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The Determination of Algae Group as Bioindicator of Water Quality Change Affected by Mercury Release from Artisanal Small-Scale Gold Mining (ASGM)

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Highlights:

- Algal communities could reflect water quality changes impacted by ASGM activities.
- The total mercury concentration in the river water in several regencies of Indonesia ranged from <0.04 to 20 $\mu g.L^{-1}$, while in the sediment the maximum value was 13,500 $\mu g.kg^{-1}$.
- Low density of benthic *Navicula* indicated an increase of mercury content in sediment.

Abstract. Artisanal small scale gold mining (ASGM) practices typically use mercury for amalgamation. Near water environments this can degrade water quality and aquatic biota, including algae. Changes in algal communities can reflect water environment disturbance. The aim of this study was to determine if algae can be used as bioindicator of river water quality impacted by ASGM activities. The research was conducted from July to October 2018 at thirty sampling sites along rivers near ASGM areas in several regencies of Indonesia. Composite samples of water and sediment were collected. A plankton net and brushing methods were used to collect planktonic and benthic algae, respectively. The physicochemical parameters of the water and the sediment as well as the dominant algae genera were analyzed statistically with principal component analysis. The results showed that the total mercury concentration in the water ranged from <0.04 to 20 $\mu g.L^{-1}$, while in the sediment the maximum value was 13,500 $\mu g.kg^{-1}$. The total mercury content in the sediment was negatively correlated with the dominant benthic *Navicula* at a significance level of $p < 0.05$. This means that a low density of benthic *Navicula* can be proposed as a bioindicator of water quality, indicating the increase of mercury pollution in sediment.

Keywords: *algae; abundance; gold mining; mercury contamination; multivariate analysis.*

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1 Introduction

Artisanal small-scale gold mining is a conventional mining system, which is performed informally by individual miners and small enterprises with limited capital investment. ASGM is usually operated near aquatic ecosystems such as rivers to collect sedimented gold ore from the riverbed, using river water in the mining process. ASGM activities occur in different regions of Indonesia and peaked in 2010 with 850 spots [1].

ASGM activities systematically cause the deterioration of water quality due to siltation [2], erosion, high turbidity, and contamination with toxic substances such as mercury (Hg) from the amalgamation process [3]. Mercury is a very toxic heavy metal and is usually absorbed as methyl mercury species. It potentially accumulates in lower trophic levels such as algae and can be transferred to higher organisms through the food chain. A structural alteration of the aquatic biota community due to toxic contamination may be affected by pollution-tolerant organisms that dominate the community. The water will be more harmful to consume because of the presence of toxic accumulated species.

A bioindicator is a comprehensive biological method to screen the health status of aquatic systems by the biological responses of organisms to changes in physicochemical water parameters [4]. The presence or absence of identified species reflects the character of the habitat where they are usually found [5]. Algae are autotrophic aquatic organisms that have the ability to produce oxygen by photosynthesis and either grow as planktonic or benthic forms. Algae are ideally suitable for water quality assessment due to their short life cycle and rapid response to water quality changes. Besides that, they are also ubiquitous, especially in tropical environments.

Specific organisms have specific responses [6]. The small size of algae compared to other aquatic organisms makes them potentially more sensitive to pollutants at low concentrations. They are able to attach to substrates and therefore are more frequently exposed to pollution [7]. Algae respond to water quality, where tolerant species will have large populations over a long period of time in polluted water, while less tolerant species will be selectively eliminated by interspecific competition or predators [8]. Lobo, *et al.* (2017) have reported that diatoms and cyanobacteria were dominantly found in the Tapajós River basin in the Brazilian Amazon near an ASGM area [2].

The multivariate approach has been used to determine the relationship between bioindicators and environmental characteristics. Cluster and principal component analysis (PCA) have been performed for the determination of benthic foraminifera as bioindicator [9]. A unimodal canonical correspondence analysis

(CCA) was applied to assess river quality in a subtropical Austral river system by investigating benthic diatoms and macroinvertebrates [10]. Recently, Chazanah, *et al*. (2018) applied PCA to determine ecological status parameters of the Upper Citarum River in Indonesia based on benthic macroinvertebrates [11]. However, references related to algae as bioindicator of river water quality near ASGM areas are still limited, particularly in Indonesia.

