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Seasonal variations of lipophilic marine toxins in phytoplankton and shellfish and identification of potential causative microalgae in the southern coast of Korea

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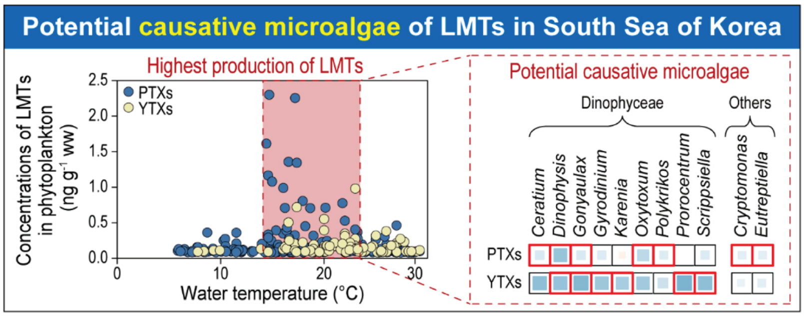
HIGHLIGHTS

- PTX2 was dominant in spring phytoplanktons, whereas hYTX was prevalent in summer.
- hYTX persisted longer in mussels, suggesting species-specific toxin retention.
- LMT concentrations showed strong correlations with seawater temperatures.
- Several unreported microalgal genera were strongly associated with LMT levels.
- Human health risks from LMTs were low across all seafood consumption scenarios.

GRAPHICAL ABSTRACT



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ABSTRACT

Lipophilic marine toxins (LMTs), including pectenotoxins (PTXs) and yessotoxins (YTXs), are emerging contaminants in Korean coastal waters. This study investigated the seasonal patterns, spatial distribution, and potential microalgal producers of LMTs in phytoplankton, wild mussels, and commercial shellfish collected along the southern coast of Korea in 2023. PTX2 was predominant in phytoplankton during early spring, while homo-YTX (hYTX) became dominant from late spring to summer. PTX2 was not detected in mussels, likely due to its rapid excretion, whereas hYTX remained detectable through September. Correlation analysis revealed limited associations between toxin levels and known producers such as *Dinophysis* and *Gonyaulax*. However, several other genera, including *Oxytoxum*, *Gyrodinium*, and *Cryptomonas*, showed significant correlations under specific temperature conditions, suggesting their potential roles in LMT production. hYTX was also detected in commercial mussels, scallops, and pen shells, with the highest concentrations and slowest decline observed in

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scallops. Differences in toxin elimination rates among species likely reflect variations in exposure duration and biological characteristics such as filtration capacity. Health risk assessments using age-specific intake scenarios indicated that hazard quotient and index values remained below regulatory thresholds. These findings underscore the need for expanded monitoring of LMTs and their potential sources to support seafood safety.

1. Introduction

Harmful algal blooms (HABs) have become increasingly prevalent and widespread in recent decades due to changes in climatic conditions, oceanic currents, and anthropogenic nutrient enrichment. Some of the microalgal species responsible for HABs naturally produce marine biotoxins [1,2]. This expansion has contributed to a global increase in the incidence and geographic distribution of shellfish toxin contamination, posing substantial risks to public health and marine economies [3]. To date, over 200 marine biotoxins have been identified [4], many of which bioaccumulate through trophic transfer in marine organisms such as crustaceans, fish, and bivalves [5,6]. Human exposure through the consumption of contaminated shellfish can lead to serious health consequences [7].

Among these biotoxins, lipophilic marine toxins (LMTs), including okadaic acid (OA), dinophysistoxins (DTXs), pectenotoxins (PTXs), yessotoxins (YTXs), and azaspiracids (AZAs), are frequently reported in both shellfish and seawater samples worldwide [8,9,5]. In South Korea, LMTs have been consistently detected in coastal waters and shellfish [10–12], indicating the presence of toxin-producing microalgal species. Several harmful taxa identified in Korean coastal waters, such as *Cochlodinium polykrikoides*, *Alexandrium* spp., *Dinophysis acuminata*, *Gonyaulax spinifera*, and *Pseudo-nitzschia* spp., are known or suspected to produce LMTs [10,11,13]. Specifically, *G. spinifera* and *D. acuminata* are associated with the production of YTXs and PTXs, respectively. On a global scale, YTXs are mainly produced by *Protoceratium reticulatum* and *Lingulodinium polyedrum* [14-16], while PTXs originate from *D. fortii* and *D. caudata* [17-19]. Other notable marine biotoxins, such as cyclic imines (CIs) and brevetoxins (BTXs), are produced by species including *Karenia selliformis*, *K. brevis,* and *Alexandrium ostenfeldii* [20-22].

Environmental factors, including seawater temperature, salinity, and nutrient availability, have a significant influence on marine biotoxin production. For instance, *Ostreopsis* cf. *ovata* exhibits increased toxin production at temperatures above 20 °C under stable nutrient conditions [23], while *A. minutum* becomes more cytotoxic under phosphate-limited environments [24]. Similarly, *Gymnodinium catenatum* produces elevated levels of saxitoxins in nitrate-rich conditions [25]. Although toxin production often peaks during the exponential growth phase, substantial variation exists among species and environmental contexts [25]. These observations highlight the species-specific nature of toxin biosynthesis and underscore the importance of understanding the environmental drivers that regulate these processes. In the South Sea of Korea, region-specific environmental stressors influence the dynamics of LMTs. One such stressor is the seasonal intrusion of Yellow Sea Bottom Cold Water (YSBCW) through the northern slope of the Jeju Strait, a distinct hydrographic process that induces thermohaline inversion and enhances vertical stratification during summer and autumn [26]. These conditions reduce vertical mixing and limit nutrient transport to the surface, potentially stabilizing phytoplankton assemblages and promoting toxin accumulation. The region is also affected by the eastward extension of Yangtze River Diluted Water, which brings low-salinity, nutrient-rich water and facilitates the formation of frontal systems that may retain blooms in surface layers [27]. In addition, semi-enclosed bays along the southern coast, such as Jinhae Bay and Gamak Bay, are subject to chronic eutrophication caused by aquaculture effluents and riverine inputs. These areas are often characterized by imbalanced nutrient stoichiometry, seasonal hypoxia, and increased prevalence of dinoflagellates, including taxa implicated in LMTs production [28]. Together, these hydrographic and anthropogenic factors provide a basis for understanding spatial and temporal variation in LMTs in this region.

The southern coast of Korea, which accounts for over 90 % of the aquaculture production of Korea, represents a critical region for seafood supply and safety [29]. In response, national monitoring programs have been established to manage shellfish toxin risks. According to the Ministry of Food and Drug Safety [30], regulatory thresholds are enforced only for three major shellfish toxin groups: 160 μg kg^{-1} as OA equivalents (EQ) for diarrhetic shellfish poisoning (DSP), 800 μg kg^{-1} as saxitoxin EQ for paralytic shellfish poisoning (PSP), and 200 μg kg^{-1} as domoic acid EQ for amnesic shellfish poisoning (ASP). In contrast, other toxins, including YTXs, PTXs, and AZAs, remain unregulated, although their occurrence in Korean coastal waters has been increasingly reported in recent years [10–12]. Notably, discrepancies between the presence of known LMT-producing microalgae and measured toxin concentrations suggest the possible involvement of overlooked or unidentified causative species. This highlights the limitations of current surveillance systems and the need for expanded, more targeted monitoring strategies.

To address these emerging concerns, this study aims to improve the understanding of LMT dynamics along the southern coast of Korea by pursuing the following objectives: (1) to investigate the temporal and spatial distribution of LMTs in phytoplankton and wild mussels, (2) to identify key significant environmental factors associated with the occurrence and variability of LMTs, (3) to determine candidate microalgal species responsible for LMT production using statistical analyses, and (4) to evaluate the potential human health risks associated with LMTs exposure through shellfish consumption. These efforts are intended to support the development of a more effective monitoring and early warning system for emerging marine biotoxins in Korean coastal waters.

2. Materials and methods

2.1. Sampling and water quality parameter measurements

Field sampling was conducted monthly from February to November 2023 at 12 coastal stations along the southern coast of Korea (S1–S12; Fig. 1a). To minimize the influence of diel vertical migration of dinoflagellates and ensure consistency across sampling events, all field sampling was conducted during daylight hours (10:00–17:00), when many dinoflagellate species are known to migrate toward the surface for photosynthesis [31,32]. At each station, phytoplankton samples (n = 95) were collected using a 20-μm mesh plankton net and pre-filtered through a 200-μm mesh sieve to remove large suspended particles and zooplankton. The 20–200 μm size fraction of suspended particulate matter (SPM) was subsequently concentrated onto 20-μm nylon net filters (Millipore, Merck, Darmstadt, Germany) and immediately stored at –20 °C for further analysis. Mussels (*Mytilus* spp., n = 99) were also collected monthly from the same locations, with more than ten individuals pooled per site. After collection, soft tissues were homogenized and stored at –20 °C. In addition to field samples, domestic shellfish products (n = 64) were purchased from a seafood market in Busan City between June and November 2023 to assess potential LMTs exposure through human consumption routes (Fig. 1a). All samples were transported to the laboratory under frozen conditions. Environmental parameters, including seawater temperature, salinity, pH, and dissolved oxygen (DO), were measured in situ using a multi-parameter water quality sonde (YSI 6600v2, YSI Inc., Yellow Springs, OH). Concentrations of nutrients (i.e., NO_2^-, NO_3^-, NH_4^+, PO_4^{3-}, and SiO_2) in seawater were analyzed using an automated nutrient analyzer (LACHAT Quikchem

8000, Hach Company, Loveland, CO), following standard colorimetric protocols (Table S1).

2.2. Phytoplankton community analysis

To evaluate phytoplankton abundance and species composition, 500 mL of surface seawater was collected and preserved with Lugol's iodine solution at a final concentration of 3 %. The preserved samples were settled by decantation and concentrated to a final volume of 50 mL. For microscopic analysis, a 1 mL aliquot of the concentrated sample was transferred to a Sedgewick–Rafter counting chamber and examined under a light microscope at 200–400 × magnification. Phytoplankton was identified to the genus or species level based on morphological characteristics using standard taxonomic references [33]. While this method cannot reliably distinguish cryptic or morphologically similar taxa, it remains a widely used and practical approach for broad-scale ecological assessments. Comparative studies have shown that molecular techniques, such as 18S rDNA sequencing, may improve taxonomic resolution for specific groups but also involve limitations related to detection bias and incomplete reference databases [34,35].

