

Spatial distribution and toxic potential of *Alexandrium* spp. associated with paralytic shellfish poisoning (PSP) on the west coast of South Sulawesi

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Abstract. Paralytic shellfish poisoning (PSP) is a type of seafood poisoning that endangers human health. PSP toxins are produced by microscopic plankton of the genus *Alexandrium*. This study aimed to analyse the spatial distribution and abundance of *Alexandrium* sp. with emphasis on the profile and potential toxins produced on the west coast of South Sulawesi Province. Sampling was carried out at 8 stations. The results showed that *Alexandrium* sp. was found at all observation stations with abundance ranging from 500 to 4,200 cells L⁻¹. The concentration of PSP toxicity in seawater samples ranged from 0.8 to 2.5 µg STX eq L⁻¹. In conclusion, the west coast of South Sulawesi has a high potential for PSP poisoning cases in the community. Regular monitoring efforts, provision of educational information, and control of shellfish consumption are needed to minimise the risk of poisoning.

Keywords: abundance, *Alexandrium* sp., human health, microscopic, paralytic shellfish poisoning, spatial distribution.

Introduction. Paralytic shellfish poisoning (PSP) is caused by a group of neurotoxic alkaloids that accumulate in the bodies of shellfish and fish, posing a threat to human health (Hess, 2010; Bazzoni et al., 2020; Bresnan et al., 2021). These toxins consist of more than 50 analogues, including saxitoxin (STX), characterised by the trialkyl tetrahydropurin skeleton. Microscopic plankton from the genus *Alexandrium* sp. secrete the poison (Li et al., 2024). The widespread toxin is found in various coastal waters of the world, such as the northeastern United States, the northeastern coast of the Malaysian Peninsula, the southeastern coastal sea of Hiroshima, Japan, the southeast coast of Korea, the Gulf of Brest, France, and the Patagonian fjord in Chile, Chile. This marine biotoxin is often studied due to its high prevalence and risk in food webs (Leal & Cristiano, 2022; Li et al., 2024).

The resulting toxins accumulate on the feeder filter organism and then are transferred through the food web to higher trophic levels (Bresnan et al., 2021). Consumption of seafood contaminated with PSP can cause symptoms ranging from tingling, numbness, nausea, vomiting, and diarrhea to paralysis and death, making it a serious problem worldwide in the ecological and economic fields (Lim et al., 2006; Hess, 2010; Bresnan et al., 2021).

Cases of poisoning by PSP have been widely reported, such as food poisoning due to STX accumulated in geoducks detected through the urine of patients in Japan

(Watanabe et al., 2024). Incidence of toxicity in the natural environment was reported through ecophysiological studies of *A. tamarense* (Chen et al., 2024). Cases of harmful algae in Atlantic Europe from 1987 to 2018 were reported based on diversity as well as spatial and temporal distribution (Bresnan et al., 2021).

Harmful algae are caused by Diarrhetic Shellfish Toxins (DSTs), which have been reported in a vast geographical area from southern Spain to northern Scotland and Iceland, leading to the closure of many shellfish harvesting areas (Bresnan et al., 2021). A study on the relationship between PSP abundance and environmental variables found that the decline in water quality affected the dynamics of micro-phytoplankton communities in a lagoon, facilitating the growth of harmful algae blooms (HABs) (Law et al., 2023).

Studies on the composition of the phytoplankton community of *Alexandrium* sp. have been widely investigated, such as the relationship with different nutrient conditions (Pichardo-Velarde et al., 2024), biogeochemical conditions (Lee et al., 2024), the effect of light and temperature (Lim et al., 2006), and ecophysiological conditions (Chen et al., 2024). However, episodic sampling has not yet provided a broader understanding of the distribution of *Alexandrium minutum* spatially at some of the related locations in terms of environmental variables. Insights into the dynamics of phytoplankton communities and environmental drivers are essential to understanding this species (Law et al., 2023).

