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Research article

Cypermethrin insecticide residue, water quality and phytoplankton diversity in the lychee plantation catchment area

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Abstract: Lychee plantation areas are typically located at varying elevations on mountains to ensure proper drainage. This placement has direct effects on stream and river water flows and consequently influences pesticide residue, water quality and aquatic biodiversity. This research aims to examine the relationships between cypermethrin residue, water quality and phytoplankton diversity in the lychee plantation catchment area in Phayao Province, Thailand, from January to May 2022. The study area was divided into six sampling sites. Water samples were collected for the investigation of cypermethrin residual, physicochemical and biological water quality parameters. The water quality index was used as an overall measurement of water quality. The study also examined the diversity of phytoplankton species and the relationship among cypermethrin residue, water quality and phytoplankton diversity were studied using canonical correspondence analysis. The findings revealed an increasing trend of cypermethrin residue, with the maximum concentration reaching 29.43 mg/L in March. The trend of decreasing water quality scores from Station S1 to Station S5 indicated the influence of land use changes and human activities, especially in the community area (S5), which was characterized by deterioration of water quality. A total of 174 phytoplankton species were categorized into 5 divisions, with Chlorophyta accounting for 61.49% of the total, followed by Bacillariophyta (28.16%) and Cyanophyta (6.32%). The highest Shannon's diversity index and evenness were observed at Stations S3 and S4, respectively. The canonical correspondence analysis revealed an interesting relationship among cypermethrin residue, ammonia nitrogen, chlorophyll a and three algal species: *Pediastrum simplex* var. *echinulatum*, *Pediastrum duplex* var. *duplex* and *Scenedesmus acutus* at Station S3. This research implies that pesticide residue and water quality have a direct impact on phytoplankton distribution, illustrating the environmental challenges that occur in various geographical areas. This information can be applied to assist in the development of future sustainable land use management initiatives.

Keywords: pesticide residue; water quality index; phytoplankton community; algal biodiversity; lychee plantation

1. Introduction

Pesticides are chemical substances that are used to prevent, reduce or eliminate the harmful effects of insects, weeds, fungi and plant pathogens. Overuse of pesticides for agricultural and nonagricultural purposes has led to the presence of chemical residues in surface and groundwater sources, which is a serious public health risk that can negatively affect human health and the environment [1,2]. Pesticides contaminate aquatic ecosystems through a variety of mechanisms, including runoff, spray dispersion, leaching and tile drainage [3,4]. Only 0.1% of pesticides affect their intended target; the remaining 99.9% damage the environment [5]. Although pesticides are designed to eliminate fungi, insects, and other pests, their mode of action also impacts nontarget organisms, such as algae, which are the primary producers in aquatic ecosystems [6].

The Mae Yian Stream is located in Phayao Province, Thailand, where the water flows through an area with a variety of activities; along the stream, there are agricultural activities, farms, cattle ranches and fish farming, and it flows through a densely populated urban area. Lychee Orchard, which has a total planting area of 1,949.6 hectares, is the most extensive agricultural operation in this part of the province [7]. The infestation of fruit borers, a pest that causes product damage, is the most common problem. It causes 65.41% of the damage to lychee fruit [8]. The level of cypermethrin residue in lychee samples ranged from 0.077 mg/kg in China to 2.86 mg/kg in Thailand, indicating that it is widely used in several regions of Asia [9,10]. Furthermore, cypermethrin is not only found in lychee fruit samples but also frequently detected in agricultural watersheds in northern Thailand [11].

Pesticide-contaminated water has a negative impact on phytoplankton communities, which are important primary producers in aquatic food chains [12]. Munaron et al. [13] and Wijewardene et al. [14] studied the effects of pesticides on phytoplankton communities and found that they are significantly affected by the toxicity of pesticides. Pesticides inhibit algae development by decreasing chlorophyll concentration and cell activity, decreasing carbohydrates, proteins and flavonoids and increasing superoxide dismutase enzymatic activity [15,16]. Phytoplankton communities are threatened by individual pesticides and pesticide mixtures. Furthermore, the correlation between nutrients and pesticide content results in stressors to the structure of the phytoplankton community [13,14]. However, these effects depend on the concentration of the pesticide and the frequency of exposure [17]. Furthermore, pesticides may have indirect impacts on phytoplankton communities through their toxic effects on zooplankton respiration, consequently influencing phytoplankton populations [18,19].

Numerous previous studies have investigated pesticide residues in water in agricultural areas [20–22]. Several studies have examined the detrimental effects of pesticides on phytoplankton [4,23], while some have focused on the relationship between phytoplankton and water quality in one or more geographic regions [24]. Nevertheless, few studies have examined the connection among pesticide residue, water quality, and phytoplankton distribution. Consequently, the objective of this study was to examine the relationship between these factors in a lychee plantation catchment area that has a wide range of altitudes and a variety of land uses. It is important to understand the impact of diverse land use patterns and geographical differences on changes in water quality and phytoplankton diversity and provide important data for the future environmental management of this region.

2. Materials and methods

2.1. Study area and sampling sites

The study was carried out in Muang district, Phayao Province, Thailand. The geographical and land use characteristics of the study area ranged from the upstream and agricultural zones to the community area, with altitudes between 800 and 400 meters above sea level. From January to December 2022, phytoplankton, water quality and cypermethrin residue samples were collected at six sampling stations, including the Mae Yian waterfall station (S1), lychee orchard station (S2), fish farming station (S3), agricultural farming station (S4), urban community station (S5) and Mae Yian and Mae Tum stream confluence station (S6). (Figure 1)