2.3. Extraction and purification of LMTs in biological samples

Extraction and purification of LMTs in biological samples were performed according to established methods [12]. For bivalve samples, shells were removed and soft tissues from more than 20 individuals were pooled and homogenized. A 2 g aliquot of the homogenized tissue was transferred to a centrifuge tube containing 9 mL of methanol (MeOH) and subjected to sonication for 10 min to enhance extraction efficiency. The mixture was then centrifuged at 3500 rpm for 10 min, and the supernatant was collected. This extraction step was repeated twice, and the combined supernatants were adjusted to a final volume of 20 mL. For purification, the methanolic extract was diluted with Milli-Q water to reduce the MeOH concentration to below 20 %, then loaded onto a Strata-X SPE cartridge (30 mg, 3 mL, Phenomenex, Torrance, CA), which was preconditioned with 3 mL each of MeOH and Milli-Q water. The cartridge was rinsed with 15 % MeOH and eluted with MeOH containing 1 % ammonium hydroxide. The eluate was evaporated to dryness under a gentle stream of nitrogen gas, reconstituted in 1 mL of MeOH containing 1 % ammonium hydroxide, and stored at –20 °C until analysis. For phytoplankton samples (20–200 μm SPM), the frozen filters were thawed and immersed in 3 mL of MeOH in a centrifuge tube. The mixture was gently swirled for 1 min, followed by 5 min of sonication. After centrifugation at 3500 rpm for 10 min, the supernatant was collected. This extraction was repeated three times, resulting in a final extract volume of approximately 10 mL. The combined extract was filtered through a 0.22-μm syringe filter and stored at –20 °C for subsequent analysis.

2.4. Instrumental analysis

Certified reference materials for LMTs, including OA, DTX1, DTX2, YTX, homo-YTX (hYTX), PTX2, AZA1–5, gymnodimine A (GYM), 13-desmethyl spirolide C (SPX), and domoic acid (DA), were obtained from the National Research Council Canada (Ottawa, ON, Canada), Cifga (Lugo, Spain), and Sigma-Aldrich (St. Louis, MO), depending on availability. PTX11 was purchased from Sigma-Aldrich, and BTX1–3, and BTX5 were obtained from LKT Laboratories (St. Paul, MN). Quantitative and qualitative analysis of the 19 target LMTs were conducted using liquid chromatography-tandem mass spectrometry (LC-MS/MS). An Agilent 1290 Infinity II LC system coupled to an Agilent 6470 MS/MS (Agilent Technologies, Santa Clara, CA) was used for LMTs analysis. Chromatographic separation was carried out on a Waters X-Bridge C18 column (150 mm × 3.0 mm i.d., 5 μm particle size), maintained at 25 °C. The mobile phase consisted of solvent A (Milli-Q water) and solvent B (90:10, v/v, acetonitrile:water), each containing 0.05 % ammonium hydroxide. The instrument operated in multiple reaction monitoring (MRM) mode for the detection of target analytes. Detailed LC conditions and MS/MS parameters are provided in Tables S2 and S3.

2.5. Quality control

Analytical performance was validated by assessing linearity, limits of detection (LOD), limits of quantification (LOQ), recovery, and precision, as summarized in Table S4. Calibration curves were generated for each toxin using standard solutions at six concentration levels. For most toxins, calibration points included 1, 2, 5, 10, 25, and 50 ng mL^{-1}, whereas BTXs were calibrated at 5, 10, 25, 50, 100, and 200 ng mL^{-1}. Samples exceeding the upper calibration limit were appropriately diluted to fall within the quantification range. The LOD and LOQ were calculated as 3.143 and 10 times the standard deviation (SD), respectively, based on replicate measurements (n = 7) of mussel matrix samples spiked with 1 ng of each standard (5 ng for BTXs). Recovery tests

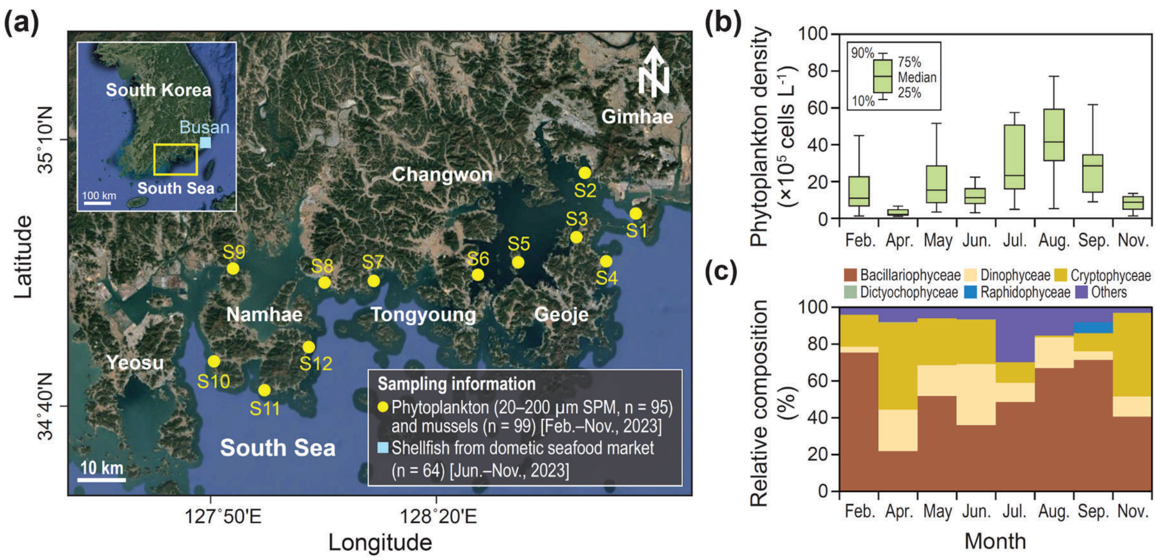

Fig. 1. (a) Sampling locations for phytoplankton (20–200 μm SPM), wild mussels, and commercial shellfish products along the southern coast of Korea. **(b)** Monthly variation in phytoplankton cell density from February to November 2023. **(c)** Relative composition of dominant phytoplankton classes during the study period.

were conducted by fortifying blank mussel samples ($n = 4$) with 25 ng of each toxin, followed by the same extraction and purification procedures described above. Method precision was evaluated using the coefficient of variation (CV) across replicate analyses.

2.6. Statistical analysis

Normality was evaluated using the Shapiro–Wilk test in R software (version 4.4.1). As the data did not meet the assumptions of normality, Spearman's rank correlation analysis was employed to assess relationships among LMT concentrations, environmental variables, and the abundances of potentially toxic microalgae. Prior to analysis, all variables, including LMT concentrations, environmental parameters, and microalgal cell densities, were transformed using the square root function to reduce skewness. Concentration values below the LOD were substituted with LOD/2. All correlation analyses were performed using the R packages '*vegan*' and '*dplyr*', with statistical significance set at $p < 0.05$.

2.7. Estimation of LMTs depuration kinetics

The toxin depuration rate constant (k) and corresponding half-life ($t_{1/2}$) for wild mussels from the southern coast of Korea and commercial mussels and scallops from the domestic market were estimated by fitting a first-order exponential decay model using nonlinear least squares regression (Equation (Eq.) 1). The model was implemented in R software using the '*nlsLM()*' function from the '*minpack.lm*' package. For this analysis, wild mussels were collected from the southern coast of Korea, while commercial mussels and scallops were obtained from seafood markets. Because the physiological condition (e.g., reproductive status) of market-sourced shellfish could not be determined, depuration modeling for these samples was intended to reflect post-harvest toxin persistence under consumer-relevant storage conditions, rather than in situ elimination dynamics.

$$C_t = C_0 \times e^{-kt} \tag{1}$$

Where C_t is the toxin concentration at time t, and C_0 is the initial concentration. k denotes the first-order depuration rate constant (month^{-1}), which was estimated using nonlinear least-squares regression based on observed toxin concentrations. The estimated k values were 0.91 month^{-1} for mussels and 0.59 month^{-1} for scallops. In the case of pen-shells, the depuration rate constant could not be determined due to insufficient decline in toxin levels during the observed period. The half-life ($t_{1/2}$) of LMTs was calculated using Eq. 2:

$$t_{1/2} = \frac{\ln(2)}{k} \tag{2}$$

2.8. Dietary exposure assessment of LMTs

To assess the potential health risks associated with LMT exposure through shellfish consumption, a dietary exposure assessment was conducted using intake data from the Korean National Health and Nutrition Examination Survey (KNHANES, 2016–2018) [36]. The evaluation focused on mussels and pen shells, in which LMTs were detected. Human exposure was estimated using four dietary intake scenarios (S1–S4), established in accordance with FAO/WHO guidelines [11,37]. The estimated daily intake (EDI, ng kg^{-1} bw d^{-1}) was calculated using the following equation (Eq. 3).

$$EDI = (C_s \times DI_s)/bw \tag{3}$$

Where C_s is the LMT concentration in shellfish (ng g^{-1} wet weight (ww)), DI_s is the daily intake of shellfish (g d^{-1}), and bw is the body weight (kg). A standard body weight of 60 kg was applied based on KNHANES data. To evaluate potential chronic health risks, the hazard quotient (HQ) and hazard index (HI) were calculated as follows (Eqs. 4 and 5).

$$HQ = (EDI/HbGV) \times 100 \tag{4}$$

$$HI = \sum_{n=1}^{i} HQ_n\% \tag{5}$$

The health-based guidance value ($HbGV$) was set at 1500 μg YTX-EQ d^{-1}, derived by multiplying the acute reference dose (aRfD) of 25 μg YTX-EQ kg^{-1} bw d^{-1} [38] by the standard Korean body weight. The HI was calculated by summing HQ values across the different intake scenarios.

3. Results and discussion

3.1. Phytoplankton community and LMTs-producing microalgae

In 2023, phytoplankton biomass along the southern coast of Korea increased markedly during the warmer months (April to June), with the highest abundance recorded in June (Fig. 1b). This seasonal increase was accompanied by compositional shifts in the phytoplankton community. Bacillariophyceae dominated throughout the year, comprising an average of 51 % of total phytoplankton biomass, followed by Cryptophyceae (23 %), Dinophyceae (15 %), Raphidophyceae (0.82 %), and Dictyochophyceae (0.08 %). Minor taxa collectively accounted for 10.1 % (Fig. 1c and Table S5), reflecting seasonal dynamics consistent with previous studies in the region [10,11]. Notably, the relative abundance of dinoflagellates increased markedly during spring and early summer, reaching 22 %, 16 %, and 33 % in April, May, and June, respectively. This seasonal trend suggests an increased presence of potentially toxic microalgae during this period, thereby elevating the risk of shellfish contamination by LMTs.