However, the study on the spatial distribution and abundance of *Alexandrium* sp. plankton in several aquatic locations in Indonesia has not been fully presented. Therefore, this study aimed to analyse the spatial distribution and abundance of plankton *Alexandrium* sp. as well as to examine the profile and potential of PSP toxins produced on the west coast of South Sulawesi, Indonesia. The results of this research provide important insights into the distribution patterns and concentrations of PSP toxins in the region during the transition season.

Material and Method

Description of the study locations. This research was conducted during May-June 2024 on the west coast of South Sulawesi, Indonesia (Figure 1). Sampling was carried out at the beginning of the transition season (May-June), at eight stations, namely; 1) Pangkajene, Watang Sawitto District, west coast of Pinrang Regency, 2) Pare-Pare Bay Ujung Labuh, Pare-Pare District, 3) Sumpang Binangae Village, waters of Barru Regency, South Sulawesi, 4) Mattiro Uleng Village beach, Pangkep Regency, South Sulawesi, 5) Bonto Bahari Village, Maros Regency, South Sulawesi, 6) Losari Beach, Ujung Pandang District, Makassar City, South Sulawesi, 7) Tamasajaju Village, Takalar Regency, South Sulawesi, and 8) Tarowang Beach, Tarowang District, Jeneponto Regency, South Sulawesi.

Sampling. Seawater sampling was carried out twice at each station. Sampling was carried out during the transition season, namely, from the rainy season to the dry season. According to climate data from the Indonesian Meteorology, Climatology, and Geophysics Agency (BMKG), the west coast of South Sulawesi, around the research site, generally experiences a transition period from May to June. Sampling was carried out using Niskin bottles at a depth of 0.5 m from the surface. The samples that have been taken were then stored in a cold box at 4°C and then analysed in the laboratory.

Analysis of plankton *Alexandrium* sp. Analysis of *Alexandrium* sp. plankton was carried out using microscopic methods. Seawater samples were filtered using a 20 µm plankton net and then observed under a microscope with a magnification of 400x. Cell identification and counting were carried out with reference to the plankton identification book (Steidinger & Jangen, 1997). The number of cells was calculated in several predetermined fields of view. The average number of cells per field of view was then used to calculate abundance per litre of water expressed in units of cells per litre (cells L⁻¹).

