

Ecological diagnosis of Lake Batur (Bali, Indonesia) post-disturbance using multimetric phytoplankton indices

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Abstract. *Suryani SAMP, Sudiarta IG, Darmadi NM, Edi DGS, Sudiarta IK, Pratama GAS, Janaguna IMA, Sugiana IP. 2025. Ecological diagnosis of Lake Batur (Bali, Indonesia) post-disturbance using multimetric phytoplankton indices. Biodiversitas 26: 4982-4990.* Plankton communities are rapid responders to environmental change and serve as sensitive indicators of ecological stress in tropical volcanic lakes. In July 2025, Lake Batur (Bali, Indonesia) experienced a major fish mortality linked to hypolimnetic upwelling and nutrient enrichment from aquaculture. To assess post-disturbance conditions, we sampled three sites with varying aquaculture intensity—Seked (low), Buahhan (moderate), and Trunyan (high, mortality epicenter)—one week after the event. Field measurements included temperature, pH, dissolved oxygen, conductivity, redox potential, nutrients, and sulfide, while phytoplankton analysis covered diversity (Shannon–Wiener), evenness (Pielou), dominance (Simpson), and saprobity (Dahuri). Results revealed clear spatial contrasts. Trunyan showed the strongest stress signals, with oxygen depletion, negative redox potential, and elevated ammonia, while Seked and Buahhan displayed milder alterations. In total, 23 phytoplankton genera were identified, dominated by diatoms such as *Ulnaria* and *Actinotaenium*. Trunyan exhibited reduced richness, lower diversity ($H' = 1.84$), and higher dominance ($D = 0.27$), indicating a shift toward opportunistic taxa. Saprobitiy values showed a gradient of organic pollution, increasing from Seked (1.5) to Trunyan (2.0), consistent with aquaculture intensity. These findings highlight the value of integrating multimetric plankton indices with physicochemical data to distinguish natural upwelling effects from anthropogenic nutrient loading. While diatom persistence suggests some resilience, recovery of sensitive taxa depends on reducing nutrient inputs and regulating aquaculture. This integrative framework offers a practical diagnostic tool for adaptive lake management and contributes to achieving clean water, climate action, and aquatic biodiversity goals.

Keywords: Ecological indices, fish mortality, organic pollution, plankton, volcanic lakes

INTRODUCTION

Plankton form the dynamic foundation of aquatic food webs and drive critical biogeochemical processes, including carbon fixation, oxygen production, and nutrient cycling. As primary producers, they supply energy to higher trophic levels and regulate ecosystem productivity. Their short life cycles and high sensitivity to environmental fluctuations make them effective sentinels of aquatic health, often detecting stress signals long before such impacts are visible in fish or higher organisms (Akbarurasyid et al. 2023; Kumar and Singh 2023). This diagnostic role is especially valuable in tropical volcanic lakes, where thermal and nutrient dynamics can change abruptly and generate cascading ecological responses.

Lake Batur, in Bali, Indonesia located within the caldera of Mount Batur, is Bali's largest freshwater body and provides multiple ecosystem services, including domestic water supply, fisheries, transportation, and aquaculture. In recent decades, aquaculture, particularly Floating Net Cages (FNC) for Nile tilapia, has expanded beyond the lake's carrying capacity, leading to increased nutrient loading, organic enrichment, and eutrophication risk (Lusia et al. 2023). Semi-enclosed bays such as

Trunyan and Buahhan further exacerbate vulnerability, as limited water exchange allows accumulation of organic matter and restricts oxygen renewal. Beyond aquaculture, catchment pressures, including deforestation, agriculture, and domestic waste inputs, compound ecological stress and reduce resilience.

The volcanic setting adds unique hazards: under prolonged stratification, the hypolimnion accumulates reduced compounds such as hydrogen sulfide and ammonia. When meteorological or seismic events disturb the water column, these reduced waters can rise into the surface layer, depleting oxygen and creating toxic conditions that cause mass fish kills. Such events have been recorded repeatedly, most notably in 2011 and again in July 2025, when severe mortality in the Trunyan area was marked by surface discoloration and sulfur odors (Fukushima et al. 2017). These incidents underscore how natural hazards and aquaculture-derived enrichment interact to shape ecological risk.

Despite routine water chemistry monitoring, detailed plankton community assessments after acute disturbances remain scarce for Lake Batur. Evidence from other tropical volcanic lakes shows that disturbance can restructure plankton assemblages—favoring opportunistic taxa, suppressing

sensitive species, and altering diversity–evenness patterns (Claflin et al. 2024). Recovery potential exists (Urrutia-Cordero et al. 2021), but is shaped by both environmental conditions and anthropogenic pressures. Without post-event plankton analysis, these dynamics remain speculative. Importantly, phytoplankton-based indices are increasingly recognized in Indonesia's national water quality monitoring frameworks by SNI 06-4157-1996 (BSN 1996), where they complement physicochemical parameters by providing biological diagnostics of organic enrichment and ecological status.

A single biological metric often underestimates ecosystem change when multiple stressors interact. A multimetric approach—integrating abundance, diversity, evenness, dominance, and saprobity—offers a more comprehensive diagnosis of stress and resilience (Meyer et al. 2024). Diversity indices capture richness and distribution balance; dominance indices reveal competitive skew; saprobity indices directly assess organic pollution based on bioindicators. In volcanic lakes subject to aquaculture, this framework can help distinguish between physical disturbance effects (e.g., upwelling) and those exacerbated by nutrient inputs.

