HAYATI
Journal of Biosciences

Vol. 28 No. 3, July 2021 199-211
DOI:10.4308/hjb.28.3.199
ISSN: 1978-3019
EISSN: 2086-4094

Diversity and Abundance of Phytoplankton in the Coastal Waters of South Sulawesi

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ARTICLE INFO

Article history:
Received May 31, 2021
Received in revised form June 30, 2021
Accepted 13 July, 2021

KEYWORDS:
Bacillariophyceae,
Cyanophyceae,
Dinophyceae,
Harmful Algal Blooms,
Ceratium furca

ABSTRACT

Phytoplankton are primary producers that can be used as seawater condition indicators. Certain phytoplankton can proliferate, causing harmful algal blooms (HABs). The coastal waters of South Sulawesi, Indonesia are under pressure from land-based processes and activities resulting in inputs of organic and inorganic materials. This study analysed phytoplankton diversity and abundance in coastal waters around South Sulawesi. Phytoplankton were sampled and seawater parameters (salinity, temperature, turbidity, pH, nitrate concentration) measured *in-situ* at six stations around seven major river estuaries in three seaways (Makassar Strait, Flores Sea, Gulf of Bone). Phytoplankton taxonomic composition, abundance and indices of diversity (H'), evenness (E), and dominance (D) were analysed. Phytoplankton from 31 species and three classes (Bacillariophyceae, Cyanophyceae, Dinophyceae) were identified. Phytoplankton abundance and community structure differed significantly between sites and seaways but were not significantly correlated with water quality parameters although Dinophyceae abundance correlated significantly with observed pollution levels. Phytoplankton abundance was strongly influenced by the Dinophyceae, especially *Ceratium furca*, a potential HAB species; Cyanophyceae had the strongest influence on species richness but least on community structure. *C. furca* abundance was strongly correlated negatively with species richness, H' and E, and positively with D, indicating negative impacts of this species on phytoplankton communities.

1. Introduction

Situated in the Coral Triangle and Wallacea biodiversity hotspots (Barber 2009; Michaux 2010; Ambo-Rappe and Moore 2019), the coastal waters around the coasts of South Sulawesi, Indonesia sustain valuable and biodiverse biotic communities (Saleh 2019; Furkon *et al.* 2020). Increasing human activities in recent decades have resulted in anthropogenic impacts including pollution (Edinger *et al.* 1998; Heery *et al.* 2018; Ambo-Rappe and Moore 2019; Duarte *et al.* 2020). Phytoplankton are small, often single-celled plants which, as primary producers, are vital to marine an estuarine food webs (Statham 2012; Day *et al.* 2012; Cermeño *et al.* 2013). Phytoplankton can serve as an indicator of aquatic ecosystem health (Borja *et al.* 2011; Hosmani 2013). In particular, phytoplankton abundance can provide information on the actual and potential productivity of aquatic ecosystems, the ability of the aquatic environment to support particular species of interest, and can be used as biological indicators (bioindicators) of water quality, including eutrophication and other forms of pollution (Borja *et al.* 2011; Kitsiou and Karydis 2011; Hosmani 2013; Parmar *et al.* 2016; Hemraj *et al.* 2017; Yeanny 2018; Pradisty *et al.* 2020). Phytoplankton community composition and abundance can greatly influence fisheries production, especially in estuarine waters (Day *et al.* 2012).

However, the functional roles of marine ecosystems can be affected by changes in phytoplankton community structure and abundance (Cermeño *et al.* 2013; Trombetta *et al.* 2019; Wurtsbaugh *et al.* 2019). Although phytoplankton are crucial for marine ecosystem health and productivity, population explosions of certain types of phytoplankton, called

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harmful algal blooms (HABs), can exceed the carrying capacity of the ecosystem and have negative impacts on other organisms, including mass die-offs of fish and other organisms due to anoxic conditions (O'Neil *et al.* 2012; Statham 2012; Paerl *et al.* 2014; Trombetta *et al.* 2019; Wurtsbaugh *et al.* 2019). Algal blooms due to explosive phytoplankton population growth can also impact the aesthetic, cultural and social value of coastal areas (Wurtsbaugh *et al.* 2019).

Knowledge regarding phytoplankton communities is important for the management of marine and coastal areas and resources. The objectives of this research were to determine the biodiversity and abundance of phytoplankton at strategic points around South Sulawesi and to examine the relationship between phytoplankton communities and physical-chemical factors in these coastal waters.

2. Materials and Methods

2.1. Study Sites

This research was conducted in the estuarine and coastal waters of South Sulawesi Province, Indonesia from January to March 2020. Seven sites (Figure 1) were selected through purposive sampling, based on the rationale was that rivers tend to carry nutrient loads from the land to the sea, and are considered likely to influence seawater quality and phytoplankton communities. The sites were also selected to represent the three coasts of South Sulawesi which face three different sea areas: Makassar Strait to the west, the Flores Sea to the South and the Gulf of Bone to the east. These sites comprised coastal waters around the estuary of the largest river in each of seven districts/cities around the province: Saddang

