and organic pollution compared to the upstream and flood control locations. Therefore, the presence of phytoplankton was higher due to the impact of aquaculture activities.

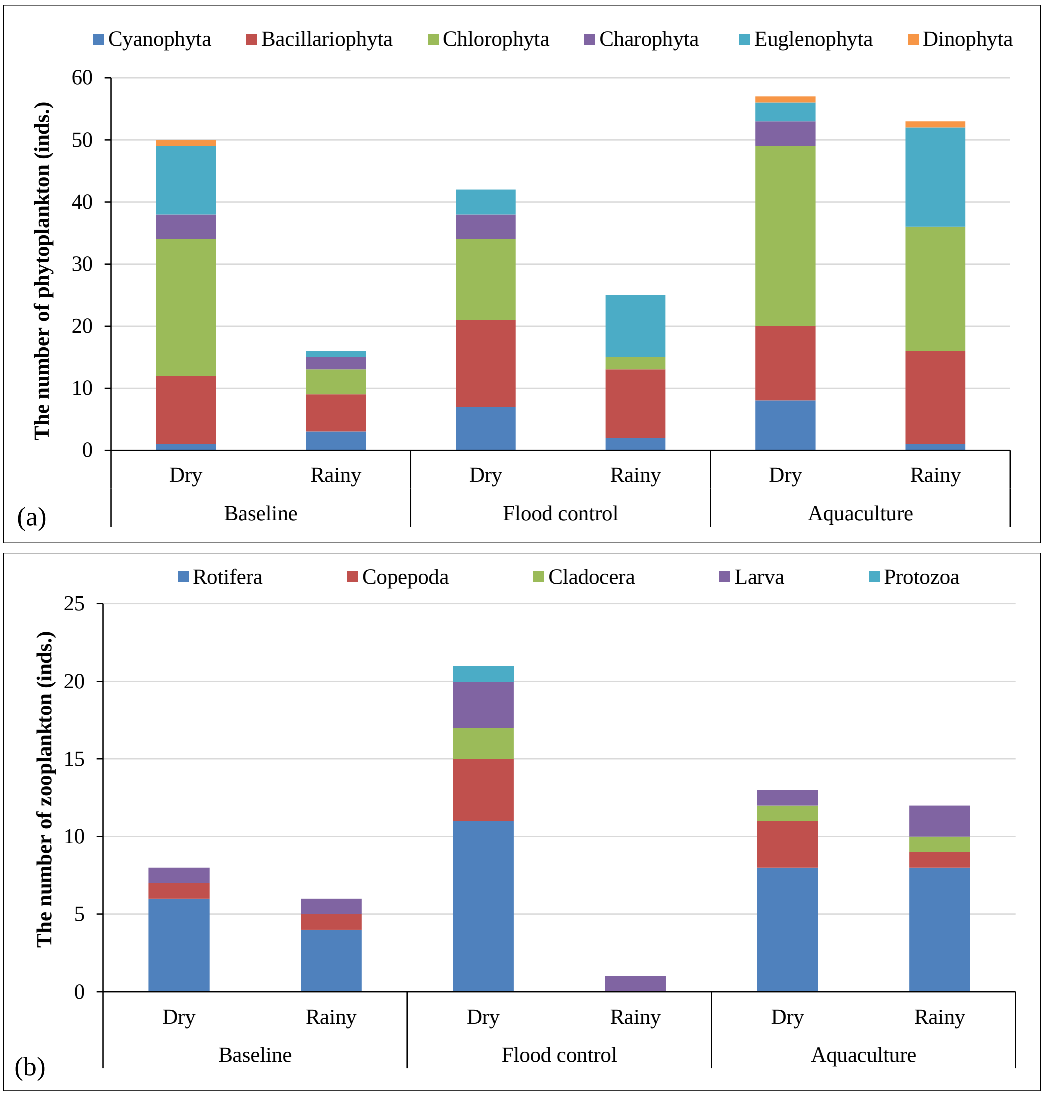


Figure 4. Seasonal variation of phytoplankton (a) and zooplankton (b) in water bodies