Despite long-standing concerns about eutrophication and recurrent fish kills in Lake Batur, no prior study has implemented a comprehensive multi-metric, plankton-based assessment within a post-disturbance context. Previous investigations have predominantly focused on physicochemical monitoring or employed single biological indices, which, while informative, provide only a partial view of ecosystem change. This narrow focus leaves a critical gap in understanding how multiple, interacting stressors simultaneously influence plankton community structure and overall ecological condition. Addressing this gap is essential for developing more holistic diagnostic tools and guiding effective management strategies in tropical volcanic lakes.

This study investigates the post-disturbance plankton community of Lake Batur one week after the July 2025 fish mortality event. By combining in situ physicochemical profiling with multimetric plankton indices (diversity, evenness, dominance, and saprobity), our objective is to demonstrate how integrated metrics can disentangle natural drivers (e.g., upwelling-induced hypoxia) from anthropogenic pressures (e.g., nutrient loading from aquaculture), and

provide a sensitive diagnostic framework for ecological stress and recovery potential in volcanic lakes.

MATERIALS AND METHODS

Site description

Field sampling was conducted at three stations in Lake Batur, Bali ($08^{\circ}17'10''$ - $08^{\circ}13'17''$ S, $115^{\circ}22'25''$ - $115^{\circ}25'48''$ E) (Figure 1), representing a gradient of ecological stress. Seked, on the southwestern shore, is an open-water area with low aquaculture activity and strong hydrodynamic exchange, serving as a reference site. Buahan, on the southeastern shore, is adjacent to moderate floating net cage aquaculture and receives inflows from agricultural catchments, indicating intermediate nutrient input. Trunyan, on the northeastern shore, is a semi-enclosed bay with dense cage aquaculture and limited water circulation, making it prone to nutrient buildup and hypoxia; this station was the epicenter of the July 2025 mass fish mortality (Figure 2).

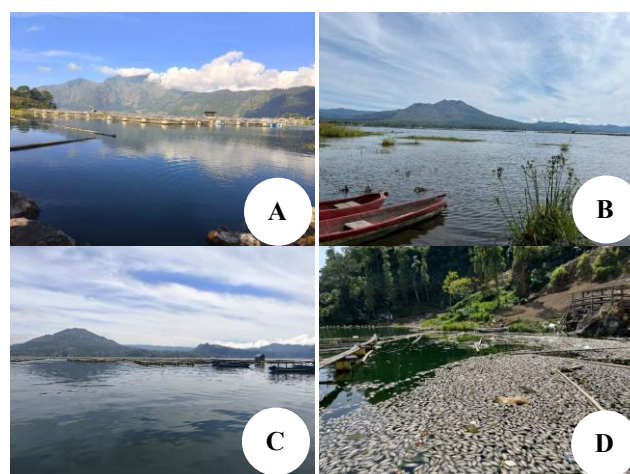


Figure 2. General view of each sampling location in Lake Batur, Bali, Indonesia. A. Seked: open water, low aquaculture pressure; B. Buahan: moderate aquaculture and agriculture inflows; C. Trunyan: semi-enclosed bay with high cage density and disturbance epicenter; D. Fish mortality event on Trunyan

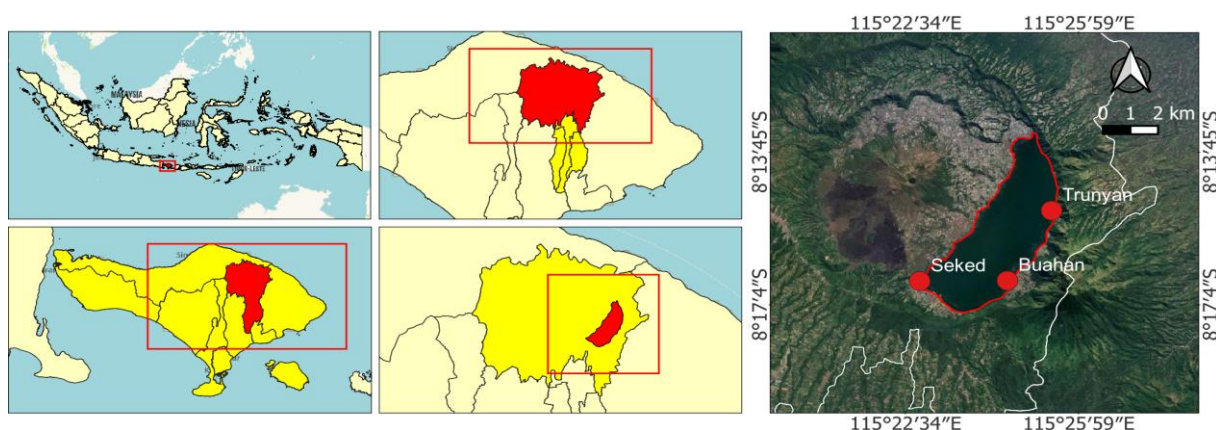


Figure 1. Map of Lake Batur, showing the three sampling stations (Seked, Buahan, Trunyan) in Kintamani, Bangli, Bali, Indonesia. Stations were selected to represent a gradient of ecological stress from low (Seked) to high (Trunyan)

Sampling was performed one week after the mortality event to capture acute stress conditions before recovery began. Water and plankton samples were collected at all three sites to enable direct comparison of community responses under different disturbance intensities (Figure 1).

