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Responses of Phytoplanktonic Chlorophyll-a Composition to Inorganic Turbidity Caused by Mine Tailings

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Inorganic turbidity can limit light penetration in water and reduce phytoplankton photosynthesis. Anthropogenic activities such as mining can produce or augment the amount of suspended inorganic particles in water. Recent mining disasters in Brazil have released tons of mine tailings into aquatic ecosystems, with known and unknown negative consequences for aquatic life, biodiversity, and ecosystem services beyond the human and material losses. Here, we investigated the effects of inorganic turbidity on phytoplankton chlorophyll content and composition caused by sediments from two areas in Lake Batata, one natural and the other impacted by bauxite tailings. We experimentally compared the effects of different levels of turbidity (12, 50, and 300 NTU) caused by the addition of sediments from the two lake areas on a chlorophyll-a gradient (5, 15, and 25 μg/L). Inorganic turbidity did not consistently reduce chlorophyll-a concentrations. In treatments with high chlorophyll-a, high turbidity was associated with lower chlorophyll-a concentrations at the end of the experiment. On the other hand, in low-chlorophyll treatments, high turbidity was associated with higher chlorophyll-a concentrations. In treatments with sediments from the natural area, overall chlorophyll-a levels were higher than in treatments with sediments from the impacted area. Phagotrophic algae dominated both in treatments with sediments from the impacted area (Chrysophyceae 34%, Chlorophyceae 26%, and Cyanobacteria 22% of total density) and in treatments with sediment from the natural area (Euglenophyceae 26%, Chrysophyceae 23%, and Chlorophyceae 20%). We conclude that high turbidity does not lead to a reduction in chlorophyll-a concentrations and sediment from the natural area allowed higher chlorophyll-a levels, indicating that impacted area sediment affected more phytoplankton.

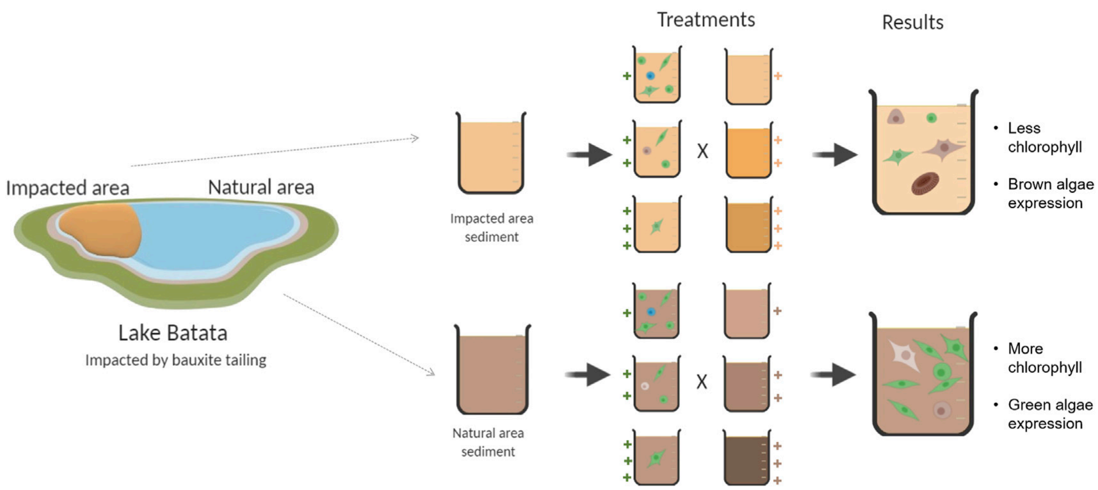
Keywords: inorganic turbidity, phytoplankton, chlorophyll-a, freshwater ecosystems, bauxite tailing

1 INTRODUCTION

Turbidity is an important feature of aquatic ecosystems. It can be caused by dissolved organic matter or suspended particles in the water column and is usually measured by lateral dispersion (90°) of an incident light beam. Turbidity is often considered an aquatic environmental stressor because it directly modifies the scattering, absorption, and attenuation of light penetration in water, thereby affecting primary production and aquatic metabolism (Kirk, 1985). Suspended solids responsible for increasing water turbidity can derive from natural processes such as glacier melting (Dierssen et al., 2002), cyanobacterial blooms or high densities of planktonic microalgae (more often in shallow lakes) (Descy et al., 2013), and sediment resuspension by wind, benthivorous fish, or lateral flooding (Donohue and Garcia-Molinos, 2009). Recent studies suggest that climate warming can intensify turbidity by increasing evaporation rates and reducing lake depths (Jeppesen et al., 2014; Menezes et al., 2019). This tendency, together with seasonal variation in freshwater ecosystems, can exacerbate turbidity variation, creating larger range gradients, especially on floodplains (Sorribas et al., 2016).

Turbid waters (e.g., with suspended organic or inorganic solids) are often associated with low aesthetic value, limited recreational use, pollution, disease transmission, and human health impact, with increased treatment costs for consumption (Davies-Colley and Smith, 2001). Nowadays, inorganic turbidity is considered one of the most important aquatic pollutants (Parkhill and Gulliver, 2002), including turbidity generated by anthropogenic activities (Bentley et al., 2016). Anthropogenic interventions in the landscape increase soil erosion and sediment transport to freshwater environments, which are among the most threatened ecosystems in the world (Malmqvist and Rundle, 2002; Cantonati et al., 2020). Some examples of anthropogenic alterations are agricultural expansion, the development of large industries, and mining activities. These activities can alter sediment dynamics and transport to rivers and lakes, profoundly altering drainage basins (de Jong et al., 1995). One of the first large-scale mining environmental impacts known in Brazil is the discharge of 25,000 m^3 of bauxite tailings daily for 10 years (1979–1989) in Lake Batata; a restoration project was initiated in 1989 (Esteves et al., 1990). Recently, large mining disasters in Brazil have released tons of waste into aquatic ecosystems. In 2015, a dam maintained by the company Samarco Mineração S. A. collapsed in the city of Mariana, Minas Gerais state, discharging approximately 60 million m^3 of iron waste that spread along 660 km of the Doce River. A thick layer with low nutritional value was created along the river, increasing heavy-metal concentrations and causing silting, animal mortality, material damage, and loss of human lives (IBAMA, 2015; Grilo et al., 2018). In 2019, another dam owned by Vale S. A. collapsed in the city of Brumadinho, also in Minas Gerais. This accident released 12 million m^3 of iron ore tailings into the Paraopeba River and resulted in severe environmental effects and even more loss of life (Thompson et al., 2020).

The effects of mine tailings on aquatic environments can differ from those of natural sediments. For example, tailings from the Mariana dam collapse have been linked to increased cytogenotoxicity (Quadra et al., 2018) and potential risk of DNA damage (Segura et al., 2016). In the plankton, the harmful effects of tailings may also be related to the fine particles (smaller than 50 μm) that according to laboratory tests tend to remain in suspension for long periods (Roland and Esteves, 1998). Since the inorganic particulate matter that composes tailings has low nutritional value and hinders zooplankton filtering (Levine et al., 2005), the tailings may reduce zooplankton density, reproduction, and feeding rates (Bilotta and Brazier, 2008). Although turbidity may be capable of structuring bacterioplankton communities (Sánchez et al., 2017), inorganic turbidity caused by tailings is not necessarily harmful as it can form aggregates with particulate material and



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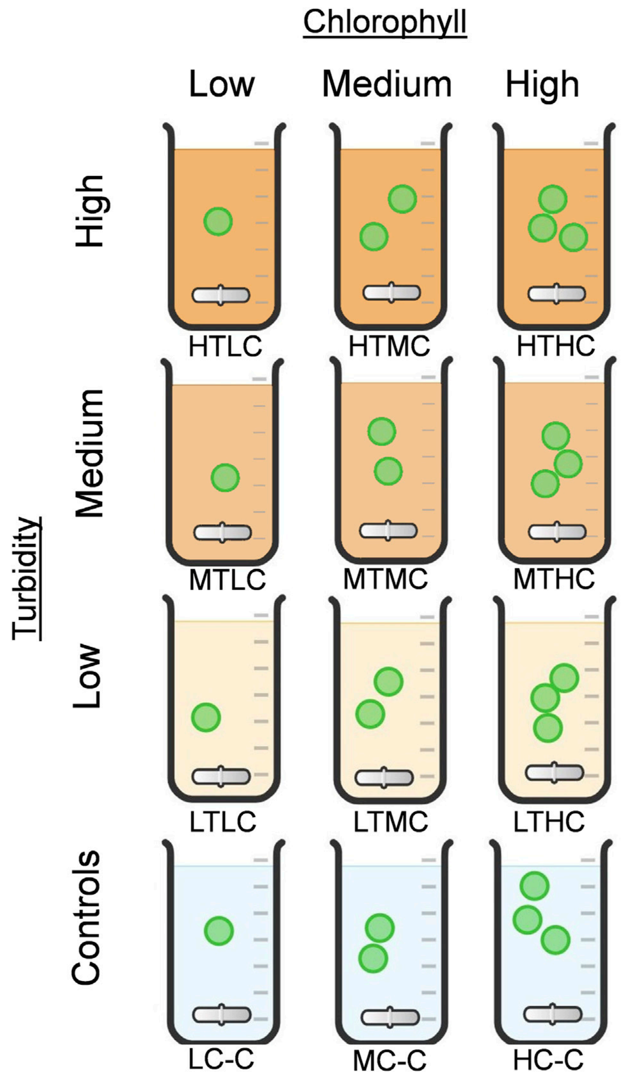