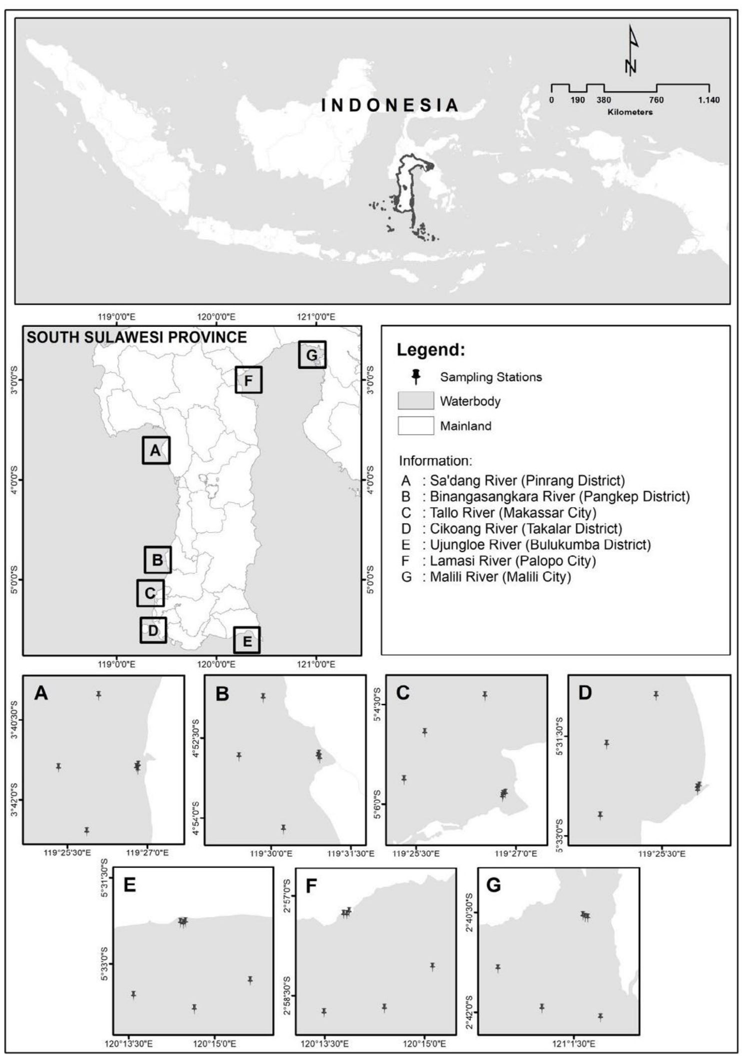

Figure 1. Research area in South Sulawesi, Indonesia showing sampling sites and stations

River in Sidrap District, Binangasangkara River in Pangkep District, and Tallo River in Makassar City (Makassar Strait); Cikoang River in Takalar District and Ujung Loe River in Bulukumba District (Flores Sea); Lamasi River in Palopo City and Malili River in Malili City (Gulf of Bone).

2.2. Survey Method and Data Analysis

Data collection at each estuarine site took place at six stations. These comprised three inshore stations close to the mouth of the major river selected and three stations further offshore but still within the area influenced by the river outflow (Table 1). At each of the stations, five physical and chemical water quality parameters were measured using a multi-function water quality checker (TOA DKK Model WQC24-1-2): water temperature (°C), salinity (ppt), turbidity (NTU), pH, and nitrate concentration (mg/l). Station parameters also included a subjective estimate of the visible sources of pollution, especially nutrient

Table 1. Site and station geographical coordinates and characteristics

Site	Station	Latitude S	Longitude E	Distance	Current	Visible pollution sources
			Makassar Strait			
Pinrang	PI3	5°5'50.65"	119°26'50.57"	Inshore	upstream	medium
Pinrang	PI8	5°4'22.52"	119°26'32.16"	Offshore	upstream	low
Pinrang	PI9	5°4'55.60"	119°25'37.75"	Offshore	middle	low
Pinrang	PI14	5°5'51.65"	119°26'48.58"	Inshore	middle	medium
Pinrang	PI15	5°5'53.44"	119°26'47.93"	Inshore	downstream	high
Pinrang	PI20	5°5'38.18"	119°25'19.17"	Offshore	downstream	low
Pangkep	PN3	4°52'48.32"	119°30'53.91"	Inshore	upstream	high
Pangkep	PN8	4°51'44.90"	119°29'50.98"	Offshore	upstream	medium
Pangkep	PN9	4°52'51.13"	119°29'23.75"	Offshore	middle	high
Pangkep	PN14	4°52'50.64"	119°30'52.95"	Inshore	middle	medium
Pangkep	PN15	4°52'53.51"	119°30'54.71"	Inshore	downstream	high
Pangkep	PN20	4°54'13.07"	119°30'13.89"	Offshore	downstream	high
Makassar	MK3	5°5'50.65"	119°26'50.57"	Inshore	upstream	high
Makassar	MK8	5°4'22.52"	119°26'32.16"	Offshore	upstream	medium
Makassar	MK9	5°4'55.60"	119°25'37.75"	Offshore	middle	low
Makassar	MK14	5°5'51.65"	119°26'48.58"	Inshore	middle	high
Makassar	MK15	5°5'53.44"	119°26'47.93"	Inshore	downstream	high
Makassar	MK20	5°5'38.18"	119°25'19.17"	Offshore	downstream	medium
			Flores Sea			
Takalar	TA3	5°32'15.06"	119°26'3.66"	Inshore	upstream	low
Takalar	TA8	5°30'53.64"	119°25'24.60"	Offshore	upstream	low
Takalar	TA9	5°31'37.74"	119°24'40.02"	Offshore	middle	low
Takalar	TA14	5°32'16.74"	119°26'1.86"	Inshore	middle	low
Takalar	TA15	5°32'19.14"	119°26'1.92"	Inshore	downstream	low
Takalar	TA20	5°32'42.30"	119°24'34.20"	Offshore	downstream	medium
Bulukumba	BL3	5°32'17.64"	120°14'24.42"	Inshore	upstream	medium
Bulukumba	BL8	5°33'33.96"	120°13'35.04"	Offshore	upstream	low
Bulukumba	BL9	5°33'48.00"	120°14'38.82"	Offshore	middle	low
Bulukumba	BL14	5°32'18.60"	120°14'27.30"	Inshore	middle	high
Bulukumba	BL15	5°32'17.16"	120°14'29.64"	Inshore	downstream	medium
Bulukumba	BL20	5°33'18.42"	120°15'37.44"	Offshore	downstream	low
			Gulf of Bone			
Palopo	PL3	2°57'17.04"	120°13'47.04"	Inshore	upstream	medium
Palopo	PL8	2°58'45.78"	120°13'29.46"	Offshore	upstream	low
Palopo	PL9	2°58'42.00"	120°14'23.94"	Offshore	middle	low
Palopo	PL14	2°57'17.22"	120°13'49.98"	Inshore	middle	medium
Palopo	PL15	2°57'14.82"	120°13'51.96"	Inshore	downstream	high
Palopo	PL20	2°58'4.74"	120°15'7.26"	Offshore	downstream	low
Malili	ML3	4°52'48.32"	119°30'53.91"	Inshore	upstream	low
Malili	ML8	4°51'44.90"	119°29'50.98"	Offshore	upstream	medium
Malili	ML9	4°52'51.13"	119°29'23.75"	Offshore	middle	medium
Malili	ML14	4°52'50.64"	119°30'52.95"	Inshore	middle	medium
Malili	ML15	4°52'53.51"	119°30'54.71"	Inshore	downstream	medium
Malili	ML20	4°54'13.07"	119°30'13.89"	Offshore	downstream	medium