During the study period, three major LMT-producing species, such as *G. spinifera*, *D. acuminata*, and *K. brevis*, were identified, corresponding to producers of YTXs, PTXs, and BTXs, respectively (Fig. 2 and Table S6). *D. acuminata* appeared earliest and exhibited the broadest temporal distribution, with cell densities detectable from February to September and peaking at 14,000 cells L^{-1} in May. *G. spinifera* was primarily detected in May, reaching a maximum of 1700 cells L^{-1}, while *K. brevis* emerged later, peaking at approximately 1200 cells L^{-1} in August. This succession, *D. acuminata* in early spring, *G. spinifera* in late spring, and *K. brevis* in summer, likely reflects species-specific thermal preferences. *K. brevis* is known to bloom at higher temperatures [39], whereas *D. acuminata* prefers cooler spring conditions [40]. *G. spinifera*, a eurythermal species, persists across a broad temperature range [11], which may account for its intermediate seasonal occurrence.

When compared to prior observations in the region, the seasonal patterns of LMT-producing microalgae in 2023 were generally consistent with those observed in 2020 and 2021, particularly in terms of succession timing [10,11]. In all three years, *D. acuminata* emerged first and remained dominant over an extended period, followed by *G. spinifera* and *K. brevis*. However, the cell densities of both *D. acuminata* and *G. spinifera* in 2023 were comparatively lower than those in previous years, possibly due to interannual variability in environmental conditions, such as seawater temperature and nutrient availability, which are known to influence bloom intensity and duration [41,42]. Overall, relatively high densities of LMT-producing microalgae were observed between April and August, corresponding with seasonal increases in seawater temperature. This recurring pattern across multiple years suggests a period of elevated LMT contamination risk. Enhanced monitoring during the spring and summer months is therefore recommended to mitigate potential threats to seafood safety in the region.

3.2. Spatiotemporal distributions of LMTs in phytoplankton and mussels

LMTs exhibited distinct spatiotemporal patterns and compositional profiles in phytoplankton and mussels along the southern coast of Korea

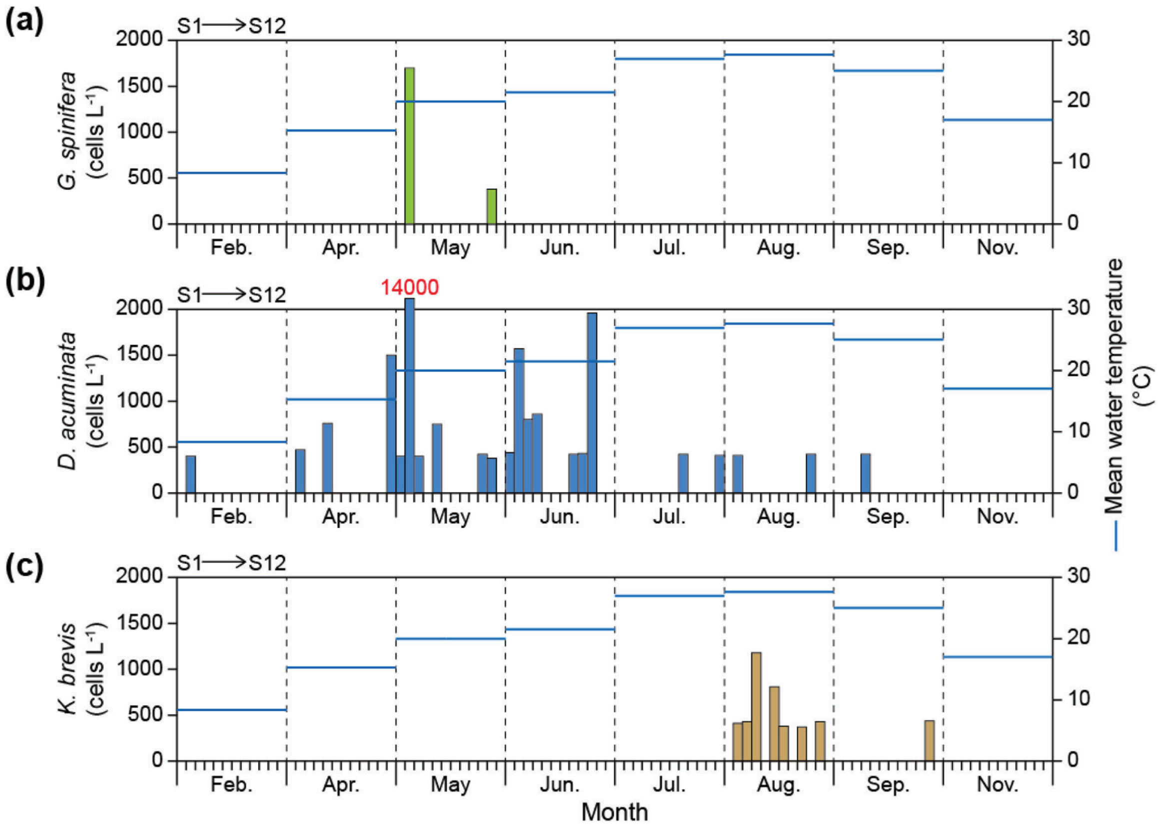

Fig. 2. Monthly variation in cell densities of three known toxin-producing microalgae species along the southern coast of Korea in 2023. **(a)** *Gonyaulax spinifera*, **(b)** *Dinophysis acuminata*, and **(c)** *Karenia brevis*. Blue lines represent the mean seawater temperature across all sampling stations.

during 2023 (Fig. 3, Fig. S1, and Tables S7 and S8). In phytoplankton, PTX2 was the dominant toxin during the early sampling period, particularly from February to April, with peak concentrations exceeding 900 ng g^{-1} ww at stations near Yeosu and Namhae (S7–S12). As the season progressed, PTX2 levels declined, while the relative contribution of hYTX increased markedly from May to July. This temporal shift in toxin composition likely reflects the seasonal succession of dominant toxin-producing microalgae, with *D. acuminata* predominating in early spring and *G. spinifera* in late spring and early summer. These patterns suggest that LMT profiles in the particulate phase are closely linked to changes in phytoplankton assemblage, consistent with previous findings [10,11]. Spatially, LMT concentrations in phytoplankton were consistently higher at stations near Yeosu and Namhae compared to those near Geoje (S1–S6). This regional variation may be attributed to differences in bloom dynamics and local hydrographic conditions, including freshwater inputs and circulation patterns. Following peak levels in April, toxin concentrations declined rapidly and became largely undetectable in phytoplankton by July, indicating limited persistence of particulate-phase LMTs.

In contrast, mussels exhibited a delayed temporal pattern of LMTs accumulation. The highest LMT concentrations were observed in July, and elevated levels persisted through September, even after toxin levels in phytoplankton had declined. Spatially, this pattern diverged from that observed in phytoplankton, as mussels from Geoje exhibited higher toxin concentrations than those from Yeosu and Namhae. This discrepancy may be explained by the semi-enclosed nature of bays around Geoje, where restricted water exchange could prolong exposure and facilitate greater accumulation in filter-feeding organisms. Such hydrodynamic conditions are known to enhance the retention of particulate and dissolved pollutants, increasing the risk of bioaccumulation in bivalves [43]. Additionally, environmental factors such as water residence time, physicochemical characteristics, and sediment properties can significantly influence bioaccumulation efficiency [44].

The LMTs composition in mussels also differed from that of phytoplankton. While hYTX remained the dominant compound in mussel tissues, OA and DTX1 were also detected at relatively higher concentrations than in phytoplankton. Notably, PTX2 was not detected in any mussel samples during the monitoring period. This absence is likely due to compound-specific depuration kinetics. PTXs are known to have relatively short biological half-lives in shellfish and undergo rapid transformation and elimination [45,46]. Specifically, PTX2 is quickly converted into its seco acid form (PTX2-sa) upon uptake and is efficiently excreted, reducing its detectability in tissue samples [47,48]. These findings have important implications for monitoring programs. Given the persistence of LMTs in mussels beyond the bloom period of causative microalgae, monitoring should not be limited to periods of high phytoplankton abundance. In particular, extended surveillance is recommended for semi-enclosed coastal areas where hydrodynamic retention may lead to increased bioaccumulation. Such an approach is essential to ensure accurate exposure assessments and safeguard public health.

3.3. Identification of potential causative microalgal taxa associated with LMTs

To identify potential causative taxa responsible for LMTs production in phytoplankton, statistical analyses were conducted using phytoplankton community and LMTs concentration data obtained in 2023, in conjunction with historical datasets from 2020 and 2021 [10,11]. Detailed cell densities of suspected LMT-producing genera included in this analysis are provided in Table S9. Despite the frequent detection of PTX2 and hYTX as dominant LMTs along the southern coast of Korea, no significant correlations were found between their concentrations and the cell abundances of *D. acuminata and G. spinifera*, respectively