FIGURE 1 | Experimental design: combinations of three chlorophyll levels (Low, Medium, High) and turbidity (Low, Medium, High), forming nine categories of triplicate treatments including controls. HT: High Turbidity; MT: Medium Turbidity; LT: Low Turbidity; HC: High Chlorophyll; MC: Medium Chlorophyll; LC: Low Chlorophyll.

become important sources of nitrogen and phosphorus for bacteria, considerably changing the trophic dynamics in turbid environments (Gerbersdorf and Wieprecht, 2015). However, because transparency decreases, turbidity caused by suspended tailings can affect visually oriented species, for example increasing predation effort by visually oriented planktivorous fish (Lin and Pellegrini Caramaschi, 2005), reducing predation on zooplankton and favoring an increase in their density, which in turn can affect primary producers through trophic-cascade effects (Sweka and Hartman, 2001; Liljendahl-Nurminen et al., 2008).

Another major effect of suspended material is light attenuation in the water (Izaguirre et al., 2012), with subsequent loss of phytoplankton photosynthesis (Lind et al., 1992; Phlips et al., 1995). In addition to reducing phytoplankton density and growth rate, light attenuation can also modify communities by promoting the prevalence of resistant species (Kruk and Segura, 2012; Bortolini et al., 2014). In environments that become artificially turbid, the phytoplankton composition may shift toward algae groups that are better adapted to low light conditions, such as *Microcystis aeruginosa*, which can outcompete green algae for light (Yang and Jin, 2008). In other examples, Cyanobacteria dominance shifted toward Cryptophytes in a mesocosm with turbidity from glacial flour (Cianci-Gaskill et al., 2020), and in turbid shallow lakes, diatoms such as *Fragilaria* or *Cyclotella* may dominate (Izaguirre et al., 2015). In general, large groups of diatoms can be resuspended together with sediments by wind action, and are likely to be selected in shallow, shaded environments (Crossetti et al., 2012). These are often classified in Kruk's morpho-functional Group V, which is composed mainly of mixotrophic or phagotrophic unicellular flagellates. These organisms can compete better in turbid environments since they do not depend exclusively on light availability to acquire organic carbon (Kruk et al., 2010; Costa et al., 2019).

Turbid environments can vary widely in turbidity over time, due to seasonal environmental changes, which can also affect plankton distribution, generating gradient patterns. Considering that the effects of turbidity on primary production depend on the concentration and type of suspended particles, and also that both natural and anthropogenic turbidity are increasing in aquatic ecosystems, it is crucial to understand their role in fundamental processes such as phytoplankton primary production. By combining different levels of chlorophyll-a with different levels of inorganic turbidity, we experimentally tested the following hypotheses: 1) chlorophyll contents will be higher in treatments with lower inorganic turbidity; 2) high inorganic turbidity will promote a shift in phytoplankton composition by selecting species adapted to low light conditions; and 3) turbidity caused by inorganic sediments from an area impacted by mine tailings will have a stronger negative effect on chlorophyll concentration than will turbidity caused by natural sediments.

2 MATERIALS AND METHODS

2.1 Experimental Design

The experiment was conducted in the Laboratory of Aquatic Ecology (UFJF, Minas Gerais, Brazil) with sediment originally collected in Lake Batata, an Amazonian floodplain lake in the state of Pará, Brazil. The sediments were collected from the natural area (non-impacted) and the impacted area (with remaining bauxite tailings). Lake Batata was chosen as a model ecosystem because of its historical impact from bauxite tailings, as described below. The water and phytoplankton community evaluated in the experiment were collected from a lake in the UFJF Botanical Garden, also described below.

Before the experiment, the water collected in the Botanical Garden lake was incubated for 24 h in a thermostated cabinet (WTW model TS 606/2-i) at a constant temperature of 18°C, the mean temperature of the region (Moreira, 2014). This procedure was required to keep the aquatic communities acclimated since changes in the original temperature could modify plankton metabolism and affect the experimental results. After the 24-h acclimation period, the water samples were divided to make stock solutions for treatment setup. The stock solutions received three different quantities of sediment according to the desired turbidity level. This procedure was conducted for both types of sediments in Lake Batata, i.e., from the impacted area (Impacted Batata, IB) and the non-impacted area (Natural Batata, NB). For individual treatments, we used 500-ml beakers filled with 400 ml of stock solution and covered with aluminum foil.

For each type of sediment (IB and NB), the experimental treatments were assembled to test the effects of three levels of inorganic turbidity: High (HT), Medium (MT), and Low (LT), and three levels of chlorophyll-a: High (HC), Medium (MC), and Low (LC). Three controls contained only High chlorophyll-a (HC-C), Medium chlorophyll-a (MC-C), or Low chlorophyll-a (LC-C) (**Figure 1**). Treatments were labeled by turbidity level, followed by chlorophyll-a level. For example, the treatment with high turbidity (HT) and high chlorophyll-a (HC) was labeled "HTHC". This coding is used throughout the text. Each treatment was conducted in triplicate, including controls.

Turbidity treatments were standardized to represent the three levels: HT = 300 NTU, MT = 50 NTU, and LT = 12 NTU. These values correspond to the highest, median, and lowest values historically recorded in Lake Batata (MRN, 2018). Turbidity was measured by an Instrutherm TD-300 turbidimeter. The chlorophyll-a levels were established as follows. The "high chlorophyll-a" threshold was based on the maximum chlorophyll-a level reached in the water at the Botanical Garden lake after concentration with a 25 μm-mesh plankton net, averaging 25 μg/L. "Medium chlorophyll-a" was a mixture containing 50% from HC and 50% LC, resulting in 15 μg/L on average. "Low chlorophyll-a" corresponded to the natural chlorophyll concentration in the water, 5 μg/L on average. Further details can be found in **Supplementary Material**, **Supplementary Section S1**.

The treatments were randomized to prevent stochastic effects on the results. They were further conditioned in a thermostated cabinet at 18°C, with constant stirring on a WTW Oxitop IS 12 stirring plate with magnetic bars (4 cm × 0.5 cm) over the 7 days of the experiment. In the experimental conditions, the particulate material was constantly resuspended, reproducing local environmental conditions for phytoplankton, for example in case of a natural event such as wind resuspension or other turbidity-increasing impacts. An LED light was kept inside the thermostated cabinet, with 12-h light and dark photoperiods. An International Light IL 14004 radiometer was used to measure the irradiance at each point of the stirring plate, which ranged from 434 $\mu W/cm^2$ (min) to 496 $\mu W/cm^2$ (max), average 445 ± 19.8 $\mu W/cm^2$. Before each daily measurement, the pH of treatments was measured with a Hanna HI 8424 pH meter.

Water samples from all treatments and controls were taken at the beginning (t0) and the end of the experiment (t7) period. Water samples (except for total phosphorus analyses) were filtered through a 1.2-μm-pore glass-fiber filter and later analyzed for dissolved organic carbon (DOC), dissolved nitrogen (DN), and dissolved inorganic phosphorus or orthophosphate (DP) concentrations. DOC and DN were analyzed following sodium persulfate digestion in a Shimadzu 5000A TOC L Analyzer; TP and DP were estimated by the molybdenum-blue method (Wetzel and Likens, 1991).

2.2 Model Ecosystem

The sediments used in the experiments were collected from Lake Batata. Lake Batata is located on the floodplain of the Trombetas River and is ecologically important because of the bauxite tailings that were continuously dumped into the lake between 1979 and 1989. Nowadays, the deposited bauxite tailings cover approximately 30% of the lake area. Lake Batata is a unique environment with a suite of studies conducted since a long-term restoration project started in the late 1980s (Esteves et al., 1990; Esteves, 1998; Scarano et al., 2018; Josué et al., 2021). The restoration project consisted of replanting the impacted area with native species in order to keep the impacted sediments attached and immobilized on the lake margins and increase the organic matter content of the sediments (Dias et al., 2011). Even after the restoration actions, which are still in progress, the lake continues to have two distinct areas, one natural (Natural Batata, NB) and the other impacted (Impacted Batata, IB). Because of its importance, Lake Batata was used as a model system in this study.