The aim of this study was to evaluate algae as bioindicator of water quality deterioration in rivers near ASGM areas using multivariate analysis. We hypothesized that the presence or absence of certain algae genera could indicate water quality changes due to Hg contamination from ASGM. Study sites were selected in several regencies of Indonesia (Figure 1). They correspond to the regions in the western part of Indonesia prioritized by the Ministry of Environment and Forestry for Hg inventory. The results of this research can be referenced for water quality management in the river basin near ASGM areas.

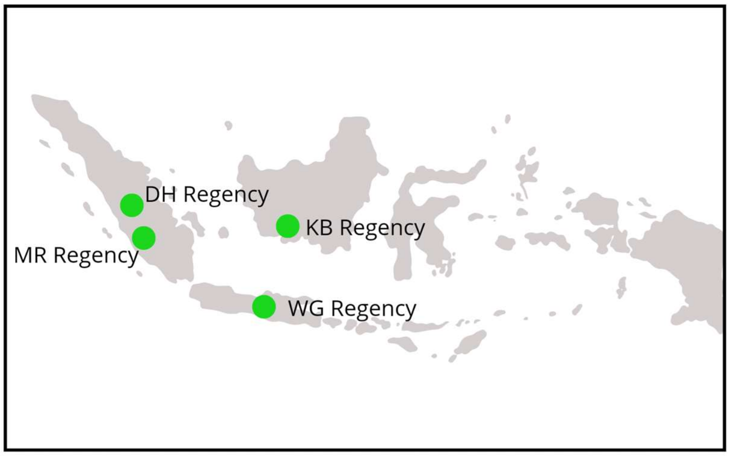


Figure 1 Study sites near ASGM areas in four regencies in Indonesia.

2 Materials and Methods

2.1 Study Area

Several rivers near ASGMs areas in WG, MR, DH, and KB Regencies were selected as study sites in this study (Figure 1). The research was conducted from July to September of 2018 during the dry season at thirty sampling sites. The sites represented areas potentially contaminated by ASGM activities, with the upper stream used as control.

In WG Regency, six sampling sites (S1-S6) were selected in streams near ASGM areas. The gold processing in this area uses mills, known as *gelundung*, to grind the ore. In MR Regency, sampling was carried out in four sub-basins, i.e., MR1 River (S7-S8), MR2 River (S9-S10), MR3 River (S11-S12), and MR4 River (S13-S14). In this area, the ASGM activities were mostly operated using an excavator to remove ore from rock mines near the river system and panning to concentrate the gold. In DH Regency, ten sites were selected along the MM River (S15-S19) and HH River (S20-S24). The conventional mining system around the MM River is dominated by *gelundung* machines, while floating mining (*dompeng*) was operated along the HH River. In KB Regency, the sampling sites were at the AT River (S25-S30). Various small-scale gold mining techniques were performed in this location.

2.2 Sampling Methods

Based on the different types of habitats, sampling was conducted in two categories, for planktonic (S1-S6 and S28-S30) and benthic (S7-S27) algae, respectively. Algae were sampled from stones in riffles of shallow streams using a soft, clean brush in an area of 20 x 30 cm for benthic algae. Planktonic algae were collected using a plankton net in a pool of a large stream or river. The planktonic samples were immediately fixed with 37% of formaldehyde.

Physicochemical water parameters such as water velocity, depth, pH, conductivity, total dissolved solids, and dissolved oxygen were measured directly at each site. Composite samples of surface water and sediment were collected using a water sampler, trowel, and Eckman grab. Further analysis was conducted to determine the concentration of Hg, nutrients ($NO_3^-$and PO_4^{3-}), total suspended solids, specific gravity, particle size distribution, cation exchange, and organic carbon fraction.

2.3 Chemical Analysis

Mercury extraction was performed based on SNI 6989.78: 2011 for water and sediment using US EPA 7471B. Subsequently, total Hg (T-Hg) concentrations were determined by spectrophotometry using inductively coupled plasma mass spectrophotometry (ICP-MS). The NO_3^-, PO_4^{3-}, and total suspended solids were determined using a brucine–spectrophotometer, the stannous chloride–spectrophotometer method, and the gravimetric method, respectively. Meanwhile, the physicochemical sediment parameters particle size distribution, organic carbon fraction, and cation exchange were measured by sieve analysis, spectrophotometry, and the volumetric method, respectively.

