ILMU KELAUTAN: Indonesian Journal of Marine Sciences *June 2026 Vol 31(2):133-144* *e-ISSN 2406-7598*

Morphometric Features of *Noctiluca scintillans* from Jakarta Bay

Radixa Radhya Ramadhan Haryanto[1,2], Meutia Samira Ismet[2], Adriani Sunuddin[2],
Inna Puspa Ayu[3], Muhammad Izzat Nugraha[4], Alfaiz Arselan[2], Kesha Mufthiy Java Tanaya[2],
Dea Fauzia Lestari[2], Dondy Arafat[2], Nadya Cakasana[2], Beginer Subhan[2]*

[1]Magister Program of Marine Science, Graduate School, IPB University
[2]Department of Marine Science and Technology, Faculty of Fisheries and Marine Science, IPB University
[3]Department of Aquatic Resources Management, Faculty of Fisheries and Marine Science, IPB University
Jl. Raya Dramaga, Kampus IPB Dramaga Bogor, 16680 West Java, Indonesia.
[4]Biological Oceanography Laboratory, Graduate School of Agricultural Science, Tohoku University
468-1 Aramaki Aza Aoba, Aoba-ku, Sendai, Miyagi, 980-8572, Japan
Email: beginersubhan@apps.ipb.ac.id

Abstract

Noctiluca scintillans is a mixotrophic dinoflagellate commonly associated with eutrophic coastal systems and bloom dynamics. This study aims to characterize the morphometric variability of N. scintillans in Jakarta Bay, a tropical coastal environment strongly influenced by anthropogenic nutrient enrichment, and to evaluate how cellular morphology reflects functional and ecological responses under eutrophic conditions. Plankton samples were collected in February 2024 and analyzed using high-resolution microscopy to quantify key morphometric traits, including cell diameter, biovolume, aspect ratio, surface area-to-volume (SA:V) ratio, and nucleus-to-cytoplasm (N:C) ratio. Differences between red (RNS) and green (GNS) morphotypes were assessed using non-parametric statistical analyses, and preserved measurements were corrected to estimate live cell size. A total of 121 cells were analyzed, with RNS overwhelmingly dominating the population. RNS exhibited significantly larger cell diameter and volume than GNS, while SA:V ratios differed significantly between morphotypes, indicating functional differences in size-related morphology. In contrast, aspect ratio did not differ significantly, suggesting overall conservation of cell shape across morphotypes. Estimated live cell sizes indicate that N. scintillans populations in Jakarta Bay are dominated by relatively small cells compared to those reported from temperate regions. Variability in the N:C ratio further suggests heterogeneity in cellular physiological states within the population. Overall, these findings establish a morphometric baseline for N. scintillans in Jakarta Bay and highlight the value of morphometric traits as integrative indicators of physiological variability and environmental forcing in tropical eutrophic coastal systems.

Keywords: *Noctiluca scintillans, Dinoflagellate, Morphometric variability, Functional traits, Jakarta Bay*

Introduction

Noctiluca scintillans is a mixotrophic dinoflagellate that plays a crucial role in marine ecosystems, characterized by distinct morphological features and ecological functions (Gomes *et al*., 2018). It has relatively large, spherical cells with a central vacuole for nutrient storage, and while it possesses flagella for movement, its motility is less pronounced compared to other dinoflagellates (Padmakumar *et al*., 2010; Harrison *et al*., 2011). This organism is a primary predator in the planktonic food web, capable of ingesting various prey, including phytoplankton and bacteria (Piontkovski *et al*., 2021). *N. scintillans* also exhibits bioluminescence, which is thought to act as a defense mechanism against predators in low-light conditions (Chen *et al*., 2023).

N. scintillans had two morphotypes: the red form (RNS) and the green form (GNS), each showcasing different cellular structures, habitats, and nutritional modes. The RNS is widespread in marine environments and functions strictly as a heterotroph, primarily feeding on phytoplankton and bacteria, whereas the GNS engages in a symbiotic relationship with the alga *Pedinomonas noctilucae*, facilitating mixotrophy through both heterotrophic feeding and partial photosynthesis (Parvathi *et al*., 2021; Choi *et al*., 2024). These morphotypes show distinct geographic distributions and adaptations to environmental variations, such as nutrient availability and light intensity (Ollevier *et al*., 2021).

The phenomenon of red tides, marked by significant phytoplankton blooms that can include *N. scintillans*, results in the discoloration of seawater and is mainly triggered by nutrient over-enrichment from human activities, leading to rapid eutrophication (Zhang *et al*., 2017). In tropical coastal waters of Indonesia, eutrophication driven by elevated nutrient inputs has been shown to substantially alter

*) Corresponding author

https://ejournal.undip.ac.id/index.php/ijms
DOI: 10.14710/ik.ijms.31.2.133-144

Received : 13-06-2025
Accepted : 20-02-2026

phytoplankton community composition and structure, with dinoflagellates frequently contributing to bloom events (Munru *et al*., 2024). Such blooms can cause serious ecological issues, including hypoxia and toxin accumulation, which can adversely affect marine life and human health (Wang *et al*., 2018; Dela-Cruz *et al*., 2002). Given its global distribution, *N. scintillans* is a notable contributor to these environmental phenomena.