Field data collection

At each station, physicochemical parameters were measured in situ, including temperature (°C), pH, dissolved oxygen (DO, mg L⁻¹), electrical conductivity (µS cm⁻¹), and oxidation–reduction potential (ORP, mV). Each parameter was measured in triplicate using a portable multi-parameter meter (MultiCOM-300, Water Quality Tester) and a DO meter (Hanna HI9146). Additional samples were collected for laboratory analysis of Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), ammonia (NH₃), total phosphorus (P), sulfate (SO₄²⁻), and hydrogen sulfide (H₂S), following APHA (2017) standards at the Bali Provincial Health Laboratory. Due to logistical constraints, laboratory analyses were based on a single composite sample per station; we acknowledge that this approach may reduce site-specific representativeness, but it still provides a useful overview of station-level differences.

Phytoplankton samples were collected using the pouring method. At each station, approximately 300 L of surface water was collected in triplicate using a clean plastic bucket and subsequently filtered through a plankton net with a mesh size suitable for phytoplankton (typically 25 µm). The concentrated filtrates from each replicate were transferred into separate 100 mL polyethylene bottles. Samples were preserved immediately by adding Lugol's iodine solution to a final concentration of approximately 1% to arrest biological activity and preserve cell morphology. Preserved samples were stored in dark, cool conditions during transport and subsequently analyzed in the laboratory for taxonomic identification, counting, and community index calculations.

Plankton identification

Phytoplankton were analyzed using a Sedgwick–Rafter counting chamber (50 × 20 × 1 mm) under a binocular light microscope at 10 times magnification. Each sample was gently homogenized before subsampling. Counts were performed in triplicate across the entire chamber to minimize error, and organisms were identified to the genus level following Reynolds et al. (2002).

Data analysis

Plankton density

Phytoplankton abundance was calculated based on the number of individuals observed in the Sedgwick–Rafter counting chamber and adjusted to the total volume of water sampled in the field. The counts from the microscope observations were converted into units of cells per liter by considering the concentration factor from the filtration process and the total volume of water filtered in the field (300 L). All observations were carried out in triplicate, and

the average value was used as the final abundance for each genus. The calculation followed the formula:

$$N = n + \frac{Vt}{Vo} + \frac{Acg}{Aa} + \frac{1}{Vd}$$

Where: N: Abundance (cells L⁻¹), n: Number of individuals counted, Vt: Volume of concentrated sample (100 mL), Vo: Volume of Sedgwick–Rafter observed (1 mL), Acg: Area of chamber observed (1000 mm²), Aa: Total area of the chamber (1000 mm²), Vd: Volume of water filtered in the field (300 L).

Diversity, evenness, and dominance indexes

Phytoplankton community structure was quantified using diversity (Shannon–Wiener index, H'), evenness (Pielou's index, J), and dominance (Simpson's index, C). The diversity index describes species richness and the distribution of individuals among taxa; the evenness index measures how evenly individuals are distributed among the observed taxa, and the dominance index quantifies the extent to which a few taxa dominate the community. All calculations were based on genus-level abundance data obtained from phytoplankton counts. The Shannon–Wiener diversity index (H') was calculated as:

$$H' = - \sum_{i=1}^S p_i \ln p_i$$

Where: S: Total number of genera, p_i ln p_i: Proportion of individuals belonging to genus *i* relative to the total abundance, H' < 1.0: Low diversity (unstable/impacted community), 1.0 ≤ H' ≤ 3.0: Moderate diversity (moderately stable community), H' > 3.0: High diversity (stable community) (Odum 1993; Magurran 2013)

Pielou's evenness index (J) was calculated as:

$$J = \frac{H'}{\ln S}$$

Where: H': Shannon–Wiener diversity index, S: Total number of genera, J < 0.4: Low evenness (domination by few taxa), 0.4 ≤ J ≤ 0.6: Moderate evenness, J > 0.6: High evenness (balanced community structure)

The Simpson's dominance index (C) was calculated as:

$$C = \sum_{i=1}^S p_i^2$$

Where: p_i ln p_i: Proportion of individuals belonging to genus *i*, C close to 0: Low dominance (no single taxon dominates), C around 0.5: Moderate dominance, C close to 1: High dominance (community strongly dominated by one or a few taxa)

Saprobity index

The saprobic index was applied following Dahuri (1995) to assess organic pollution in Lake Batur using phytoplankton as bioindicators. Phytoplankton genera were grouped into four categories: A (Ciliata – polysaprobic), B (Euglenophyta – α -mesosaprobic), C (Chlorococcales and Diatoms – β -mesosaprobic), and D (Peridineae, Chrysophyceae, Conjugaceae – oligosaprobic). Index values (X) were calculated from the relative occurrence of these groups following the equation below. According to Dahuri (1995), values close to -3 indicate heavily polluted, polysaprobic waters; values around 0 correspond to β -mesosaprobic (moderately polluted) conditions; while values approaching $+3$ indicate clean waters dominated by oligosaprobic taxa. Thus, although numerically higher values (e.g., 2.0) appear "larger," they actually represent less polluted conditions within this classification scheme.

$$X = \frac{(C + 3D - B - 3A)}{(A + B + C + D)}$$

Statistical analysis

Data collected from the three stations were first tested for normality using the Shapiro–Wilk test, which confirmed that all variables were normally distributed ($p > 0.05$). Subsequently, a one-way Analysis of Variance (ANOVA) was applied to evaluate differences among stations. When significant differences were detected ($p < 0.05$), Tukey's Honest Significant Difference (HSD) post hoc test was performed to identify specific pairwise differences. All statistical analyses were conducted using RStudio version 4.2.