2.4 Biological Analysis

The algae were observed in three replicates from each sampling point using a light microscope (Omano, Japan) with 100x magnification. The identification was carried out up to genus level according to Bellinger & Sigee (2015) [12], Necchi Jr. (2016) [13], and Wehr (2015) [14]. The algae density was measured by counting the algae cells in 40 of the 1000 grids of a Plastic Sedgwick Rafter Counting Chamber, in which 30 grids were expected to reveal the presence of 90-95% species [12]. Several different equations were applied for measuring the density of planktonic and benthic algae [15]. Additionally, the relative density was also calculated to reveal the dominant genera based on relative density >20% [16].

2.5 Data Analysis

Statistical analysis was performed using the statistical software package SPSS IBM 25. All variables were transformed into Log10 (x) to normalize the data distribution. Normality was tested using the Shapiro–Wilk test ($\alpha \leq 0.05$). The abundance of all taxa was expressed as relative density (>20%) prior to further analysis. PCA was conducted to extract and classify the number of variables based on Eigenvalue >1 using the varimax method into a new main factor with loading score >0.5 (strong correlation).

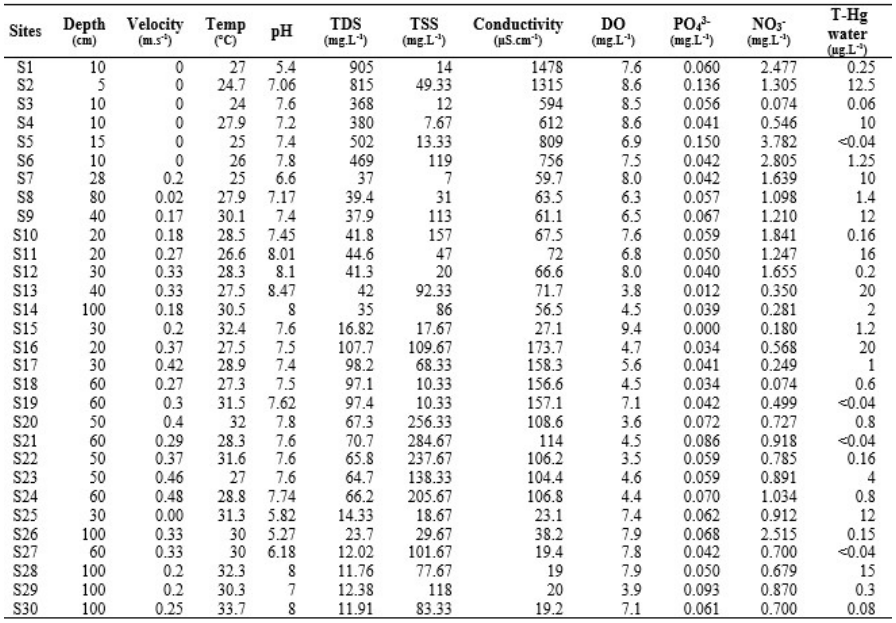
All of the 23 physicochemical water and sediment variables were included in a PCA analysis. Next, each group of factors was analyzed by linear regression to determine the environmental variables that most affected certain dominant algae genera. Factors with a probability level of 0.05 were considered statistically significant. The result was used to determine the algae genera that can potentially be used as bioindicators to reflect physicochemical water and sediment parameter changes.

3 Results and Discussion

3.1 Physicochemical Characteristics of Water and Sediment

The physicochemical characteristics of the water and sediment samples from the thirty sites in four regencies are given in Tables 1 and 2, respectively. As a key parameter of ASGM activities, the total Hg (T-Hg) concentration in water and sediment samples was considerably different among the four locations. The measured Hg concentration in the water was mostly found to exceed its acceptable level (1 $\mu g.\ L^{-1}$) according to Government Regulation of Indonesia Number 82 of 2001, on Water Quality Management and Water Pollution Control.

Table 1 Physicochemical water characteristics in 30 sites along rivers near ASGM areas in four regencies. Sites S1-S6 were located in WG Regency; S7-S14 in MR Regency; S15-S24 in DH Regency; and S25-S30 in KB Regency.