Jakarta Bay is a key area experiencing *N. scintillans* blooms due to its tropical climate and significant anthropogenic activities that have degraded the coastal ecosystem (Nugraha *et al*., 2020; Damar *et al*., 2021). Damar *et al.* (2012) also stated that Jakarta Bay has the most pronounced eutrophication symptoms compared to other bay such as Lampung Bay and Semangka Bay. With thirteen rivers feeding into the bay, the influx of organic matter with high nitrate levels contributes to eutrophication, setting the stage for algal blooms and oxygen depletion (Kusuma *et al*., 2015; Prayitno and Afdal, 2019). The amount of input flowing from the rivers into the bay varies with the season. These impacts can even be amplified when flooding occurs, especially during the rainy season (Dsikowitzky *et al.,* 2018). In highly disturbed tropical coastal systems such as Jakarta Bay, protist communities have been shown to respond sensitively to local environmental forcing and habitat disturbance gradients, highlighting the ecological context in which bloom-forming taxa such as *N. scintillans* proliferate (Borbee *et al*., 2023).

Within this highly eutrophic and environmentally dynamic setting, *N. scintillans* represents a biologically compelling model for examining how cellular traits respond to local ecological pressures. Recent studies have shown genetic differentiation among red-morphotype populations of *N. scintillans* in Jakarta Bay, which also hosts both morphotypes (Nugraha *et al*., 2025). This dual presence opens avenues for research on the cellular morphology and morphometrics of this dinoflagellate, enhancing our understanding of its biology. This study aims to document the morphometric variability of *N. scintillans* in Jakarta Bay, focusing on cellular modifications and morphology to provide detailed insights into its adaptations in this ecologically significant area.

Materials and Methods

Time and location

This study was conducted to examine the morphology and biological parameters of *N. scintillans* collected from the waters of Marunda Beach, Cilincing District, North Jakarta, Indonesia. Sampling was carried out in February 2024, while laboratory analyses were conducted at the Microbiology Laboratory 1, Department of Aquatic Resources Management, Faculty of Fisheries and Marine Science, IPB University. The sampling locations were selected randomly using the simple random sampling method to ensure the representativity of the obtained data.

Sample collection

Samples were obtained by filtering 20 liters of water using a plankton net with a mesh size of 30 μm; the collected water was measured using a 10-liter capacity bucket. Each filtered sample was transferred into a sample bottle, to which five drops of 36% formalin were added as a preservative. The sampling procedure was conducted four times, with a 10-meter interval between collection points, ensuring that each sample accurately represented the environmental conditions of the study site. Water parameters, including temperature, salinity, and dissolved oxygen (DO), were measured using refractometers, thermometers, and DO meters.

Image acquisition

Image acquisition was performed by integrating a binocular microscope with a digital camera using the AxioVision software, resulting in 121 high-quality images at 10x magnification. Each image was captured to observe key cellular features, including the nucleus, tentacles, oral pouch, and rod organ, following references from Fukuda and Endoh (2006). These images served as the foundation for morphological analysis and morphometric parameter measurements, which were conducted using ImageJ software.

Morphometric analysis

The morphometric analysis process begins with image calibration using the scale bar in AxioVision via the “Straight tools” function to ensure measurement accuracy. The parameters measured include vertical diameter, horizontal diameter, and nuclear diameter. *N. scintillans* cells are assumed to be spherical, allowing the calculation of cell diameter as the average of the vertical and horizontal diameters, as illustrated in Figure 1. Additionally, calculating the nucleus-to-cytoplasm ratio (N:C) follows a series of steps: converting the image to 8-bit grayscale mode to enhance contrast, determining the nuclear area by adjusting the threshold settings, and measuring the nuclear and total cell areas using the Wand Tool. The obtained area data serve as the basis for computing the N:C ratio, which provides insights into the physiological condition of the cells.

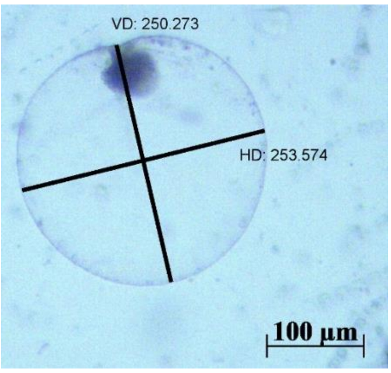

Figure 1. Morphometric measurements of vertical diameter (VD) and horizontal diameter (HD) of *Noctiluca scintillans* cells.