Historically, sediments from NB have had higher total nitrogen (TN), dissolved organic carbon (DOC), and organic matter (OM) contents than IB (Roland and Esteves, 1993; Leal et al., 2004). However, due to restoration, the sediment organic-matter content was recently found to be very similar in NB and IB (Josué et al., 2021). NB also has higher interstitial water content, indicating a higher water-retention capacity (Callisto and Esteves, 1996a; Leal et al., 2003), and the sediments have a muddy-appearing organic layer composed of fine particles (Callisto and Esteves, 1996a), mainly fine sand and silt. In contrast, the IB sediments contain a large clay fraction, which remains suspended in the water column for a longer time (Callisto and Esteves, 1996b; Roland and Esteves, 1998) and in shallow areas is often resuspended by wind, increasing the turbidity. The bauxite tailings in IB are inert and nontoxic to phytoplankton and are composed mainly of silicates (47%), aluminum oxide (21%), and iron oxide (21%) (Lapa, 2000).

2.3 Sediment Samples

Sediment was collected from the uppermost 10 cm in NB. For IB we collected 10 cm of sediment just below the surface organic layer, which was formed following the lake's restoration project. The organic layer was easily distinguishable in the field by its darker color, reaching a depth of nearly 6 cm in the restored areas, as also reported by Penha (2015).

Before the experimental treatments were assembled, the sediments were placed in sealed Erlenmeyer flasks, sterilized in an autoclave for 20 min, and dried at 60°C for 24 h (Quaggio and Raij, 1979). After cooling, the sediments were macerated to homogenize the particles, since the granulometry could affect the experimental results by creating noise through the turbidity effect (Merten et al., 2014; Yao et al., 2014). The grain size was analyzed to assess the mean size of particles. After maceration, sediment samples were sifted through sieves of different mesh sizes (1 mm, 500 μm, 250 μm, 150 μm, 75 μm, and <75 μm) coupled to a TecnoFund model AEP agitator to separate the material according to particle fractions, and classified according to the Wentworth scale (Buchanan, 1984). Organic-matter content in sediment aliquots was analyzed by loss-on-ignition for 4 h at 550°C, according to Carmouze (1994). All sediments were taken to the laboratory in the Federal University of Juiz de Fora (UFJF, Juiz de Fora, Minas Gerais) to set up the experiment.

2.4 Water Samples

Water samples were taken from an artificial lake in the UFJF Botanical Garden (21°44′18″ S, 43°22′07″ W). The water used in the experiments was sieved through a 68-μm plankton net to remove zooplankton that could affect the results (further details in **Supplementary Material**). To characterize the water samples, we analyzed the water temperature (°C), pH, oxidation/reduction potential (mV), electrical conductivity (μS/cm), turbidity (NTU), dissolved oxygen (mg/L and %), and total dissolved solids (mg/L), which were measured with a Horiba model U-50 multiparameter probe. Total chlorophyll-a of cyanobacteria and eukaryotic algae was measured *in situ* using a phytoplankton analyzer (PHYTO-PAM, Walz, Germany). Chlorophyll-a concentrations were measured for total chlorophyll-a (total Chl-a) and the main algal groups as given by the fluorometer: blue-green (Blue Chl-a), green (Green Chl-a), and brown (Brown Chl-a) as determined by the fluorescence readings at four wavelengths (470 nm, 520 nm, 645 nm, and 665 nm, respectively) (Schreiber et al., 1998). PHYTO-PAM separates algal groups by using the measurements of these four excitation wavelengths, according to the absorbance spectra of their light-harvesting complexes (LHC), which act as antennae pigments. For instance, Cyanobacteria show a strong signal at the 645 nm channel, most green algae show a signal at the 470 nm channel, and the majority of diatoms show a strong signal at 470 and 520 nm wavelengths. The equipment was calibrated using *Anacystis* sp. as the reference for "blue-green algae", *Ankistrodesmus* sp. as the reference for "green algae", and *Phaeodactylum* sp. as the reference for "brown algae" (Heinz Walz GmbH, 2003). Below we refer to algal groups by the fluorometric response, as chlorophyll groups as given by PHYTO-PAM, considering Cyanobacteria as blue-greens or "blue algae"; Chlorophyceae, Euglenophyceae, and Zygnematophyceae as "green algae"; and Chryptophyceae, Chrysophyceae, Bacillariophyceae, and Dinophyceae as "brown algae" (Schreiber, et al., 1998; Beecraft et al., 2017). PHYTO-PAM was also used to determine the daily algal yield, which corresponds to the effective quantum yield of photosystem II in an incident PAR radiation beam. These measurements can help to understand the photosynthetic performance of communities.

Phytoplankton samples from the initial (t_0) and final (t_7) experiment times were preserved with acid Lugol's iodine solution and conditioned in the dark. Phytoplankton abundance was estimated using an Olympus IX71 inverted microscope, with the settling technique according to Utermohl (1958). Cells, filaments, and colonies were counted at ×40 magnification in random fields until the taxon accumulation curve stabilized. Taxa were identified to genus level and categorized as major taxonomic groups, using taxonomic keys (Komárek and Anagnostidis, 1998, 2005; van den Hoek et al., 1995).

2.5 Data Analysis

A pilot experiment indicated that the sediment suspension (only sediments and water) contributed to a small chlorophyll-a signal (here termed background chlorophyll-a) and could therefore affect the treatment readings by PHYTO-PAM. We corrected for this source of bias by subtracting the treatment readings at the initial time (containing the sum of real chlorophyll-a and background reading from sediment) from the control values (containing equivalent real chlorophyll-a value) for each treatment. This difference, the background chlorophyll-a calculated for each treatment, was then subtracted from each chlorophyll-a value generated on each day during the course of the experiment (details in **Supplementary Material**, Topic 2). The values resulting from this correction were termed "corrected chlorophyll".

Nutrients and limnological parameters were submitted to paired t-tests in R software (R Core Team, 2019) to assess the variation between initial (t_0) and final (t_7) concentration values. The stoichiometric molar ratios between dissolved fractions of carbon (C), nitrogen (N), and phosphorus (P), i.e., C:N, N:P, and C:P, were calculated from the DOC, DN, and DP concentrations. We compared our results to the C:N:P ratio for tropical freshwater plankton calculated by (They et al., 2017; reference C:N:P ratios of 307:30:1), considering the particular features and dynamics of these environments that affect the nutrient dynamics.

Chlorophyll-a values were compared between treatments with a repeated-measures GLM (General Linear Model) analysis, also in R. In these models, we indicated the temporal non-independence of data, with "time" as a random factor. For comparison between sediment types, we used "sediment type" (IB or NB) as a comparison factor and "time" as the random factor. Bonferroni adjustment was used for post-hoc comparisons.

Chlorophyll-a values by treatment over the incubation time were submitted to linear regression in JMP-SAS 14 software to obtain general trend lines and linear-regression equations ($\boldsymbol{Y} = \boldsymbol{ax} + \boldsymbol{b}$) in which b, which we term "slope", is the associated coefficient of variation that indicates if the regression line is assuming an increasing or decreasing trend. This parameter helped us to understand the chlorophyll-a tendencies over time. For all statistical analyses, we used a significance level of 95% with $\alpha = 0.05$.

3 RESULTS

3.1 Sediment and Water Characterization

The sediments from Lake Batata were predominantly coarse and medium-grained sand for NB and medium and fine-

TABLE 1 | Granulometric composition of sediments (NB) and (IB) by particle size, sediment classification by particle size, and amount of sediment retained in sieves (g) and in percentage (proportional to sample size 25 g).

Sediment	Particle size (aprox.)	Sediment classification	Percentage of sample (g)	Percentage of sample (%)
NB	1 mm	Very coarse sand	3.53	14.1
	500 µm	Coarse sand	5.19	20.7
	250 µm	Medium sand	9.20	36.8
	150 µm	Fine sand	4.86	19.4
	75 µm	Very fine sand	1.4	5.7
	<75 µm	Silty clay	0.7	2.9
IB	1 mm	Very coarse sand	2.06	8.2
	500 µm	Coarse sand	2.17	8.7
	250 µm	Medium sand	14.58	58.3
	150 µm	Fine sand	5.39	21.6
	75 µm	Very fine sand	0.1	0.3
	<75 µm	Silty clay	0.1	0.3

NB means Natural Batata and IB means Impacted Batata sediments.

grained sand for IB (**Table 1**). Organic-matter contents were 21.48% for NB and 20.43% for IB.