enrichment (low, medium, high), the distance from the coast (inshore or offshore), and the position relative to the prevailing current direction within each set of three stations (upstream, middle and downstream). The rationale for these was that phytoplankton communities would likely differ in abundance and/or composition depending on the levels of pollution (including parameters not measured in the water quality analysis), and that effects would likely be less further offshore and/or upstream compared to further inshore and/or in the middle (i.e. exposed to the major river outflow) or downstream of the river and other sources of pollution.

Phytoplankton samples were obtained by collecting 100 l samples of seawater and straining them through a No. 25 plankton net (Bengen 1999). The plankton retained in the net were preserved in Lugol 4% solution. Phytoplankton were identified and counted in the Chemical Oceanography Laboratory of the Marine Science Department at Universitas Hasanuddin based on references including books (e.g. Davis 1955; Yamaji 1976) and the on-line database AlgaeBase (Guiry and Guiry 2021). Representative specimens were photographed under the microscope.

2.3. Phytoplankton Abundance

Phytoplankton abundance was calculated using the equation in APHA (2012):

$$N = n \times \frac{a}{A} \times \frac{v}{Vc} \times \frac{1}{V} \qquad (1)$$

Where:

N = plankton abundance (cells L^{-1})
n = number of plankton counted (cells)
a = covered glass area (mm^2)
v = concentrated water volume (ml)
A = microscope viewing area (mm^2)
Vc = volume of water under the covered glass (ml)
V = volume of water filtered (L). Abundance was calculated for the community as a whole, by class and by species

2.4. Phytoplankton Community Structure

The phytoplankton community structure was analysed through the calculation of three ecological indices based on the equations in Odum (1998) as follows:

The Shannon-Wienner Diversity Index (H')

$$H' = -\sum_{i=1}^{S} pi\ Log(pi) \qquad (2)$$

where:

H' = diversity index;
pi = proportion of the ith species = ni/N
ni = number of individuals of the i^{th} species (ind/cm)
N = number of individuals of all species (ind/cm)
S = number of species identified

The Shannon-Wienner Evenness Index (E)

$$E = H' / Log(S) \qquad (3)$$

where:

E = evenness index
H' = diversity index
S = number of species identified

The Simpson Dominance Index (D)

$$C = \sum_{i=1}^{s} \left(\frac{ni}{N}\right)^2 \qquad (4)$$

where:

ni = number of individuals of the ith species (ind/cm)
N = number of individuals of all species (ind/cm)

2.5. Data Analysis

The phytoplankton and environmental data were tabulated and analysed descriptively. Community structure and distribution analyses were conducted and graphics produced in Microsoft Excel 2010. The ecological indices were evaluated as follows: (i) Diversity Index: low diversity $H' \leq 2$; moderate diversity $2 < H' \leq 3$; and high diversity $H' > 3$; (ii) Dominance Index: low dominance $0 < C \leq 0.5$; moderate dominance $0.5 < C \leq 0.75$; and high dominance $0.75 < C \leq 1$; (iii) Evenness Index: community under pressure: $0 < E \leq 0.5$; unstable community $0.5 < E \leq 0.75$; stable community $0.75 < E \leq 1$ (Morris *et al.* 2014). Correlations between phytoplankton community characteristics and environmental parameters were analysed in R Version 3.6.0 (R Core Team 2019) in the RStudio Version 1.1.456 environment (RStudio Team 2016) using the glm (general linear model) function, with significance evaluated at the 95% (*), 99% (**) and 99.9% (***) confidence limits (α = 0.05, 0.01, and 0.001, respectively).

3. Results

3.1. Water Quality Parameters

Water quality parameters measured at each site (Table 2) show considerable between-site variation

Table 2. Water quality parameters at seven sites around the coats of South Sulawesi

Parameter	Unit	Pinrang		Pangkep		Makassar		Takalar		Bulukumba		Palopo		Malili	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Temperature	ppt	30.13	1.33	30.30	1.47	31.13	1.55	30.70	1.47	30.70	1.16	30.37	1.17	31.00	1.10
Salinity	°C	16.45	11.59	28.30	1.06	21.75	5.71	29.80	0.40	28.58	3.38	28.43	1.73	22.00	6.67
pH		7.80	0.28	8.01	0.05	7.87	0.19	7.86	0.17	7.87	0.34	7.89	0.06	7.88	0.10
Turbidity	NTU	26.68	18.93	45.43	1.92	34.08	9.43	48.30	0.76	43.15	9.66	45.42	2.78	34.97	11.34
Nitrate	mg/l	0.532	0.013	0.567	0.034	0.595	0.021	0.510	0.050	0.582	0.050	0.608	0.025	0.597	0.008

as well as within-site variation, the latter evidenced by the high standard deviation (SD) values for several parameters at most sites. The Takalar site had the highest mean salinity and Pinrang the lowest. Mean water temperature and pH were highest at the Pangkep site, and lowest in Pinrang which also had the lowest turbidity and lowest nitrate concentration. The Palopo site had the highest nitrate concentration.

3.2. Phytoplankton Taxonomic Composition

Phytoplankton identified belonged to three classes, the Bacillariophyceae, Cyanophyceae, and Dinophyceae (Table 3, Figure 2). Overall, the phytoplankton community in the coastal waters of South Sulawesi tended to be dominated by the Bacillariophyceae, followed by the Dinophyceae. The Cyanophyceae was the least abundant class at five of the seven sites and overall.