Sites	Depth (cm)	Velocity ($m.s^{-1}$)	Temp (°C)	pH	TDS ($mg.L^{-1}$)	TSS ($mg.L^{-1}$)	Conductivity ($\mu S.cm^{-1}$)	DO ($mg.L^{-1}$)	PO_4^{3-} ($mg.L^{-1}$)	NO_3^- ($mg.L^{-1}$)	T-Hg water ($\mu g.L^{-1}$)
S1	10	0	27	5.4	905	14	1478	7.6	0.060	2.477	0.25
S2	5	0	24.7	7.06	815	49.33	1315	8.6	0.136	1.305	12.5
S3	10	0	24	7.6	368	12	594	8.5	0.056	0.074	0.06
S4	10	0	27.9	7.2	380	7.67	612	8.6	0.041	0.546	10
S5	15	0	25	7.4	502	13.33	809	6.9	0.150	3.782	<0.04
S6	10	0	26	7.8	469	119	756	7.5	0.042	2.805	1.25
S7	28	0.2	25	6.6	37	7	59.7	8.0	0.042	1.639	10
S8	80	0.02	27.9	7.17	39.4	31	63.5	6.3	0.057	1.098	1.4
S9	40	0.17	30.1	7.4	37.9	113	61.1	6.5	0.067	1.210	12
S10	20	0.18	28.5	7.45	41.8	157	67.5	7.6	0.059	1.841	0.16
S11	20	0.27	26.6	8.01	44.6	47	72	6.8	0.050	1.247	16
S12	30	0.33	28.3	8.1	41.3	20	66.6	8.0	0.040	1.655	0.2
S13	40	0.33	27.5	8.47	42	92.33	71.7	3.8	0.012	0.350	20
S14	100	0.18	30.5	8	35	86	56.5	4.5	0.039	0.281	2
S15	30	0.2	32.4	7.6	16.82	17.67	27.1	9.4	0.000	0.180	1.2
S16	20	0.37	27.5	7.5	107.7	109.67	173.7	4.7	0.034	0.568	20
S17	30	0.42	28.9	7.4	98.2	68.33	158.3	5.6	0.041	0.249	1
S18	60	0.27	27.3	7.5	97.1	10.33	156.6	4.5	0.034	0.074	0.6
S19	60	0.3	31.5	7.62	97.4	10.33	157.1	7.1	0.042	0.499	<0.04
S20	50	0.4	32	7.8	67.3	256.33	108.6	3.6	0.072	0.727	0.8
S21	60	0.29	28.3	7.6	70.7	284.67	114	4.5	0.086	0.918	<0.04
S22	50	0.37	31.6	7.6	65.8	237.67	106.2	3.5	0.059	0.785	0.16
S23	50	0.46	27	7.6	64.7	138.33	104.4	4.6	0.059	0.891	4
S24	60	0.48	28.8	7.74	66.2	205.67	106.8	4.4	0.070	1.034	0.8
S25	30	0.00	31.3	5.82	14.33	18.67	23.1	7.4	0.062	0.912	12
S26	100	0.33	30	5.27	23.7	29.67	38.2	7.9	0.068	2.515	0.15
S27	60	0.33	30	6.18	12.02	101.67	19.4	7.8	0.042	0.700	<0.04
S28	100	0.2	32.3	8	11.76	77.67	19	7.9	0.050	0.679	15
S29	100	0.2	30.3	7	12.38	118	20	3.9	0.093	0.870	0.3
S30	100	0.25	33.7	8	11.91	83.33	19.2	7.1	0.061	0.700	0.08

The highest concentration of T-Hg in the water was 20 $\mu g.L^{-1}$ at two sampling sites, namely S13 (MR) and S16 (DH) (Table 1). This may have been caused by the location of S13 in the downstream, which potentially receives more pollutant input from rivers in other districts that have notable ASGM activities. Meanwhile, the ASGM that was actively operated along the MM River seems to have caused the high level of T-Hg at S16. It was also positively correlated with an increase of the physicochemical parameters of the water samples, such as TDS, TSS, and conductivity, and a decrease of DO (Table 1).

The various operating systems of ASGM using technically different processes and durations are suggested to affect the amount of Hg used and released into local water bodies. Furthermore, the environmental conditions also contribute to the distribution of Hg in the river. Gold mining activities cause an increase of suspended solids and heavy metals because the soil is eroded [16-18]. In addition, the dewatering process affects a high level of electrical conductivity in the river [19].