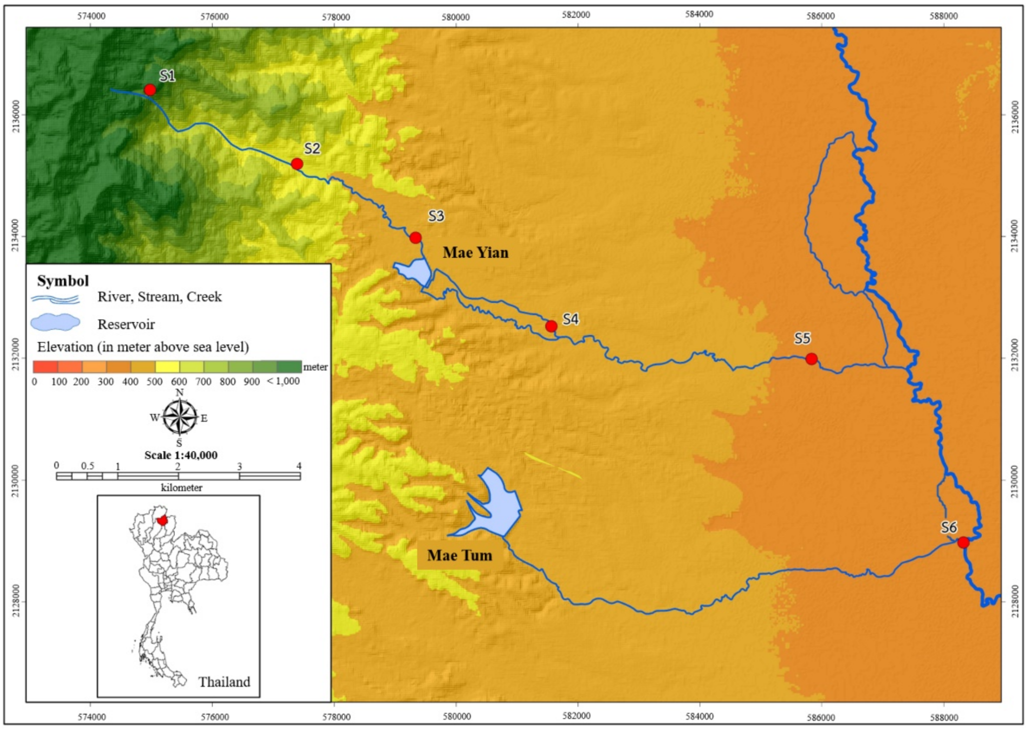

Figure 1. Study area and sampling sites.

2.2. Analysis of cypermethrin residue in water

The residue of cypermethrin insecticide in water was analyzed using the modified method of Mihaylova et al. [25]. Briefly, water samples were collected in an amber glass bottle. Then 100 mL was filtered using a 45 µm nylon membrane filter and extracted three times with 60 mL of dichloromethane for each extraction. The extracted organic materials were then concentrated by a rotary evaporator. The completed sample was mixed with 10 mL of methanol and added to the vial for high-performance liquid chromatography (HPLC) analysis.

The cypermethrin residue was examined. Using a mobile phase consisting of methanol, acetonitrile and water (38:38:24, v/v/v) with a flow rate of 1.0 mL/min and an injection volume of 10 µL, the eluate was detected at 235 nm at a temperature of 20 °C. The percent recovery of the pesticides studied was estimated by spiking deionized water with three concentrations (0.5, 1.0 and 10.0 mg/L) of each pesticide. The spiked samples were extracted according to the extraction procedure described in the above section and analyzed by HPLC. The precision of the method was evaluated by the relative standard deviation (RSD, %) of the areas of six replicate injections of each pesticide at three concentrations (0.5, 1.0 and 10.0 mg/L) [25]. Sensitivity was determined by establishing the limit of detection (LOD) and the limit of quantification (LOQ). The LOD and LOQ of cypermethrin were calculated by preparing spiked solutions of cypermethrin at low concentrations in signal-to-noise ratios of 3:1 and 10:1, respectively [26].

2.3. Physicochemical and biological analysis of water quality

Water temperature, conductivity and pH were measured in the field using a portable Multi-Parameter CyberScan PCD650 (Thermo Scientific, Singapore). The turbidity of the water was determined using a turbidimeter (Thermo Scientific, Germany). Ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N) and orthophosphate (PO_4^{3-}) were measured using a HACH Spectrophotometer Model 890 (HACH, USA). The dissolved oxygen (DO) and the biochemical oxygen demand (BOD) were analyzed using the azide modification method [27]. Total coliform bacteria (TCB) and fecal coliform bacteria (FCB) were determined as the most probable number (MPN) counts using the multiple-tube fermentation technique [27]. The chlorophyll a content was analyzed according to Saijo [28] and Wintermans and De Mots [29]. The water quality index (WQI) was calculated using DO, BOD, NH_4-N, TCB and FCB [30].

2.4. Sampling and identification of phytoplankton communities

Phytoplankton samples were collected by filtering 20 liters of a water sample with a plankton net and squeezing aquatic plants or the surface of a rock with a brush to collect epiphytic algae. The samples were fixed with Lugol's iodine solution to preserve the collected phytoplankton. The Sedgewick Rafter Counting Chamber (T. Science, Thailand) was used for the counting of phytoplankton under a light microscope. The number of species and the number of individuals were used to calculate the diversity index (H') and evenness (J') [31]. Taxonomic identification was carried out using monographs based on the specialized taxonomic literature [32–34].

2.5. Statistical analyses

All experiments were carried out in triplicate. The results are expressed as the average ± standard deviation (SD). All data were statistically analyzed using analysis of variance and Duncan's multiple range test (DMRT) to verify significant differences between treatments at $p \leq 0.05$. The concentration of the cypermethrin residues, the quality of the water and the phytoplankton species were calculated for their correlation using canonical correspondence analysis (CCA) by Past 4.3. Pearson's correlation was also used to determine the relationship between indicators of water quality and cypermethrin residues.

3. Results and Discussion

3.1. Cypermethrin residue in surface water

The cypermethrin residues in the surface water were monitored using HPLC. Initially, the standard curve between 0 and 50 mg/L was established using seven calibration levels (0, 0.5, 1, 5, 10, 25 and 50 mg/L cypermethrin) to assess sensitivity. The LOD and the LOQ were determined with values of 0.08 and 0.26 mg/L, respectively. Using three concentrations (0.5, 1.0 and 10.0 mg/L), the percent recovery of cypermethrin was determined at values of 98.39, 101.12 and 101.07, respectively. In addition, the RSD was calculated to evaluate the precision of the method, i.e., 0.32, 0.35 and 0.18%, respectively (Table 1).