Examples of 30 out of the 31 phytoplankton species identified are shown in Figures 3, 4, and 5. These 31 species comprised 20 members of the Bacillariophyceae, 4 members of the Cyanophyceae and 7 members of the Dinophyceae.

3.3. Phytoplankton Abundance

Phytoplankton abundance varied between stations (Table 4). The Pangkep District station had by far the highest phytoplankton abundance (5,094,333 cells/l), with a community dominated by members of the Class Dinophyceae.

3.4. Phytoplankton Community Structure

Based on the three ecological indices calculated (Table 5), the phytoplankton community structure varied between the seven study sites around the coast of South Sulawesi. The Diversity Index (H') was low (<2) at all sites, but was highest at the Bulukumba District site (Flores Sea), followed by the Malili District site (Gulf of Bone) and by far the lowest at the Pangkep District site (Makassar Strait). The Evenness Index (E) was highest at the Palopo City site (Gulf of Bone) followed by Bulukumba, and was also lowest at the Pangkep site. The Dominance Index (D) was by far the highest at the Pangkep District site, followed by the other two Makassar Strait coast sites (Makassar and Pinrang), and lowest at the Palopo City site. The large standard deviations indicate significant differences in the taxa present as well as their relative abundance at each of the six stations within each site.

3.5. Phytoplankton Distribution

Out of the 31 species identified in this study, on average 18 were found at each site and 7.4 at each station, with high between-station variation at most sites (Table 6). Six taxa were found at all sampling sites: *Chaetoceros* sp., *Coscinodiscus, Pleurosigma* sp., and *Thalassiosira* (Bacillariophyceae), *Oscillatoria* sp. (Cyanophyceae) and *Ceratium furca* (Dinophyceae). Seven taxa were found at just one site, all of which belonged to the Class Bacillariophyceae. Three taxa were found at all stations in any one site, comprising two species of Bacillariophyceae, *Chaetoceros* sp. at the Makassar (Makassar Strait) and Malili (Gulf of Bone) sites, and Coscinodiscus in Takalar (Flores Sea); and one species of Dinophyceae, *Ceratium furca* at the Pangkep site (Makassar Strait). Based on seaway, 27 species were identified from the Makassar Strait (3 sites), and 21 each from the Flores Sea (2 sites) and Gulf of Bone (2 sites). A Venn diagram (Figure 6) shows the overlap in taxonomic composition between seaways based on presence-absence data.

3.6. Correlations between Phytoplankton Community, Location and Site Characteristics

The correlations between phytoplankton community characteristics and site characteristics (Table 7) show that all phytoplankton abundance and community structure indicators except species richness were significantly influenced by location (site and seaway). The site(s) differing significantly varied between the variables or indicators. Pangkep had significantly higher total phytoplankton abundance, Dinophyceae abundance, *Ceratium furca*

Table 3. Taxonomic classification of phytoplankton identified from seven sites around the coats of South Sulawesi

Class	Order	Family	Species
Bacillariophyceae	Pennales	Asterionellaceae	*Asterionellopsis* sp.
		Chaetoceraceae	*Chaetoceros* sp.
		Fragilariaceae	*Flagillaria* sp.
			Thalassiosira sp.
			Thalassionema sp.
	Naviculales	Amphipleuraceae	*Amphiprora* sp.
		Pleurosigmataceae	*Pleurosigma* sp.
			Gyrosigma sp.
		Plagiotropidaceae	*Plagiotropis* sp.
		Naviculaceae	*Navicula* sp.
			Navicula pupula
	Centrales	Chaetoceraceae	*Bacteriastum* sp.
		Biddulphiaceae	*Biddulphia sinensis*
		Lithodesmiaceae	*Ditylum* sp
		Coscinodiscaceae	*Coscinodiscus* sp.
		Hemiaulaceae	*Hemiaulus* sp.
		Nitzchiaceae	*Melosira* sp.
	Surirellales	Surirellaceae	*Surirella linearis*
	Cymbellales	Cymbellaceae	*Cymbella minuta*
Cyanophyceae	Oscillatoriales	Oscillatoriaceae	*Oscillatoria* sp.
	Rhizosoleniales	Rhizosoleniaceae	*Rhizosolenia setigera*
			Rhizosolenia sp.
			Rhizosolenia imbricata
Dinophyceae	Peridiniales	Protoperidiniaceae	*Protoperidinium* sp.
	Gonyaulacales	Ceraticeace	*Ceratium furca*
			Ceratium fusus
			Ceratium trichoceros
			Ceratium triops
		Gymnodiniceae	*Gymnodium* sp.
	Dinophysiales	Dinophysiaceae	*Dinophysis caudata*