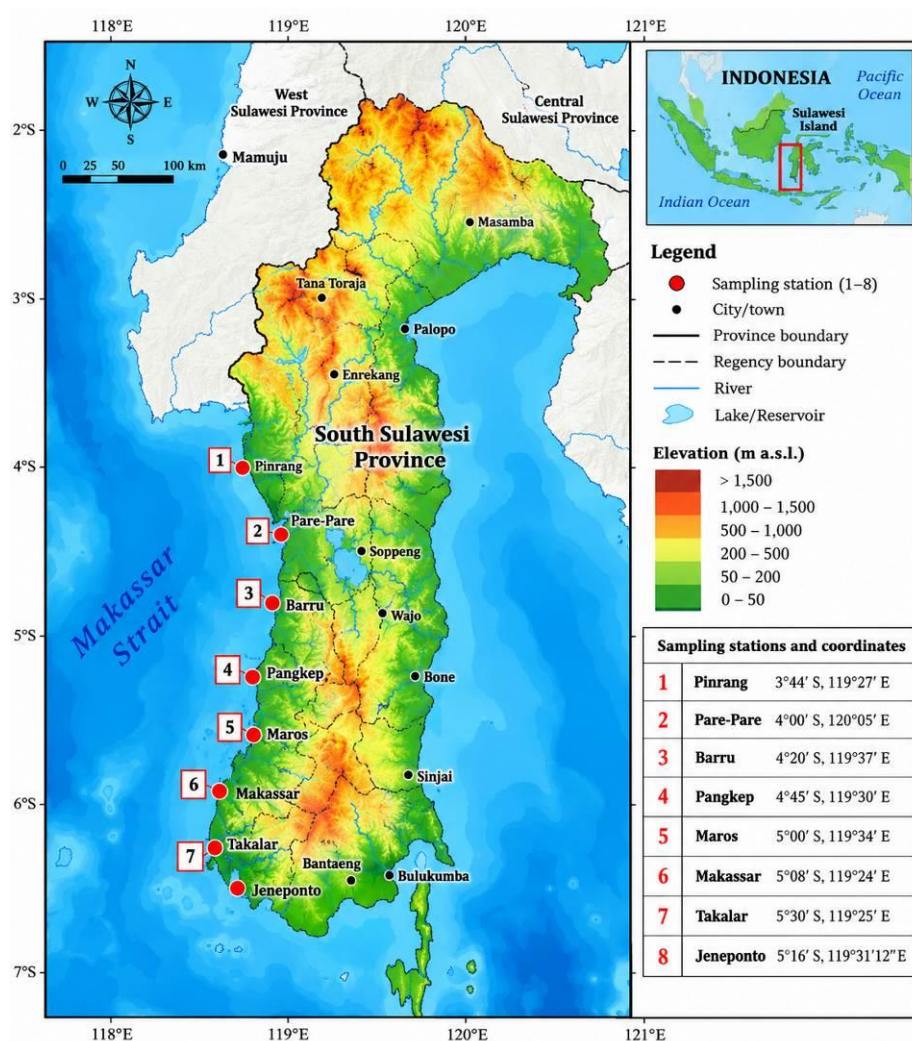


Figure 1. Map and geographic coordinates of sampling stations along the west coast of South Sulawesi, Indonesia. The eight sampling stations were located in Pinrang (Station 1), Pare-Pare (Station 2), Barru (Station 3), Pangkep (Station 4), Maros (Station 5), Makassar (Station 6), Takalar (Station 7), and Jeneponto (Station 8). These stations represent coastal areas along the west coast of South Sulawesi, providing a spatial framework for investigating environmental conditions and their variability across the study area.

PSP poison analysis. The concentration of PSP toxins in seawater samples was analysed using the high-performance liquid chromatography (HPLC) method (Steidinger & Jangen, 1997). PSP toxins in seawater samples were extracted using 0.1 M acetic acid. The results of the analysis were expressed in units μg Saxitoxin Equivalent (STX eq) L^{-1} .

Statistical analysis. Data on the abundance of *Alexandrium* sp. and the concentrations of paralytic shellfish poisoning (PSP) toxins were analyzed descriptively to characterize their distribution and variation among sampling stations. Pearson's correlation analysis was used to evaluate the relationship between *Alexandrium* sp. abundance and PSP toxin concentrations, while one-way analysis of variance (ANOVA) was performed to determine differences in *Alexandrium* sp. abundance among sampling stations. All statistical analyses were conducted using SPSS version 20, with statistical significance set at $p \leq 0.05$.

Results and Discussion. The distribution and abundance of *Alexandrium* sp. plankton are shown in Table 1 and Figure 2. Plankton was found at all 8 sampling stations, with abundance varying in each.

Table 1

Category of *Alexandrium* sp. (cells L⁻¹) abundance and the triggering factors at each sampling station on the west coast of South Sulawesi