Cell abundance

Cell abundance measurements were conducted using a Sedgewick Rafter Cell, following APHA (2017) standards. The cell count per liter was calculated based on the proportional relationships among the counting strip dimensions, the volume of the concentrated sample, and the dilution factor, as outlined in the following equation:

$$No/ml = \frac{C \times 1000\ mm^3}{L \times D \times W \times S} \text{.............. (1)}$$

$$N = No/ml \times \frac{Vt}{Vd} \times Df \text{............... (2)}$$

Where: N: number of cells per liter (sel.L^{-1}); No/ml: number of cells per millimeter (sel.mL^{-1}); C: number of organisms counted; L: length of each strip (mm); D: depth of a strip (mm); W: width of a strip (mm); S: number of strips counted; Vt: concentrated sample volume (ml); Vd: filtered volume (liter); Df: dilution factor

Aspect ratio

The morphometric aspect, such as aspect ratio (the proportion of horizontal diameter to vertical diameter), was calculated to determine the tendency of cell shape. The aspect ratio value was obtained by dividing the major axis by the minor axis (Sullivan, 2019). The formula used is as follows:

$$Aspect\ Ratio = \frac{Mayor\ axis}{Minor\ axis} \text{ .... (3)}$$

Surface area and volume

The biovolumetric and surface area calculations of *N. scintillans* were conducted with the assumption that the cell shape is spherical. These measurements were derived using geometric formulas, with the volume and surface area calculated as follows:

$$V = \frac{\pi}{6} \times a^3 \text{............. (4)}$$

$$A = \pi \times a^2 \text{ .... (5)}$$

Where: V= Cell volume (µm^3); A= Cell surface area (µm^2); π= 3,14; a = Diameter (µm)

Estimation of live cell volume

Given that formalin fixation is known to cause cell shrinkage by approximately 39.36% (Yang *et al*., 2017), a correction factor was applied to the preserved cell measurements to estimate the original live cell volume. Then, the diameter of the estimated original live cell was calculated using the geometric equation. The estimation was performed using the following formula:

$$V_{live} = \frac{V_{fixed}}{1-S} \text{ .... (6)}$$

$$D_{live} = \left(\frac{V_{live} \times 6}{3{,}14}\right)^{\left(\frac{1}{3}\right)} \text{ .... (7)}$$

Where: V_{live}= estimated live cell volume (µm^3); V_{fixed} = measured preserved cell volume (µm^3); S = shrinkage factor (espressed as a decimal, e.g., 0.3936); and D_{live} = estimated live cell diameter (µm).

Surface Area-to-Volume ratio (SA:V)

The calculated surface area and volume values were then used to determine the surface area-to-volume (SA:V) ratio, which is often regarded as an indicator of a cell's physiological state (Harris and Theriot, 2018). The ratio was obtained using the following formula:

$$SA{:}V = \frac{Surface\ Area}{Volume} \text{ .... (8)}$$

Nucleus-to-Cytoplasm ratio (N:C)

The nuclear and cytoplasmic areas of *N. scintillans* cells were measured to calculate the nucleus-to-cytoplasm ratio. This ratio is often considered a critical indicator of cellular physiological conditions, as the proportion between nuclear and cytoplasmic sizes can reflect metabolic activity levels and cellular adaptations to environmental changes (Balachandra *et al.*, 2022). This ratio was only used for RNS due to the lack of clarity in the image to distinguish the nucleus from GNS, as the cell was filled with endosymbionts. The ratio was determined using the following formula:

$$N:C = \frac{Nucleus\ area}{Cell\ area - Nucleus\ area} \ldots\ldots \quad (9)$$

Kruskal-Wallis test

The Kruskal-Wallis test was used to evaluate significant differences between red Noctiluca (RNS) and green Noctiluca (GNS) based on the measured parameters. This non-parametric test was chosen because the data did not meet the normality assumptions, making a parametric approach unsuitable. The data from both groups were ordered and ranked, and then the sum of the ranks for each group was compared to detect any differences in value distribution. Using a statistical package in R, the analysis was carried out comprehensively to determine whether the median differences between RNS and GNS were statistically significant ($p < 0.05$). The results of this test provided the basis for further interpretation regarding morphological differences or other characteristics between the two types of Noctiluca.

Result and Discussion

Abundance and water parameters

The calculations indicate that the abundance of *N. scintillans* across four replicates reached 475 cells.m^{-3}, 600 cells.m^{-3}, 275 cells.m^{-3}, and 325 cells.m^{-3}. Water quality measurements revealed that the sea surface temperature ranged from 29.5–29.9 °C, salinity was within 33.2–33.6 ppt, dissolved oxygen (DO) concentrations were between 4.7–5.6 mg.L^{-1}, and pH was slightly alkaline, ranging from 7.49–7.56.