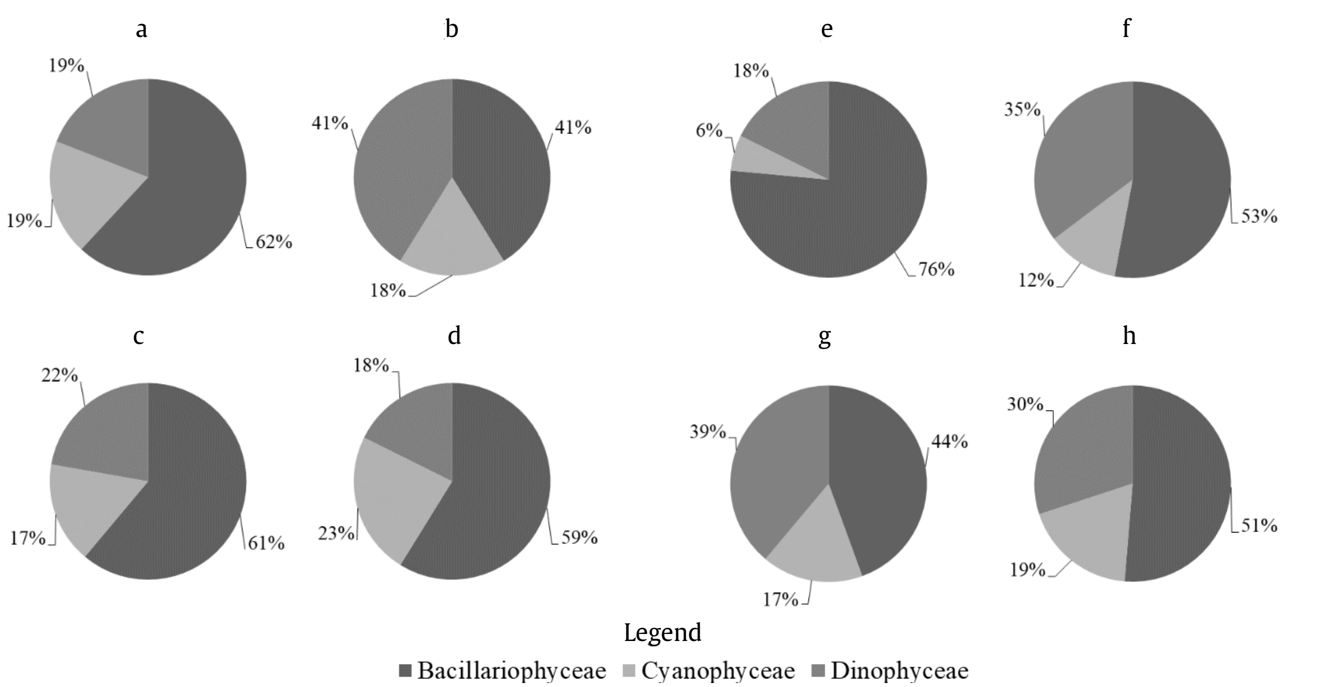

Figure 2. Phytoplankton species by class at seven coastal sites around South Sulawesi (a = Pinrang, b = Pangkep, c = Makassar, d = Takalar, e = Bulukumba, f = Palopo, g = Malili, h = all stations combined)

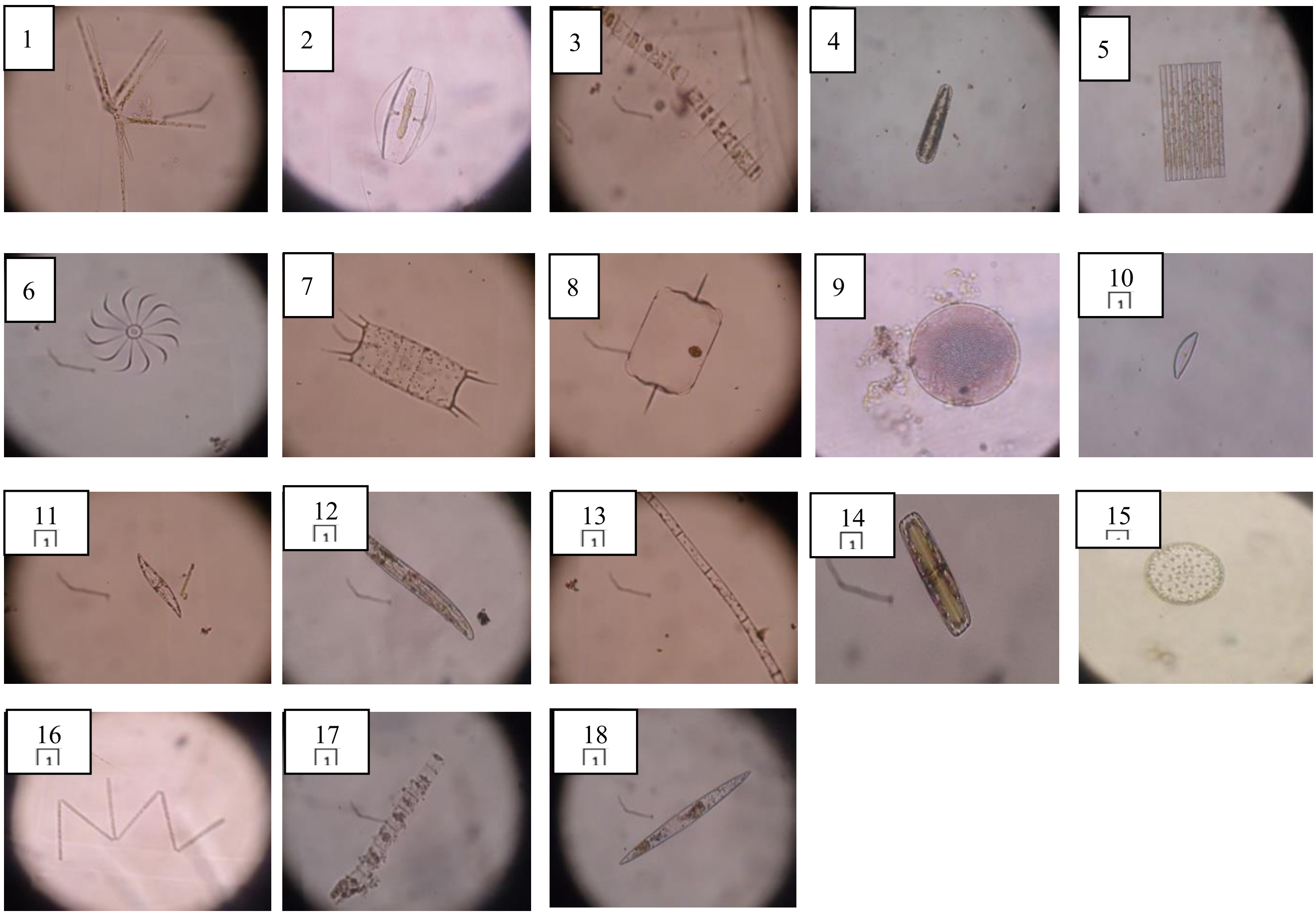

Figure 3. Phytoplankton of the class Bacillariophyceae from coastal waters around South Sulawesi, Indonesia: (1) *Asterionellopsis*, (2) *Amphiprora*, (3) *Chaetoceros* sp., (4) *Surirella linearis*, (5) *Flagillaria* sp., (6) *Bacteriastum*, (7) *Biddulphia sinensis*, (8) *Ditylum* sp., (9) *Coscinodiscus*, (10) *Cymbella minuta*, (11) *Pleurosigma*, (12) *Gyrosigma*, (13) *Hemiaulus*, (14) *Plagiotropis*, (15) *Thalassiosira*, (16) *Thalassionema*, (17) *Melosira* sp., (18) *Navicula* sp.