Similarly, higher levels of zooplankton were recorded in the dry season than in the rainy season (Figure 4-b). According to Nguyen et al. (2020), the enrichment of zooplankton in the dry season was associated with the abundant phytoplankton, which is the main food source of zooplankton [56]. The presence of Rotifera was determined to be dominant and seasonally varied, typically in flood control areas (Figure 4b). In the flood control area, all five groups appear in the dry season, but only the Larva group was detected in the rainy season. In the aquaculture area, the composition of zooplankton species did not change much between the two seasons. In summary, the plankton composition in the study area tends to be lower in the dry season and fluctuates significantly in the upstream and flood control areas.

3.3. Abundance and Diversity of Plankton

The density of phytoplankton in the upstream, flood control, and aquaculture areas in the dry season was 1506, 1386, 3214 cells/L, respectively. That was 165, 56 and 780 cells/L in the rainy season, respectively. The abundance of phytoplankton in the dry season is higher than in the rainy season in the whole water body. This result is in agreement with the study in Sai Gon River [58]. One of the primary reasons for this variation is higher light intensity and higher nutrient content, which favours maximum phytoplankton growth [10]. In addition, the study of Haque et al. (2021) [11] also demonstrated that an increase in precipitation and turbidity in the wet season could be factors responsible for the low abundance. Table 3 shows that the abundance of phytoplankton in the aquaculture area was significantly higher than that of the other two water bodies. The diversity of species composition in water bodies is also shown by the H' index. In the dry season, the H' index in water bodies is in descending order as follows: upstream area (4.15) > fisheries (4.04) > flood control (2.63). Meanwhile, in the rainy season, the H' index is in descending order of aquaculture area (3.83) > flood control area (3.10) > upstream area (1.42). Based on the H' index, the water quality in the dry season in the upstream and aquacultural areas is considered clean, and the water quality in the flood control area was mildly polluted. In contrast, the water quality in the flood control and aquaculture areas is evaluated as clean, and that in the upstream area was polluted during the rainy season (Table 3). In addition, the uniformity index (J') shows that the diversity of phytoplankton is not uniform due to the large variation between species and between seasons. This indicates that many factors affect the plankton composition, leading to unstable species structure.

Table 3. The abundance, diversity (H') and uniformity (J') of plankton

Group	Sites	Abundance		H’		J’	
		Dry	Rainy	Dry	Rainy	Dry	Rainy
Phytoplankton	Baseline	1,506	165	4.15	1.42	0.78	0.65
	Flood control	1,386	56	2.63	3.10	0.59	0.88
	Aquaculture	3,214	780	4.04	3.83	0.78	0.81
Zooplankton	Baseline	584	584	2.22	1.29	0.96	0.81
	Flood control	13,250	125	2.23	-	0.69	-
	Aquaculture	7,072	1,039	1.50	1.63	0.78	0.86

The sign “- “indicates that the value of H' cannot be determined because there are less than 2 species.

The density of zooplankton is arranged in descending order in the dry season in the flood control area (13,250 individuals/m^3) > aquaculture area (7072 individuals/m^3) > upstream area (584 individuals/m^3). That order was changed in the rainy season: aquaculture area (1039 individuals/m^3) > upstream area (584 individuals/m^3) > flood control area (125 individuals/m^3). The density of zooplankton in the study was much lower than in other water bodies in An Giang (15,358–66,618 individuals/m^3) [29]. The density of zooplankton in the dry season was also higher than in the rainy season, except for the upstream area. This trend of increasing density is consistent with nutrient fluctuations (Table 2) because high nutrient content is a good condition for phytoplankton growth, and phytoplankton is a food for zooplankton. This result is consistent with the assessment in the previous study by Lien et al. (2020) [29]. The diversity index H' for zooplankton was lower than for phytoplankton (Table 3). Based on the H' index of zooplankton, it shows that water quality in the dry season reaches a low level of pollution (upstream and flood control areas) and a high pollution level (aquaculture area) in the rainy season. The J’ index of zooplankton was relatively uniform in the upstream area in both seasons. Meanwhile, the structure of zooplankton populations in the flood control area and fisheries is not uniform, showing that the aquatic system has not reached a stable state.