No.	Location/station	Range of abundance (cells L ⁻¹)	Categories of abundance	Triggering factors
1.	Coast of Pangkajene Village, Watang Sawitto District, on the west coast of Pinrang Regency	500-2500	Low Medium	Nutrient, temperature, and environmental conditions (Manaff et al., 2023)
2.	Coastal waters of Pare-Pare Bay, Ujung Labuh Village, Ujung District of Pare-Pare City	800-2800	Low Medium	Nutrient, salinity, and environmental conditions (Brading et al., 2011)
3.	Coastal waters of Sumpang Binangae Village, Barru Regency	1350-4000	Medium High	Nutrient, salinity, temperature, anthropogenic (Kremp et al., 2019)
4.	Coastal waters of Mattiro Sompe Village, Pangkep Regency	1500-4200	Medium High	Nutrient, salinity, and environmental conditions (Laabir et al., 2013)
5.	Coastal waters of Bonto Bahari Village, waters of Maros Regency	800-2500	Low Medium	Nutrient and environmental conditions (Law et al., 2023)
6.	Coastal waters of Losari Village, Ujung Pandang District, Makassar City	1000-3500	Low High	Nutrient, salinity, and anthropogenic (Sari & Rukminasari, 2022)
7.	Coastal waters of Tamasaju Village, waters of Takalar Regency	1300-3300	Medium High	Nutrient, salinity, and environmental conditions (Salgado et al., 2015)
8.	Coastal waters of Tarowang Village, Tarowang District, Jeneponto Regency	800-2300	Low Medium	Nutrient and environmental conditions (Shimada et al., 2010)

Note: For the purposes of this study, plankton abundance was classified as low (< 1,000 cells L⁻¹), moderate (1,000–2,500 cells L⁻¹), and high (> 3,000 cells L⁻¹). These thresholds were adopted as operational criteria for this study and should not be interpreted as universally applicable abundance categories (Wu et al., 2010; Joo et al., 2012).

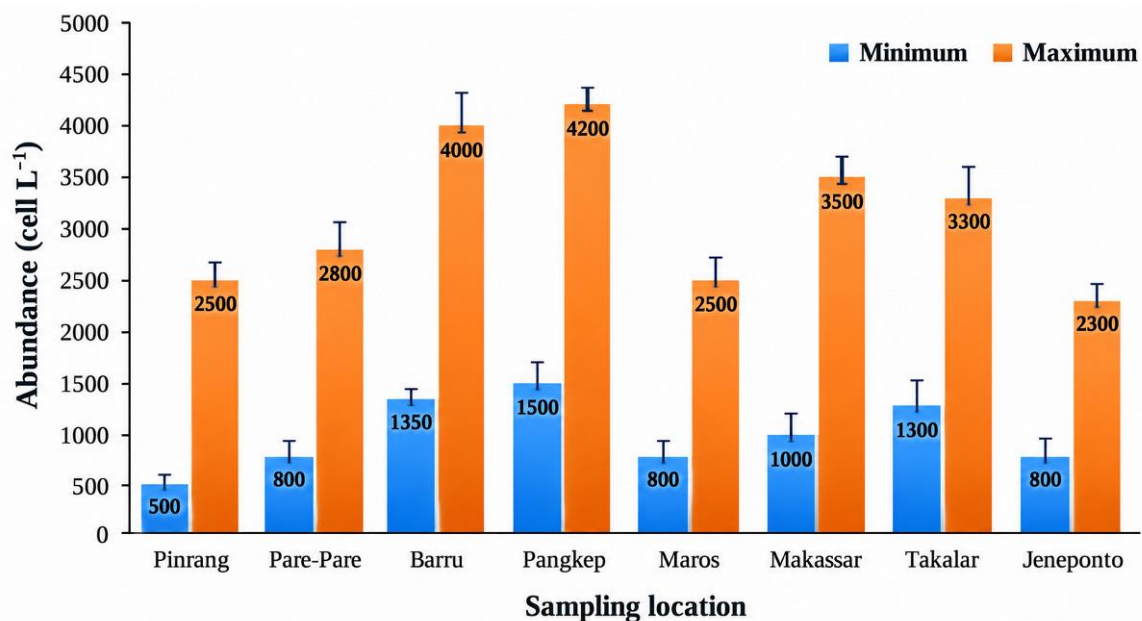


Figure 2. Daily abundance of *Alexandrium* sp. at sampling stations on the west of South Sulawesi.