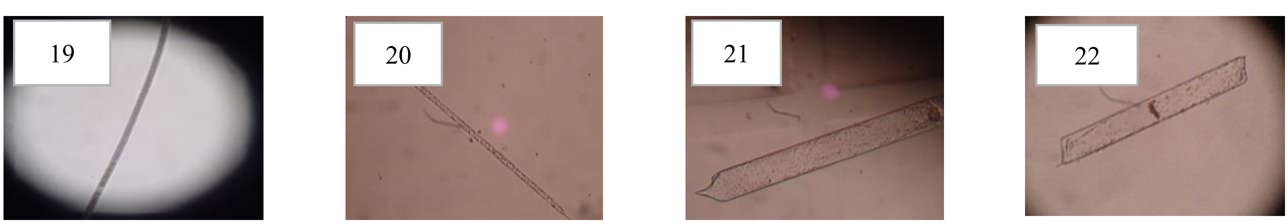

Figure 4. Phytoplankton of the class Cyanophyceae from coastal waters around South Sulawesi, Indonesia (19) *Oscillatoria* sp., (20) *Rhizosolenia setigera*, (21) *Rhizosolenia* sp., (22) *Rhizosolenia imbricate*

Figure 5. Phytoplankton of the class Dinophyceae from coastal waters around South Sulawesi, Indonesia: (24) *Protoperidinium*, (25) *Ceratium furca*, (26) *Ceratium fusus*, (27) *Ceratium trichoceros*, (28) *Ceratium triops*, (29) *Gymnodium*, (30) *Dinophysis caudata*

Table 4. Phytoplankton abundance at seven sites in coastal waters around South Sulawesi, Indonesia

Station	Abundance by class (cells/l)					
	Bacillariophyceae		Cyanophyceae		Dinophyceae	
	Mean	SD	Mean	SD	Mean	SD
Pinrang	27,111	29,055	6,944	9,375	8,722	13,531
Pangkep	2,333	1,886	944	1,143	849,056	876,135
Makassar	95,389	104,958	1,222	1,601	42,278	78,511
Takalar	15,611	16,583	444	502	889	1,544
Bulukumba	3,333	2,098	2,167	2,536	3,111	5,456
Palopo	2,611	1,512	833	753	2,778	3,257
Malili	32,944	37,693	1,111	1,601	5,000	4,050

Table 5. Ecological indices of phytoplankton community structure at seven sites in coastal waters around South Sulawesi, Indonesia

Station		Diversity index H'			Evenness index E			Dominance index D		
Code	Name	Mean	SD	Category	Mean	SD	Category	Mean	SD	Category
A	Pinrang	1.066	0.279	low	0.543	0.171	moderate	0.512	0.154	low
B	Pangkep	0.365	0.277	low	0.176	0.117	low	0.849	0.114	high
C	Makassar	0.851	0.512	low	0.420	0.261	low	0.601	0.249	moderate
D	Takalar	1.090	0.231	low	0.615	0.129	moderate	0.451	0.102	low
E	Bulukumba	1.589	0.515	low	0.824	0.174	high	0.268	0.151	low
F	Palopo	1.540	0.258	low	0.851	0.079	high	0.251	0.061	low
G	Malili	1.189	0.471	low	0.663	0.288	moderate	0.453	0.237	low

Table 6. Distribution of phytoplankton taxa at seven sites in the coastal waters around South Sulawesi

Species	Prevalence-number of stations at each site						
Name	Pinrang	Pangkep	Makassar	Takalar	Bulukumba	Palopo	Malili
Asterionellopsis	-	-	-	-	1	-	-
Amphiprora	-	-	-	-	2	-	-
Chaetoceros sp.	4	2	6	2	1	3	6
Surirella linearis	3	-	-	-	2	-	-
Flagillaria sp.	3	-	-	-	-	-	-
Bacteriastum	2	1	-	-	-	-	3
Biddulphia sinensis	-	5	2	2	2	2	1
Ditylum sp.	2	1	-	-	-	1	-
Coscinodiscus	2	2	4	6	4	3	4
Cymbella minuta	-	-	1	1	-	-	
Pleurosigma	1	1	2	4	4	3	1
Gyrosigma	2	-	1	1	3	1	-
Hemiaulus	-	-	-	-	-	-	1
Plagiotropis	2	-	1	1	3	-	-
Thalassiosira	3	2	3	5	4	4	3
Thalassionema	4	-	2	2	2	-	-
Melosira sp.	-	-	-	-	-	1	-
Navicula	3	-	2	1	1	1	2
Navicula pupula	2	-	-	-	-	-	-
Nitzchia sp.	-	1	-	-	-	-	-
Oscillatoria sp.	5	3	5	3	5	5	2
Rhizosolenia setigera	3	2	1	1	-	2	3
Rhizosolenia sp.	1	3	1	1	-	-	2
Rhizosolenia imbricata	1	-	-	1	-	-	-
Protoperidinium	1	5	4	1	-	4	5
Ceratium furca	4	6	5	1	3	2	5
Ceratium fusus	2	1	-	-	-	1	2
Ceratium trichoceros	2	2	-	-	1	1	2
Ceratium triops	-	2	-	-	-	-	3
Gymnodium	-	3	5	-	-	2	5
Dinophysis caudata	-	3	2	3	1	1	2
Total number of species detected	21	17	18	17	18	17	18
Number of species/station (mean±SD)	8.7±3.2	7.5±2.9	7.8±1.2	6.0±0.9	6.7±2.1	6.2±1.2	8.7±5.1