Cell morphology

The *N. scintillans* population in Jakarta Bay comprised two morphotypes. The red morphotype (RNS) accounted for 119 observed cells, whereas only two green morphotype (GNS) cells were recorded. As shown in Figure 2, RNS exhibited transparent, balloon-shaped cells with visible flagella and short tentacles, while GNS cells contained the endosymbiont *Pedinomonas noctilucae* and displayed a coarse cell surface.

Cell size

Morphometric measurements presented in Figure 3 show significant differences between the two morphotypes of *N. scintillans*. The red morphotype (RNS) has a diameter ranging from 186.79 – 465.03 µm, with a mean of 307.1 ± 49.79 µm, while the green morphotype (GNS) has a mean diameter of 190.95 ± 8.58 µm. This diameter variation correlates with cell volume; RNS cells range from 3.41×10^{6}–5.16×10^{7} µm^{3}, averaging $1.6 \times 10^{7} \pm 8.1 \times 10^{6}$ µm^{3}, compared to GNS cells' smaller average volume of $3.7 \times 10^{6} \pm 4.9 \times 10^{5}$ µm^{3}.

The Kruskal–Wallis test indicated a significant difference in diameter distribution between morphotypes ($\chi^2 = 5.7545$, df = 1, p = 0.01645).

Estimation of live cell size

The estimated live cell measurements (Figure 3) represent cell dimensions prior to preservation. The red morphotype (RNS) exhibited estimated live cell diameters ranging from 220.25–544.79 µm, with a mean of at 362.1 ± 58.7 µm, whereas the green morphotype (GNS) showed a mean diameter of 225.15 µm. Correspondingly, estimated live cell volumes of RNS ranged from 5.59×10^{6}–8.42×10^{7} µm^{3}, with a mean of $2.7 \times 10^{7} \pm 1.3 \times 10^{7}$ µm while GNS cells had a smaller mean volume of $6.0 \times 10^{6} \pm 8.1 \times 10^{5}$ µm^{3}.

Aspect ratio

Morphometric measurements of *N. scintillans* cells were based on vertical and horizontal diameters. Vertical diameters ranged from 179.48–456.98 µm, while horizontal diameters ranged from 185.44–467.09 µm, resulting in aspect ratios of approximately 1.0–1.1, indicating that most cells are symmetrical or nearly spherical. A small number of specimens exhibited aspect ratios exceeding 1.3, indicating horizontal elongation. The Kruskal–Wallis test showed no significant difference in aspect ratio distribution between morphotypes ($\chi^2 = 2.1424$, df = 1, p = 0.1433).

Surface Area-to-Volume ratio (SA:V)

Surface area-to-volume ratios differed between morphotypes of *N. scintillans*. RNS exhibited SA:V values ranging from 0.013 to 0.032, whereas GNS showed values ranging from 0.03 to 0.032, as shown in Figure 4. The Kruskal–Wallis test indicated a statistically significant difference in SA:V ratios between morphotypes ($\chi^2 = 5.7545$, df = 1, p = 0.01645).

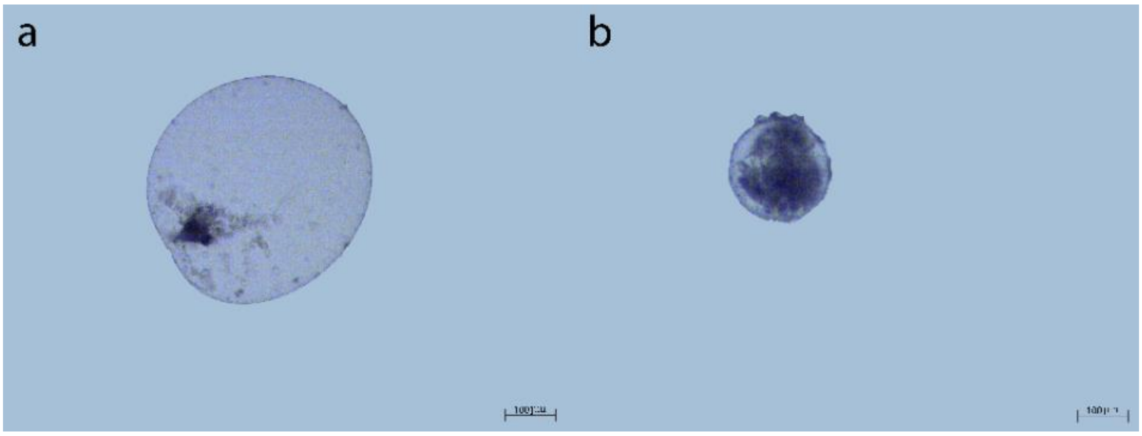

Figure 2. Cells of *Noctiluca scintillans*: a) Red *N. scintillans* (RNS) and b) Green *N. scintillans* (GNS).