Nutrient contents of water from the UFJF Botanical Garden lake were 30.7 ± 0.9 µg/L TP, 6.8 ± 0.4 µg/L DP 3.7 ± 0.1 mg/L DOC, and 0.2 ± 0.05 mg/L DN. At the time of the analysis, water turbidity was 25.2 NTU and pH was 7.4 (**Table 2**). The chlorophyll-a concentration in the lake was approximately 5.51 ± 0.22 µg/L. The green, brown, and blue pigment bands were, on average, 46.2, 46.9, and 5.2% respectively.

3.2 Experimental Results

3.2.1 Chlorophyll-a Trends

Chlorophyll-a in the NB sediment treatments ranged from 4.76 µg/L in MTLC to 34.32 µg/L in HTHC. Chlorophyll-a in IB sediment treatments ranged from 5.31 µg/L in LTLC to 30.89 µg/L in HTHC (**Figure 2**). Comparing treatments by sediment type showed that NB and IB were significantly different ($F = 8.53$, $p < 0.01$). For NB sediment, there were effects of turbidity ($F = 51.36$, $p < 0.01$), chlorophyll-a levels ($F = 423.02$, $p < 0.01$), and the interaction between them ($F = 3.04$, $p = 0.01$). For IB sediment, turbidity also had a significant effect in treatments ($F = 32.57$, $p < 0.01$), as well as chlorophyll levels ($F = 513.29$, $p < 0.01$) and the interaction ($F = 14.02$, $p < 0.01$). Post-hoc comparison tests for NB treatments showed that low-turbidity treatments were not significantly different from medium-turbidity treatments for both sediment types, but all chlorophyll-a treatments differed from each other (**Table 3**).

The slopes of chlorophyll-a overtime for NB treatments ranged from –1.06 to 0.82 (**Figure 3**), and chlorophyll-a in treatments LTLC and MTMC significantly increased over time (ANOVA, $p < 0.05$). The slopes of chlorophyll-a overtime for IB ranged from –1.28 (MTHC) to 0.82 (LTHC). LC treatment slopes were directly proportional to turbidity levels, and high-chlorophyll-a slopes were inversely proportional to turbidity, decreasing as turbidity increased (**Figure 3**).

Algal yields ranged between 0.07 and 0.7 in NB sediment treatments. For IB sediments, algal yields ranged between 0.17 and 1.12 (**Figure 4**).

3.2.2 Pigments and Taxonomic Composition

In NB treatments, dominant species belonged mostly to the green group (51–53% average) and brown group (46–48%), especially in LC treatments. For other treatments such as MC, the green group was dominant (61–74%, **Figure 2**). The same was found for HC treatments, where the green group was also dominant (i.e., HTHC = 51–73%, **Figure 2**).

For IB sediment treatments, in LC and MC the green group dominated (55–98%) and (63–83%), respectively. In treatment MTHC the brown group (69%) prevailed, followed by the green group (30%). In HC treatments, the phytoplankton composition varied along the turbidity gradient. For instance, in LT the green group slightly dominated over (48%) over the brown group (43%), in MT the brown group dominated (69%) over the green group (30%), and in HT the green group predominated (73%).

In the IB treatments, Chrysophyceae, Cryptophyceae, Euglenophyceae, and Chlorophyceae were the dominant groups. The phytoplankton composition did not change drastically in most of the treatments except for IB HTHC and HTLC (**Figures 5**, **6**). In the NB treatments, Euglenophyceae and Dinophyceae dominated, followed by Chlorophyceae and Cyanobacteria. In the HTLC treatment, Cyanobacteria increased markedly from the initial (t_0) to the final (t_7) time of the experiment. Other treatments also showed an increase in the Cyanobacteria contribution (e.g., HTMC, MTHC, MTLC, and LTHC).

3.2.3 pH, Nutrient Concentrations, and Stoichiometric Ratios

During the experiment the pH varied between 7.45 and 8.97 in NB and between 7.49 and 8.98 in IB. Both showed significant changes ($p < 0.05$) over time for LT treatments of NB sediment and most IB treatments (**Table 4**). In the NB treatments, DOC concentrations varied from 4.0 to 8.3 mg/L, DN from 0.18 to 0.87 mg/L, TP from 24.92 to 179.22 µg/L, and DP from 3.74 to 15.74 µg/L. In the IB treatments, DOC concentrations varied from 4.2 to 5.7 mg/L, DN from 0.14 to 0.27 mg/L, TP from 35.47 to 134.87 µg/L (**Table 5**), and DP from 6.2 to 10.8 µg/L. There was

TABLE 2 | Limnological characterization of the water in the UFJF Botanical Garden lake.

Parameter	Values
Water temperature (°C)	27.4
pH	7.4
Oxidation/reduction potential (mV)	262.5
Electrical conductivity (µS/cm)	0.03
Turbidity (NTU)	25.2
Dissolved oxygen (mg/L)	11.5
Dissolved oxygen (%)	147.4
Total dissolved solids (g/L)	0.021

significant variation ($p < 0.05$) over the incubation time for DOC in LT treatments of NB sediment and MT treatments of IB sediment. For DN, only the MTLC treatment of NB showed significant variation over the incubation time (**Table 6**).

N:P ratios ranged from 3:1 to 11:1 in NB and from 1:1 to 5:1 in IB. The C: N ratios ranged from 18:1 to 56:1 for NB and from 44:1 to 72:1 for IB, with a tendency to decrease toward the end of the experiment. The C:P ratios ranged from 181:1 to 307:1 in NB and from 86:1 to 253:1 in IB (**Table 7**).

4 DISCUSSION

One of the main factors that influence aquatic photosynthesis is light availability in the water column, which is closely linked to turbidity (Kirk, 1985). Turbidity levels are increasing in many aquatic ecosystems as a result of anthropogenic factors such as urbanization, agricultural and industrial expansion, and mining activities (Rodrigues et al., 2018). In this study, we experimentally assessed the effect of turbidity on phytoplanktonic chlorophyll-a by combining different levels of chlorophyll-a and turbidity. Our results showed that despite the expected turbidity-shading effects, photosynthesis continued even in the high-turbidity treatments, with a prevalence of green and brown algae in water with both sediments tested (NB and IB) at the end of the experiment. The turbidity effect was stronger with IB sediments and in treatments with higher initial chlorophyll-a levels.

4.1 Turbidity Effects on Chlorophyll-a Concentrations

In general, it is expectable that high turbidity will reduce light incidence in the water and negatively affect primary production, reducing chlorophyll-a content in more-turbid systems, as we hypothesized here. In our experiments, the high-chlorophyll-a treatments showed lower and negative slopes as turbidity increased, but the low-chlorophyll-a treatments had increasing slopes along with turbidity, confirming our first hypothesis.

A tendency toward growth of primary producers in turbid environments has been reported in systems where wind resuspends the sediment periodically, such as estuaries (Pinckney et al., 2011) and shallow lakes. In these systems, internal nutrient remobilization can cause eutrophication (Søndergaard et al., 2003). In Lake Batata, resuspension of sediments in the impacted area increases chlorophyll-a concentration by increasing the nutrient supply (Panosso, 1993). In these cases, nutrients stored in the sediments are often resuspended in the water column, favoring phytoplankton primary production (Nõges and Nõges, 1999). Nutrient availability may be an associated explanation for our findings in the low and medium-chlorophyll treatments, as we