*Note: - = not detected

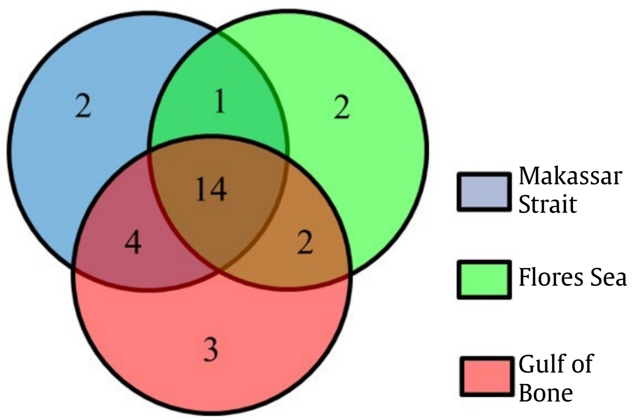

Figure 6. Venn diagram of phytoplankton species distribution by seaway

abundance and Dinophyceae species richness, with Malili also having significantly higher Dinophyceae species richness but not abundance. Makassar had significantly elevated Bacillariophyceae abundance and Pinrang had significantly elevated Cyanophyceae abundance. The ecological indices varied significantly between sites, as could be expected from the mean and standard deviation data shown in Table 5. The Diversity Index H' for the Pangkep and Makassar sites differed significantly with each other and with all other sites. The Evenness Index E did not differ significantly between the four Flores Sea and Gulf of Bone sites, but differed significantly between these sites and each of the three Makassar Strait sites as

Table 7. Correlations between phytoplankton community and site/station characteristics (glm function in R)

Horizontal: variables tested	Phytoplankton abundance					Species richness		Ecological indices		
Vertical: correlation factors	Total	Bacillariophyceae	Cyanophyceae	Dinophyceae	*C. furca*	Total	Dinophyceae	H'	E	D
Total phytoplankton abundance								***	***	***
Bacillariophyceae abundance	***							**	**	**
Cyanophyceae abundance	***	ns						ns	ns	ns
Dinophyceae abundance	***	ns	ns					***	***	***
Ceratium furca abundance	***	ns	ns	***				(-)***	(-)***	***
Phytoplankton species richness	ns	ns	**	ns	(-)***			ns	**	ns
Dinophyceae species richness	ns	ns	ns	ns	ns	***		ns	*	*
Site	*	*	***	**	**	ns	*	**	**	**
Seaway	*	ns	*	ns	ns	ns	**	**	***	***
Current flow	ns	*	ns	ns	ns	ns	*	ns	ns	ns
Distance offshore	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Perceived pollution	(-)*	ns	ns	*	ns	ns	**	ns	ns	ns
Temperature	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
salinity	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
pH	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
TDS	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
nitrate	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns

ns = not significant at $\alpha = 0.05$; * = significant at $\alpha = 0.05$; ** = significant at $\alpha = 0.01$; *** = significant at $\alpha = 0.001$

well as between each of the Makassar Strait sites. The Dominance Index D for three sites (Pangkep, Makassar and Malili) each differed significantly with all six other sites, but did not differ significantly between the other four sites. Significant correlations with seaway included total phytoplankton abundance and which were significantly higher in the Makassar Strait. Dinophyceae species richness was significantly lower in the Flores Sea, although Dinophyceae abundance did not differ significantly between seaways. Makassar Strait had significantly lower H' and E and higher D compared to the other two seaways which did not differ significantly from each other.

Total phytoplankton community abundance and species richness had no statistically significant correlation with any water quality parameter or within-site position. However three site characteristics were significantly correlated with some phytoplankton community variables: seawater temperature, the position relative to the river mouth and prevailing currents (current flow on Table 7), and perceived levels of pollution based on qualitative field observations. Dinophyceae abundance correlated with temperature. Mean total species richness was significantly lower upstream, while mean Dinophyceae species richness and Bacillariophyceae abundance were higher downstream from the river mouth. Visible or perceived pollution level was positively correlated with total phytoplankton abundance as well as Dinophyceae abundance and species richness.

Very strong relationships (significant at $\alpha = 0.001$) included positive correlations between abundance of each family and total phytoplankton abundance, indicating that each family had a strong influence on the overall abundance. However, each of the three families appeared to have a different form of relationship with community structure. Cyanophyceae abundance was strongly correlated with total species richness, but had no significant correlation with the ecological indices of community structure (H', E, and D). Conversely, the Bacillariophyceae abundance strongly correlated with all three ecological indices but not with total species richness. The abundance of Dinophyceae as a whole and *Ceratium furca* (the most abundant and prevalent species of this class) in particular were very strongly correlated with all three ecological indices, negatively with H' and E and positively with D. *Ceratium furca* abundance was also very strongly and negatively correlated with total phytoplankton species richness.

4. Discussion

The phytoplankton identified from the seven sites around the coast of South Sulawesi belonged to three classes, of which the Bacillariophyceae were the most diverse (Figure 2, Table 6) and the most abundant (Table 4) at six out of the seven sites. The exception was the Pangkep site where the Dinophyceae were by far the most abundant family and contributed an equal number of species to the Bacillariophyceae (Figure 2). The Bacillariophyceae (diatoms) tend to be found in rivers, mostly together with the Chlorophyceae (green algae), and can dominate phytoplankton communities in riverine environments, either all year round or seasonally (Boney 1975; Ozbay 2011; Georg *et al.* 2012; Ishaq *et al.* 2013; Farhadian *et al.* 2015; Allan *et al.* 2021). Many of the Bacillariophyceae have widespread distributions and play an important role in aquatic food chains, including riverine, estuarine and marine environments (Boney 1975; Farhadian *et al.* 2015; Kale and Karthick 2015; Allan *et al.* 2021). The prevalence of these species indicates that the study sites are likely to support coastal and marine food webs.