Distribution patterns and abundance of *Alexandrium* sp. As shown in Figure 2, the minimum abundances at Pinrang, Pare-Pare, Barru, Pangkep, Maros, Makassar, Takalar, and Jeneponto, were, respectively, 500, 800, 1350, 1500, 800, 1000, 1300, and 800 cells L⁻¹, while the maximum values were, respectively, 2500, 2800, 4000, 4200, 2500, 3500, 3300, and 2300 cells L⁻¹. *Alexandrium* sp. can produce PSTs, including saxitoxin (STX) and some derivatives. This group of toxins poses significant risks, causing neurotoxic syndromes (Castrec et al., 2018).

The highest abundance was found at Pangkep, Barru, Makassar, and Takalar, with values ranging from 3300-4200 cells L⁻¹, while, the other locations were in the medium category, namely Pare-Pare, Pinrang, Maros, and Jeneponto, with abundance of 2300-2800 cells L⁻¹. Blooming events of *Alexandrium* sp. are often reported to occur in various parts of the world, including America, Japan, France, Korea, Chile (Lee et al., 2024). Kim et al. (2002) examined the coastal waters of Korea and found that the population of *A. tamarensis* experienced a significant increase between March and May.

The proliferation of *Alexandrium* sp. in the marine environment adjacent to the western coastline of South Sulawesi is influenced mainly by nutrient concentrations, eutrophication processes, various water quality metrics, and human-induced activities. Collectively, these determinants establish an environment conducive to the proliferation and reproduction of these harmful dinoflagellates (Lestari et al., 2021; Khokhar et al., 2022; Sari & Rukminasari, 2022).

The presence and amount of *Alexandrium* sp. in waters tend to fluctuate due to a variety of factors, including meteorological and oceanographic conditions related to stratification, salinity, and temperature differences in coastal waters (Condie et al., 2019). The availability and distribution category varied in each study location.

The triggering factors contributing to the growth and abundance differ from one location to another, as shown in Table 1, including nutrients, salinity, temperature, anthropogenic factors, and environmental conditions (Bill et al., 2016). In general, water temperature plays an important role in the process of cyst germination and vegetative cell growth (Kim et al., 2002).

Study locations with anthropogenic influences could be a trigger for the abundance of *Alexandrium* sp. Previous studies reported the effect of increased nutrition from waste (Baek et al., 2020; Pichardo-Velarde et al., 2024).

Anthropogenic activities (human, industrial and household activities) can also trigger the abundance of *Alexandrium* sp., as previously reported (Baek et al., 2020; Pichardo-Velarde et al., 2024), which may be related to increased nutrition from waste (Lestari et al., 2021).

The increase in microalgae density has an impact on the environment. When the density of microscopic algae cells is very high, non-toxic algae can become harmful to ecosystems and aquatic animals, reducing dissolved oxygen levels and damaging fish gills (Tan et al., 2023).

Various factors contribute to the phenomenon of increasing toxic algae, including local hydrological events, global changes that affect species selection based on temperature preference, N:P ratios related to eutrophication, accidental displacement of marine species, trophic level, and the rise of toxin-producing strains due to genetic modifications in previously harmless strains (Castrec et al., 2018; Felpeto et al., 2024; Möller et al., 2024). These factors often interact in a complex and varied manner across different geographic regions. The impact of HABs phenomenon is expected to increase in line with the rising use of coastal waters for aquaculture and shellfish farming globally (Castrec et al., 2018).

The content of saxitoxin in the plankton *Alexandrium* sp. The content of saxitoxin varied between stations, with the highest value found on the Pangkep shore with a content of 1.37 µg L⁻¹, followed by Barru coast with a value of 1.3 µg L⁻¹, Makassar with 1.05 µg L⁻¹, and Takalar with 0.92 µg L⁻¹. (Figure 3). This indicates that these stations have a high potential risk of poisoning.