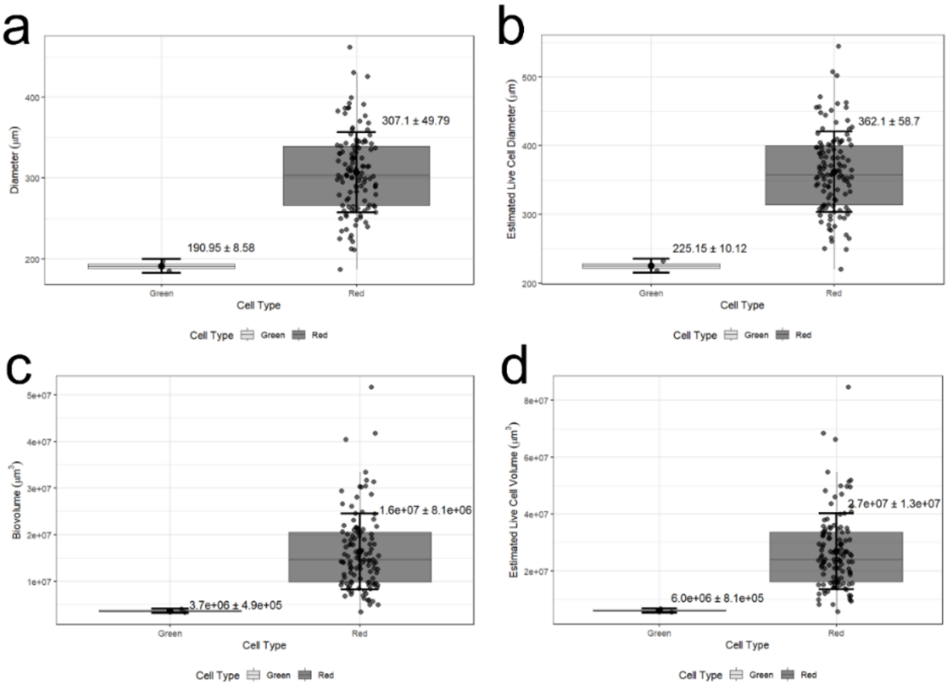

Figure 3. Boxplot of morphometric measurements and calculations of *Noctiluca scintillans*: a) cell diameter, b) estimated live cell diameter, c) cell volume, and d) estimated live cell volume.

Nucleus-to-Cytoplasm ratio (N:C)

The nucleus-to-cytoplasm (N:C) ratio was quantified for the red morphotype (N. scintillans RNS) from Jakarta Bay only, due to the limited visibility of the nucleus in green morphotype cells. As shown in Figure 4, the N:C ratio of RNS cells exhibited moderate variability, ranging from 0.0037 to 0.1553, with a mean value of 0.04 ± 0.02. Most observations were clustered around intermediate values, indicating a relatively consistent proportional relationship between nuclear and cytoplasmic areas across the sampled population. This distribution suggests heterogeneity in cellular composition among RNS cells in Jakarta Bay, while maintaining an overall stable nuclear-to-cytoplasmic proportion within the population.

While the morphometric analyses reveal clear variability in cell size, shape, surface area-to-volume ratios, and nucleus-to-cytoplasm proportions of *N. scintillans* in Jakarta Bay, the biological and ecological significance of these patterns requires further interpretation. In tropical eutrophic systems such as Jakarta Bay, cellular morphology is shaped not only by taxonomic identity but also by environmental forcing, resource availability, and metabolic constraints. The following discussion therefore interprets the observed morphometric traits within a broader functional and ecological framework.

The morphometric characteristics of *N. scintillans* observed in Jakarta Bay reveal consistent size- and shape-related patterns that reflect functional responses to a tropical eutrophic environment rather than random phenotypic variability. Recent studies increasingly emphasize that phytoplankton cell morphology represents an integrative response to environmental forcing, particularly under nutrient-rich and thermally stable conditions where metabolic constraints strongly influence cell size and geometry (Orizar and Lewandowska, 2025). The dominance of relatively small cell sizes across morphotypes, together with significant differences in cell diameter and surface area-to-volume (SA:V) ratios, suggests that morphological traits in *N. scintillans* are tightly regulated by environmental drivers acting on cellular metabolism and resource exchange efficiency.