Based on the Canadian sediment quality guidelines for the protection of aquatic life (i.e., 170 $\mu g.kg^{-1}$) [20], the Hg content in the sediment tended to be accumulated below the standard. However, Hg accumulation was more than fifty times the standard level in the sediment of S6 (13,500 µg.kg^{-1}) and S22 (11,100 µg.kg^{-1}), respectively (Table 2). It was estimated that ASGM operation at both sites was located close to the water system. The effluent or tailing that was flushed directly into the water system caused the distribution of Hg in the water and the sediment. PSLB3 (2018) has reported that ASGM activities in WG and DH Regencies use Hg in their gold mining process [21].

Table 2 Physicochemical sediment characteristics at 30 sites near rivers in ASGM areas in four regencies. Sites S1-S6 were located in WG Regency; S7-S14 in MR Regency; S15-S24 in DH Regency; and S25-S30 in KB Regency.

Site	Organic-carbon (%)	CEC (me.100g^{-1})	Specific gravity	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	T-Hg sediment (µg.kg^{-1})
S1	0.21	2.71	2.77	8.4	14.7	69.7	7.2	691.73
S2	0.36	7.19	2.78	9.2	6.6	80.2	4	537.27
S3	0.23	15.54	2.77	22.8	29.4	44.3	3.5	<0.04
S4	0.542	10.59	2.77	27.6	71.8	0.6	0.6	35.79
S5	0.656	9.6	2.68	4	64.5	24.5	7	37.14
S6	0.38	7.28	2.73	9.1	14.5	54.7	21.7	13,500
S7	0.539	1.79	2.72	17.7	80.9	0.8	0.6	<0.04
S8	0.863	0.271	2.73	53.9	45.6	0.5	0.5	<0.04
S9	0.511	0.543	2.79	61.9	36.7	1.4	1.4	<0.04
S10	0.468	0.381	2.76	72.5	25.5	2	2	<0.04
S11	0.862	1.36	2.72	32.6	55.3	10.5	1.6	<0.04
S12	0.636	3.75	2.78	31.9	67.1	0.7	0.3	<0.04
S13	0.262	0.605	2.73	66.3	33.3	0.4	0.4	<0.04
S14	0.669	0.762	2.72	44.5	52.4	1.6	1.5	<0.04
S15	0.689	2.12	2.79	66.7	33.2	0.1	0.1	37.09
S16	0.663	0.217	2.78	76.6	23.4	0	0	12.27
S17	0.558	0.57	2.79	78.3	21.6	0.1	0.1	35.77
S18	0.316	0.476	2.71	67.1	32.8	0.1	0.1	12.98
S19	0.369	0.847	2.75	71.5	28.4	0.1	0.1	35.76
S20	0.367	0.793	2.77	84.4	15.5	0.1	0.1	<0.04
S21	0.319	0.953	2.72	23.6	61.2	0	0	11.12
S22	0.226	0.899	2.79	23.1	54.8	0	0	11,100
S23	0.328	0.635	2.79	77.1	22.8	0.1	0.1	517.91
S24	0.328	0.953	2.79	59.9	40	0.1	0.1	71.51
S25	0.283	0.476	2.73	30.5	69.1	0.2	0.2	345.66
S26	0.448	0.318	2.62	12.3	69.9	12.8	5	37.11
S27	0.304	0.846	2.69	13.4	76.8	7.6	2.2	8.48
S28	0.647	1.54	2.66	0	44.9	39.4	15.7	<0.04
S29	0.441	0.953	2.75	3.5	96	0.3	0.2	<0.04
S30	1.09	2.33	2.61	0	15.3	61.1	23.6	<0.04

On the other hand, the Hg content in the sediment showed the lowest level or was under the detection limit at all sampling sites in MR Regency. PSLB3 (2018) has reported that there was no evidence of the use of Hg in ASGM activities in that area [21]. The amount of Hg in the tailings was 0.005 µg.kg^{-1}, which is below the permissible limit (5 µg.L^{-1}) based on State Minister of Environment Republic of Indonesia Decree No.202/2004 on Effluent Standard for Gold and/or Copper Ore Mining Business and/or Activities.

In addition, the sediment at sites S7-S14 was mostly composed of gravel and sand (Table 1). The gravel and sand released into the river were commonly generated by semi-mechanical ore crushing in ASGM [3]. The Hg distribution in the sediment showed that there was a decrease of total Hg content with an increase of particle size. Smaller particles have a larger specific surface area that is beneficial to binding heavy metals [22].