RESULTS AND DISCUSSION

General condition of water quality post fish mortality event

One week after the fish mortality event, the three sampling locations exhibited markedly different physical and chemical profiles. Trunyan, being the epicenter of the event, recorded the most stressed conditions, characterized by depressed dissolved oxygen, negative Oxidation–Reduction Potential (ORP), and elevated ammonia levels relative to the other sites (Table 1). Seked and Buahan, while still affected by the disturbance, presented comparatively moderate alterations in water quality. Variations across all sites in parameters like pH, conductivity, and organic load reflect spatial differences in the disturbance's intensity and in the degree of water column mixing.

The severe reduction in dissolved oxygen at Trunyan, coupled with a negative ORP, most plausibly indicates an influx of anoxic hypolimnetic water into the surface layer—a phenomenon documented in tropical lakes following disruptions of stratification. Tropical lakes are known to trap oxygen-poor bottom waters that, once mixed upward (for instance, by wind-triggered convection). These chemical changes, if not addressed, can cause rapid shifts in surface chemistry and lead to fish mortality events (Fukushima et

al. 2017, et al. 2022). The negative ORP readings further suggest the initiation of strong reducing conditions typical of in situ decomposition processes. As organic materials, such as dead fish, uneaten feed, and fish waste, settle and degrade, microbial respiration can deplete oxygen and foster reducing environments that favor the accumulation of reduced species like ammonia (Li et al. 2024).

Meanwhile, Seked and Buahan, which displayed milder parameter shifts, likely escaped the brunt of both hypolimnetic intrusion and organic loading. The spatial gradient may reflect variations in aquaculture density or farm management across the lake: areas closer to dense cage operations can receive higher organic and nutrient input, increase biochemical oxygen demand, and alter redox conditions more sharply (de Leon et al. 2024). Accordingly, the observed Seked–Trunyan gradient reflects both natural drivers (hypolimnetic upwelling affecting oxygen and redox dynamics) and anthropogenic stressors (organic loading from floating net cages), with aquaculture effects more evident at Buahan and Trunyan, while Seked remains relatively protected. As a result, the differences in water chemistry among the sites underscore how physical mixing processes and localized organic enrichment shape the ecological aftermath of the mortality event.

Checklist and plankton community dynamics

Checklist of plankton

Across all stations, a total of 23 plankton genera were recorded, representing six major classes: Bacillariophyceae, Chlorophyceae, Cyanophyceae, Dinophyceae, Euglenophyceae, and Zygnematophyceae (Table 2). The highest genus richness was observed at Seked (23 genera), followed by Buahan (22 genera) and Trunyan (20 genera). Bacillariophyceae dominated the assemblage at all sites, with multiple diatom genera consistently present across stations. Chlorophyceae and Cyanophyceae were also widely distributed, while Dinophyceae and Euglenophyceae were less frequently encountered. The slightly reduced richness at Trunyan suggests a potential loss of sensitive taxa in response to post-disturbance conditions.

Table 1. Water quality at each station of Lake Batur, Bali, Indonesia

Parameter	Seked	Buahan	Trunyan
Temperature (°C)	25.5 ± 1.1	21.5 ± 0.6	23.9 ± 0.2
pH	8.42 ± 0.06	8.37 ± 0.04	8.32 ± 0.01
DO (mg/L)	5.9 ± 0.4	5.8 ± 0.2	5.2 ± 0.1
Conductivity (µS/cm)	1775 ± 51	1590 ± 79	1840 ± 10
ORP (mV)	39 ± 4	40 ± 7	-49 ± 44
BOD (mg/L)*	0.9	1.3	1.1
COD (mg/L)*	28	32	28
NH ₃ (mg/L)*	< 0.001	< 0.001	0.052
P (mg/L)*	0.148	0.23	0.163
SO ₄ ²⁻ (mg/L)*	260.882	257	253.053
H ₂ S (mg/L)*	< 0.01	< 0.01	< 0.01

Note: *: One-time measurement only in the laboratory, <: The value is below the measurement limit of the tool

The plankton community across the three stations was dominated by diatoms (Bacillariophyceae), which are known for their ecological versatility and ability to persist under a range of nutrient and light conditions (Hilaluddin et al. 2020). Their strong dominance in Lake Batur may also be reinforced by silica availability from volcanic sediments that sustain frustule production, as well as by their tolerance to fluctuating oxygen and reducing conditions that prevailed after the disturbance. Genera such as *Cyclotella* (F.T.Kützing) A.de Brébisson, 1838, *Navicula* Bory, and *Nitzschia* A.H.Hassall, 1845—common indicators of nutrient enrichment—were consistently present at all sites, suggesting resilience to short-term disturbance. The presence of Chlorophyceae (e.g., *Coelastrum* Nägeli, 1849, *Eudorina* Ehrenberg, 1832) alongside Cyanophyceae (*Oscillatoria* Vaucher ex Gomont, 1892, *Spirulina* Turpin ex Gomont, 1892) (Figure 3) reflects a mixed trophic state, as green algae often flourish in mesotrophic conditions while cyanobacteria are favored under eutrophic, high-nutrient, and occasionally low-oxygen environments (Paerl and Otten 2016; Visser et al. 2016). The slightly lower richness observed at Trunyan compared to Seked and Buahan may be linked to environmental stressors such as reduced dissolved oxygen, elevated ammonia, and negative oxidation–reduction potential, which can selectively disadvantage more sensitive taxa (Glibert et al. 2016; Gobler 2020). Such conditions can favor opportunistic, bloom-forming cyanobacteria and certain diatoms, while reducing the diversity of less tolerant groups. The occurrence of Dinophyceae (*Gymnodinium* F.Stein, 1878) and Euglenophyceae (*Euglena* Ehrenberg, 1830) (Table 3), although in low richness, is consistent with post-disturbance environments where motile and mixotrophic taxa have a competitive advantage in exploiting fluctuating nutrient and light regimes (Park et al. 2013). However, a limitation of the study is the lack of detailed pre-disturbance plankton data, which restricts our ability to separate short-term disturbance responses from long-term ecological trends. Interpretations, therefore, rely on comparisons with earlier published surveys (Sulawesty and Satya 2013; Sipayung et al. 2024). The composition pattern supports the view that the disturbance triggered a community restructuring along a stress gradient, with Trunyan showing the strongest shift.