In addition, the study applied WQI and H' to compare water quality assessment using physicochemical factors and biological indicators (Table 4). In the upstream areas of the Tien and Hau rivers, the results of the water quality assessment are not consistent between the use of WQI and H’, except for the seasonal trend. In the rainy season, the water quality tends to decrease. Specifically, the results of water quality assessment in the dry season using WQI and H' indices of phytoplankton and zooplankton were medium, clean, and lightly polluted, respectively. This heterogeneity is also found in flood control and aquaculture areas. Notably, the water quality in the aquaculture area was rated bad based on the WQI values. However, it was evaluated as very clean using the H' index of phytoplankton. On the other hand, water quality assessment using WQI and the H' plankton index in aquaculture areas gives acceptable results. This inconsistency in the water quality assessment based on WQI and H’ was reported in the study of Ding et al. (2021) [59]. Therefore, more research on this topic is needed.

Table 4. Assessment of water quality using WQI and H'

Par.	Baseline (T1, H1)		Flood control (FC1-FC2)		Aquaculture (AQ1-AQ3)	
	Dry	Rainy	Dry	Rainy	Dry	Rainy
WQI	68	43	77	53	26	31
Rating	Medium	Bad	Good	Medium	Bad	Bad
H' (Phytoplankton)	4.15	1.42	2.63	3.10	4.04	3.83
Rating	Clean	Polluted	Mild polluted	Clean	Clean	Clean
H' (Zooplankton)	2.22	1.29	2.23	-	1.50	1.63
Rating	Mild polluted	Polluted	Mild polluted	-	Polluted	Polluted

3.4. The Seasonal Predominance of Plankton

SIMPER analysis identified 20 dominant phytoplankton species (contributing > 5% of total densities) in both seasons (Table 5). Two species of *Melosira granulata* (Bacillariophyta) and *Pediastrum duplex* (Chlorophyta) were recorded with the highest predominance in the dry season in upstream water bodies and flood control. Meanwhile, *Melosira granulata* (Bacillariophyta) and *Anabaena sp.* (Cyanophyta) were determined to be the most dominant in the aquaculture area. In the rainy season, the predominance in the upstream waters tends to shift to the Cyanophyta group, with two species (*Lyngbya circumcreta* (Cyanophyta) and *Melosira granulata* (Bacillariophyta)). The dominant species in the flood control area in the rainy season has been recorded similarly to the agriculture area in the dry season. However, the dominant species composition in aquaculture areas in the rainy season was not clearly defined.

Table 5. List of dominant plankton species (unit: % contribution)

Species	Dry season			Rainy season		
	BL	FC	AQ	BL	FC	AQ
Phytoplankton						
Lyngbya circumcreta	-	-	-	69.1	-	-
Melosira granulata	19.43	53.81	24.09	30.9	25.34	7.99
Anabaena sp	-	-	14.64	-	21.41	-
Cyclotella sp	-	-	-	-	16.59	-
Synedra ulna	-	-	-	-	9.58	-
Scenedesmus obliquus	9.53	-	-	-	-	15.04
Cyclotella meneghiniana	8.25	-	-	-	-	7.89
Scenedesmus bicaudatus	5.13	-	-	-	-	7.66
Scenedesmus quadricauda	7.33	-	-	-	13.54	6.89
Actinastrum hantzschii	-	-	-	-	-	6.23
Pediastrumc duplex	-	-	-	-	-	5.62
Crucigenia fenestrata	5.87	-	-	-	-	-
Scenedesmus bijugatus	5.13	-	-	-	-	-
Pediastrum simplex	-	17.94	-	-	-	-
Pediastrum duplex	12.47	5.38	-	-	-	-
Planktothrix sp	-	-	8.83	-	-	-
Oscillatoria princeps	-	-	7.86	-	-	-
Microcystis aeruginosa	-	11.21	7.81	-	-	-
Micractinium pusillum	-	-	6.36	-	-	-
Oscillatoria sp	-	-	5.23	-	-	-
Other species	26.86	11.66	25.18	0	13.54	42.68