The ecological indices differed significantly between sites and seaways (Table 7). An H' value over 3 indicates high biodiversity and a relatively stable community (Odum 1998; Morris *et al.* 2014). Although Table 5 shows that no sites had a high diversity index (H'), values of the evenness and dominance indices (E and D) indicate that the sites on the Flores Sea and Gulf of Bone coasts had relatively stable phytoplankton communities with no excessively dominant species. Meanwhile all three Makassar Strait sites were significantly different and showed signs of communities under stress, with the lowest diversity indices, low to moderate evenness and moderate to high dominance.

The Pangkep site not only had by far the highest phytoplankton abundance, exceeding 5 million cells/l, but also a distinctive species composition with a high proportion (Table 4) and high diversity (Table 6) of Dinophyceae. Of the 7 members of the Dinophyceae present at this site, *Ceratium furca* was the most abundant at all six stations. While present at all sites, *C. furca* was highly dominant at the Pangkep site, accounting for over 99% of the total phytoplankton abundance at this site. A previous study at the same site (Rashidy *et al.* 2013) also found a high relative abundance of the genus *Ceratium*, a genus which is known to have a tendency to population explosions forming blooms which can cause anoxic conditions and thereby result in mass kills of fish and other marine organisms (Mulyani *et al.* 2012; Ibrahem and Al-Shawi 2015; Yurimoto *et al.* 2015; Cavalcante *et al.* 2016). In general, the Dinophyceae tend to have a high capacity for rapid adaptation to environmental change, and can increase rapidly under favourable conditions (Lagus *et al.* 2004; Cavalcante *et al.* 2016). This dominance calls for vigilance to detect and, if possible, mitigate potential harmful algal blooms (HABs).

The high phytoplankton population abundance as well as the high proportion of Dinophyceae at the Pangkep site could be related to anthropogenic activities, including nutrients in the water. Nutrient levels (nitrate and ammonium) were relatively high at all the study sites, exceeding the Indonesian water quality standards for aquatic (marine) organisms under Decree of the Minister for the Environment of the Republic of Indonesia No. 51/2004 (nitrates <0.008 mg/l and ammonium <0.3 mg/l). The nutrients present and the patterns of nutrient release can influence phytoplankton abundance and community composition (Hallegraeff 2010; Ozbay 2011; Paerl and Paul 2012; Ibrahem and Al-Shawi 2015). Although concentrations of the nutrients measured (nitrate and ammonia) at the Pangkep site were similar to those at the other sites surveyed, there may have been other nutrients (e.g. phosphates) not measured in this study. Potential sources of nutrients observed in the area around this site included brackish-water aquaculture ponds (fish and shrimps), poultry farming (chickens and ducks), and the direct discharge of sewage and other human wastes. Furthermore, the temperatures recorded at this and other sites were sufficiently elevated that they could have enabled or contributed to accelerated phytoplankton reproduction (Zohary *et al.* 2021).

Although river discharge and related physical and chemical parameters can significantly influence the distribution and composition of phytoplankton communities (Bharathi *et al.* 2018), this was not supported by any strong correlations between the water quality parameters measured and phytoplankton community characteristics recorded in this study. There were indications that phytoplankton communities may differ upstream and downstream (relative to prevailing currents) of river plumes, and may be influenced by water temperature, but the correlation was weak. This lack of a clear signal related to water quality parameters could be due to a combination of several factors. One of these is time; while the phytoplankton communities and seawater properties were sampled at the same time, the observed phytoplankton communities would have been influenced by conditions in the period preceding the sampling, which might have changed over time. For example, although nitrate concentrations were similar (and quite high) at all sites, there may have been peaks in concentration (e.g. releases of effluent from brackish-water tambak aquaculture ponds) which had been used up by phytoplankton and other photosynthetic organisms or dispersed by the time of sampling at the Pangkep site. Conversely, the high nutrients at some other sites could be recent, for example due to flooding during recent severe weather events, and the phytoplankton communities might not yet have reacted to the conditions measured. Another possibility is that one or more main driving factors were not measured. For example, phosphate is also a nutrient which can influence phytoplankton abundance and community composition (Mackey *et al.* 2007). However, despite the limitations of this study, the results provide an overview of phytoplankton abundance and diversity in this region. They also raise a warning that coastal waters around South Sulawesi may be at risk of experiencing HABs, with a potentially higher risk in the Makassar Strait compared to the Flores Sea and Gulf of Bone coasts.

5. Conclusion

Phytoplankton communities at the seven study sites around the coast of South Sulawesi, Indonesia comprised a total of 31 identified species belonging to three classes (Bacillariophyceae, Cyanophyceae, and Dinophyceae). Six species were found at all seven sites, including *Ceratium furca*, a member of the Dinophyceae which can cause harmful algal blooms (HABs) as well as Bacillariophyceae thought to be important in aquatic food webs (e.g. *Chaetoceros* sp). Diversity was low overall, but highest at the Bulukumba site. The Pangkep District site phytoplankton community was the most abundant but had the lowest diversity and evenness, with strong dominance by *C. furca*. The results indicate that negative influence of anthropogenic activities is higher in the Makassar Strait where estuarine and coastal phytoplankton communities are more likely to produce HABs than at the sites in the Flores Sea and Gulf of Bone. However, the ubiquity of high nutrient (nitrate and ammonium) concentrations calls for further research and efforts to reduce the flow of nutrients into the coastal waters all around this province.

Acknowledgements

This research was supported by a Master Program of Education Leading to Doctoral Degree for Excellent Graduates (PMDSU) Scholarship from The Ministry of Research, Technology, and Higher Education (grant number SP DIPA- 042.06.1.401516/2018). The authors would like to thank all who contributed to this study, in particular the Marine Science and Fisheries Faculty, Hasanuddin University, Makassar and Muh. Isman, Mustono, Nurissatul, Diyen Anggaraeni, Reza Hidayat Siregar, Fajar Fajrin and Fajria Sari who assisted in the collection of samples in the field.

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