Plankton community dynamics

Phytoplankton density varied markedly among the three stations, with Trunyan recording the highest value (1,480 cells L⁻¹), followed by Seked (466 cells L⁻¹) and Buahan (333 cells L⁻¹) (Figure 4.A). The ANOVA results confirmed that the differences were highly significant ($F = 103.23$, $p < 0.01$). Tukey's HSD test further showed that density at Trunyan (superscript b) was significantly higher than at Seked and Buahan (both superscript a). At the same time, no significant difference was observed between Seked and Buahan. All stations were dominated by Bacillariophyceae, contributing more than half of the total abundance, with the remainder composed primarily of Zygnematophyceae, Chlorophyceae, Cyanophyceae, and smaller proportions of Dinophyceae and Euglenophyceae (Figure 4.B).

Table 2. Plankton checklist data

Class	Genera	Station		
		Seked	Buahan	Trunyan
Bacillariophyceae	<i>Amphipleura</i>	+	+	+
Bacillariophyceae	<i>Amphora</i>	+	+	+
Bacillariophyceae	<i>Aulacoseira</i>	+	-	-
Bacillariophyceae	<i>Bacillaria</i>	+	+	-
Bacillariophyceae	<i>Cyclotella</i>	+	+	+
Bacillariophyceae	<i>Fragilaria</i>	+	+	+
Bacillariophyceae	<i>Gyrosigma</i>	+	+	+
Bacillariophyceae	<i>Melosira</i>	+	+	+
Bacillariophyceae	<i>Navicula</i>	+	+	+
Bacillariophyceae	<i>Nitzschia</i>	+	+	+
Bacillariophyceae	<i>Stephanodiscus</i>	+	+	-
Bacillariophyceae	<i>Tabellaria</i>	+	+	+
Bacillariophyceae	<i>Ulnaria</i>	+	+	+
Chlorophyceae	<i>Coelastrum</i>	+	+	+
Chlorophyceae	<i>Eudorina</i>	+	+	+
Chlorophyceae	<i>Stigeoclonium</i>	+	+	+
Cyanophyceae	<i>Nostoc</i>	+	+	+
Cyanophyceae	<i>Oscillatoria</i>	+	+	+
Cyanophyceae	<i>Spirulina</i>	+	+	+
Dinophyceae	<i>Gymnodinium</i>	+	+	+
Euglenophyceae	<i>Euglena</i>	+	+	+
Zygnematophyceae	<i>Actinotaenium</i>	+	+	+
Zygnematophyceae	<i>Closterium</i>	+	+	+
Total		23	22	20

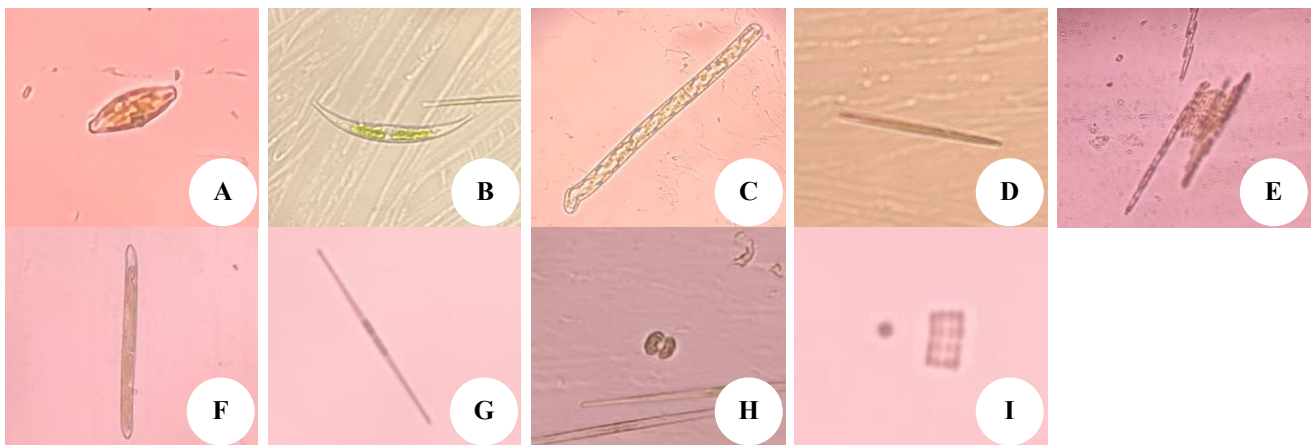


Figure 3. Genera of plankton found in Batur Lake, Bali, Indonesia. A. *Amphora*, B. *Closterium*, C. *Oscillatoria*, D. *Amphipleura*, E. A group of *Bacillaria*, F. *Gyrosigma*, G. *Ulnaria*, H. *Actinotaenium*, alongside *Ulnaria*, I. *Fragilaria*