3.2 Composition of Algae

A total of 32 genera were identified as planktonic algae at 9 sites of 2 rivers (Table 3). The genera with a relative density greater than 20% were *Synedra*, *Nitzschia*, *Navicula*, *Gomphonema*, and *Achnanthes*. Moreover, 61 genera of benthic algae were found at 21 sites (Table 3). These were *Phormidium*, *Microspora*, *Synedra*, *Navicula*, *Gyrosigma*, *Gomphonema*, *Cymbella*, and *Achnanthes*, which were classified as the dominant benthic algae.

The relative density showed that the algae in the 30 sites along rivers near ASGM areas were dominated by Baccilariophyta, a member of the diatoms. Diatoms are microscopic algae abundant in freshwater aquatic ecosystems as a food source for invertebrate organisms [23]. Diatoms are also found in all freshwater habitats as planktonic and benthic forms in standing and flowing waters [14].

The planktonic algae were mainly dominated by *Synedra*, at 54.55%. Furthermore, the genus of *Synedra* was also abundantly found as benthic algae, at 59.64%. According to Stevenson (1996), other algae can be found, either as planktonic or benthic forms, such as *Fragilaria*, *Synedra*, and *Nitzschia* [24]. Meanwhile, the percentages of other benthic algae with relative abundance more than 50% were *Navicula* at 54.05% and *Phormidium* at 50%.

Table 3 shows that *Navicula* tended to be found in the river in MR Regency (S7-S14), where the excavator gold mining technique was used and a high proportion of larger sediment particles such as gravel and sand were found. The dominance of *Navicula* indicates stable sediment and moderate siltation 16]. On the other hand, *Phormidium* was mostly identified in high levels of river water depth (Table 3), where the light intensity is lower. *Phormidium* is a cyanobacteria that is adaptive to living under conditions of less than 0.1% light intensity [25].

Table 3 Composition of dominant (relative density >20%) planktonic and benthic algae in rivers near ASGM areas. Sites S1-S6 were located in WG Regency; S7-S14 in MR Regency; S15-S24 in DH Regency; and S25-S30 in KB Regency.

Sites	Taxa								
	Baccilariophyta							Chlorophyta	Cyanophyta
	Achnanthes	*Cymbella*	*Gomphonema*	*Gyrosigma*	*Navicula*	*Nitzschia*	*Synedra*	*Microspora*	*Phormidium*
S1			27.27*						
S2							54.55*		
S3									
S4			21.62*			21.62*			
S5			27.27*		31.82*				
S6			21.05*		36.84*	21.05*			
S7					30.12**				
S8			34.03**						
S9			23.19**	31.94**	30.42**				
S10			30.26**		33.85**				
S11									
S12							59.64**		
S13					54.05**				
S14			28.71**		20.79**				
S15	29.81**								
S16							30.19**		
S17							26.3**		35.69**
S18	29.77**								42.95**
S19									21.83**
S20	26.22**								
S21									28.49**
S22									
S23							33.65**		
S24			33.71**						
S25		21.62**						36.04**	21.17**
S26									50**
S27					21.78**				30.69**
S28			27.59*						
S29	26.67*								
S30									

3.3 Determination of Algae as Bioindicator

PCA was performed with varimax rotation to simplify the large data set of physicochemical and biological variables, which were distributed into several main factor groups. The PCA results showed that planktonic algae from 9 data sets and 23 variables were reduced to 7 factor groups with loading score >0.5 (Table 4).

However, the dominant algae were distributed in only 4 groups. As shown by the factor loading matrix in Table 4, PC2 contained *Achnanthes*, dissolved oxygen (DO), TSS, cation exchange capacity (CEC), and gravel. PC5 contained *Gomphonema*, *Synedra*, and pH with a loading score of >0.5 (medium correlation). PC4 contained *Navicula*, nitrate, and Hg in the sediment. Finally, PC6 contained *Nitzschia* and Hg in the water with a high loading score of >0.7.

On the other hand, another PCA resulted in 8 groups of factors from 21 data sets with 27 variables. The dominant benthic algae were distributed into 4 main factor groups, as shown in Table 5. PC2 had high loading of *Cymbella*, *Microspora*, *Phormidium*, pH and organic carbon. PC3 contained *Gomphonema*, *Gyrosigma*, *Navicula*, and total Hg in the sediment. Meanwhile, *Synedra* and water velocity belonged to another principal component group (PC4). Lastly, *Achnanthes* had a good correlation with temperature and Hg of water in the sixth principal component group (PC6).