The monitoring period was January to May 2022 and covered the period from agricultural land preparation through lychee harvest. In January, the amount of residue increased from Station S1 to Station S5 but decreased at Station S6, where the Mae Yian and Mae Tum streams converge. Farmers began spraying cypermethrin for fruit border control in February, and cypermethrin residue increased significantly from January to March. The highest residue level was observed in March, notably at Station S4, where a level of 29.43 mg/L was detected. In April and May, the cypermethrin residue decreased significantly. In April, the highest concentrations of cypermethrin residues were found at Station S4, while no cypermethrin residues were detected at Station S1. In May, no significant differences in residues were found between the sampling stations. (Figure 2). In summary, cypermethrin contamination of surface water in the investigated area was consistent with the agricultural practices of the lychee producers, whose insecticide spraying period began in the middle of February and peaked in March. This finding indicates that the time of application of cypermethrin was the primary factor in the contamination of surface water in the lychee catchment area. The presence of some agrochemicals may have been attributable to geological composition, but contamination of the water samples with high concentrations of pesticides demonstrated the excessive application of pesticides at a landscape scale. In general, there was a stronger tendency toward temporal variation than toward spatial variation [35]. In addition, according to Vryzas et al. [36], pesticide residues can be detected at higher concentrations after rainfall. This finding is consistent with our results, as tropical storms occurred during the month of March, resulting in significant rainfall in several regions [37].

Another observation was that the altitude of the area was a crucial factor in determining the level of residue, as seen at Stations S1–S3 (steep slopes) (Figure 1), where the residue levels were lower than those at Stations S4–S6. The use of pesticides on mountains has increased the transfer of pesticides to surface water. High application of pesticides on steep slopes, high and intense rainfall and well-developed preferential flow pathways have transported a large percentage of pesticide residues from their application site to nearby environmental regions [11]. Lastly, the confluence of two streams is an additional factor that influenced the cypermethrin residue, as evident at Station 6, where the level of residue reversed direction compared to that at Station S5. Pesticide concentrations decreased with increasing distance from the application area [38]. However, the merging of two rivers can either increase or decrease the concentration of pesticides, depending on the composition of the combined waters [39].

Table 1. Percentage recovery of the pesticides, limit of detection (LOD) and limit of quantification (LOQ) by HPLC.

Cypermethrin (mg/L)	% Recovery	RSD
0.5	98.39	0.32
1.0	101.12	0.35
10.0	101.07	0.18
LOD	0.08	
LOQ	0.26	

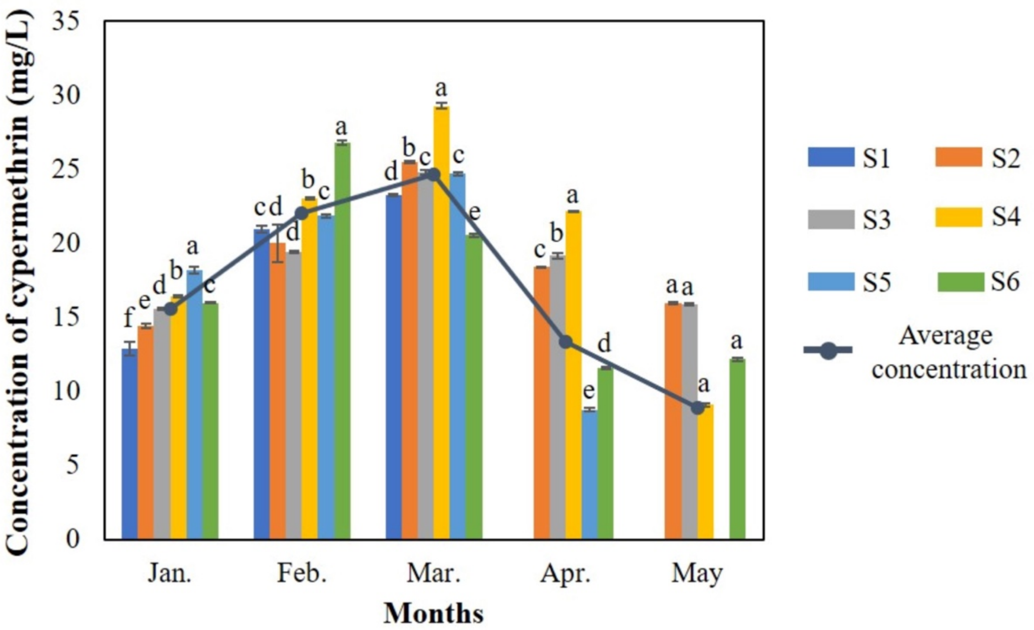

Figure 2. Cypermethrin residue in surface water from January to May 2022. The same letters are not significantly different at $P \leq 0.05$.

3.2. Physicochemical and biological analysis of water quality

The analysis of water quality using 12 parameters from January to May is shown in Figure 3. The average water temperature varied from 22–26.9 °C and increased with season, with the cold dry season occurring from January to February and the summer season occurring from March to May. Weather changes have a tremendous influence on the environment. Higher water temperatures result from an increase in air temperature, and both variables are also impacted by seasons in different geographic areas [40]. The pH and conductivity decreased significantly from Station S1 to Station S4, with Stations S1 and S2 being upstream of a flow, where the dissolution of various minerals caused the pH and conductivity to be relatively high. The terrains of Stations S1, S2 and S3 are sloped, which can influence the flow rate of water and the leaching of minerals into the water source. The presence of inorganic dissolved compounds such as chloride, nitrate, sulfate and phosphate anions is a significant factor that affects the conductivity of electricity [41].