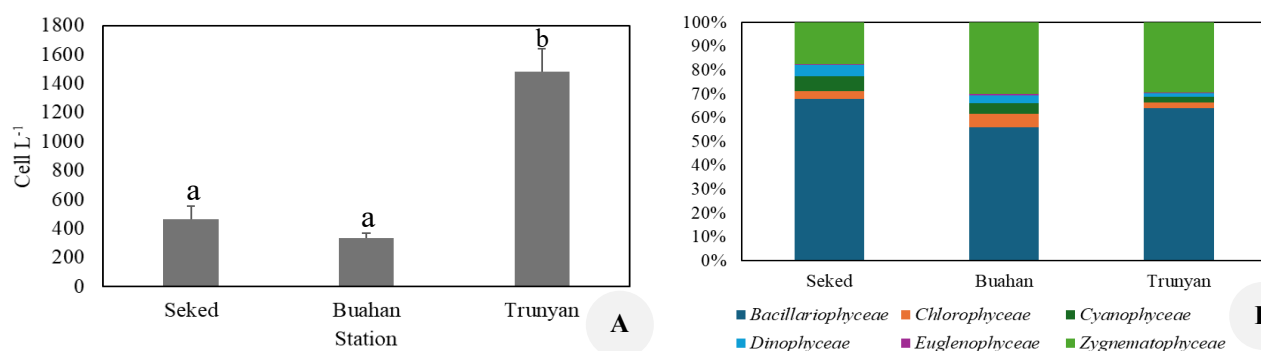


Figure 4. A. Plankton density of each station, B. Dominant plankton classes

Table 3. Genera dominated the plankton in Batur Lake, Bali, Indonesia

Genera	Seked	Buahan	Trunyan
<i>Amphiptera</i>	9.66%	2.62%	2.20%
<i>Amphora</i>	1.34%	2.62%	0.82%
<i>Aulacoseira</i>	0.88%	0.00%	0.00%
<i>Bacillaria</i>	10.73%	3.00%	0.00%
<i>Cyclotella</i>	1.34%	1.42%	2.87%
<i>Fragilaria</i>	4.29%	4.87%	4.85%
<i>Gyrosigma</i>	0.64%	0.37%	0.89%
<i>Melosira</i>	0.86%	0.72%	4.39%
<i>Navicula</i>	1.34%	0.97%	2.53%
<i>Nitzschia</i>	2.15%	1.36%	0.76%
<i>Stephanodiscus</i>	3.92%	0.67%	0.00%
<i>Tabellaria</i>	2.15%	1.12%	2.53%
<i>Ulnaria</i>	28.70%	36.37%	42.24%
<i>Coelastrum</i>	0.48%	1.87%	1.47%
<i>Eudorina</i>	2.23%	3.18%	0.89%
<i>Stigeoclonium</i>	0.60%	0.60%	0.15%
<i>Nostoc</i>	0.30%	0.24%	0.09%
<i>Oscillatoria</i>	5.63%	3.75%	2.20%
<i>Spirulina</i>	0.30%	0.42%	0.08%
<i>Gymnodinium</i>	4.62%	3.12%	1.35%
<i>Euglena</i>	0.39%	0.66%	0.23%
<i>Actinotaenium</i>	14.49%	26.62%	28.05%
<i>Closterium</i>	2.95%	3.37%	1.41%
Total	100%	100%	100%

In contrast, green algae (Chlorophyceae) and cyanobacteria contributed only modest proportions, while motile taxa such as *Gymnodinium* and *Euglena* occurred sporadically at low levels. Sensitive genera were less represented at Trunyan, consistent with environmental stress from oxygen depletion and elevated ammonia. Compared to previous surveys in Lake Batur, overall phytoplankton density was lower, indicating that the mortality event and subsequent upwelling altered nutrient dynamics and suppressed community complexity. The decline in richness and evenness at Trunyan, together with higher dominance, illustrates a clear shift toward opportunistic and disturbance-tolerant taxa. This restructuring highlights the strong influence of both physical (hypolimnetic intrusion) and anthropogenic (aquaculture loading) stressors on post-disturbance community dynamics.

The markedly higher phytoplankton density at Trunyan compared to Seked and Buahan indicates a localized bloom-like condition in the aftermath of the fish mortality event.

Nutrient enrichment from physical processes such as hypolimnetic upwelling and biological inputs from decomposing fish carcasses and residual feed likely contributed to this biomass increase (Casa et al. 2020). However, when compared to previous observations in Lake Batur, the total phytoplankton density recorded in this study is notably lower. Earlier surveys, such as Sipayung et al. (2024), reported mean densities exceeding 4000 cells L⁻¹ in the lake's productive zones under stable stratification and active aquaculture periods—nearly triple the highest value recorded at Trunyan in the present study. This reduction in total density could reflect the combined effects of recent disturbance, altered nutrient dynamics, and possible loss of sensitive taxa that had previously contributed to higher baseline biomass. The dominance of Bacillariophyceae at all stations, particularly at Trunyan, is consistent with their capacity to rapidly exploit nutrient pulses following mixing events (Winder et al. 2008; Sarmiento et al. 2009). Genera-level patterns, especially the prominence of *Ulnaria* (Kützing) P. Compère, 2001 and *Actinotaenium* (Nägeli) Teiling, 1954, suggest that post-disturbance conditions favored both nutrient-responsive diatoms and disturbance-tolerant green algae.