Zooplankton						
Filinia longiseta	33.33	-	-	-	-	-
Trichocerca pusilla	33.33	-	-	-	-	-
Microcyclops varicans	33.33	-	-	-	-	-
Copepoda nauplius	-	76.37	66.75	100	100	16.77
Brachionus falcatus	-	8.18	-	-	-	-
Pseudodiaptomus sp	-	5.45	-	-	-	-
Brachionus caudatus	-	-	33.25	-	-	-
Polyarthra vulgaris	-	-	-	-	-	51.51
Philodina roseola	-	-	-	-	-	23.39
Other species	-	-	-	-	-	-

The symbol "-" means species with no dominant contribution.

For zooplankton, *Microcyclops varicans* (Copepoda), *Filinia longiseta*, and *Trichocerca pusilla* (Rotifera) completely dominated the dry season zooplankton in upstream water bodies. Meanwhile, only one new species predominated in the rainy season (*Copepod nauplius*). In the flood control area, the predominant plankton species were *Copepoda nauplius* of Larva (accounting for 76.37%), *Brachionus falcatus* of Rotifera (accounting for 8.18%), and *Pseudodiaptomus sp.* of Copepoda (accounting for 5.45%). Similar to the upstream area, *Copepoda nauplius* completely dominated in the rainy season in the flood control area. In contrast, the number of dominant zooplankton species in aquaculture areas was more determined in the rainy season. In the dry season, *Copepoda nauplius* and *Brachionus caudatus* dominated at 66.75 and 33.25%, respectively. In the rainy season, dominance was only recorded for *Copepoda nauplius* (16.77%), with the addition of two new species of the Rotifera group, including *Polyarthra vulgaris* (51.51%) and *Philodina roseola* (23.39%). The increase in the number of dominant species belonging to the Rotifera group can be explained by the short life cycle and the ability to adapt to environmental changes [60, 61]. In addition, Table 4 shows that *Copepoda nauplius* is dominant in most of the water bodies in the study area. This result is consistent with previous research by Nguyet and Dang (2014) [62] on surface water bodies in the rainy season in Vinh Long province. This species has a wide ecological distribution, occurs quite commonly in natural water bodies, and thrives in environments with mild organic pollution. This is also consistent with the results of the water quality analysis, which showed high organic matter (BOD and COD) in both seasons. In addition, the predominance of Brachionus in the dry season in aquaculture areas indicates nutrient-rich environments [21, 63]. A discharge from aquaculture ponds may affect water quality in this area compared to other studied water bodies. Overall, the distributions of zooplankton species show significant changes on a seasonal scale.

3.5. The Relationship between Surface Water Quality and Plankton

The results of the CCA analysis show the dominance of physicochemical factors in the aquatic environment for phytoplankton (Figure 5) and zooplankton (Figure 6). The results of this study determined that 10 water quality parameters explained 89.02% of the total variation of the 15 dominant species in the dry season and 85.45% of the total variation of the 11 dominant species in the rainy season. Temperature, TSS, $N\text{-}NH_4^+$, $P\text{-}PO_4^{3-}$ and coliform promote the predominance of *Anabaena sp.*, *Micractinium pusillum*, *Oscillatoria sp.*, *Oscillatoria princeps*, and *Planktothrix sp.* in the dry season. These species were recorded as belonging to the Cyanophyta group. According to Ma et al. (2021), Cyanophyta was significantly affected by temperature [64]. The predominance of *Cyclotella meneginiana*, *Actinastrum hantzschii*, *Pediastrum duplex*, *Scenedesmus obliquus*, and *Scenedesmus quadricauda* in the rainy season was associated with higher temperature, pH, BOD, COD, $N\text{-}NH_4^+$, $P\text{-}PO_4^{3-}$ and coliform compared with other species. These species were determined to be positively correlated and belong to the groups Bacillariophyta and Chlorophyta. Previous studies reported that temperature, $N\text{-}NH_4^+$ and $P\text{-}PO_4^{3-}$ are the first factors affecting the composition and density of phytoplankton [65, 66].