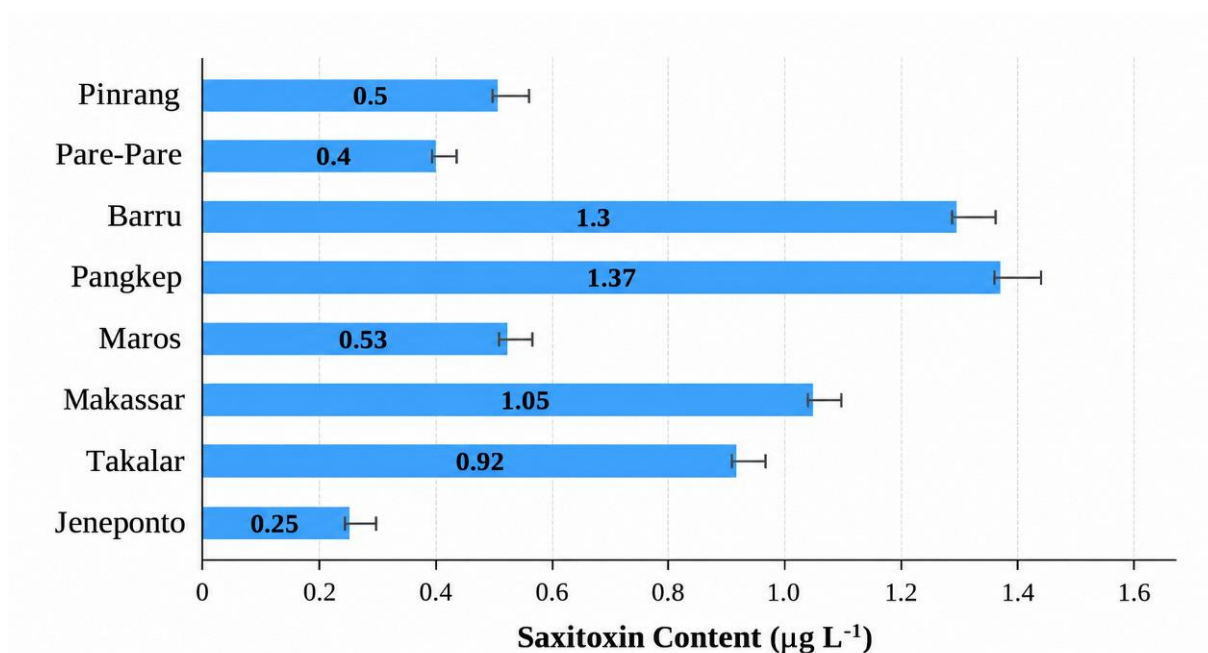


Figure 3. Saxitoxin content in each study location on the west coast of South Sulawesi.

The stations with lower saxitoxin content include Pinrang, Pare-Pare, Maros, and Jeneponto coastal stations, with respective values of 0.5 µg L⁻¹, 0.4 µg L⁻¹, 0.53 µg L⁻¹, and 0.25 µg L⁻¹ (Figure 3). Sampling stations with lower abundance show lower toxic potential.

Stations that had medium to high saxitoxin content include Makassar, Barru, and Pangkep, with values ranging from 1.05 to 1.37 µg L⁻¹. Levels above 1 µg L⁻¹ increase the risk of poisoning symptoms. Three stations had saxitoxin content levels exceeding the safe limit, which indicates a significant risk. Consuming seafood from these locations can lead to symptoms of paralytic poisoning, such as difficulty in breathing, paralysis, or even death when not handled properly (Lawrence et al., 2005). At the Takalar station, the content of saxitoxin was 0.92 µg L⁻¹, included in the intermediate category. This content is close to the threshold that can be a health risk. At Jeneponto, Pare-Pare, Pinrang, and Maros stations, values ranged from 0.25 to 0.53 µg L⁻¹. These values are relatively low but still pose a potential risk with long-term accumulation of toxins, which may be affected by various factors including temperature, salinity, light and nutrients (Laabir et al., 2013; Caruana et al., 2020).