Following PCA, the multiple regression linear analysis using a stepwise method explained that there were significant relationships between several of the environmental parameters and certain genera of algae (Table 6). *Achnanthes*, *Navicula*, and *Synedra* as planktonics were significantly affected by most of the water parameters. The result showed that there was no significant influence of total Hg in the water and sediment on the planktonic algae. This indicates that dominant planktonic algae were not suitable for monitoring Hg contamination along the rivers of the 9 sampling sites. This could be caused by the ability of planktonic algae to move and migrate to avoid pollutant exposure. Another study has shown that periphytic or attached algae are able to assess and monitor the degree of pollution impacted by gold mining activities [16].

Table 4 Variables and factor loadings after varimax rotation of planktonic algae in PCA.

Variables	**Components**						
	PC1	**PC2**	**PC3**	**PC4**	**PC5**	**PC6**	**PC7**
Depth (cm)	-0.73						
pH					0.87		
Temperature (°C)	-0.79						
DO (mg.L^{-1})		-0.74	0.52				
TDS (mg.L^{-1})	0.61						
TSS (mg.L^{-1})		0.88					
Conductivity (μs.cm^{-1})	0.61						
Nitrate (mg.L^{-1})				0.93			
Orthophosphate (mg.L^{-1})							0.97
Hg-water (μg.L^{-1})						-0.91	
Organic Carbon (%)	-0.95						
CEC (me.100 g^{-1})		-0.64					
Specific Gravity	0.96						
Gravel (%)	0.61	-0.58					
Sand (%)			-0.96				
Silt (%)			0.97				
Clay (%)	-0.65		0.53				
Hg-sediment (μg.kg^{-1})				0.79			
Achnanthes		**0.83**					
Gomphonema					**0.61**		
Navicula				**0.81**			
Nitzschia						**0.78**	
Synedra					**-0.64**		
Eigenvalue	5.40	3.52	3.42	3.32	2.43	2.31	1.98
% of total variance	23.46	15.32	14.86	14.45	10.58	10.04	8.62
% of cumulative	23.46	38.78	53.63	68.08	78.66	88.70	97.31

Notes: Values in bold correspond to the absolute value of loading >0.50

Table 5 Variables and factor loadings after varimax rotation of benthic algae in PCA analysis.

Variables	Components							
	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8
Depth (cm)					0.81			
Water velocity (m.s^{-1})				0.86				
pH	-0.60	-0.55						
Temperature (°C)						0.85		
DO (mg.L^{-1})	0.59							-0.51
TSS (mg.L^{-1})								0.85
TDS (mg.L^{-1})	-0.81							
Conductivity (µs.cm^{-1})	-0.82							
Orthophosphate (mg.L^{-1})							0.84	
Nitrate (mg.L^{-1})	0.58						0.58	
Hg-water (µg.L^{-1})						-0.66		
Organic-Carbon (%)		-0.78						
CEC (me.100 g^{-1})					-0.61			
Specific Gravity	-0.65				-0.63			
Gravel	-0.91							
Sand	0.82							
Silt	0.83							
Clay	0.77							
Hg-sediment (µg.kg^{-1})			-0.63					
Achnanthes						**0.87**		
Cymbella		**0.90**						
Gomphonema			**0.59**					
Gyrosigma			**0.75**					
Navicula			**0.88**					
Synedra				**0.75**				
Microspora		**0.90**						
Phormidium		**0.52**						
Eigenvalue	5.99	3.54	2.67	2.45	2.45	2.42	2.07	2.00
% of total variance	22.17	13.13	9.87	9.08	9.06	8.98	7.68	7.42
% of cumulative	22.17	35.29	45.16	54.24	63.30	72.28	79.96	87.38

Notes: Values in bold correspond to the highest absolute value of loading >0.50

Table 6 shows that *Navicula* and nitrate had a strong positive relationship (R^2 = *0.665*). This indicates that *Navicula* is tolerant to an increase of nitrate in river water near an ASGM area. *Navicula* is one of the genera that have a positive response to high nutrient levels in water caused by decomposing organic matter [10]. However, *Achnanthes* showed the strongest negative correlation with dissolved oxygen (R^2 = *0.742*), while *Synedra* and pH had a weaker negative correlation (R^2 = *0.474*) in water. This means that *Achnanthes* had good tolerance to low dissolved oxygen levels in the water. *Achnanthes* is able to live under reduced light conditions due to the dense canopy and high turbidity. Similar to *Achnanthes*, *Synedra* demonstrated intermediate ability to adapt to low levels of pH. According to Gasse & Tekaia, the species of *Synedra* have specific tolerance to different levels of acidity and alkalinity [26].