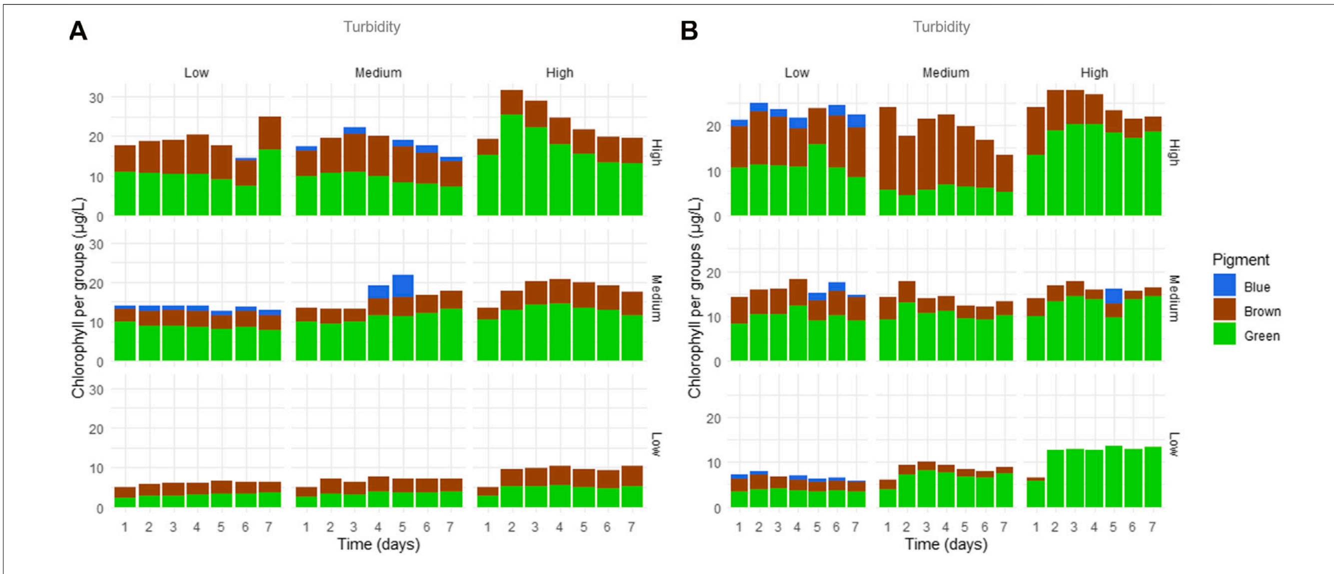

FIGURE 2 | Chlorophyll-a variation (µg/L) by time (days) responding to turbidity levels. **(A)**, NB results; **(B)**, IB results. Horizontal labels above graphs show initial turbidity levels and vertical lateral labels show chlorophyll-a levels forming experimental design combinations. Colors refer to chlorophyll groups. Chlorophyll-a scales differ between **(A)** and **(B)**. NB means Natural Batata and IB means Impacted Batata.

TABLE 3 | Post-hoc tests by sediment (NB and IB) and treatment. Only statistically significant ($p < 0.05$) results are shown.

Sediment	Treatment comparison		p
NB	HT	MT	<0.01
	HT	LT	<0.01
	HC	MC	<0.01
	HC	LC	<0.01
	MC	LC	<0.01
IB	HT	MT	<0.01
	HT	LT	<0.01
	HC	MC	<0.01
	HC	LC	<0.01
	MC	LC	<0.01

NB means Natural Batata and IB means Impacted Batata. HT: High Turbidity; MT: Medium Turbidity; LT: Low Turbidity; HC: High Chlorophyll; MC: Medium Chlorophyll; LC: Low Chlorophyll.

recorded high phosphorus concentrations. Furthermore, in the low-chlorophyll-a treatments, the light spread and was reflected inside the systems as diffuse radiation, which can be better used by fewer phytoplankton cells. Productivity in the low-chlorophyll-a treatments may have been favored by light scattering, a factor determined by the properties of suspended particles, which can benefit phytoplankton in turbid systems because of the light wavelengths used for photosynthesis, generating different chlorophyll responses (Falkowski and Raven, 2007; Kirk, 2011). In our treatments, the light might not have been a limiting factor in the low-turbidity treatments because of the small size of the beakers used as microcosms, since there was not enough volume to create an aphotic zone. We, therefore, compare this situation to natural environments at the surface of the water column, where, besides not being light-limited, algae exposed to photoinhibition can benefit from microhabitats formed by suspended particles in glacier meltwater-fed lakes (Sommaruga, 2015), estuaries (MacIntyre and Cullen, 1996), or tropical ponds (Mayer, 2020). Further, particulate matter is reported to facilitate algae aggregation (Guenther and Bozelli, 2004), and in our experiment, it may have prevented the cells from sinking and helped in light-capturing in treatments with less competition. Sediment could have acted as a substrate for bacterial aggregation, facilitating nutrient cycling through bacterial-phytoplankton metabolism coupling in low-chlorophyll-a treatments (Zak and Grigal, 1991; Naeem et al., 2000; Barlett and Leff, 2010).

Along with competition for light, another plausible explanation for the decreasing slope patterns in treatments with high initial chlorophyll-a (HTHC, MTHC, and LTHC) is that sediment particles, together with shading from phytoplankton cells, could reduce light availability in the systems, resulting in low light availability for phytoplankton absorption; alternatively, the systems may have reached support capacity, limiting resources for phytoplankton growth. The values for algal yield were mostly below 0.83, a threshold where the phytoplankton community is under light stress in performing photosynthesis (Dau, 1994; Schreiber, 2004; Falkowski and Raven, 2007). Therefore, our findings support the hypothesis that inorganic turbidity may be an important bottom-up control factor by causing light limitation to primary production in aquatic ecosystems and reducing chlorophyll-a concentrations in these systems, especially in treatments with

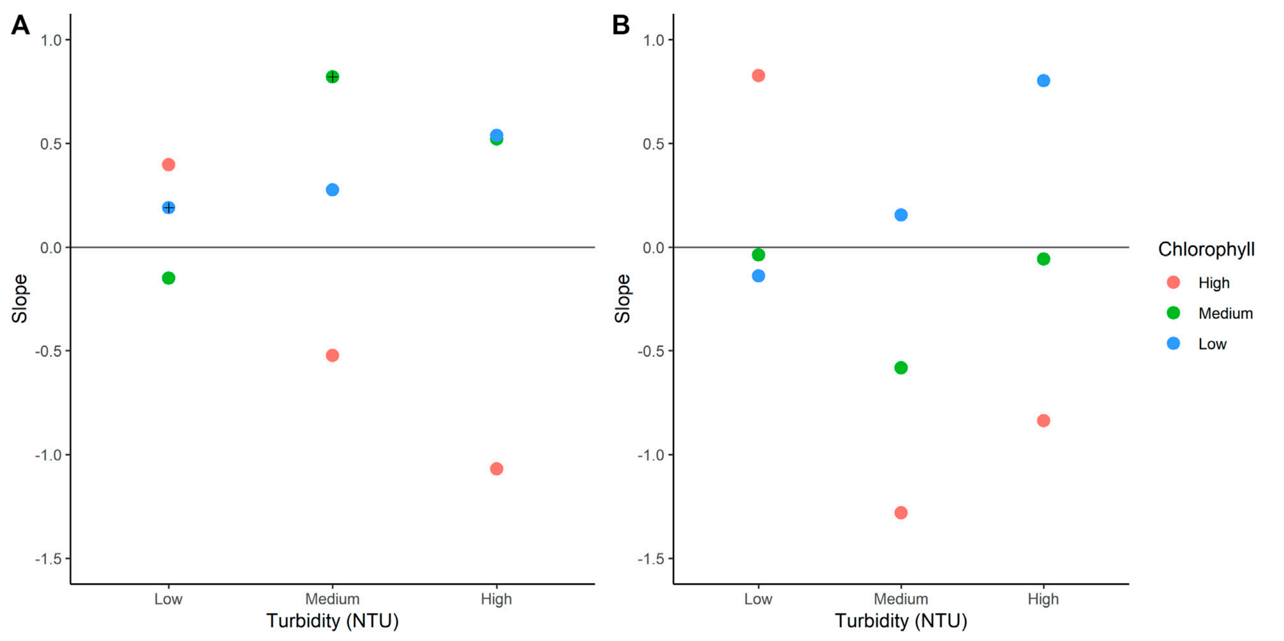

FIGURE 3 | Treatment slopes by sediment concentration. **(A)**, NB results; **(B)**, IB results. Each dot shows the calculated slope of chlorophyll values over time. Turbidity levels are indicated on the *x*-axis and chlorophyll-a levels are separated by color. Treatments with significant changes in slope are highlighted (+). NB means Natural Batata and IB means Impacted Batata.

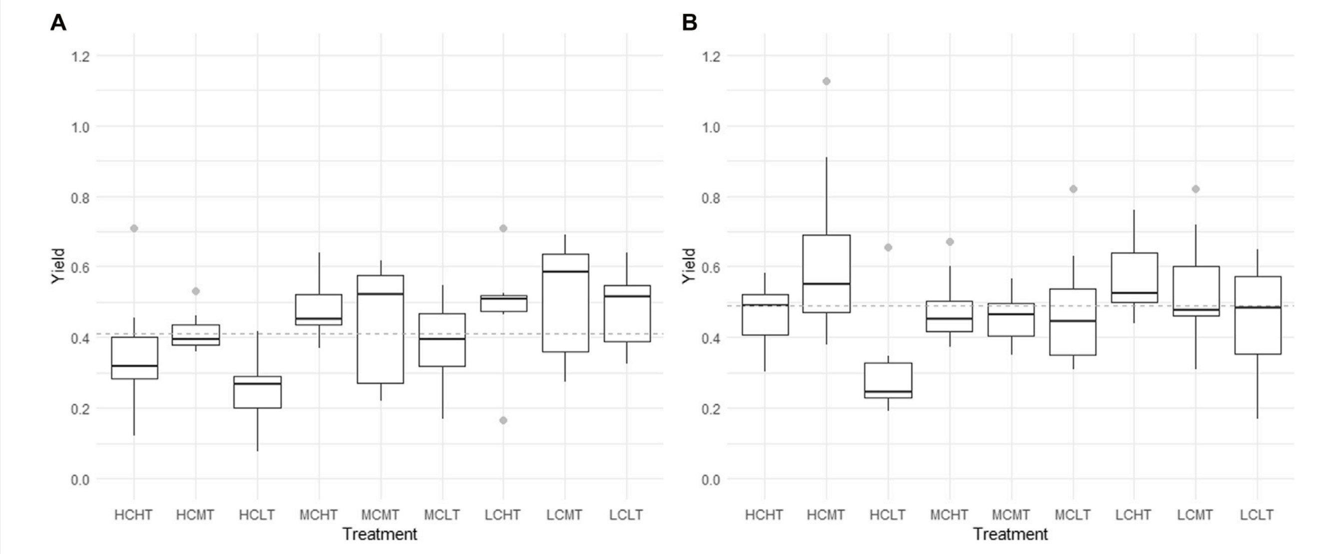

FIGURE 4 | Differences in algal yield among treatments of the sediments. **(A)**, NB results; **(B)**, IB results. NB means Natural Batata and IB means Impacted Batata. HT: High Turbidity; MT: Medium Turbidity; LT: Low Turbidity; HC: High Chlorophyll; MC: Medium Chlorophyll; LC: Low Chlorophyll. The gray dotted line shows the mean yield value for NB (0.41) and for IB (0.49) treatments.