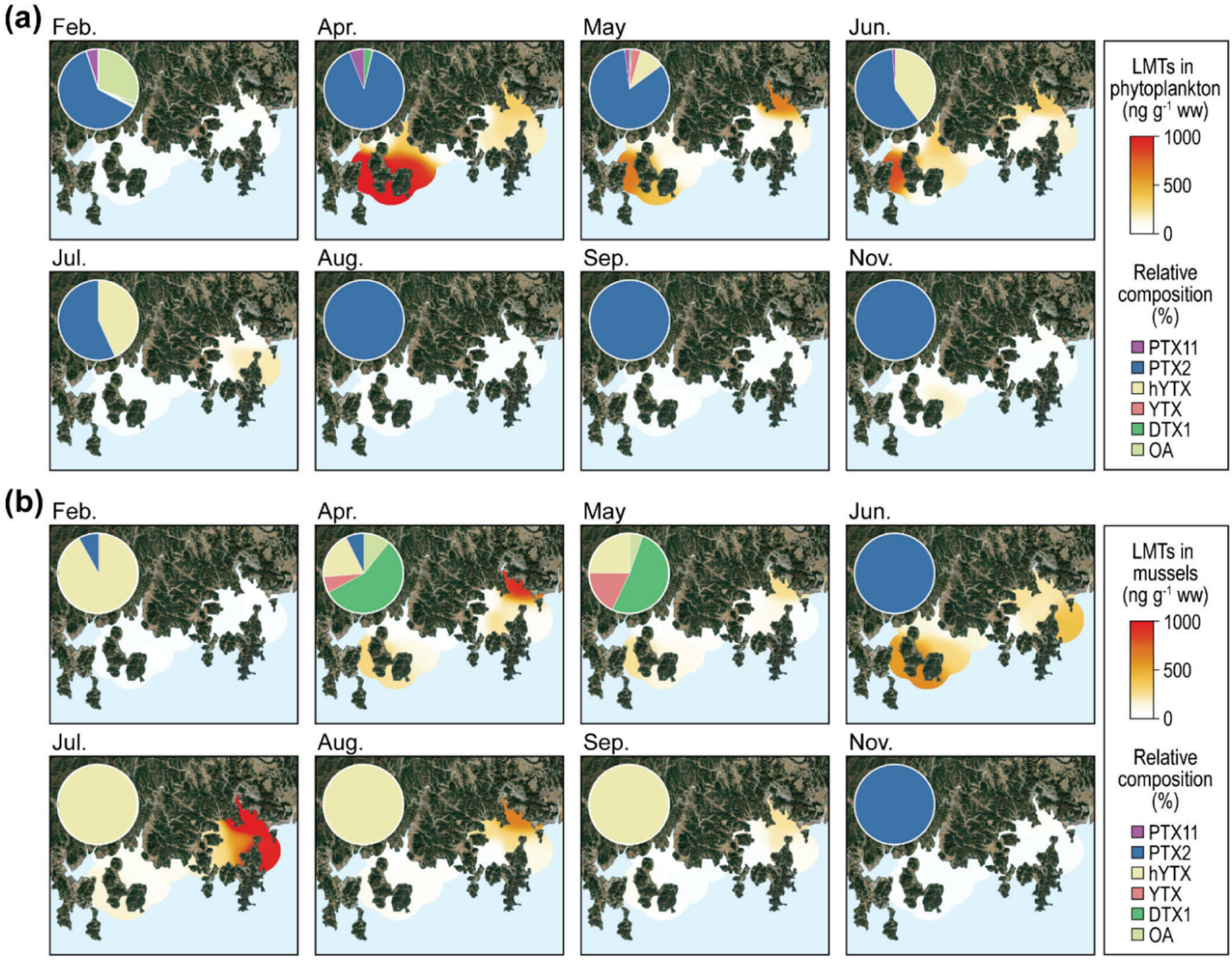

Fig. 3. Monthly variation in the spatial distribution and toxin profiles of LMTs along the southern coast of Korea from February to November 2023. **(a)** Color shading on the map indicates total LMT concentrations in phytoplankton samples (20–200 μm SPM), and pie charts show the relative proportions of individual LMT analogs. **(b)** Corresponding results for wild mussels collected from the same stations, with toxin concentrations visualized by color gradients and compositional data presented as pie charts.

(Fig. S2). Similar results have been reported in previous studies, indicating that toxin concentrations are not necessarily proportional to the abundance of these genera [10,11]. Although *D. acuminata* and *G. spinifera* have been widely regarded as indicative genera for PTXs and YTXs, respectively, previous studies have shown that other dinoflagellates can also contribute to their production. For example, PTXs have been identified in *D. fortii* and *D. caudata* [17-19], and *P. reticulatum* and *L. polyedra* are identified as producers of YTXs [14-16]. In this study, none of these established toxin-producing species were detected during the periods of elevated PTX and YTX concentrations. This discrepancy suggests the possible involvement of unrecognized or cryptic taxa. Correlation analysis with environmental variables further indicated that toxin occurrence was associated with specific temperature ranges, supporting the need to consider environmental filtering when identifying potential causative species. PTX concentrations peaked at seawater temperatures between 14 °C and 18 °C, while YTX concentrations were highest within a slightly warmer range of 18–25 °C (Figs. 4a and 4b). These trends align with the ecological characteristics of *D. acuminata*, which exhibits optimal growth and toxin production between 18 °C and 24 °C [40,49], and *G. spinifera*, a photothermophilic species with a broad thermal tolerance [11].

Given the absence of significant correlations with known LMT-producing taxa, temperature-filtered correlation analyses were conducted to identify microalgal genera statistically associated with elevated LMT concentrations. The applied temperature ranges (14–18 °C for PTXs and 18–25 °C for YTXs) were empirically defined based on observed toxin distributions in the 2020, 2021, and 2023 datasets, in which peak concentrations were consistently detected within these respective intervals (Fig. 4a and 50b). This approach, previously applied in identifying potential BMAA producers in coastal waters [51], enabled refined association analysis within environmentally relevant windows. For PTXs, Spearman's correlation analysis identified seven genera with significant positive relationships (Fig. 4c). Among these, *Dinophysis* sp., a well-established PTX producer, exhibited the highest correlation coefficient ($r = 0.361$, $p < 0.05$). *Gonyaulax* sp., previously implicated in LMT production, also showed a significant correlation. Additionally, five other genera, such as *Oxytoxum*, *Ceratium*, *Polykrikos*, *Eutreptiella*, and *Cryptomonas*, were significantly associated with PTX concentrations, despite not being previously reported as toxin producers. These findings suggest the possibility of overlooked or cryptic producers and underscore the need for further toxicological and molecular investigations.

Similarly, YTX concentrations were significantly correlated with six genera, including *Gonyaulax* sp. ($r = 0.430$, $p < 0.05$), a known YTX producer (Fig. 4c). Other associated genera included *Prorocentrum* sp.,

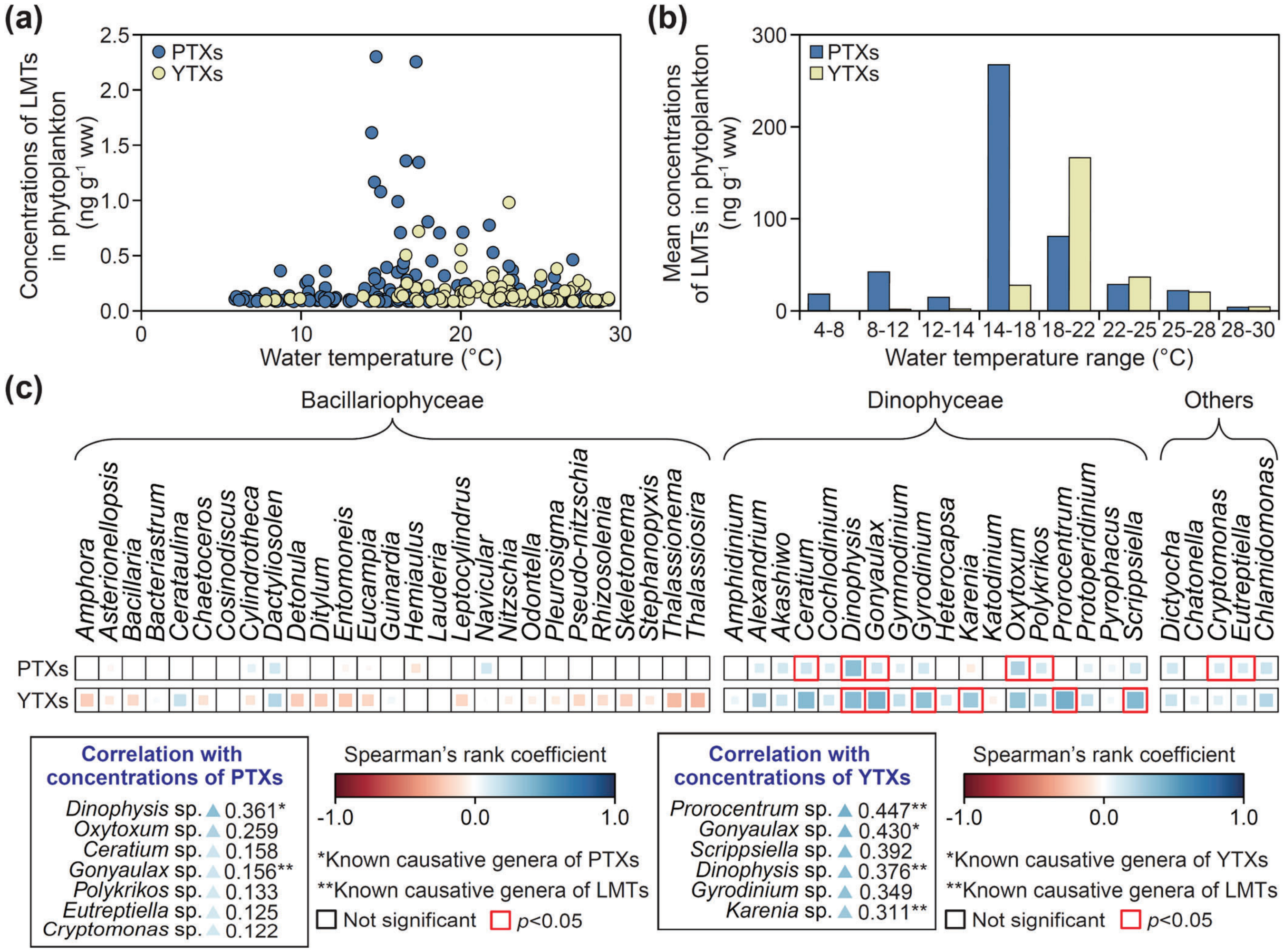

Fig. 4. **(a)** Relationship between seawater temperature and concentrations of PTXs and YTXs in phytoplankton. **(b)** Mean concentrations of PTXs and YTXs across defined temperature intervals. **(c)** Spearman's rank correlations between LMT concentrations and microalgal genera within temperature-specific ranges. Significant correlations ($p < 0.05$) are highlighted, and known toxin-producing are marked with an asterisk (*).

Dinophysis sp., and *Karenia* sp., all previously implicated in LMT production. Notably, *Scrippsiella* sp. and *Gyrodinium* sp. also exhibited significant correlations. While *Scrippsiella* has not been reported to produce LMTs, *Gyrodinium* has demonstrated neurotoxic activity in mouse bioassays, suggesting potential latent toxicity [52]. Field observations of PSP-related incidents involving unidentified *Gyrodinium* species in the Adriatic Sea [53] suggest a possible role for this genus in toxin dynamics. These results highlight the importance of including less-characterized but statistically linked taxa in future toxin monitoring efforts. Overall, these findings suggest that a combination of environmental factors and complex multi-species interactions may drive the occurrence of LMTs in phytoplankton. Future studies integrating molecular identification techniques and targeted toxin profiling are warranted to elucidate the specific roles of these candidate taxa in LMT production and to improve early-warning monitoring systems.