When investigating the turbidity of the water, Station S6 had the highest turbidity level because it is the confluence of the Mae Yian Stream with other streams with different water qualities and its water flows constantly. The presence of turbidity prevents the transmission of light and other environmental factors, resulting in increased sedimentation and siltation, which can be detrimental to aquatic habitats, especially for algae [42]. Therefore, high water turbidity levels can have a direct effect on the abundance of phytoplankton, as seen at Station 6, where the lowest abundance of phytoplankton was observed (Figure 5B).

DO and BOD are crucial environmental indices that are essential indicators for the evaluation of river ecosystems [43,44]. Across all sampling stations, the levels of DO and BOD tended to be inversely related. DO levels decreased markedly at Stations S4, S5 and S6, particularly at Station S4 (agricultural farming station), where the DO level decreased to 3 mg/L (Figure 3), which was below the standard for surface water quality [45]. The level of DO could be a factor that has a direct effect on phytoplankton abundance, which was markedly lower at station S4 than at stations S3 and S5 (Figure 5B). Low levels of dissolved oxygen can limit the availability of oxygen for cellular respiration, thereby reducing the growth and abundance of phytoplankton [46]. Furthermore, in low-oxygen environments, phytoplankton can face increased competition from bacteria, which can thrive in low-oxygen conditions. This competition for limited resources may further restrict the growth of phytoplankton [47]. Simultaneously, BOD level exhibited a significant upward trend, with its concentrations ranging from 1.31–2.82 mg/L. According to Verma and Singh [48], moderately polluted water sources have BOD values between 2 and 8 mg/L. Therefore, Stations S3 to S6 had BOD values within the specified range and were categorized as moderately polluted water. On the basis of these results, it was found that the levels of DO and BOD changed in response to variations in geographical land use and human activities. Organic waste, specifically domestic household waste from population activity and animal sewage, as well as agricultural land wastewater, are sources of organic pollutants that have the greatest influence on DO and BOD concentrations [49,50].

Nutrients, especially nitrogen and phosphorus, are important factors that influence the growth of algae [51,52]. Station S3 had the highest average ammonia content at 0.33 mg/L, followed by that at Station S5 at 0.27 mg/L, as Station S3 is in a fisheries area and Station S5 is in a highly populated community. Similarly, orthophosphate and nitrate concentrations were high at Stations S3, S5 and S6, with Station S5 showing the highest average orthophosphate content of 0.18 mg/L. This station is in a local community, which is an important factor in the amount of orthophosphate in water sources [53]. Plants in agricultural areas obtain their nutrients from the N, P and K groups. These nutrients may enter a water body when provided in excess compared to the needs of the plants [54]. Station S6 had the highest nitrate nitrogen values at 1.47 mg/L. This finding could have been due to the impact of the water quality of another stream connected to our studied stream that flows through a paddy area notable for its high rate of nitrogen fertilizer application. Consequently, this scenario led to a high concentration of nitrate at Station S6. According to Gu and Yang [55], more than 60% of the nitrogen fertilizer applied to rice fields is lost in the form of ammonia, nitrate and nitrous oxide instead of being absorbed by rice plants. However, reports indicate that most of the nitrogen used in paddy fields is in the form of ammonia rather than nitrate [56–58].