Table 6 Linear regression coefficients between dominant algae and physicochemical characteristics of water and sediment in rivers near ASGM areas.

Genera	Water					Sediment	Model
	Temp	Velocity	Nitrate	DO	pH	T-Hg	
Planktonic							
Achnanthes				0.742			y = 57.63 - 51.7x
Navicula			0.665				y = 0.85 + 0.17x
Synedra					0.474		y = 4.21 – 3.61x
Benthic							
Achnanthes	0.331						y = 1.27 + 0.07x
Cymbella					0.397		y = 2.58 – 2.04x
Navicula						0.308	y = 1.02 + 0.11x
Synedra		0.207					y = 0.62 + 1.16x
Microspora					0.385		y = 2.97- 2.48x
Phormidium					0.303		y = 4.51- 4.04x

The regression linear analysis revealed that benthic algae genera were found to be correlated with both water and sediment factors in rivers near ASGM areas. However, the coefficient of determination showed that the models mostly had a weak correlation (Table 6). It was expected that there were other unidentified environmental variables influencing the dominant benthic algae.

Achnanthes was positively affected by temperature ($R^2 = 0.331$), while *Synedra* was influenced by water velocity ($R^2 = 0.207$). This demonstrates that those genera have a good response to an increase in temperature and velocity of river water at a certain level. *Achnanthes minutissima* is a species that is able to live under high temperature conditions [27].

However, Hg accumulation in the sediment was negatively correlated to the abundance of *Navicula* ($R^2 = 0.308$) (Table 6). In addition, pH was the only variable that negatively affected the dominance of *Cymbella*, *Microspora*, and *Phormidium*, with an R^2 value of 0.397, 0.385, and 0.303, respectively. This indicates that those genera had low abundance in water with a high pH value and exhibited good response to a decrease in pH level. Filamentous algae such as *Phormidium* and *Microspora* can be found in acidic water systems [28,29].

The results suggest that Hg accumulation in the sediment, as a key parameter of river water quality deterioration due to gold mining activities, significantly affected *Navicula* as a benthic organism. If there was an increase of 1 $\mu g.kg^{-1}$ total Hg content in the sediment, the relative density of *Navicula* would decrease by 0.11%. This means that the abundance decrease of *Navicula* is a potential bioindicator of Hg accumulation in the sediment. Peres *et al*. (1997) have reported that exposure to MeHg reduced the cell density of diatoms by 2.5 times for 34 days [30]. They also state that pollutants from the sediment significantly affected MeHg density. The abundance of *Navicula aquaedurae* clearly decreased with

MeHg initial doses in the water of 0.5 $\mu g.L^{-1}$ and 2 $mg.kg^{-1}$ in the sediment source over 34 days.

In contrast, the genera that were not significantly influenced by Hg were suggested to each have their own different responses to certain pollutants. *Phormidium* and *Microspora* have been reported as genera that are tolerant and resistant to copper [31]. The accumulation of pollutants in microorganisms can impact their cellular system. Algae are able to accumulate Hg, thus affecting their cell division, photosynthetic pigments, and cell membrane. Inorganic Hg was mainly deposited in the nucleus, while organic Hg was detected in the nucleus and cytoplasm [8]. Further studies on their cellular properties are needed to gain a comprehensive understanding of algae as bioindicator of Hg pollution.

4 Conclusions

In conclusion, the Baccilariophyta group was found to be an algae group that can indicate water general quality deterioration in rivers near ASGM areas. It was also shown that benthic algae better reflect parameters of their surrounding water and sediment than planktonic algae. Statistical analysis showed that *Navicula* as a benthic organism has potential as a bioindicator of water quality change due to Hg contamination. The low relative abundance of *Navicula* as benthic form was able to indicate significant accumulation of Hg content in the sediment of the rivers near ASGM areas.

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