Consistent with this trait-based interpretation, both red (RNS) and green (GNS) morphotypes observed in this study fall within the “small cell” category as defined by Dela-Cruz *et al*. (2003), with mean diameters well below the 525 µm threshold. Smaller cell sizes in *N. scintillans* have been associated with physiologically active populations and favorable nutritional conditions, whereas larger cells tend to occur during senescent or deteriorating phases (Murray and Suthers, 1999; Dela-Cruz *et al*., 2003). In Jakarta Bay, a coastal system characterized by high nutrient loading and eutrophic conditions, the prevalence of small cells may indicate a population with elevated metabolic activity and capacity for rapid community-level responses. Such dominance of small size classes under nutrient-rich and dynamic environmental conditions has been linked to shifts in phytoplankton community structure, where cell size emerges as a key trait mediating responses to changes in resource availability and light regimes (Guislain *et al*., 2025). Furthermore, long-term observations have shown that warming and stratification can favor smaller phytoplankton size classes, underscoring the coupling between size structure and rapid ecological responses in nutrient-enriched systems (Jang *et al*., 2025).

Temperature likely plays a key role in shaping the observed morphometric patterns of *N. scintillans*. According to the temperature–size rule, elevated environmental temperatures favor smaller phytoplankton cell sizes due to increased metabolic rates and limitations in oxygen diffusion (Marañón *et al*., 2012). Sea surface temperatures in Jakarta Bay

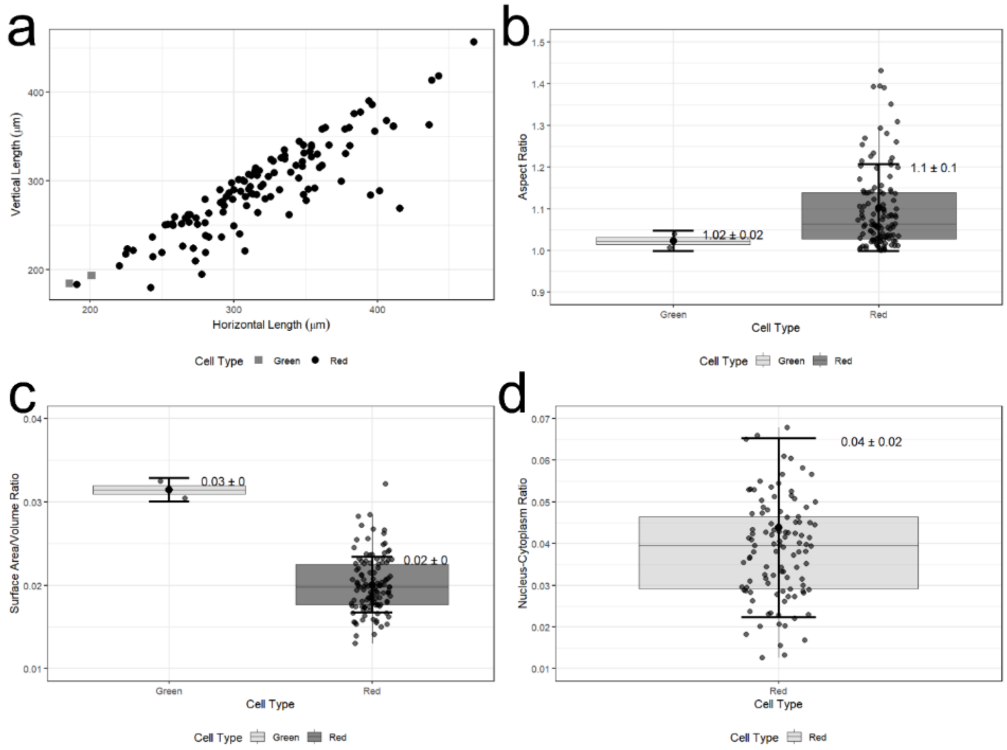

Figure 4. Measurement and calculation results of *Noctiluca scintillans*: a) vertical and horizontal diameter, b) cell aspect ratio, c) cell SA:V ratio, and d) cell N:C ratio.

during the sampling period exceeded 29 °C, conditions under which reduced cell size may enhance metabolic efficiency and mitigate respiratory stress. Regional comparisons summarized in Table 1 further support this interpretation, as *N. scintillans* populations from tropical and subtropical waters consistently exhibit smaller cell sizes than those from temperate regions, such as the North Sea, where diameters may exceed 1,000 µm (Ollevier *et al*., 2021). Similar size patterns have been reported from other low-latitude systems including Jakarta Bay (Dela-Cruz *et al*., 2003; Miyaguchi *et al*., 2006; Nugraha *et al*., 2025), reinforcing the strong influence of thermal regime on *N. scintillans* morphology under contrasting climatic conditions, in line with evidence showing temperature as a critical driver of phytoplankton growth and distribution (Ji *et al.,* 2025).