The strong dominance of *Ulnaria* at Trunyan (42.24%) highlights a marked community shift compared to pre-disturbance conditions reported by Sipayung et al. (2024), where this genus contributed a much smaller fraction to the phytoplankton assemblage and overall density exceeded 4000 cells L⁻¹ in the lake's productive zones. In the earlier survey, Bacillariophyceae were also the leading group but were represented by a broader set of genera, including *Fragilaria* H.C. Lyngbye, 1819, *Cyclotella*, and *Melosira* C.A. Agardh, 1824, resulting in higher diversity and more balanced community structure. In contrast, the present data show a disproportionate expansion of *Ulnaria* relative to other diatoms, coinciding with reduced contributions from chlorophytes and cyanobacteria. This shift underscores a simplification of the phytoplankton community following the mass fish mortality event, with post-upwelling conditions favoring the proliferation of a single nutrient-responsive genus rather than the more even representation observed in pre-disturbance periods. In earlier work on Lake Batur, Bacillariophyceae also dominated, but with a more diverse representation of Chlorophyceae and Cyanophyceae, contributing to overall higher diversity and evenness values (Sulawesty and Satya 2013). The current lower

representation of these groups, particularly cyanobacteria, may be linked to suboptimal light or temperature regimes post-upwelling, as well as competition with fast-growing diatoms in the nutrient-enriched surface layer (Liu et al. 2022).

Multimetric ecological indices

Diversity, evenness, and dominance indices

The results of the Analysis of Variance (ANOVA) revealed significant differences among locations for all three community indices. Diversity (H') differed highly significantly ($F = 28.24$, $p < 0.01$), evenness (E) also differed significantly ($F = 18.62$, $p < 0.01$), and dominance (D) showed a significant difference as well ($F = 9.01$, $p < 0.05$). Tukey's HSD test indicated that diversity and evenness were significantly higher at Seked compared to Buahan and Trunyan, whereas dominance was significantly higher at Trunyan compared to Seked and Buahan (Table 4).

The relatively high diversity and evenness at Seked indicate a community with balanced representation among taxa, a condition often associated with a stable environment where resources and ecological niches are equitably shared. That suggests that recent ecological disturbances have less impact on Seked, allowing a wider range of phytoplankton genera to coexist without one or a few dominating the community. In Buahan, intermediate diversity and evenness values point toward moderate ecological stress, potentially linked to nutrient enrichment or localized environmental changes that favor certain genera over others. Here, some opportunistic taxa may be gaining an advantage, but the overall taxonomic balance remains partially preserved. At Trunyan, the lowest diversity and evenness, combined with the highest dominance, signal a strong departure from ecological equilibrium. This pattern implies that the phytoplankton community is highly skewed toward a limited number of dominant genera, a phenomenon typically driven by environmental filtering and competitive exclusion following disturbance events.

These findings are consistent with observations in other volcanic lakes that have experienced large-scale fish mortality, where sudden nutrient release from decomposing biomass, altered oxygen dynamics, and increased turbidity create conditions favorable for fast-growing, opportunistic phytoplankton species (Glibert et al. 2016; Paerl and Otten 2016). The elevated dominance at Trunyan likely reflects the proliferation of such taxa, which can quickly monopolize available resources under disturbed conditions, outcompeting less tolerant species. Furthermore, when compared to historical data from Lake Batur, where diversity indices (H') often exceeded 2.00 (Nirasari et al. 2018; Sipayung et al. 2024), the present values, especially the marked drop at Trunyan, represent a substantial decline in community complexity. This reduction not only highlights the immediate ecological consequences of the mortality event but also underscores the potential for long-term shifts in ecosystem functioning if recovery processes are slow. The combination of low diversity, reduced evenness, and high dominance thus serves as a clear ecological signal of post-disturbance restructuring in the phytoplankton community (Baho et al. 2020).

Table 4. Community structure of plankton in Batur Lake, Bali, Indonesia

Indexes	Seked	Buahan	Trunyan
Diversity (H')	2.42±0.02 ^a	2.10±0.15 ^b	1.84±0.08 ^b
Evenness (E)	0.76±0.01 ^a	0.68±0.05 ^b	0.61±0.03 ^b
Dominance (D)	0.14±0.02 ^a	0.21±0.05 ^a	0.27±0.04 ^b

The conclusions of this study indicate that the mass fish mortality event in Lake Batur was triggered by a combination of natural factors, namely hypolimnetic upwelling, and anthropogenic pressure from aquaculture, which caused varying water conditions between locations, with Trunyan being the most affected (low oxygen, high ammonia, negative ORP). The structure of the plankton community underwent significant changes, characterized by the dominance of opportunistic genera, reduced diversity, and increased saprobity indices, indicating a gradient of organic pollution. These findings underscore the importance of controlling the intensity of floating net cages, implementing routine monitoring based on multimetric plankton as an early warning system, and efforts to rehabilitate the lake through waste management and conservation of water catchment areas, to maintain the resilience of the lake ecosystem and support the achievement of SDGs related to clean water, climate, and aquatic ecosystems.