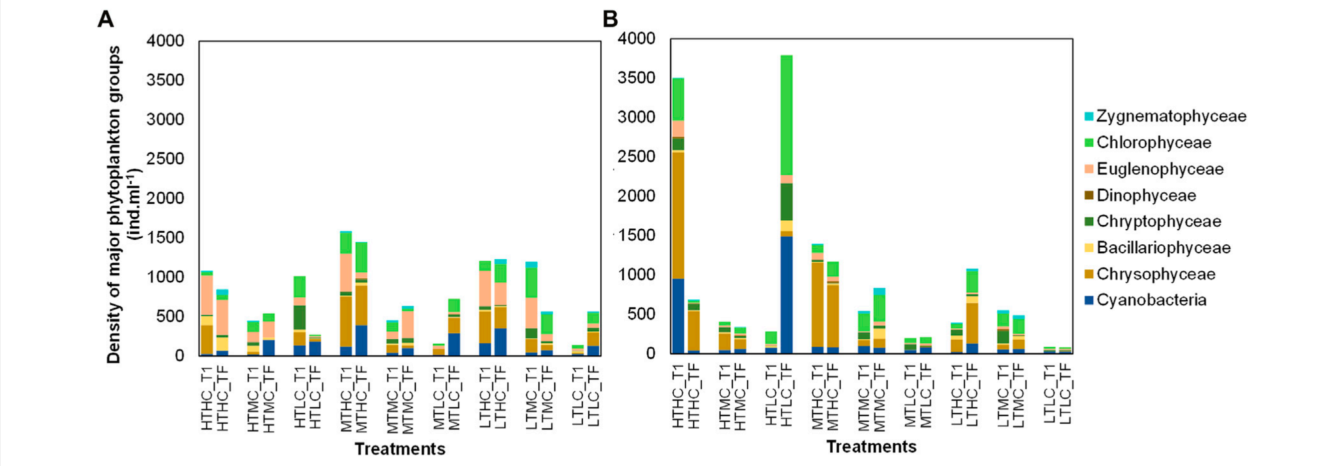

FIGURE 5 | Density (ind/mL) of main phytoplankton groups by sediment and by treatment at the initial time (T1) and final time (TF). **(A)**, NB results; **(B)**, IB results. NB means Natural Batata and IB means Impacted Batata. HT: High Turbidity; MT: Medium Turbidity; LT: Low Turbidity; HC: High Chlorophyll; MC: Medium Chlorophyll; LC: Low Chlorophyll.

high initial chlorophyll-a. One consequence of this process could be the reduction of carbon transfer to herbivorous zooplankton and higher trophic levels (Kirk, 1991). For instance, cladocerans in turbid water can be strongly affected because most are filter-feeders (Hart, 1988; Kirk, and Gilbert, 1990).

Studies on natural systems impacted by bauxite tailings have reported lower primary and secondary production (Cole et al., 1992; Grobbelaar, 1992; Cuker, 1993), along with reductions in diversity, density, or biomass of phytoplankton in impacted areas (Huszar, 2000). However, communities can change in composition to groups that are better adapted to the new conditions. In our experiment, it is also likely that the plankton organisms that persisted might have adapted to low light conditions by developing compensatory mechanisms. Some of the mechanisms may involve reducing the respiration rate, increasing the concentration of photosynthetic pigments, and even changing the proportions of accessory pigments to increase photon capture, in a process called ontogenetic chromatic adaption (Müller et al., 2003; Reynolds, 2006; Kirk, 2011).

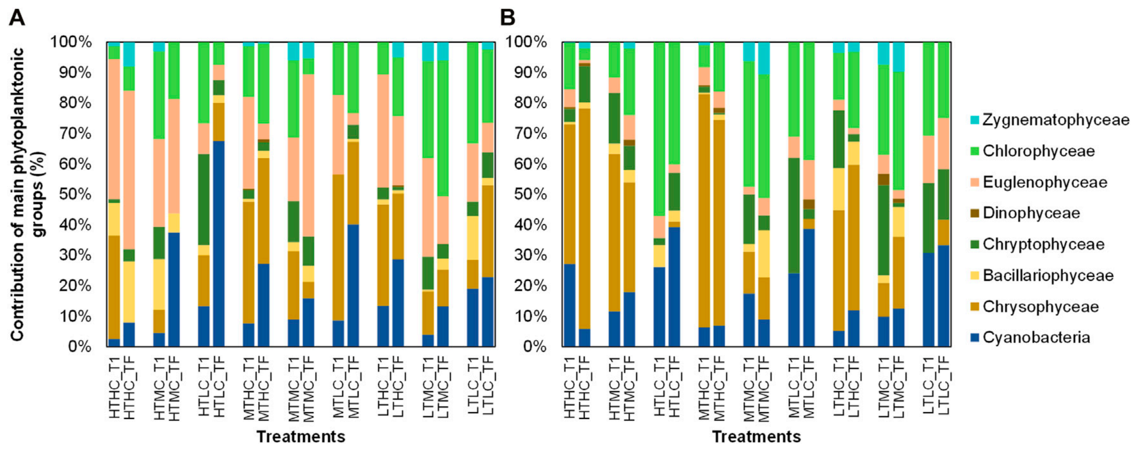

FIGURE 6 | Percent contribution (%) of main phytoplankton groups by sediment and by treatment at the initial time (T1) and final time (TF). **(A)**, NB results; **(B)**, IB results. NB means Natural Batata and IB means Impacted Batata. HT: High Turbidity; MT: Medium Turbidity; LT: Low Turbidity; HC: High Chlorophyll; MC: Medium Chlorophyll; LC: Low Chlorophyll.

TABLE 4 | pH values by sediment type (NB and IB) and treatment type at the beginning and end of the experiments.

Sediment	Treatment	pH	
		Initial	Final
NB	HTHC	8.97 ± 0.33	8.86 ± 0.31
	HTMC	8.46 ± 0.2	8.75 ± 0.3
	HTLC	8.24 ± 0.26	8.06 ± 0.27
	MTHC	8.27 ± 0.17	8.2 ± 0.2*
	MTMC	7.98 ± 0.16	8.13 ± 0.14
	MTLC	7.73 ± 0.11	7.55 ± 0.11*
	LTHC	7.93 ± 0.12	8.07 ± 0.14
	LTMC	7.61 ± 0.1	8.6 ± 0.13*
	LTLC	7.45 ± 0.08	7.26 ± 0.08*
IB	HTHC	8.17 ± 0.23	7.57 ± 0.18*
	HTMC	8.89 ± 0.37	8.8 ± 0.26*
	HTLC	8.98 ± 0.32	9.03 ± 0.67
	MTHC	7.73 ± 0.09	7.18 ± 0.12
	MTMC	8.12 ± 0.14	8.15 ± 0.13*
	MTLC	8.25 ± 0.16	7.92 ± 0.13*
	LTHC	7.49 ± 0.11	7.57 ± 0.18*
	LTMC	7.78 ± 0.08	7.84 ± 0.09*
	LTLC	7.87 ± 0.01	7.6 ± 0.12*

Asterisk (*) indicates a significant difference ($p < 0.05$) between initial and final values. NB means Natural Batata and IB means Impacted Batata. Treatment acronyms are a combination of HT: High Turbidity; MT: Medium Turbidity; LT: Low Turbidity; HC: High Chlorophyll; MC: Medium Chlorophyll; LC: Low Chlorophyll.