Beyond temperature-driven effects on cell size, seasonal variation in light availability and hydrographic conditions also appears to influence population structure in Jakarta Bay. A pronounced asymmetry in morphotype abundance was observed, with RNS overwhelmingly dominating the population and only two GNS cells recorded. This imbalance is unlikely to be incidental and may reflect seasonal environmental conditions prevailing during the rainy period, when increased freshwater input and altered hydrographic conditions typically influence nutrient dynamics and turbidity in tropical coastal systems (Wirasatriya *et al.,* 2021). GNS relies on the photosynthetic activity of its endosymbiont *Pedinomonas noctilucae*, rendering it particularly sensitive to light availability. Reduced solar radiation and increased turbidity have been shown to suppress photosynthetic performance in symbiotic dinoflagellates under low-light environments (Matthews *et al*., 2023), suggesting similar sensitivities in GNS. Although consistent size differences between morphotypes were detected, the extremely limited number of GNS cells restricts the statistical robustness of morphotype comparisons, and interpretations involving GNS should therefore be considered preliminary. Multi-seasonal sampling will be required to assess whether shifts in RNS–GNS dominance correspond predictably to changes in light regime and water column stability.

In contrast to the pronounced variability observed in cell size and morphotype composition, aspect ratio analysis indicated that most *N. scintillans* cells exhibited near-spherical shapes, with no statistically significant differences between morphotypes. This finding suggests that overall cell shape is relatively conserved, even when substantial variation in cell size is present, consistent with trait-based studies showing that phytoplankton cell shape tends to be less plastic than size due to functional constraints (Orizar and Lewandowska, 2025). Occasional horizontal elongation observed in some specimens may therefore reflect transient physiological states or developmental stages rather than stable morphological divergence. In planktonic protists, conservation of cell shape has been linked to hydrodynamic constraints and trade-offs that influence swimming efficiency, encounter rates, and overall ecological performance, while allowing size-related traits to respond more flexibly to environmental pressures (Ryabov *et al*., 2021).

Unlike the largely conserved aspect ratio, SA:V ratios differed significantly between morphotypes (Figure 4), highlighting the functional importance of

Tabel 1. Reported cell size ranges of *N. scintillans* from tropical, subtropical, and temperate regions based on previous studies

Authors	Location	Climate	Cell Type	Size (µm)
This study	Jakarta Bay, Indonesia	Tropical	RNS	186-465
Nugraha *et al.* (2025)	Jakarta Bay, Indonesia	Tropical	RNS	95-338
Padmakumar *et al.* (2010)	Southwest coast of India	Tropical	RNS	500-1000
Zhang *et al.* (2017)	Hong Kong	Subtropical	RNS	372
Wang *et al.* (2018)	Jiaozhou Bay, China	Subtropical	RNS	333-541
Nakamura (1998)	Seto Inland Sea, Japan	Temperate	RNS	380-660
Ara *et al.* (2013)	Sagami Bay, Japan	Temperate	RNS	300-800
Nugraha *et al.* (2025)	Miyagi, Japan	Temperate	RNS	203-580
Nugraha *et al.* (2025)	Mie, Japan	Temperate	RNS	250-671
Mikaelyan *et al.* (2014)	Black Sea	Temperate	RNS	514-536
Ollevier *et al.* (2021)	North Sea, Belgium	Temperate	RNS	261-1121
Mikaelyan *et al.* (2014)	Adriatic Sea	Temperate	RNS	468-507
This study	Jakarta Bay, Indonesia	Tropical	GNS	184-197
Nugraha *et al.* (2025)	Jakarta Bay, Indonesia	Tropical	GNS	114-233
Parvathi *et al.* (2021)	Kochi, India	Tropical	GNS	400-800

size-related morphology. Higher SA:V ratios, typically associated with smaller cells, enhance diffusive exchange across the cell membrane and facilitate nutrient uptake, gas exchange, and waste removal (Menden-Deuer and Lessard, 2000; Shetty, 2007). Beyond diffusion efficiency, recent experimental evidence indicates that changes in SA:V also represent an adaptive response to environmental stressors such as salinity fluctuations, promoting buoyancy control and physiological stability in phytoplankton (Orizar and Lewandowska, 2025).

Despite the limited number of GNS observations, the elevated SA:V values observed in GNS may therefore reflect a metabolic configuration that supports efficient resource acquisition under conditions of fluctuating oxygen availability, freshwater input, and osmotic stress. Phytoplankton exposed to variable salinity, nutrient, and light conditions exhibit shifts in stoichiometry and physiological allocation patterns, indicative of adaptive responses to resource limitation and environmental change (Orizar *et al*., 2024). In coastal and estuarine eutrophic systems such as Jakarta Bay, enhanced microbial respiration and organic matter degradation frequently lead to reduced dissolved oxygen concentrations, particularly under high nutrient loading (Krishna *et al.,* 2025). Eutrophic conditions and subsequent bloom decomposition have been linked to significant reductions in dissolved oxygen in coastal waters (Heisler *et al.,* 2008), and small phytoplankton cells with high surface area-to-volume ratios often exhibit enhanced nutrient uptake and competitive advantage under variable environmental conditions (Mai *et al.,* 2022). Nutrient imbalance and fluctuating resource conditions have been shown to shape phytoplankton community structure and functional trait expression, further supporting the link between environmental stress and morphological strategies (Li *et al*., 2026).