The novelty of this study lies in applying a multimetric approach integrating structural (diversity, evenness, dominance) and functional (saprobity) indices with physicochemical profiling immediately after a major fish mortality event. While most prior work in Indonesia has relied on either chemical monitoring or single biological indicators, our integrated analysis provides a more sensitive and ecologically relevant diagnosis of post-disturbance stress. This framework not only distinguishes between natural upwelling effects and anthropogenic nutrient loading but also offers a replicable model for other volcanic and tropical lake systems under aquaculture pressure.

Saprobity index

The saprobity index provides a standardized scale for assessing organic pollution based on the composition of indicator phytoplankton groups. Values generally range from -3 (heavily polluted, polysaprobic conditions) to +3 (clean, oligosaprobic conditions), with intermediate values indicating varying degrees of organic enrichment. Lake Batur varied among sampling stations, with 1.5 at Seked, 1.8 at Buahan, and 2.0 at Trunyan (Table 5). According to the classification by Dahuri (1995), Seked falls into the slightly polluted category, Buahan is classified as slightly to moderately polluted, and Trunyan lies at the upper limit of the slightly polluted range, approaching moderately polluted conditions. These values reflect differences in ecological pressure among the three sites, likely influenced by varying inputs of organic matter and anthropogenic activities around the lake.

Table 5. Saprobity index of plankton on each station of Batur Lake, Bali, Indonesia

Category	Class	Genera	Density (average)		
			Seked	Buahan	Trunyan
Polisaprobik	A	<i>Ulnaria, Closterium, Actinotaenium, Cyclotella, Amphipleura</i>	131	70	156
α -Mesosaprobik	B	<i>Bacillaria, Aulacoseira, Tabellaria, Fragilaria, Navicula</i>	197	126	436
β -Mesosaprobik	C	<i>Gymnodinium, Amphora, Gyrosigma, Eudorina, Coelastrum, Stephanodiscus, Melosira</i>	271	100	440
Oligosaprobik	D	<i>Oscillatoria, Euglena, Nostoc, Spirulina, Nitzschia, Stigeoclonium</i>	799	704	3407
Saprobity index			1.5	1.8	2.0

For international readers, it's important to note that the Indonesian saprobity index classification builds upon the Central European saprobic system but has been adapted to regional conditions, including tropical freshwater ecosystems. Polysaprobic taxa (e.g., *Ulnaria*, *Closterium* Nitzsch ex Ralfs, 1848) dominate under high organic loads, α -mesosaprobic taxa (e.g., *Fragilaria*, *Navicula*) indicate moderate enrichment, β -mesosaprobic groups (e.g., *Amphora* Ehrenberg ex Kützing, 1844, *Gyrosigma* Hassall, 1845) reflect slight enrichment, while oligosaprobic taxa (e.g., *Oscillatoria*, *Euglena*) thrive in cleaner waters.

The variation in saprobity index values across the three stations indicates a gradient in water quality closely related to the intensity of organic pollution. Trunyan, with the highest value (2.0), suggests the dominance of polysaprobic and α -mesosaprobic phytoplankton groups, which are generally tolerant of high organic loads (Dahuri 1995). This pattern reflects excessive nutrient inputs, likely associated with domestic waste discharge and intensive floating net cage (KJA) aquaculture, which can accelerate eutrophication and disrupt aquatic ecosystem balance (Paerl and Otten 2016). Buahan, with an index of 1.8, represents an intermediate condition between Seked and Trunyan, indicating increasing pollution pressure but not yet as severe as in Trunyan. In contrast, Seked, with the lowest index (1.5), exhibits a higher proportion of oligosaprobic and β -mesosaprobic taxa, indicative of waters with low to moderate organic loads and a relatively well-preserved environment that is closer to natural conditions (Wetzel 2001; Tekebayeva et al. 2024). Ecologically, the shift in phytoplankton community composition toward the dominance of tolerant taxa in sites with higher saprobity index values highlights the biotic response to nutrient enrichment (Reynolds 2006; Kumar et al. 2023). This finding is consistent with previous studies on volcanic lakes experiencing anthropogenic stress and land-use changes in their catchment areas, where organic load increases lead to marked changes in plankton structure and trophic status (Glibert et al. 2016).

In summary, the study revealed that Trunyan experienced the most severe post-disturbance conditions, with low oxygen, negative ORP, high ammonia, reduced phytoplankton diversity, and increased saprobity index compared to Seked and Buahan. Lake Batur's recovery, therefore, requires reducing nutrient inputs and aligning aquaculture with the lake's carrying capacity. Key actions include stricter regulation of floating net cages, efficient feed use, and adoption of Integrated Multi-Trophic Aquaculture (IMTA) to recycle excess nutrients. Routine plankton-based monitoring

should complement physicochemical measures as an early-warning system. Catchment interventions—reforestation, riparian buffers, and domestic wastewater treatment—are also essential. Recovery is possible given diatom resilience, but long-term sustainability depends on community participation, policy enforcement, and incentives for adaptive practices. These measures directly align with the Sustainable Development Goals, particularly SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and SDG 14 (Life Below Water), by reducing organic loading, strengthening ecosystem resilience, and safeguarding aquatic biodiversity. The fish mortality event was driven by aquaculture pressure and natural upwelling, underscoring the need to limit cage density and manage nutrient loading. Plankton responses confirmed their value as early-warning indicators, highlighting the importance of routine biological monitoring. Reducing nutrient inflows from both aquaculture and the watershed is critical to restoring ecological balance. With adaptive aquaculture and participatory governance, Lake Batur retains strong recovery potential, but failure to act risks recurrent mortality events and long-term biodiversity loss.

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