3.4. Seasonal distributions and potential risks of LMTs in commercial shellfish

To evaluate potential human health risks associated with LMTs in

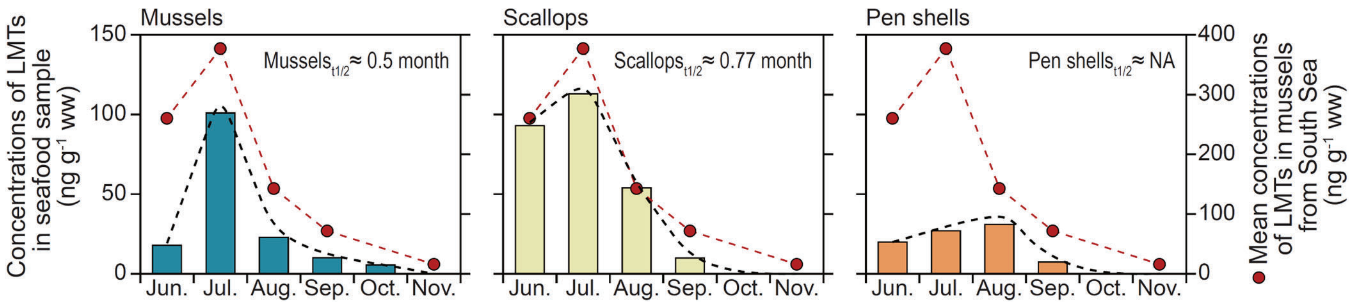

Fig. 5. Monthly variation in hYTX concentrations in mussels, scallops, and pen shells collected from domestic seafood markets, shown from left to right. Estimated toxin half-lives ($t_{1/2}$) for each species are indicated. Red dashed lines represent the mean hYTX concentrations in field-collected mussels from the southern coast of Korea.

seafood products, a total of 64 commercial shellfish samples were collected between June and November 2023. Among these, LMTs were detected in 13 samples, and in all cases, the only identified toxin was hYTX. The toxin was found in mussels, scallops, and pen shells, with maximum concentrations of 101, 113, and 31 ng g^{-1} ww, respectively (Fig. 5). Concentrations were highest during the summer months (June–July) and declined thereafter, showing a seasonal pattern similar to that observed in wild mussels from the South Sea. Although toxin concentrations in commercial seafood were lower than those in wild mussel samples, the parallel temporal trends likely reflect the geographic origin of the products, which were primarily sourced from Yeosu, Tongyeong, and Myeongji along the southern coast of Korea. Notably, the decline in hYTX concentrations occurred earlier in seafood mussels than in wild mussels. Based on the temporal patterns, the estimated half-life of hYTX was approximately one month in wild mussels, 0.5 months in seafood mussels, and 0.77 months in scallops. Due to limited sample availability, the half-life in pen shells could not be determined. The relatively rapid decline in toxin concentrations observed in commercial shellfish is likely attributable to post-harvest depuration in clean seawater prior to market distribution. In contrast, wild mussels remained continuously exposed to toxin-producing phytoplankton in the natural environment, resulting in prolonged toxin retention. Among the three species examined, scallops exhibited both the highest hYTX concentrations and the slowest elimination rate. These findings are consistent with previous studies, which have shown that scallops can accumulate higher levels of LMTs, likely due to their larger body size and greater filtration capacity [54,55,5].

To assess human health risks, HQ and HI values were calculated across age-specific consumption scenarios. Estimated daily intake rates for mussels, scallops, and pen shells ranged from 1.1–15.19 g d^{-1}, 0.24–23.73 g d^{-1}, and 0.03–6.97 g d^{-1}, respectively. The highest HQ values were observed in July, with mussels and scallops presenting greater risk estimates than pen shells. Children aged 7–12 years exhibited the highest intake rates and correspondingly the highest HQ and HI values across all age groups (Table 1). Although all detected hYTX concentrations were below the EFSA acute toxicity threshold of 3.75 mg YTX-EQ kg^{-1} [38], the HI value for this group exceeded 1.0. Based on established risk assessment criteria [56], an HI greater than 1.0 indicates a potential for cumulative non-carcinogenic health effects. These findings highlight the relevance of age-specific exposure assessment in evaluating chronic risks associated with LMTs. In conclusion, while hYTX was detected in commercial shellfish during the spring and summer, the associated health risk was minimal. The concentrations in market samples closely reflected those observed in wild mussels from the same region. Nevertheless, given the widespread consumption of shellfish in Korea, continued monitoring is essential to prevent potential intoxication events and to protect public health. Although this risk assessment was based on acute exposure thresholds, the potential for chronic exposure through repeated consumption, particularly among high-intake subpopulations, warrants further investigation. Additionally, regional dietary habits and seasonal events may lead to temporary increases in shellfish intake, potentially elevating short-term exposure risk. While only hYTX was detected in this study, the possibility of co-occurrence with other unknown toxins cannot be ruled out. Such mixtures may exert additive or synergistic toxic effects that are not captured by single-compound risk assessments. Thus, integrated long-term monitoring and cumulative risk evaluation frameworks are recommended to support more comprehensive and precautionary seafood safety management.

Table 1
Hazard quotients (HQ, %) and hazard index (HI) by age group for four dietary intake scenarios (S1–S4) of LMTs exposure through shellfish consumption.

Shellfish	Age groups (Years)	HQ (%)				HI
		S1	S2	S3	S4	
Mussel	1–2	0.039	0.778	0.105	0.514	1.436
	3–6	0.038	0.281	0.082	0.493	0.895
	7–12	0.013	0.437	0.082	0.492	1.025
	13–19	0.018	0.359	0.043	0.359	0.780
	20–64	0.019	0.392	0.092	0.527	1.029
	≥ 65	0.000	0.404	0.009	0.688	1.101
Scallop	1–2	0.000	0.000	0.000	0.000	0.000
	3–6	0.000	0.046	0.000	0.046	0.092
	7–12	0.060	0.800	0.072	0.800	1.731
	13–19	0.002	0.896	0.003	0.896	1.797
	20–64	0.003	0.544	0.004	0.822	1.373
	≥ 65	0.000	0.042	0.000	0.042	0.085
Pen shell	1–2	0.0000	0.0000	0.0000	0.0000	0.000
	3–6	0.0000	0.0000	0.0000	0.0000	0.000
	7–12	0.0011	0.3200	0.0013	0.3200	0.642
	13–19	0.0000	0.0121	0.0000	0.0121	0.024
	20–64	0.0002	0.0714	0.0002	0.1503	0.222
	≥ 65	0.0000	0.0525	0.0001	0.0525	0.105

3.5. Comparison of LMTs contamination levels with previous studies

The concentrations of LMTs detected in phytoplankton and shellfish samples in this study were compared with values reported in previous studies conducted across various coastal regions (Tables 2 and 3). In phytoplankton, PTX concentrations reached up to 1086 ng g^{-1} ww, exceeding those reported in the East Sea, Yellow Sea, and Bohai Sea, but remaining lower than the highest levels previously recorded in the South Sea [57,10–12]. Similarly, YTX concentrations in this study were higher than those reported in the Yellow and East Seas, but lower than the peak values observed in the 2020 South Sea dataset [12]. In contrast, OA and DTXs were detected at lower levels than in the East and Yellow Seas, as well as in earlier studies of the South Sea [12]. These regional differences are likely attributable to variations in the composition and abundance of toxin-producing microalgae. In the present study, *D. acuminata* and *G. spinifera* were identified as potential producers, whereas key YTX-producing species, such as *L. polyedrum* and *P. reticulatum*, were not observed. The absence of these taxa, combined with relatively low cell densities of identified producers, may explain the comparatively reduced YTX levels observed in phytoplankton.

For wild mussels collected from the southern coast of Korea in 2023, YTX concentrations reached up to 1600 ng g^{-1} ww, which were comparable to or slightly lower than levels previously reported from other Korean coastal regions [10–12]. However, these concentrations were generally higher than those reported from the East China Sea, Bohai Sea, and Galicia coast [55,5,60], but remained lower than values documented for the Adriatic Sea [58,59]. Concentrations of OA, DTXs, and PTXs in mussels were lower than those found in the Galicia coast [61], but exceeded those observed in the Bohai and East China Seas [5,63].

In commercially available shellfish products, hYTX was the only LMTs detected in scallops, mussels, and pen shells. The contamination levels were comparable to or slightly lower than those reported in similar products from China and Portugal [50,62,63]. No OA, DTXs, or PTXs were detected in any commercial samples, a pattern consistent with previous observations in which YTXs are the predominant LMTs accumulated in scallops and mussels [10,11]. Overall, these findings highlight the pronounced spatial and temporal variability of LMT contamination in both environmental and commercial shellfish. This heterogeneity likely reflects regional differences in the composition, abundance, and seasonal dynamics of toxin-producing microalgae, as well as environmental factors that influence the production and accumulation of toxins. These results underscore the importance of ongoing monitoring efforts to ensure seafood safety and enhance our understanding of the ecological processes that drive LMT distribution.

4. Conclusions

This study provides comprehensive insights into the spatiotemporal dynamics, ecological drivers, and human health risks associated with

Table 2
Reported concentrations of LMTs in phytoplankton and mussels from this study and previous studies across different coastal regions.