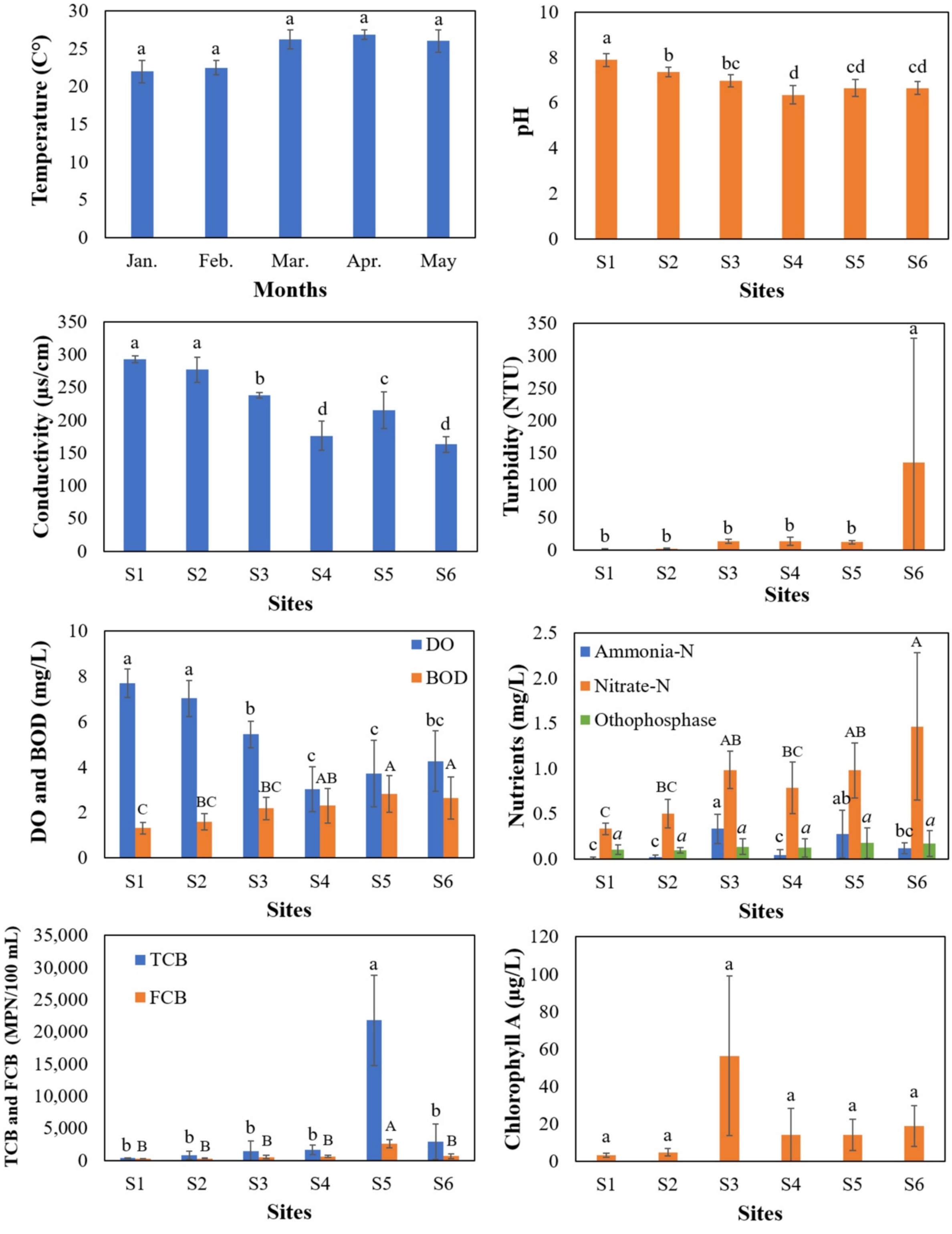

Figure 3. Physicochemical and biological parameters at six sampling stations from January to May 2022. DO = dissolved oxygen; BOD = biochemical oxygen demand; TCB = total coliform bacteria; FCB = fecal coliform bacteria. The same letters are not significantly different at $P \leq 0.05$.

TCB and FCB are indicators of deterioration of a water source. In this study, Station S5 had the highest average levels of total coliform and fecal coliform bacteria at 21,800 and 2,600 MPN per 100 mL, respectively. The amount of TCB exceeded the standards set by the Thailand Pollution Control Department, indicating contamination of water sources with sewage, mammalian waste products from various activities and discharge into drainage pipes or natural water bodies without prior treatment [59]. Although Station S5 is in a densely populated area, there is no established sewage treatment system. This must be one of the reasons why this station had the highest average total coliform and fecal coliform bacteria levels. Apirukmontri et al. [60] reported that compared to in untreated wastewater, in wastewater treatment systems, TCB and FCB levels were significantly reduced up to 15 and 2 times, respectively.

According to OECD criteria, chlorophyll concentrations indicate algal biomass in water bodies and determine the trophic status [61]. Chlorophyll a concentration was used to assess the trophic status of water, and the stations were classified as follows. Station S3 was in a eutrophic state, and Stations S4, S5 and S6 were in a mesotrophic state. Stations S1 and S2 were in an oligotrophic state. Specifically, the eutrophic status of Station S3 indicated a situation in which the water body was loaded with nutrients, causing algal blooms [62]. Furthermore, the amount of ammonia nitrogen and phytoplankton seen at this location also corresponded to this finding (Figure 3; Figure 5B).

In describing the water quality of the research area, five parameters, i.e., DO, BOD, TCB, FCB and ammonia content, were used to calculate the water quality index (WQI), which indicates the state of each water source based on station scores. The WQI scores for each station ranged from 93–32, indicating significantly excellent to deteriorated water quality. It was determined that the water quality score decreased substantially from Station S1 to Station S5 and increased at Station S6 due to the variation in land use and human activities, such as fisheries, agriculture and residential density, between stations. The station with the lowest water quality was S5, with a score between 36 and 53 (Figure 4), indicating a deterioration in water quality.

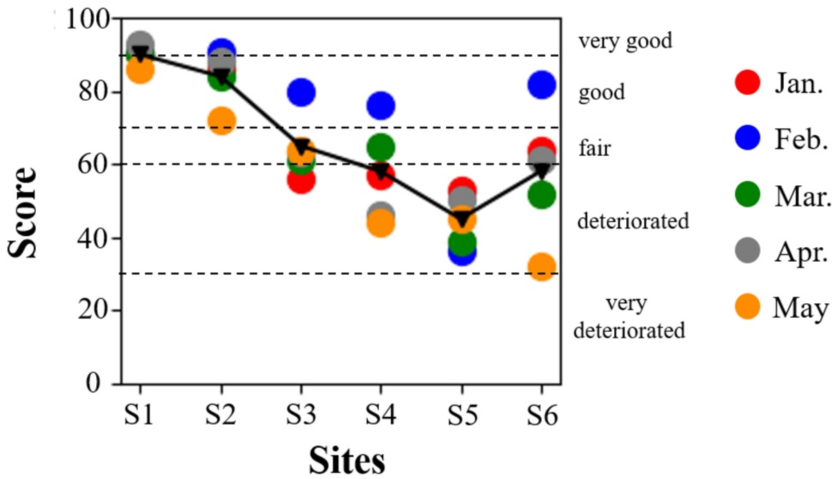

Figure 4. Water quality index (WQI) at six sampling stations from January to May 2022 (scores 0–30: very deteriorated, 31–60: deteriorated, 61–70: fair, 71–90: good, 91–100: very good).

3.3. Phytoplankton community

The study of phytoplankton diversity in the Mae Yian Stream over a five-month period (January to May) classified 174 phytoplankton species into five divisions, including Cyanophyta, Chlorophyta, Euglenophyta, Bacillariophyta and Pyrrophyta. Chlorophyta comprised 61.49% of the species, followed by Bacillariophyta (28.16%) and Cyanophyta (6.32%). The three most dominant algal species were *Navicula* sp., *Phacus* sp. and *Coelastrum astroideum* (Supplementary Table A1). The abundance of phytoplankton tended to increase from January to March, when it peaked at 1,608,500 cells/L (Figure 5 A) and then decreased considerably from April to May. On a monthly basis, Figure 5B summarizes the presence of different species observed at each sampling site, and it was determined that Station S3 had the highest number of phytoplankton, with 1,984,500 cells/L.