The results of SIMPER analysis revealed that the number of dominant zooplankton species in the dry season (7 species) was higher than in the rainy season (3 species). However, the first two coordinate axes could explain 87.22% and 100% of the variation of dominant species in the dry and rainy seasons, respectively (Figure 6a and Figure 6b). In the dry season, the variation of the dominant species *Brachionus falcatus* (Rotifera) and *Pseudodiaptomus sp.* (Copepod) positively correlated with temperature and pH. Liang et al. (2020) [43] also reported that temperature was the driving factor for the occurrence of Rotifera species in lake-river ecosystems. TSS, BOD, COD, $N\text{-}NH_4^+$ and coliform were found to control the dominance of two species *Brachionus caudatus* (Rotifera) and *Copepoda nauplius* (Larva). In the rainy season, most zooplankton had a positive correlation with all water quality parameters (except DO) and positively correlated with Axis 1 and 2. The dominant species are dominated by temperature, pH, $N\text{-}NH_4^+$, $P\text{-}PO_4^{3-}$ and coliform, especially *Polyarthra vulgaris* (Rotifera). The similar correlation has also been identified in Yellow river [14]. In addition, most phytoplankton and zooplankton species are negatively correlated with DO. The correlation between DO and plankton showed through respiration [67]. In general, the predominance of phytoplankton and zooplankton species depends on temperature, pH, $N\text{-}NH_4^+$, $P\text{-}PO_4^{3-}$ and coliform in the water bodies.