Samples & Regions	Sampling year	Lipophilic marine toxins (ng g^{-1} ww)							References
		OA	DTXs	PTXs	YTXs	AZAs	BTXs	CIs	
Phytoplankton									
Bohai Sea (China)	2018	ND[a]–163	ND–53	ND–3385	ND	ND	NA[b]	ND	He et al. [57]
South Sea (Korea)	2020	NA	NA	ND–200	ND–5700	NA	NA	NA	Kim et al. [10]
South Sea (Korea)	2021	ND	ND	ND–2100	ND–640	ND	NA	NA	Kim et al. [11]
South Sea (Korea)	2020–2021	ND	ND–61	ND–180	ND–61	ND	ND	ND	Kim et al. [12]
Yellow Sea (Korea)	2020–2021	ND–39	ND–57	ND–440	ND–9	ND	ND	ND	Kim et al. [12]
East Sea (Korea)	2020–2021	ND–38	ND–91	ND–705	ND–420	ND	ND	ND	Kim et al. [12]
South Sea (Korea)	2023	ND–9.8	ND–38	ND–1086	ND–194	ND	ND	ND	This study
Mussels									
Adriatic Sea (Italy)	2012–2014	ND–70	ND	ND	ND–3807	ND–7.1	NA	NA	Bacchiocchi et al. [58]
Adriatic Sea (Italy)	2017	ND–45	ND	ND	ND–38	ND–3.8	NA	ND–11	Talic et al. [59]
Bohai Sea (China)	2013–2014	ND[a]	ND–2.81	ND	ND–20.5	ND	NA[b]	ND–2.4	Liu et al. [5]
East China Sea (China)	2012–2013	ND–1.9	ND–2.5	ND–7	ND	ND	NA	ND–0.89	Li et al. [55]
Galicia coast (Spain)	2021–2022	ND–332	ND–235	ND	ND–104	ND	NA	ND–6	Rossignoli et al. [60]
Galicia coast (Spain)	2014	ND–890	ND–92	ND–46	ND–490	ND	NA	NA	Rodriguez et al. [61]
South Sea (Korea)	2020	NA	NA	ND	ND–1051	NA	NA	NA	Kim et al. [10]
South Sea (Korea)	2021	ND	ND	ND–17	ND–1350	ND	NA	NA	Kim et al. [11]
South Sea (Korea)	2020–2021	ND	ND	ND	ND–103	ND	ND	ND	Kim et al. [12]
Yellow Sea (Korea)	2020–2021	ND–87	ND–137	ND	ND–307	ND	ND	ND	Kim et al. [12]
East Sea (Korea)	2020–2021	ND	ND	ND	ND–46	ND	ND	ND	Kim et al. [12]
South Sea (Korea)	2023	ND–115	ND–752	ND–22	ND–1600	ND	ND	ND	This study

[a] ND: Not detected.
[b] NA: Not analyzed.

Table 3
Reported concentrations of LMTs in commercially available shellfish from South Korea and other countries.

Samples & Regions	Sampling year	Lipophilic marine toxins (ng g^{-1} ww)							References
		OA	DTXs	PTXs	YTXs	AZAs	BTXs	CIs	
Mussels									
Korea	2020	NA[a]	NA[b]	ND	ND	NA	NA	NA	Kim et al. [10]
Korea	2021	ND	ND	ND	ND–91	ND	NA	NA	Kim et al. [11]
Korea	2023	ND	ND	ND	ND–101	ND	ND	ND	This study
China	2018–2019	< 10–16	ND–16.5	< 10–13	< 20–373	NA	NA	NA	Weng et al. [62]
China	2008–2009	2–37	NA	0.5–12	NA	0.18–4.5	NA	0.1–8.9	Wu et al. [63]
Portugal	2016–2017	0.2–36	0.02–0.4	0.5–15	2.8–112	0.2–0.4	NA	NA	Alves et al. [50]
Pen shells									
Korea	2020	NA[a]	NA[b]	ND	ND–124	NA	NA	NA	Kim et al. [10]
Korea	2021	ND	ND	ND	ND–36	ND	NA	NA	Kim et al. [11]
Korea	2023	ND	ND	ND	ND–31	ND	ND	ND	This study
China	2018–2019	ND	ND	ND	ND	ND	ND	ND	Weng et al. [62]
Scallops									
Korea	2020	NA[a]	NA[b]	ND	ND–73	NA	NA	NA	Kim et al. [10]
Korea	2021	ND	ND	ND	ND–143	ND	NA	NA	Kim et al. [11]
Korea	2023	ND	ND	ND	ND–113	ND	ND	ND	This study
China	2018–2019	ND	ND	ND	< 20–80.6	NA	NA	NA	Weng et al. [62]
China	2008–2009	2–36	NA	0.6–16	NA	0.1–6	NA	0.1–7	Wu et al. [63]

[a] ND: Not detected.
[b] NA: Not analyzed.

LMTs along the southern coast of Korea. The detection of PTX2 and hYTX in phytoplankton and the predominance of hYTX in mussels underscore the importance of considering both toxin production and species-specific depuration kinetics in shellfish. Despite the known roles of *D. acuminata* and *G. spinifera*, their cell densities showed limited correlation with toxin concentrations, suggesting that other environmental variables, particularly seawater temperature and potentially overlooked microalgal taxa, contribute to the dynamics of toxin production. Correlation analyses identified several genera that were significantly associated with PTX and YTX concentrations, including *Oxytoxum*, *Ceratium*, and *Gyrodinium*. Among these, *Gyrodinium* has previously been linked to neurotoxicity and PSP-related incidents, but its capacity to produce LMTs has not been confirmed. For *Oxytoxum*, no experimental or field-based evidence of toxin production is currently available, although its consistent statistical association in this study suggests it may be ecologically relevant. Further toxicological and molecular studies are needed to clarify the potential role of these lesser-known taxa in LMT occurrence. for expanded toxin screening and molecular validation. Although hYTX was detected in commercial shellfish such as mussels, scallops, and pen shells, the overall exposure risk was low across all age groups. Nonetheless, given the increasing frequency of LMTs occurrence and high shellfish consumption in Korea, a more targeted and comprehensive monitoring framework is warranted. These results contribute to improving understanding of LMTs contamination and support the development of early warning systems to ensure marine food safety in Korean coastal waters.

Environmental implication

This study is the first to identify candidate microalgal genera potentially responsible for producing lipophilic marine toxins (LMTs) in Korean coastal waters. By integrating multi-year field data with temperature-filtered correlation analysis, we identified several previously unrecognized genera associated with LMTs occurrence. These findings enhance our understanding of the ecological complexity underlying harmful algal blooms, extending beyond known toxin producers. The results provide a scientific basis for improving toxin monitoring and early warning systems in the context of climate-driven shifts in phytoplankton communities, thereby supporting sustainable seafood safety in temperate coastal ecosystems.

CRediT authorship contribution statement

Mungi Kim: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Young Kyun Lim:** Investigation, Formal analysis, Data curation. **Hyejoo Lee:** Formal analysis, Data curation. **Chung Hyeon Lee:** Investigation, Formal analysis, Data curation. **Seung Ho Baek:** Writing – review & editing, Investigation, Formal analysis, Conceptualization. **Seongjin Hong:** Writing – review & editing, Visualization, Supervision, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.jhazmat.2025.139492.

Data Availability

Data will be made available on request.

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Supplementary materials for

Seasonal variations of lipophilic marine toxins in phytoplankton and shellfish and identification of potential causative microalgae in the southern coast of Korea

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This file includes:

Number of pages: 27

Number of Supplementary Tables: Tables S1 to S9

Number of Supplementary Figures: Figs. S1 to S2

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Supplementary Tables

Table S1. Monthly water quality parameters measured in the southern coast of Korea from February to November 2023.

Month	Sites	WT[a] (°C)	DO (mg L^{-1})	Salinity (psu)	pH	NO_2^-+NO_3^- (μM)	NH_4^+ (μM)	PO_4^{3-} (μM)	SiO_2 (μM)
Feb.	S1	10	9.9	34	8.1	4.8	2.0	0.2	2.7
	S2	8	10.2	33	8.2	1.7	0.6	0.1	3.6
	S3	7	10.3	33	8.1	1.2	0.5	0.1	2.2
	S4	11	9.7	34	8.1	3.4	1.9	0.4	6.5
	S5	7	10.4	33	8.2	1.1	0.3	0.0	1.1
	S6	7	10.7	31	8.0	17.0	3.1	0.3	17.2
	S7	7	10.4	34	8.2	1.5	0.5	0.2	6.9
	S8	8	10.1	34	8.1	3.9	1.0	0.4	5.7
	S9	8	10.2	34	8.1	2.3	1.0	0.3	3.6
	S10	8	10.1	34	8.3	2.1	0.4	0.2	1.1
	S11	10	9.9	34	8.2	3.3	0.9	0.2	3.3
	S12	8	10.2	34	8.1	2.3	1.0	0.3	3.6
Apr.	S1	15	8.1	34	8.2	2.3	1.6	0.3	8.6
	S2	15	8.2	34	8.0	5.0	5.2	0.4	11.2
	S3	15	8.2	34	7.9	2.8	3.3	0.3	9.0
	S4	15	8.2	34	7.9	3.7	2.8	0.3	8.0
	S5	15	8.3	33	8.0	1.5	1.2	0.1	5.0
	S6	15	8.4	33	7.9	13.3	3.8	0.3	11.3
	S7	17	7.9	34	7.9	0.5	0.8	0.2	18.7
	S8	16	8.0	34	7.9	4.5	2.4	0.4	12.5
	S9	16	8.2	34	7.9	4.4	5.3	0.7	12.1
	S10	15	8.2	34	8.0	4.3	3.3	0.5	8.5
	S11	15	8.2	34	8.0	1.7	1.3	0.2	6.5
	S12	16	8.1	34	8.0	1.5	1.1	0.2	9.9
May	S1	19	7.9	32	8.2	2.1	1.1	0.1	10.2
	S2	20	7.4	32	8.3	6.6	3.2	0.2	16.7
	S3	20	7.4	32	8.0	5.6	7.6	0.2	6.4
	S4	17	7.9	32	8.1	6.2	3.4	0.2	11.8
	S5	20	7.6	32	8.1	3.7	5.1	0.4	11.1
	S6	19	7.8	31	8.0	50.7	15.9	0.8	33.1
	S7	22	7.3	33	8.1	6.8	1.4	0.5	7.3
	S8	20	7.5	33	8.0	8.3	3.8	0.4	7.4
	S9	18	7.8	31	8.0	12.8	5.9	0.5	14.7
	S10	19	7.7	32	8.1	46.5	5.2	1.9	28.0
	S11	18	7.7	33	8.1	39.1	2.8	0.6	20.7
	S12	20	7.5	32	8.1	8.4	4.2	0.6	7.0
Jun.	S1	20	7.4	33	8.2	1.3	0.8	0.2	13.3
	S2	23	7.1	33	8.2				
	S3	20	7.4	33	7.9	4.5	3.8	0.3	12.8
	S4	21	7.4	33	8.1	1.7	6.6	0.2	7.9
	S5	24	7.1	33	8.0	2.1	1.1	0.2	6.3
	S6	23	7.1	32	8.0	10.2	8.4	1.0	10.9
	S7	26	6.9	33	7.3	4.6	2.8	0.4	20.8
	S8	23	7.1	33	8.0	7.1	5.4	0.6	18.2
	S9	22	7.2	33	7.9	2.8	4.0	0.4	23.4
	S10	22	7.2	33	8.0	13.5	2.4	0.6	22.6
	S11	22	7.2	32	8.1	8.4	2.6	0.3	13.6
	S12	23	7.1	32	8.1				
Jul.	S1	26	7.5	17	8.5	29.7	4.1	0.5	67.7