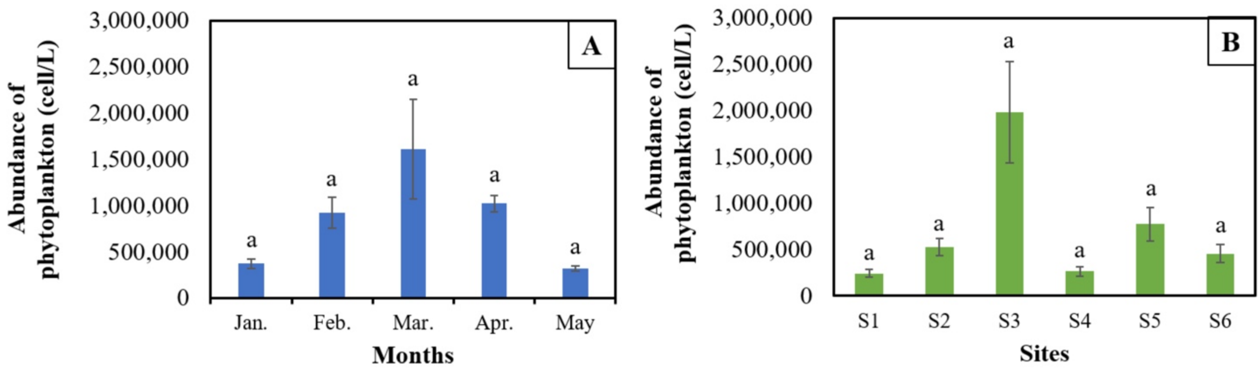

Figure 5. Abundance of phytoplankton in (A) January to May and (B) Stations S1 to S6. The same letters are not significantly different at $P \leq 0.05$.

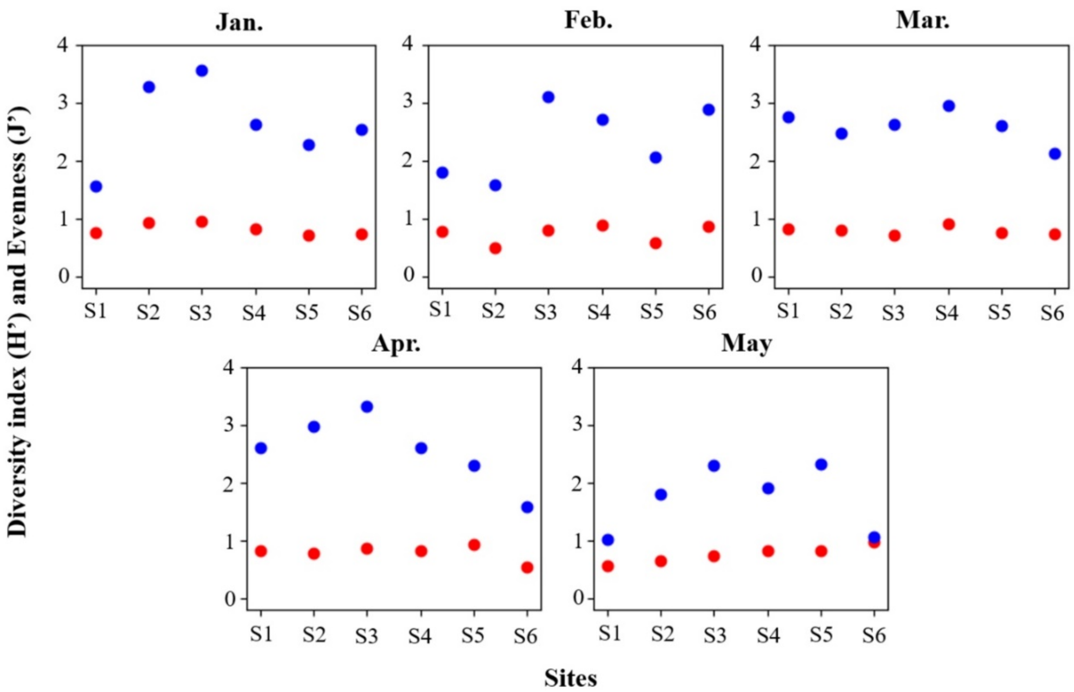

Figure 6. Shannon's diversity index (H') (Blue dot) and evenness (J') (Red dot) of phytoplankton.

Shannon's diversity (H') and evenness (J') indices were applied to the sample sites to evaluate phytoplankton diversity. Of the stations, Station S3 had the highest Shannon's diversity index for most of the study period (Figure 6), which corresponded to the maximum cell abundance at this station (Figure 5B). The evenness of species (J') in a habitat refers to how close each species is in number. Of the stations, Station S3 had the highest species evenness in January and April, whereas Station S4 had the highest evenness in February and March. In contrast, Station S6 in May had the lowest Shannon's diversity index, with the highest species evenness due to only two species of phytoplankton being observed. When considering the seasonal variation in the phytoplankton communities, the diversity index was found to be higher during the cold dry season (January-February) than during the summer season (March-May). This result is consistent with the findings of Khuantrairong and Traichaiyaporn [63], who discovered that phytoplankton communities in Doi Tao Lake in northern Thailand had the highest and lowest Shannon-Weiner diversity indices in winter and summer, respectively. The flow of nutrients into water bodies and a decrease in water availability were the most critical determinants of algal blooms and spread throughout the dry season [64–66].

Figure 7 highlights the presence of the specific species found at each sampling location. In January, February, March and April, a common phytoplankton taxon was observed at all sampling sites. However, in May, no common species were recorded. The presence of *Navicula* sp. at every sample location in January, which was a cold dry season with the lowest water level during our investigation, implied moderate to poor water quality. This finding is consistent with those of previous research that found the prevalence of *Navicula* species is an indicator of pollution-related strain on the river. High levels of nutrients during the dry season, which is characterized by low flow conditions, higher evaporation rates and lower water levels, probably contributed to the development of these species [67]. However, in February, *Nitzschia palea* was found at all sampling locations. This species has been identified as an indicator of intermediate water quality in Thailand's Ping River [68]. *Pediastrum duplex* var. *duplex* was found at all stations during the March sampling. This species is generally found in water bodies with a water quality level ranging from oligo-mesotrophic to eutrophic and is known to be resistant to water contaminants and adaptable to various water quality levels [69].