4.2 Turbidity Effects on Chlorophyll-a Pigments and Phytoplankton Composition

Different kinds of particles in suspension can cause different intensities and compositions of the light spectrum that reaches microorganisms (Kirk, 2011). As a consequence, the distribution and dominance of chlorophyll-a and other pigments may be related to light availability and quality. We hypothesized that high turbidity would cause a change in phytoplankton composition toward low-light-adapted algae; however, our results disagreed with this statement.

Mixotrophy is an algal nutrition mode that includes photosynthetic and heterotrophic sources. It allows protists to supplement their needs by absorbing organic substrates, phagocytizing particulate organic carbon and/or bacteria. However, energy acquisition from the environment does not ensure independence from photosynthesis, and light availability remains important for mixotrophic phytoplankton survival (Burkholder et al., 2008; Naselli-Flores and Barone, 2019). The use of organic nutrients when light is limited allows mixotrophic phytoplankton to maintain growth, lending an important competitive advantage over strict phototrophs and heterotrophs (Jones et al., 2009). It is important, therefore, to distinguish between forms of organic carbon acquisition performed by mixotrophs, since to some degree, most phytoplankton can absorb dissolved carbon through osmotrophy (Naselli-Flores and Barone, 2019). Individuals capable of ingesting particles and bacterial aggregates are considered phagotrophic and are normally flagellated. These terms are used here to distinguish among the most abundant genera in treatments (**Supplementary Figure S2**) and the predominant form of nutrition (**Supplementary Table S4**).

Phagotrophic algae such as Chrysophyceae can maintain heterotrophic metabolism under light-limiting conditions, thus compensating for a loss of photosynthesis (Katechakis et al., 2005). Chrysophyceae species often increase or even dominate in turbid systems (Costa et al., 2019). However, in our experiment, no consistent dominance shift in algal composition occurred between the initial and final times in treatments, disagreeing with our second hypothesis. In treatments where the brown group was dominant, phagotrophic groups such as Euglenophyceae, Crysophyceae, and Cryptophyceae were present. These organisms are capable of consuming organic carbon available in the water, facilitating survival and dominance even under low light (Kruk and Segura,

TABLE 5 | Dissolved organic carbon (DOC) and dissolved nitrogen (DN) by sediment type (NB and IB) and treatment at the beginning and end of the experiments.

Sediment	Treatment	DOC (mg/L)		DN (mg/L)	
		Initial	Final	Initial	Final
NB	HTHC	7.5 ± 0.57	8.8 ± 1.27	0.87 ± 0.07	1.14 ± 0.23
	HTMC	6.4 ± 0.15	6.9 ± 0.15	0.76 ± 0.04	0.7 ± 0.01
	HTLC	8.3 ± 5.81	6.5 ± 0.19	0.75 ± 0.21	0.66 ± 0.14
	MTHC	5.7 ± 0.29	5.9 ± 0.01	0.39 ± 0.12	0.59 ± 0.01
	MTMC	5.3 ± 0.19	6.1 ± 0.52	0.36 ± 0.13	0.4 ± 0.03
	MTLC	4.6 ± 0.15	5.5 ± 0.13*	0.24 ± 0.05	0.39 ± 0.01*
	LTHC	5.4 ± 0.07	5.4 ± 0.28	0.35 ± 0.08	0.48 ± 0.02
	LTMC	4.7 ± 0.20	5.4 ± 0.18*	0.19 ± 0.03	0.31 ± 0.08
	LTLC	4.0 ± 0.12	4.8 ± 0.14*	0.18 ± 0.06	0.25 ± 0.02
IB	HTHC	5.7 ± 0.16	4.9 ± 0.27	0.27 ± 0.08	0.28 ± 0.08
	HTMC	4.5 ± 0.05	4.6 ± 0.14	0.24 ± 0.02	0.38 ± 0.08
	HTLC	4.5 ± 0.15	5.1 ± 0.09*	0.24 ± 0.04	0.31 ± 0.05
	MTHC	5.5 ± 0.05	4.6 ± 0.18	0.27 ± 0.07	0.20 ± 0.08
	MTMC	4.2 ± 0.06	4.4 ± 0.14*	0.16 ± 0.04	0.27 ± 0.06
	MTLC	4.2 ± 0.03	5.0 ± 0.11*	0.14 ± 0.03	0.23 ± 0.02
	LTHC	4.3 ± 0.04	4.5 ± 0.01*	0.21 ± 0.02	0.35 ± 0.06
	LTMC	4.5 ± 0.01	4.4 ± 0.07	0.19 ± 0.02	0.26 ± 0.02
	LTLC	4.2 ± 0.07	4.7 ± 0.19*	0.2 ± 0.03	0.24 ± 0.06

Asterisk (*) indicates a significant difference ($p < 0.05$) between initial and final values.
NB means Natural Batata and IB means Impacted Batata. Treatments acronyms are a combination of HT: High Turbidity; MT: Medium Turbidity; LT: Low Turbidity; HC: High Chlorophyll; MC: Medium Chlorophyll; LC: Low Chlorophyll.

2012; Bortolini et al., 2014; Costa et al., 2019). Shifts to the dominance of brown algae in turbid environments were reported in semiarid regions (Costa et al., 2016), with phytoplankton shifting initially to cyanobacteria dominance and then to brown algae. In our systems, phytoplankton composition responded to turbidity, with the maintenance of initially present phagotrophic algae that further prevailed due to good adaptation to low light conditions.

Most freshwater species of green algae show wide plasticity in their responses to low light conditions (Karsten et al., 2017). In turbid systems, chlorophytes can be expected to decrease because they are sensitive to high turbidity (Reynolds et al., 2002). In our system, however, photosynthetic plasticity is a likely reason for the dominance of Chlorophyceae species in the high-chlorophyll-a treatments. This held even under high-turbidity conditions (HTLC in IB), where

TABLE 6 | Total phosphorus (TP) and dissolved phosphorus (DP), by sediment type (NB and IB) at the beginning and end of the experiments.

Sediment	Treatment	TP (μg/L)		DP (μg/L)	
		Initial	Final	Initial	Final
NB	HTHC	177.51 ± 12.5	190.17 ± 30.57	15.74 ± 5.55	13.18 ± 0.92
	HTMC	179.22 ± 12.56	137.45 ± 32.1	7.22 ± 0.24	10.08 ± 1.53
	HTLC	74.41 ± 13.41	130.4 ± 23.49*	6.61 ± 0.44	8.53 ± 0.11*
	MTHC	85.33 ± 6	80.7 ± 3.22	10.29 ± 1.89	16.63 ± 0.65*
	MTMC	46.1 ± 1.58	43.45 ± 6.86	6.96 ± 0.84	7.81 ± 0.39
	MTLC	54.79 ± 4.28	45.58 ± 14.33	5.06 ± 0.72	6.92 ± 0.26*
	LTHC	66.74 ± 3.85	72.14 ± 4.96	9.96 ± 0.9	21.1 ± 2.67*
	LTMC	31.85 ± 4.5	30.24 ± 2.03	6.46 ± 0.33	8.49 ± 0.15*
	LTLC	24.92 ± 1.25	19.79 ± 0.94*	3.74 ± 0.42	7.81 ± 0.73
IB	HTHC	35.47 ± 3.24	21.60 ± 2.70*	6.07 ± 0.31	6.39 ± 0.63
	HTMC	134.87 ± 8.77	30.28 ± 2.14*	13.17 ± 1.71	7.05 ± 1.35*
	HTLC	94.04 ± 14.85	117.66 ± 39.17	10.83 ± 2.83	14.14 ± 1.92
	MTHC	28.74 ± 0.19	28.74 ± 0.19	6.2 ± 0.26	6.60 ± 0.15
	MTMC	71.97 ± 11.57	84.8 ± 6.39	8.05 ± 0.81	10.4 ± 1.78
	MTLC	57.67 ± 5.78	36.55 ± 19.45	8.35 ± 0.49	10.49 ± 1.83
	LTHC	112.89 ± 6.89	35.61 ± 5.69*	10.01 ± 1.88	6.83 ± 0.34
	LTMC	58.25 ± 5.84	64.02 ± 4.6	8.21 ± 1.88	10.92 ± 2.73
	LTLC	43.78 ± 3.17	44.09 ± 2.94	6.52 ± 0.6	8.58 ± 0.91

Asterisk (*) indicates a significant difference ($p < 0.05$) between initial and final values.
NB means Natural Batata and IB means Impacted Batata. Treatment acronyms are a combination of HT: High Turbidity; MT: Medium Turbidity; LT: Low Turbidity; HC: High Chlorophyll; MC: Medium Chlorophyll; LC: Low Chlorophyll.

TABLE 7 | C:N, N:P and C:P ratios (in mol/L) by sediment type and treatment at the beginning and end of the experiments.