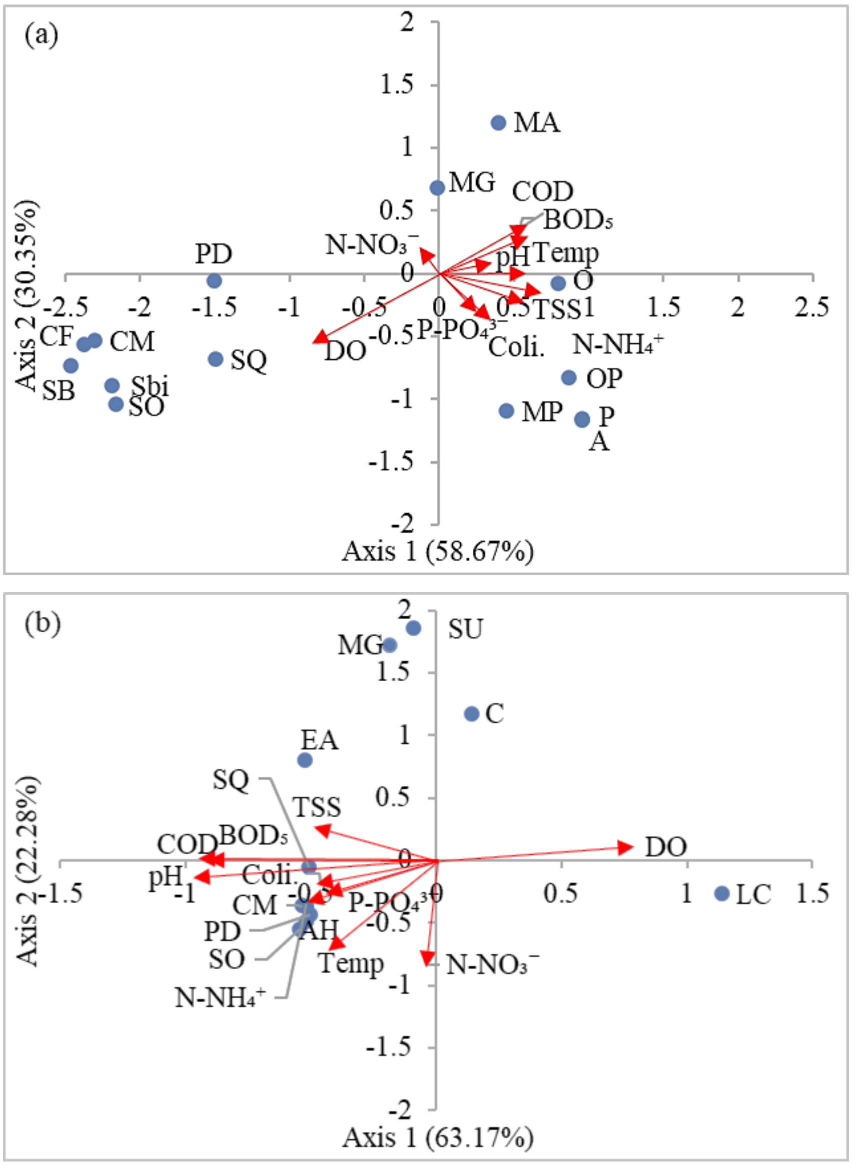
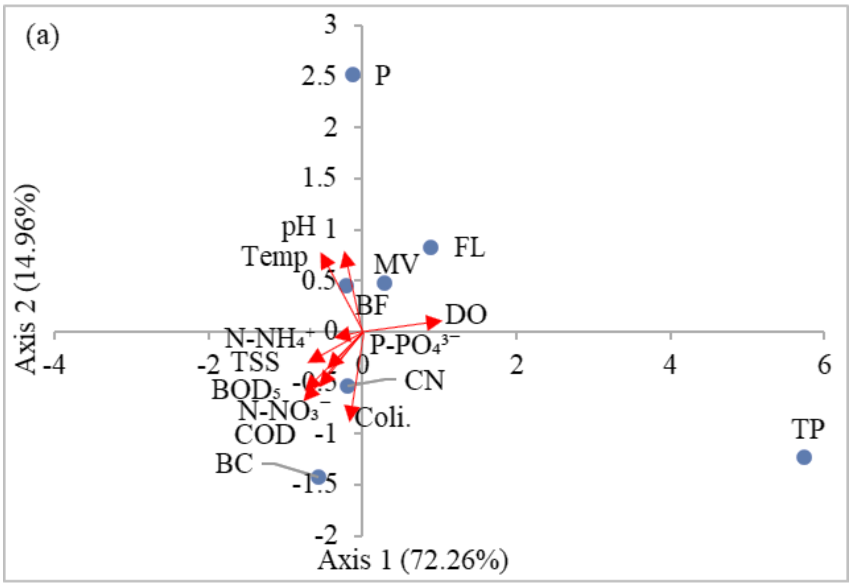


Figure 5. CCA analysis between dominant phytoplankton species and surface water. **The dominant phytoplankton species including A: *Anabaena sp.*, AH: *Actinastrum hantzschii*, C: *Cyclotella sp.*, CF: *Crucigenia fenestrata*, CM: *Cyclotella meneghiniana*, EA: *Euglena acus*, LC: *Lyngbya circumcreta*, MA: *Microcystis aeruginosa*, MG: *Melosira granulata*, MP: *Micractinium pusillum*, O: *Oscillatoria sp.*, OP: *Oscillatoria princeps*, P: *Planktothrix sp.*, PD: *Pediastrum duplex*, PS: *Pediastrum simplex*, SB: *Scenedesmus bicaudatus*, Sbi: *Scenedesmus bijugatus*, SO: *Scenedesmus obliquus*, SQ: *Scenedesmus quadricauda*, SU: *Synedra ulna.***