Another notable aspect was the presence of different algal species at Stations S2 and S3, where the highest number of common species was identified during the study period. Despite the significant differences in water quality between the two sites, Station S2 had a higher concentration of DO, while Station S3 had higher concentrations of all three nutrients and chlorophyll a. Both sampling locations had similar species of phytoplankton, namely, *Pediastrum* spp. and *Scenedesmus* spp. It is important to note that although these species belong to the same genus, they represent different species. *Pediastrum simplex* var. *sturmii* and *P. simplex* var. *clathratum* were found in water with good to moderate (oligo-eutrophic) water quality, while *P. alternans* was found in water with an average mesotrophic status [67]. The presence of the genus *Pediastrum* spp. indicated a wide range of tolerance to water quality, as it occurred under both excellent and poor water quality conditions. In their study on the ecological habitat of *Scenedesmus* in northern Thailand, Phinyo et al. [70] reported the presence of *Scenedesmus* species and their association with water quality. *S. parisiensis* was discovered in oligotrophic water. *S. acuminatus* was found in oligo-mesotrophic water, while *S. denticulatus* was found in mesotrophic water. According to Peerapornpisal et al. [71], *Pediastrum* spp. and *Scenedesmus* spp. are commonly found in mesotrophic to eutrophic environments.

Furthermore, the highest concentration of cypermethrin in the water was observed at Station S4 in March. This station was found to have a unique group of phytoplankton, including *Cosmarium* *sexangulare* f. *minama*, *Pleurotaenium trabecula* and *Closterium dianae* var. *minus*, that was not present in other months. This finding revealed a possible link between the presence of cypermethrin and the identified phytoplankton species and that they may be used as aquatic bioindicators of cypermethrin residues, demonstrating their sensitivity to the presence of this chemical in water. *Phacus* sp. was discovered at all sample locations in April. Organic pollution is often associated with a large population of euglenoids, particularly *Phacus* sp. These taxa persist in high-nutrient water habitats such as ponds, marshes and ditches [72].

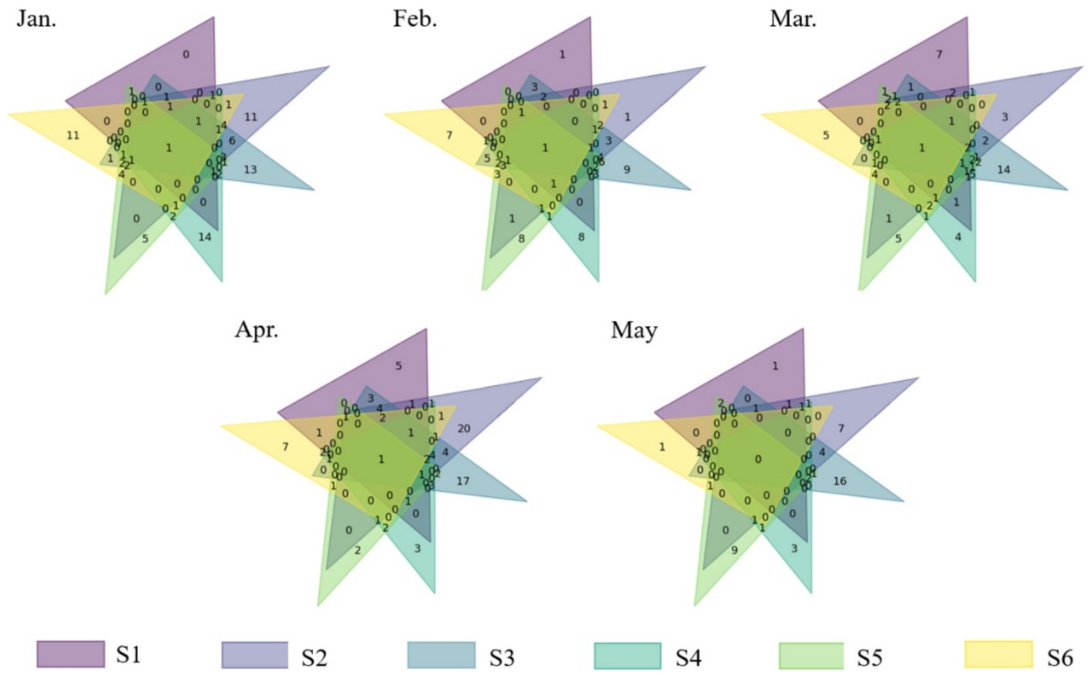

Figure 7. Distribution of phytoplankton at six sampling stations from January to May 2022.

3.4. Correlation analysis of cypermethrin residue, water quality and phytoplankton species

Figure 8 shows that the CCA results for Axes 1 and 2 accounted for 56.93% and 32.75% of the total variance in the dataset, respectively. The correlations between the cypermethrin residues, water quality parameters and phytoplankton species were classified into four groups. In Group 1, fish farming Station S3 was related to chlorophyll a, ammonia nitrogen and three algal species: *Pediastrum simplex* var. *echinulatum*, *Pediastrum duplex* var. *duplex* and *Scenedesmus acutus*. Furthermore, cypermethrin residues were shown to be strongly correlated with phytoplankton abundance and water quality parameters. The excretion of fish in fishponds leads to the accumulation of ammonia [73]. Nitrogen is generally considered the primary limiting nutrient for the growth and biomass of phytoplankton, which affects chlorophyll concentration. A study by Ding et al. [74] demonstrated that the nitrogen-to-phosphorus ratio decreased significantly at more than sixfold after an algal bloom. It is widely known that the persistence of pesticides in water bodies can be toxic to algae. In contrast, there have been reports that pesticides can also facilitate algal growth and be used as an energy source [75,76].