Sediment	Treatment	Ratio C:N (mol/L)		Ratio N:P (mol/L)		Ratio C:P (mol/L)	
		Initial	Final	Initial	Final	Initial	Final
BN	HTHC	20.2 ± 1.0	22.9 ± 0.4	6.1 ± 3.4	9.2 ± 1.3	121.1 ± 40.8	167.6 ± 18.7
	HTMC	19.9 ± 0.6	23.8 ± 5.1	11.2 ± 0.8	7.6 ± 1.3	223.4 ± 9.6	173.0 ± 28.7
	HTLC	28.5 ± 22.4	23.37 ± 0.2	12.3 ± 4.3	8.2 ± 1.7	307.2 ± 200.9	190.5 ± 7.2
	MTHC	34.4 ± 21.7	36.0 ± 4.8	4.4 ± 0.3	3.8 ± 0.2	142.7 ± 32.0	89.3 ± 3.6
	MTMC	37.1 ± 11.5	32.5 ± 1.3	5.7 ± 2.4	5.5 ± 0.2	192.4 ± 21.2	196.9 ± 23.6
	MTLC	45.7 ± 8.0	26.3 ± 2.3	5.1 ± 0.9	6.1 ± 0.3	227.8 ± 27.1	198.4 ± 6.9
	LTHC	56.7 ± 6.4	41.7 ± 8.8	3.7 ± 0.8	2.5 ± 0.3	137.2 ± 14.5	64.3 ± 6.8
	LTMC	56.1 ± 19.5	46.1 ± 6.0	3.2 ± 0.5	4.0 ± 1.1	181.0 ± 13.2	158.8 ± 8.1
	LTLC	18.36 ± 1.7	4.8 ± 0.14	4.5 ± 2.4	3.4 ± 0.6	263.9 ± 35.5	155.2 ± 11.6
BI	HTHC	50.4 ± 14.8	43.1 ± 11.2	5.0 ± 1.6	4.8 ± 1.6	253.0 ± 12.5	193.4 ± 21.6
	HTMC	44.3 ± 3.5	28.9 ± 5.1	2.0 ± 0.4	5.9 ± 1.2	86.5 ± 11.1	168.4 ± 27.9
	HTLC	45.3 ± 7.9	38.7 ± 5.4	2.4 ± 0.6	2.4 ± 0.4	108.4 ± 22.8	91.2 ± 12.7
	MTHC	50.6 ± 16.4	59.1 ± 19.5	4.7 ± 1.4	3.2 ± 1.2	222.6 ± 7.9	174.6 ± 4.3
	MTMC	61.5 ± 12.0	39.8 ± 8.8	2.2 ± 0.3	2.8 ± 0.9	131.0 ± 11.5	107.7 ± 13.8
	MTLC	72.9 ± 18.9	51.9 ± 3.7	1.8 ± 0.5	2.4 ± 0.6	125.0 ± 6.7	121.4 ± 21.4
	LTHC	48.6 ± 4.8	30.9 ± 5.9	2.3 ± 0.5	5.5 ± 1.2	108.8 ± 17.9	166.7 ± 8.1
	LTMC	55.5 ± 5.3	39.4 ± 2.6	2.6 ± 0.6	2.7 ± 0.8	141.1 ± 29.9	105.5 ± 24.7
	LTLC	48.9 ± 6.4	47.5 ± 11.3	3.3 ± 0.3	3.0 ± 0.8	161.7 ± 12.4	138.8 ± 8.7

NB means Natural Batata and IB means Impacted Batata.
Treatment acronyms are a combination of HT: High Turbidity; MT: Medium Turbidity; LT: Low Turbidity; HC: High Chlorophyll; MC: Medium Chlorophyll; LC: Low Chlorophyll.

phagotrophs such as Chrysophyceae were also present, thus maintaining most of the photosynthetic activity. Cyanobacteria species occurred in almost all treatments, perhaps because of the presence of a favorable light spectrum for this group (Luimstra et al., 2020), i.e., the blue band (430 nm). Cyanobacteria can be especially dominant under nitrogen-limiting conditions because they can perform N_2 fixation (Reynolds, 2006). In general, Cyanobacteria species are S strategists and perform well in nitrogen-limited environments (Wang et al., 2020). The Nutrient-Load hypothesis proposed by Brauer et al. (2012) states that Cyanobacteria species are better competitors in light and/or nitrogen-limited environments, so light availability and the nutrient ratio in our systems could have been favorable for Cyanobacteria to establish, since this group can grow both in low C:P (Penha, 2015) and low N:P (Schindler, 1975; Smith, 1983) ratios, as in our systems. Also, picocyanobacteria tend to increase under high inorganic turbidity (Brasil et al., 2017; Somogyi et al., 2017). This agrees with the increase in Cyanobacteria in our experiment since filamentous cyanobacteria were found at the end of the experiment, indicating an adaption to low light (Kirk, 2011). In our treatments, *Leptolyngbya* and *Chroococcus* were the most numerous species; they are considered good competitors and able to dominate in shallow and turbid environments (Scheffer et al., 1997).

4.3 Effects of Sediment Type

Even though the sediments used in our experiments came from the same lake (Lake Batata), they had different chemical compositions and physical properties, causing different turbidity effects, as shown elsewhere (Esteves et al., 1990; Roland et al., 1997). Roland and Esteves (1998) reported that particles from natural-area sediments in Lake Batata usually settle faster and more easily than the light bauxite-tailing particles (Roland and Esteves, 1998). Thus, the effect of bauxite tailings on chlorophyll-a and to some extent on photosynthesis can last longer. We hypothesized that inorganic turbidity containing bauxite tailings would generate stronger negative effects on chlorophyll-a levels, and our hypothesis was confirmed. The effect of NB sediment on chlorophyll-a was milder since NB sediment led to higher chlorophyll-a values (6.39% higher than IB) but low yield, indicating more difficult conditions for these communities to photosynthesize. NB sediment favored Crysophyceae and Euglenophyceae, which have a lower requirement for light irradiance because they can compensate through mixotrophy (Flynn et al., 2013; Mitra et al., 2016). The most likely explanation is that the NB sediment had a shading effect, allowing algae to persist but at a higher metabolic cost.

The mine-tailing sediments led to lower slopes in IB, indicating the same negative effect seen in *in-situ* measurements, where lower primary production in the impacted area has been reported (Roland, 1995; Roland et al., 2002; Guenther and Bozelli, 2004). Similar results were found in another system impacted by gold-mine tailings (Moreira et al., 2016). Nowadays, the negative effects of bauxite tailings in Lake Batata are not the same as at the beginning of the monitoring program 30 years ago. In the dry period, when the water is more turbid, phytoplankton reaches high densities because nutrient availability has increased with the recovery of the lake (Bozelli et al., 2015). In turbid environments with low phytoplankton primary production related to tailings, the principal effect on the trophic web is loss of energy transfer through trophic levels, indirectly affecting zooplankton (Bozelli and Esteves, 1995) and fish (Shoup and Wahl, 2009). In our tailings turbidity treatments, chlorophyll-a, and to some extent primary production, were maintained, mainly due to the success of phagotrophic Chlorophyceae and Chrysophyceae, groups adapted to low light conditions (Reynolds, 2006). Despite the lower chlorophyll-a values, IB sediments allowed higher yields, even higher than 0.83 in some treatments, a level at which algae are not considered to be under light stress. This may be due to the physical properties of bauxite tailings, which despite reducing light input, may have allowed favorable wavelength dispersion. This requires further investigation beyond the scope of our study.

5 CONCLUSION

Our results showed that the turbidity effect was stronger in treatments with higher sediment concentrations. However, high turbidity did not necessarily lead to a linear reduction in chlorophyll-a concentrations, and photosynthesis was maintained even with the turbidity shading effect in treatments with both sediment types (NB and IB). In NB the conditions for photosynthesis were better since treatments with this sediment type had higher chlorophyll-a values than IB, and also higher contributions of brown algae (Euglenophyceae, Dinophyceae, Bacillariophyceae). In IB, the phytoplankton was composed mainly of Chrysophiceae, Cryptophyceae, Chlorophyceae, and Cyanobacteria. Accordingly, the IB sediments affected the phytoplankton composition and chlorophyll-a more than the NB sediments.

Although the effect of turbidity on the metabolism of freshwater phytoplankton is widely known, our study advances the comprehension of how turbidity caused by mine tailings affects photosynthesis and phytoplankton composition, which may support recovery protocols and environmental policies for aquatic ecosystems.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/**Supplementary Material**, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conceptualization: PN, FR, AA, SC; Methods: PN, FR, AA, SC, NR; Resources: FR; Writing original draft: PN; Algae taxonomic composition analysis: NR; Discussion Writing, Review, and Editing: FR, AA, SC, NR.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2021.605838/full#supplementary-material

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