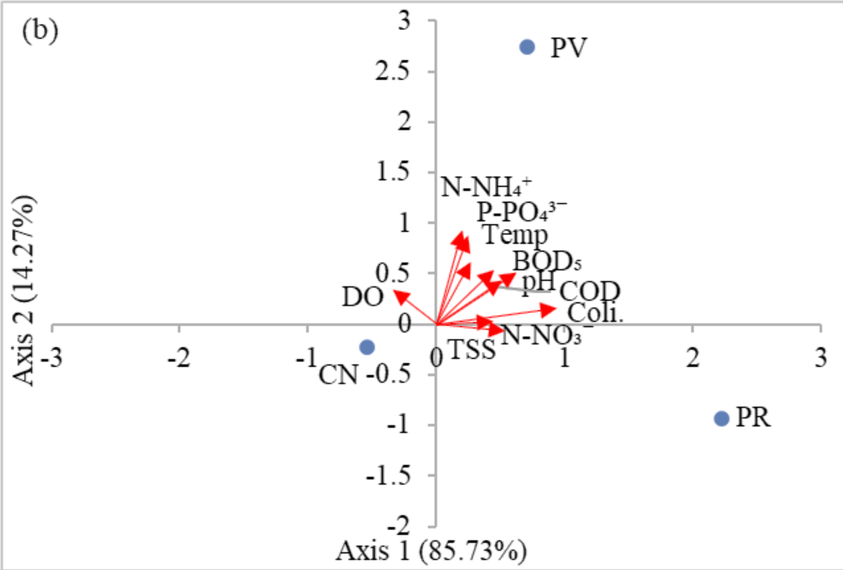


Figure 6. CCA analysis between dominant zooplankton species and surface water. The dominant zooplankton species including BC: *Brachionus caudatus*, BF: *Brachionus falcatus*, CN: *Copepoda nauplius*, FL: *Filinia longiseta*, MV: *Microcyclops varicans*, P: *Pseudodiaptomus sp.*, PR: *Philodina roseola*, PV: *Polyarthra vulgaris* and TP: *Trichocerca pusilla*.

4. Conclusion

Water quality in different areas (baseline, flood control, and aquaculture) in An Giang province was evaluated by the combination of physiochemical parameters and planktonic communities. The findings revealed that surface water quality in the study area was polluted by organic matter, total suspended solids, and coliform. This problem was observed worse in the rainy season. Generally, the water quality classification obtained from WQI ranged from moderate to bad and seasonally fluctuated. Aquaculture activities negatively impact water quality more than other areas. It was found that the density of planktonic communities in the dry season was greater than in the rainy season, which was associated with the seasonal enrichment of nutrients. The results of the water quality assessment obtained from the WQI and H' indices were different. Moreover, Chlorophyta and Rotifera were dominant over phytoplankton and zooplankton species, accounting for 35.1% and 60.7%, respectively. The results of CCA reveal that temperature, pH, DO, BOD, COD, TSS, $N\text{-}NH_4^+$, $N\text{-}NO_3^-$, $P\text{-}PO_4^{3-}$ and coliform could explain 89.02% of the variation of 15 dominant species in the dry season and 85.45% of the 11 dominant species in the rainy season. Especially temperature, pH, $N\text{-}NH_4^+$, $P\text{-}PO_4^{3-}$ and coliform significantly affected the predominance of phytoplankton and zooplankton species in the study area. It is important to recognize the relationship between the physiochemical properties of water quality and planktonic communities, as in this study, which contributes to the decision-making process on the selection of indicators for the water quality assessment. Further research is needed to study more about the different evaluations between WQI and H' in water quality assessment.

5. Declarations

5.1. Author Contributions

Conceptualization, N.T.G.; methodology, N.T.G.; software, H.T.H.N.; validation, N.T.G. and H.T.H.N.; formal analysis, H.T.H.N.; investigation, N.T.G.; resources, N.T.G.; writing—original draft preparation, N.T.G. and H.T.H.N; writing—review and editing, N.T.G.; visualization, H.T.H.N.; supervision, N.T.G.; project administration, N.T.G. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

5.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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