Based on the results, some stations, specifically Pangkep and Barru, had significant toxic potential from saxitoxin, which could harm human health and marine ecosystems. Saxitoxin concentrations above 0.8 µg L⁻¹ are considered risky for human health (Besbes et al., 2024; Zou et al., 2024).

The higher saxitoxin content in Pangkep and Barru may be influenced by environmental factors such as water temperature, salinity, and nutrient availability (Laabir et al., 2013). Water quality parameters that support the growth of *Alexandrium* sp., such as optimal salinity and high nitrogen concentrations, may explain the high production of toxins (Castrec et al., 2018).

Water quality parameters. The physical and chemical parameters of water, nutrients, temperature, salinity, environmental conditions, transparency, and the presence of pollutants, can affect the growth of aquatic organisms. Waters rich in organic matter and low in oxygen support plankton blooming, playing an important role in triggering the abundance of *Alexandrium* sp. (Lim et al., 2006). Water quality parameters at sampling stations are listed in Table 2.

Table 2

Water quality parameters at *Alexandrium* sp. sampling station on the west coast of South Sulawesi

Sampling station	Temp. (°C)	Salinity (ppt)	pH	Dissolved oxygen (mg L ⁻¹)	Turbidity (NTU)	Nitrogen concentration (µg L ⁻¹)	Phosphorus concentration (µg L ⁻¹)
Pinrang	26	28	7.8	6.5	5.2	150	10
Pare-Pare	24	28	7.9	7.0	4.0	120	8
Barru	27	29	7.9	7.0	3.7	200	15
Pangkep	29	29	8.1	7.2	3.8	180	12
Maros	25	27	7.6	6.8	4.5	160	9
Makassar	28	28	7.9	7.1	3.9	140	11
Takalar	26	26	7.7	6.0	5.0	175	13
Jeneponto	27	28	7.4	5.5	4.2	130	7

As shown in Table 2, the condition of water quality parameters at several sampling stations on the west coast of South Sulawesi affects the abundance of *Alexandrium* sp. This often causes the phenomenon of blooming and even the production of toxins in water.

Higher temperatures increase the metabolic rate and growth of *Alexandrium* sp. According to previous studies, a continuous increase in temperature (> 4°C) may trigger the blooming of *Alexandrium* sp. (Wu et al., 2022; Fuenzalida et al., 2024; Zou et al., 2024). The study suggests that dinoflagellates tend to grow better at warmer temperatures; hence, stations with higher temperatures, such as Pangkep (29°C), may show higher abundance.

Salinity at sampling sites ranges from 26 to 29 ppt. *Alexandrium* sp. generally can adapt to different salinity levels, with higher salinity can support its growth (Paredes-Mella et al., 2020). Salinity levels at Pangkep and Barru stations, each with a level of 29 ppt, can trigger higher abundance of *Alexandrium* sp.. The salinity content significantly affects the environment (Caruana et al., 2020; Sahabuddin et al., 2024).

An increase in pH can increase CO₂ availability, although very high levels can limit inorganic carbon (Middelboe & Hansen, 2007). Temperature, acidity, and carbon dioxide affect phytoplankton populations, including *Alexandrium* sp. (Seto et al., 2019). The pH values range from 7.4 to 8.1, within the optimal range for phytoplankton growth.

The dissolved oxygen content found ranged from 5.5-7.2 ml L⁻¹; this condition is conducive to phytoplankton development, including *Alexandrium* sp. The availability of dissolved oxygen in waters is closely related to the presence of phytoplankton (Salonga et al., 2022; Toporowska et al., 2010).

The turbidity value found at the sampling site ranged from 3.7 to 5.2 NTU; this could still affect *Alexandrium* sp.'s existence. Turbidity, often associated with suspended particles and phytoplankton, can significantly affect light transmission in aquatic ecosystems, consequently impacting the proliferation and spatial distribution of phytoplankton populations (Pacheco et al., 2010). Turbidity affects light accessibility and nutrient availability dynamics, which can indirectly alter the population density of the *Alexandrium* species (Bouquet et al., 2022).