Beyond surface-mediated responses such as SA:V adjustments, environmental forcing in eutrophic coastal systems is also reflected in the internal physiological organization of cells. The nucleus-to-cytoplasm (N:C) ratio is widely recognized as an indicator of cellular physiological status, reflecting the proportional allocation between nuclear and cytoplasmic compartments and shifts in metabolic activity under changing functional demands (Davydova *et al*., 2017). The broad range of N:C values observed in the red morphotype indicates heterogeneity in cellular condition within the population of *N. scintillans* in Jakarta Bay, likely reflecting asynchronous growth stages or differences in metabolic allocation among individual cells. Elevated N:C ratios in a subset of cells may be associated with increased nuclear activity related to transcriptional processes as a response to environmental stress or as preparation for cell division, consistent with documented nuclear reorganization during growth and gametogenic stages in *N. scintillans* (Fukuda and Endoh, 2006). Importantly, when considered together with the observed patterns in cell size and surface area-to-volume ratios, the pronounced N:C variability suggests that the population does not represent a uniform physiological state, but rather encompasses a spectrum of cellular conditions that may reflect underlying ecological or population-level structuring. Similar integrative links between cellular biophysical properties, physiological allocation, and environmental forcing have been demonstrated across diverse phytoplankton taxa, indicating that variation in cell size, geometry, and internal composition often reflects coordinated metabolic states rather than passive morphological variability (Wu *et al*., 2025).

When viewed beyond individual cells, the morphometric patterns documented in this study provide a coherent link between cellular-scale physiological variability and broader population differentiation. These patterns align with recent genetic evidence indicating differentiation between RNS and GNS in Jakarta Bay (Nugraha *et al*., 2025). Although the present study does not directly assess genotype–phenotype relationships, the consistent differences in cell size and surface area-to-volume ratios establish a morphological framework that complements existing molecular findings. This interpretation is further supported by trait-based studies demonstrating strong links between cell geometry, ecophysiological performance, and selective pressures in phytoplankton communities (Ryabov *et al*., 2021). Integrating morphometric, physiological, and genetic approaches in future work would therefore enable a more comprehensive assessment of population-level differentiation and adaptive responses in *N. scintillans* inhabiting highly dynamic coastal systems.

Taken together, these population-level morphometric patterns have important implications for coastal ecosystem monitoring from an applied perspective. Cell size structure, SA:V ratio, and morphotype composition respond sensitively to environmental conditions and reflect underlying environmental and physiological constraints, consistent with trait-based and morphospecies approaches widely applied in phytoplankton ecology (Weithoff and Beisner, 2019). Body size–related traits have been shown to track trophic state and other environmental gradients, supporting their use as indicators of eutrophication and ecosystem stress in coastal waters. Given the logistical constraints of routine monitoring, microscopy-based morphometric analyses may provide complementary biological context to physical and chemical measurements, particularly by capturing integrative cellular responses to environmental variability. Nevertheless, the single-time sampling design of this study limits inference regarding temporal variability, emphasizing the need for long-term, multi-seasonal observations to distinguish persistent adaptive patterns from short-term phenotypic responses.

Conclusion

This study demonstrates that morphometric traits of *N. scintillans* in Jakarta Bay capture integrative cellular responses to tropical eutrophic coastal conditions, reflecting the combined influence of environmental forcing and physiological regulation. Populations were dominated by small-sized cells with surface area-to-volume (SA:V) characteristics consistent with efficient metabolic exchange and adaptive performance under nutrient-rich conditions. Variability in the nucleus-to-cytoplasm (N:C) ratio further indicates heterogeneity in cellular physiological states within the population, while differences in cell size and SA:V between red and green morphotypes suggest sensitivity of cellular morphology to local environmental variability, although interpretations involving the green morphotype remain preliminary due to limited observations. Collectively, these findings establish a morphometric baseline for *N. scintillans* in Jakarta Bay and provide a robust foundation for future studies integrating morphological, physiological, and genetic approaches to better resolve population-level differentiation and ecological responses in tropical coastal systems.

Acknowledgement

The authors would like to express sincere gratitude to the Microbiology 2 Laboratory and Marine Biomaterial and Bioprospecting Laboratory, Faculty of Fisheries and Marine Science IPB University staff and instructors for their invaluable support and guidance throughout the course of this research. The authors also appreciate the technical assistance provided by the laboratory team, whose expertise greatly contributed to the success of this study.

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