	S2	29	7.2	17	8.5	26.8	0.7	0.2	38.1
	S3	28	7.3	18	8.4	39.1	0.8	0.1	68.6
	S4	27	6.8	18	8.5	18.7	0.9	0.2	49.4
	S5	28	6.8	20	8.4	13.2	7.4	0.4	31.2
	S6	28	7.0	21	8.0	21.2	3.6	0.2	37.4
	S7	27	7.1	27	8.1	2.8	1.4	0.1	11.4
	S8	26	7.0	29	7.8	10.6	1.8	0.4	23.5
	S9	29	7.3	13	8.4	37.5	5.3	0.4	65.2
	S10	29	7.1	17	8.7	10.6	1.6	0.1	17.1
	S11	27	7.0	27	8.0	5.6	2.9	0.2	16.7
	S12	27	7.0	27	8.1	9.5	5.3	0.5	15.7
Aug.	S1	27	8.4	27	8.1	7.6	1.4	0.2	15.5
	S2	29	9.5	24	8.1	5.7	3.3	0.2	12.3
	S3	28	8.8	26	8.0				
	S4	29	12.0	18	8.5				
	S5	29	8.6	25	8.2	2.3	2.2	0.2	2.7
	S6	28	8.6	21	8.2	25.3	3.2	0.1	32.6
	S7	30	9.5	29	8.0	3.5	1.7	0.1	4.5
	S8	29	7.2	30	7.9	12.3	4.4	0.5	13.1
	S9	29	9.2	23	8.1	7.5	4.1	0.2	27.9
	S10	28	8.6	28	8.0	8.6	3.7	0.3	19.5
	S11	29	8.1	30	8.0	9.5	3.4	0.4	13.2
	S12	29	10.3	29	8.0	73.1	12.5	1.3	69.2
	S13	24	7.0	28	8.1	1.0	3.2	0.6	24.0
Sep..	S1	25	7.0	28	8.1	1.7	3.7	0.3	14.6
	S2	25	5.6	28	7.9	2.6	5.2	0.2	4.8
	S3	23	7.2	19	8.0	54.7	3.0	0.9	73.3
	S4	25	5.5	28	7.9	8.4	3.0	0.5	16.9
	S5	23	7.0	22	8.0	30.8	3.8	0.4	32.5
	S6	26	7.1	30	8.0	5.2	1.8	0.4	13.4
	S7	26	5.6	31	7.9	14.9	2.3	1.1	32.8
	S8	25	5.4	28	7.8	20.5	4.6	1.2	39.1
	S9	25	5.5	30	7.8	16.2	3.6	1.0	29.9
	S10	25	6.8	30	8.1	12.3	1.3	0.5	24.3
	S11	26	5.3	30	7.9	33.3	5.5	1.3	49.8
	S12	16	7.5	34	7.4	9.5	1.4	0.7	19.5
Nov.	S1	16	8.4	34	7.6	5.6	2.0	0.5	25.5
	S2	15	7.6	33	7.5	3.4	1.0	0.5	6.6
	S3	14	7.5	34	7.5	9.3	1.9	0.8	19.9
	S4	16	7.9	33	7.4	3.9	2.1	0.7	12.4
	S5	16	8.5	33	7.5	2.6	1.7	0.6	29.9
	S6	15	8.4	34	7.5	1.4	0.6	0.3	5.9
	S7	17	7.6	34	7.6	10.0	2.3	0.8	21.5
	S8	16	7.7	34	7.5	14.3	3.5	1.0	26.1
	S9	16	7.4	34	7.5	12.8	2.2	0.8	23.7
	S10	17	7.9	35	7.6	6.5	2.1	0.6	18.5
	S11	17	7.7	34	7.6	1.9	0.5	0.2	16.0
	S12	10	9.9	34	8.1	4.8	2.0	0.2	2.7

Table S2. Instrumental conditions for the analysis of lipophilic marine toxins in biological samples using UPLC-MS/MS.

Instrument	HPLC: Agilent Infinity 1290 II MS/MS: Agilent 6470 triple quadrupole mass spectrometer		
Column	Waters X-Bridge C18, 3.0 mm × 150 mm, 5.0 µm		
Column temperature	25 °C		
Mobile phase	(A): 0.05% NH_4OH in water; (B): 0.05% NH_4OH in 90% ACN		
Mobile phase gradient	Time (min)	Mobile phase A (%)	Mobile phase B (%)
	0.0	70	30
	0.5	70	30
	4.0	45	55
	5.0	0	100
	8.0	0	100
	8.8	70	30
	10.0	70	30
Injection volume	5 µL		
Flow rate	0.4 mL min^{-1}		
Ion source	ESI (electrospray ionization)		
Polarity	Positive and negative		
Ion spray voltage	4000 V (positive) and –4500 V (negative)		
Gas temperature	350 °C		
Sheath gas temperature	350 °C		
Nebulizer gas	N_2 (25 psi)		
Sheath Gas	N_2 (11 psi)		

Table S3. Optimized MS/MS parameters of the tandem mass spectrometry for the quantification of 19 lipophilic marine toxins

Compounds	Molecular weight	RT (min)	Precursor ion (m/z)	Product ion (m/z)	Fragmentor (volts)	CE (volts)
YTX	1143.3	1.3	570.3 $[M-2H]^{2-}$	467.1	165	35
				501.4		25
hYTX	1157.4	2.9	577.2 $[M-2H]^{2-}$	472.2	165	32
				508.8		24
PTX2	859.07	7.8	876.5 $[M+NH_4]^+$	823.4	176	26
				841.4		22
PTX11	875.05	7.6	892.4 $[M+NH_4]^+$	839.2	173	26
				821.3		26
OA	805.02	2.8	803.46 $[M-H]^-$	255.0	245	50
				563.2		50
DTX1	819.03	4.0	817.47 $[M-H]^-$	255.0	245	50
				563.0		45
DTX2	805.02	3.2	803.46 $[M-H]^-$	255.0	255	50
				113.0		60
AZA1	842.08	6.8	842.52 $[M+H]^+$	824.3	199	32
				806.3		36
AZA2	856.11	6.9	856.52 $[M+H]^+$	838.3	209	35
				820.3		45
AZA3	828.05	6.1	828.49 $[M+H]^+$	810.3	198	35
				792.2		45
AZA4	844.05	5.8	844.48 $[M+H]^+$	826.2	202	35
				808.2		50
AZA5	844.05	5.1	844.48 $[M+H]^+$	826.3	202	30
				808.2		40
BTX1	867.07	8.4	867.5 $[M+H]^+$	849.6	155	10
				355.3		20
BTX2	895.08	8.1	895.5 $[M+H]^+$	249.3	135	35
				877.6	255	15
BTX3	897.10	7.5	897.5 $[M+H]^+$	879.8	155	15
				725.5		20
BTX5	911.2	4.7	911.5 $[M+H]^+$	893.8	155	20
				875.5		15
GYM	507.7	7.2	508.3 $[M+H]^+$	490.5	155	25
				136.1		45
SPX	691.9	7.5	692.4 $[M+H]^+$	164.2	205	55
				674.7		30
DA	311.3	1.5	312.1$[M+H]^+$	266.3	110	15
				248.3		15

Table S4. Linearity (R^2), limit of detection (LOD), limit of quantification (LOQ), recovery rates, and precision (CV) for 19 lipophilic marine toxins determined using UPLC-MS/MS.

Compounds	Linear range (ng mL^{-1})	R^2	LOD (ng g^{-1} ww)	LOQ (ng g^{-1} ww)	Recovery of spike test (n = 4, mean ± SD)	Coefficient of variation (n = 4)
YTX	1–50	0.994	0.33	1.05	96 ± 0.11	5.3
hYTX	1–50	0.996	0.35	1.12	96 ± 0.11	5.6
PTX2	1–50	0.996	0.36	1.13	95 ± 0.11	5.9
PTX11	1–50	0.996	0.49	1.59	92 ± 0.16	8.2
OA	1–50	0.997	0.41	1.23	91 ± 0.13	5.7
DTX1	1–50	0.997	0.36	1.13	93 ± 0.11	5.6
DTX2	1–50	0.999	0.35	1.12	94 ± 0.11	7.1
AZA1	1–50	0.999	0.34	1.07	94 ± 0.1	5.6
AZA2	1–50	0.999	0.35	1.12	96 ± 0.11	5.6
AZA3	1–50	0.999	0.36	1.14	95 ± 0.11	5.9
AZA4	1–50	0.999	0.3	0.96	96 ± 0.09	4.9
AZA5	1–50	0.999	0.51	1.61	96 ± 0.16	8.2
BTX1	5–200	0.999	2.75	8.75	86.7 ± 0.79	5.9
BTX2	5–200	0.999	1.72	5.46	88.7 ± 0.54	2.5
BTX3	5–200	0.999	3.49	11.1	85.6 ± 1.1	7.6
BTX5	5–200	0.999	3.61	11.4	92.3 ± 1.2	7.7
GYM	1–50	0.999	0.21	0.67	87.3 ± 0.87	6.1
SPX	1–50	0.999	0.27	0.85	90.1 ± 0.56	5.6
DA	1–50	0.999	0.45	1.41	76.1 ± 2.1	7.6

Table S5. Abundance of phytoplanktons identified in the southern coast of Korea from February to November 2023.