In Group 2, Mae Yian waterfall Station S1 was substantially related to conductivity, DO, pH and two species of benthic diatoms, *Nitzschia palea* and *Synedra ulna* (Figure 8). Benthic diatoms exhibit higher abundance in waterfalls characterized by higher water pH and conductivity due to the favorable conditions that promote the growth of diatoms resistant to such environmental parameters [68,77]. In Group 3, TCB and FCB had a significant correlation with Station S5, which was in a densely populated area close to a cattle farming area. Group 4 consisted of three locations, including the Lychee plantation station (S2), the agricultural cultivation station (S4), and the confluence of the Mae Yian and Mae Tum stream stations (S6). These stations were associated with BOD, nitrate nitrogen, water temperature, orthophosphate, water turbidity and five species of algae, including *Coelastrum astroideum*, *Nitzschia* sp., *Navicula* sp. and *Phacus longicaudatus*. In addition, a subcorrelation was observed at Station S6, where there was a close correlation with the turbidity of the water (Figure 8). Several studies have found that *Coelastrum astroideum* and *Navicula* sp. are commonly found in rivers and agricultural water bodies [78,79]. Additionally, research by Huang et al. [80] indicates that *Nitzschia* sp. and *Navicula* sp. are species frequently found in shallow and turbid water enriched with inorganic matter. At the same time, *Phacus* sp. is a species that tolerates high BOD conditions.

In addition, Pearson's correlation was applied to provide a more comprehensive analysis of the relationships between water quality indicators and cypermethrin residues. It was determined that the pH of the water was the only parameter with a significant negative correlation with the cypermethrin residue (Supplemental Table A2). The degradation of cypermethrin in water is influenced by variables such as pH, temperature and radiation exposure. In general, cypermethrin is more stable under acidic (lower pH) conditions and degrades faster under alkaline (higher pH) conditions. Lower pH levels may delay the degradation of cypermethrin, potentially resulting in higher residue levels in water [81,82]. Consistent with our findings, the highest levels of cypermethrin residue were detected at Station S4 in March (Figure 2), where the pH of the water was the lowest (Figure 3).

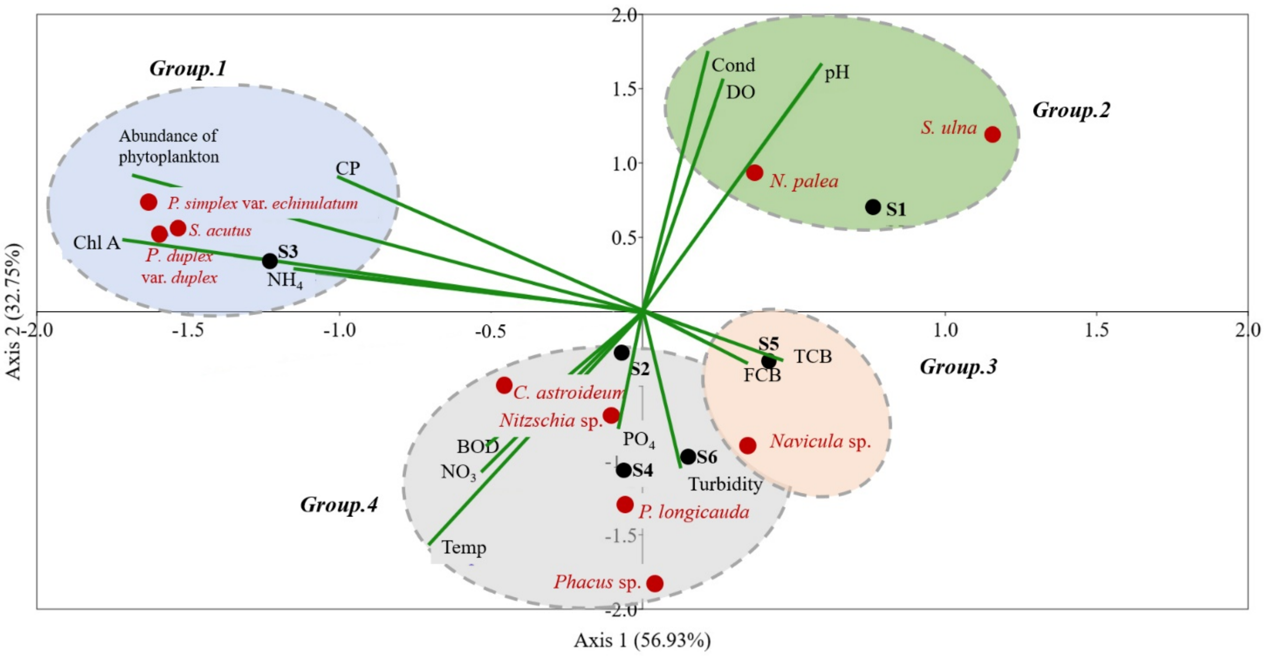

Figure 8. CCA of the cypermethrin residue concentrations, water quality parameters and phytoplankton species. CP = cypermethrin; Chl A = chlorophyll a; Cond = conductivity.

4. Conclusions

Pesticide residue in agricultural water is one of the most serious environmental challenges that harms biodiversity, particularly phytoplankton communities, which are the primary producers in aquatic food chains. In the present study, the residual cypermethrin, water quality and phytoplankton distribution were studied in a highly distinct location of a lychee plantation with variable elevations and land uses. The cypermethrin contamination in the surface water was highest in March, which corresponds to the period when farmers sprayed the highest amounts of cypermethrin. Based on the analysis of the water quality index (WQI), the water quality decreased significantly from upstream Station S1 to the flat area of Station S5. A total of 174 phytoplankton species were identified, the majority belonging to the Chlorophyta division, followed by Bacillariophyta and Cyanophyta. There were distinct correlations between cypermethrin residues, water quality and phytoplankton species at the different sites and in different months. The cypermethrin residues were highly associated with chlorophyll a and ammonium nitrogen, as well as with the abundance of three species of phytoplankton, *Pediastrum simplex* var. *echinulatum, Pediastrum duplex* var. *duplex* and *Scenedesmus acutus* at Station S3. These findings suggested that cypermethrin residues and water quality have a direct impact on the phytoplankton ecosystem. However, the distribution of phytoplankton is influenced by a multitude of environmental factors that vary by geographical location. For a comprehensive understanding, additional research on the effect of cypermethrin toxicity on the growth of these phytoplankton species is needed.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors have no conflicts of interest to declare.

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