Nitrogen concentrations ranged from 120 to 200 µg L⁻¹, while phosphorus was between 7 and 15 µg L⁻¹. These nutrients are essential for phytoplankton growth. Barru and Pangkep stations, with the highest concentrations of nitrogen (200 µg L⁻¹) and phosphorus (15 µg L⁻¹), further supported the potential for a higher abundance of *Alexandrium* sp. Nutrients such as nitrates and phosphates are often triggers for phytoplankton abundance in waters along with favourable oceanographic parameters (Irawati et al., 2022; Fuenzalida et al., 2024).

Water quality parameters measured showed that stations with higher temperatures, optimal salinity, higher pH, good, dissolved oxygen levels, and adequate nutrient concentrations tended to favour the abundance of *Alexandrium* sp. (Fuenzalida et al., 2024; Lee et al., 2024; Lim et al., 2006; Möller et al., 2024). Therefore, water quality management on the west coast of South Sulawesi is very important to monitor and

control the potential blooming of *Alexandrium* sp., which can have an impact on marine ecosystems and human health (Möller et al., 2024).

Toxins' impact on public health. The *Alexandrium* sp. can produce toxins, including saxitoxin, which may cause human poisoning through the consumption of seafood. Moreover, the abundance of *Alexandrium* sp. in waters can be an indicator of potential toxicity to ecosystems and risks to human health (Bazzoni et al., 2020).

Health disorders caused by saxitoxin primarily affect the function of the nervous system by inhibiting sodium ion channels, leading to symptoms such as difficult breathing and numbness. Severe exposure to very high abundance can cause death (Watanabe et al., 2024). By the end of 2020, the rise of marine biotoxins had caused significant social and economic damage worldwide. Among the different types of biotoxins, paralysed shellfish venom, which consists of saxitoxin and analogues (STX), is the most dangerous to humans, and can even lead to death (Leal & Cristiano, 2022; Möller et al., 2024).

Consumption of seafood contaminated with saxitoxin potentially leads to a variety of health problems, including shellfish-induced paralytic poisoning. The impact of PSP on public health is evident, including on the west coast of South Sulawesi. Individuals consuming contaminated seafood may experience symptoms such as nerve paralysis, difficulty breathing, visual impairment, and even death (Bazzoni et al., 2020; Leal & Cristiano, 2022; Watanabe et al., 2024).

Regular checks are needed on the west coast of South Sulawesi to keep people safe and healthy. This is important to stop paralytic poisoning outbreaks and manage risks better. It also helps avoid bad effects on people's health and the economy (Bazzoni et al., 2020; Wu et al., 2022). There is a need to check for saxitoxin in water often and to inform people, particularly fishermen and fish farmers, about the dangers of poisoning. These individuals must be informed regarding the dangers of consuming seafood from polluted places.

Conclusions. This study showed that plankton *Alexandrium* sp. was found in all stations with abundance ranging from 500 to 4,200 cells L⁻¹. The concentration of saxitoxin in seawater samples ranged from 0.25 to 1.37 µg STX eq L⁻¹, and there was a significant positive relationship between *Alexandrium* sp. abundance and the concentration of the poison. The west coast of South Sulawesi has the potential for cases of saxitoxin poisoning, with a low to high chance category depending on the increase in the abundance of plankton. Regular monitoring, the provision of scientific information to educate the public, and the control of consumption of these toxic contaminated organisms need to be carried out in the region to overcome the symptoms and risk of poisoning.

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Authors Contributions. SSah: Methodology, Writing – Review & Editing; ES: Formal analysis; KK: Resources, data curation; II and HH: Data collection; SSaf and SA: Investigation, Supervision; MF and RT: Conceptualization.

Conflict of Interest. The authors declare that there is no conflict of interest.

Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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