Month	Sites	Abundance of phytoplankton (×10^3 cells L^{-1})					
		Bacillariophyceae	**Dinophyceae**	**Cryptophyceae**	**Dictyochophyceae**	**Raphidophyceae**	**Others**
Feb.	S1	1076	25	7.1	ND[a]	ND	16
	S2	776	14	1.6	ND	ND	23
	S3	555	20	ND	ND	ND	ND
	S4	188	1.4	5.7	ND	ND	ND
	S5	543	8.0	11	ND	ND	ND
	S6	14	11	32	ND	ND	35
	S7	11	1.2	21	ND	ND	ND
	S8	34	5.5	23	ND	ND	2.7
	S9	258	3.0	29	ND	ND	ND
	S10	240	0.94	19	ND	ND	ND
	S11	524	0.80	6.4	0.40	ND	0.40
	S12	94	4.8	107	ND	ND	6.1
Apr.	S1	18	2.9	98	ND	ND	50
	S2	36	35	35	ND	ND	ND
	S3	4.3	19	1.7	0.43	ND	ND
	S4	22	2.0	6.4	0.4	ND	ND
	S5	4.9	32	7.6	ND	ND	18
	S6	5.7	10	15	ND	ND	10
	S7	12	4.2	84	ND	ND	14
	S8	2.9	4.9	42	ND	ND	ND
	S9	2.1	2.5	43	ND	ND	ND
	S10	3.9	15	26	ND	ND	ND
	S11	38	28	68	0.44	ND	ND
	S12	137	19	115	1	ND	ND
May	S1	1673	53	23	1.2	ND	ND
	S2	45	861	183	0.43	ND	1.3
	S3	346	80	38	0.40	ND	ND
	S4	1178	77	35	1.4	ND	ND
	S5	122	75	29	ND	ND	ND
	S6	53	77	65	ND	ND	355
	S7	115	8.6	93	ND	ND	17
	S8	40	12	91	ND	ND	ND
	S9	86	24	65	ND	ND	ND
	S10	27	8.0	53	ND	ND	ND
	S11	154	25	124	ND	ND	ND
	S12	505	21	62	ND	ND	ND
Jun.	S1	29	138	176	1.3	ND	0.9

	S2	4.7	446	110	0.4	ND	ND
	S3	252	23	92	0.8	ND	29
	S4	97	35	18	0.9	ND	11
	S5	87	34	34	2.1	ND	58
	S6	179	30	9.1	ND	ND	ND
	S7	123	248	50	ND	ND	1.9
	S8	35	37	5.0	ND	ND	1.7
	S9	91	89	38	ND	ND	ND
	S10	16	50	407	1.2	ND	248
	S11	55	40	51	0.5	ND	ND
	S12	78	145	128	0.4	ND	ND
Jul.	S1	902	509	17	ND	ND	3432
	S2	556	285	11	ND	ND	4272
	S3	96	150	28	ND	ND	38139
	S4	964	73	78	ND	ND	321
	S5	140	55	21	ND	ND	15
	S6	56	119	425	ND	ND	834
	S7	855	27	139	ND	ND	80
	S8	86	165	287	ND	ND	36
	S9	2756	16	124	ND	ND	28
	S10	5802	21	193	ND	ND	135
	S11	63	39	20	ND	ND	ND
	S12	517	41	18	ND	ND	6.2
Aug.	S1	1703	219	6.3	ND	0.8	ND
	S2	591	519	2.5	ND	2.1	ND
	S3	1565	36	1.7	ND	0.9	ND
	S4	6653	121	3.9	ND	5.5	ND
	S5	977	56	ND	ND	ND	ND
	S6	59	241	15	ND	ND	ND
	S7	652	69	5.3	ND	ND	ND
	S8	918	42	1.3	ND	ND	ND
	S9	553	138	3.7	ND	ND	5264
	S10	1814	17	ND	ND	0.4	0.42
	S11	77	46	6.1	ND	ND	3.5
	S12	25	47	5.0	ND	ND	963
Sep.	S1	906	27	ND	ND	ND	ND
	S2	1368	25	ND	ND	0.5	ND
	S3	3943	23	ND	ND	0.4	ND
	S4	545	37	35	ND	ND	49
	S5	686	106	ND	ND	ND	1.2

	S6	301	8.6	4.3	ND	ND	ND
	S7	1522	19	4.0	ND	0.4	ND
	S8	28	28	5.3	ND	ND	280
	S9	352	52	390	ND	ND	ND
	S10	313	7.0	17	ND	5.2	30
	S11	138	15	72	ND	ND	ND
	S12	16	30	168	ND	499	ND
Nov.	S1	11	13	25	ND	ND	ND
	S2	17	102	27	ND	ND	ND
	S3	201	2.2	30	ND	ND	1.7
	S4	5.1	13	192	ND	ND	27
	S5	5.9	1.1	175	ND	ND	23
	S6	809	4.1	4	ND	ND	ND
	S7	134	3.7	6	ND	ND	ND
	S8	7.9	4.8	56	0.4	ND	ND
	S9	3.6	5.3	286	0.4	ND	44
	S10	ND	3.4	277	ND	ND	ND
	S11	21	5.1	9	ND	ND	ND
	S12	1234	2.5	17	0.4	ND	ND

[a] ND: Not detected.

Table S6. Abundance of causative microalgae of marine biotoxins in the southern coast of Korea from February to November 2023.

Month	Sites	*Pseudo-nitzchia* spp. (cells L^{-1})	*Alexandrium* spp. (cells L^{-1})	*G. spinifera* (cells L^{-1})	*D. acuminata* (cells L^{-1})	*Karenia brevis* (cells L^{-1})
Feb.	S1	10690	450	ND[a]	ND	ND
	S2	12870	ND	ND	400	ND
	S3	80030	ND	ND	ND	ND
	S4	2850	ND	ND	ND	ND
	S5	58920	ND	ND	ND	ND
	S6	840	ND	ND	ND	ND
	S7	1210	ND	ND	ND	ND
	S8	780	ND	ND	ND	ND
	S9	750	ND	ND	ND	ND
	S10	2810	ND	ND	ND	ND
	S11	1600	ND	ND	ND	ND
	S12	1750	ND	ND	ND	ND
Apr.	S1	1660	ND	ND	ND	ND
	S2	1870	470	ND	470	ND
	S3	1280	ND	ND	ND	ND
	S4	1600	ND	ND	ND	ND
	S5	1140	3430	ND	760	ND
	S6	2190	870	ND	ND	ND
	S7	1270	ND	ND	ND	ND
	S8	820	ND	ND	ND	ND
	S9	830	ND	ND	ND	ND
	S10	1730	430	ND	ND	ND
	S11	2660	ND	ND	ND	ND
	S12	1880	ND	ND	1500	ND
May	S1	1592390	400	ND	400	ND
	S2	36140	16580	1700	14030	ND
	S3	334730	400	ND	400	ND
	S4	1126080	ND	ND	ND	ND
	S5	120180	ND	ND	750	ND
	S6	52010	ND	ND	ND	ND
	S7	13150	ND	ND	ND	ND
	S8	17720	ND	ND	ND	ND
	S9	64450	ND	ND	ND	ND
	S10	1260	ND	ND	420	ND
	S11	116430	ND	380	380	ND
	S12	368870	ND	ND	ND	ND
Jun.	S1	7020	ND	ND	440	ND

	S2	ND	5100	ND	1570	ND
	S3	3210	ND	ND	800	ND
	S4	33570	ND	ND	860	ND
	S5	36430	860	ND	ND	ND
	S6	ND	ND	ND	ND	ND
	S7	ND	ND	ND	ND	ND
	S8	4160	1660	ND	420	ND
	S9	62450	2170	ND	430	ND
	S10	780	ND	ND	1960	ND
	S11	2910	ND	ND	ND	ND
	S12	2200	ND	ND	ND	ND
Jul.	S1	31850	800	ND	ND	ND
	S2	41380	ND	ND	ND	ND
	S3	15880	ND	ND	ND	ND
	S4	35280	ND	ND	ND	ND
	S5	108270	430	ND	ND	ND
	S6	6410	920	ND	ND	ND
	S7	526290	ND	ND	ND	ND
	S8	20890	ND	ND	420	ND
	S9	ND	ND	ND	ND	ND
	S10	16820	1260	ND	ND	ND
	S11	24840	ND	ND	ND	ND
	S12	99000	410	ND	410	ND
Aug.	S1	774270	390	ND	ND	ND
	S2	444290	ND	ND	410	410
	S3	1487010	ND	ND	ND	430
	S4	1459740	ND	ND	ND	1180
	S5	766500	ND	ND	ND	ND
	S6	22610	ND	ND	ND	810
	S7	427110	ND	ND	ND	380
	S8	62780	ND	ND	ND	ND
	S9	43860	ND	ND	ND	370
	S10	138680	ND	ND	420	ND
	S11	2600	ND	ND	ND	430
	S12	1260	ND	ND	ND	ND
Sep.	S1	613140	ND	ND	ND	ND
	S2	515810	480	ND	ND	ND
	S3	1834150	380	ND	ND	ND
	S4	517550	ND	ND	420	ND
	S5	537470	4730	ND	ND	ND

	S6	188120	ND	ND	ND	ND
	S7	1269910	ND	ND	ND	ND
	S8	19540	ND	ND	ND	ND
	S9	36540	ND	ND	ND	ND
	S10	72130	ND	ND	ND	ND
	S11	37270	ND	ND	ND	440
	S12	860	430	ND	ND	ND
Nov.	S1	2710	ND	ND	ND	ND
	S2	11580	ND	ND	ND	ND
	S3	62480	ND	ND	ND	ND
	S4	850	ND	ND	ND	ND
	S5	1840	ND	ND	ND	ND
	S6	3650	ND	ND	ND	ND
	S7	14910	ND	ND	ND	ND
	S8	1310	ND	ND	ND	ND
	S9	1210	ND	ND	ND	ND
	S10	ND	ND	ND	ND	ND
	S11	420	ND	ND	ND	ND
	S12	830	ND	ND	ND	ND

[a] ND: Not detected.

Table S7. Concentrations of LMTs in phytoplanktons (20–200 μm SPM) collected from the southern coast of Korea from February to November 2023.

Month	Sites	Concentrations of LMTs in phytoplankton (ng g^{-1} ww)																		
		YTX	hYTX	PTX2	PTX11	AZA1	AZA2	AZA3	AZA4	AZA5	OA	DTX1	DTX2	BTX1	BTX2	BTX3	BTX5	GYM	SPX	DA
Feb.	S1	-[a]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	S2	ND[b]	9	52	21	ND	ND	ND	ND	ND	5.3	7.8	ND	ND	ND	ND	ND	ND	ND	ND
	S3	ND	ND	16	3.5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S4	ND	ND	8.7	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S5	ND	ND	3.7	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	S8	ND	ND	3.8	ND	ND	ND	ND	ND	ND	4.0	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	ND	NQ[c]	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S10	ND	ND	3.03	ND	ND	ND	ND	ND	ND	9.8	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	ND	1.6	ND	ND	ND	ND	ND	ND	2.8	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	ND	7.7	ND	ND	ND	ND	ND	ND	6.4	ND	ND	ND	ND	ND	ND	ND	ND	ND
Apr.	S1	ND	ND	47	2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S2	ND	ND	275	36	ND	ND	ND	ND	ND	ND	38	ND	ND	ND	ND	ND	ND	ND	ND
	S3	ND	ND	236	17	ND	ND	ND	ND	ND	ND	25	ND	ND	ND	ND	ND	ND	ND	ND
	S4	ND	ND	146	24	ND	ND	ND	ND	ND	ND	13	ND	ND	ND	ND	ND	ND	ND	ND
	S5	9	ND	189	20	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S6	ND	ND	19	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S7	ND	ND	21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S8	ND	ND	350	4	ND	ND	ND	ND	ND	ND	16	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	ND	102	8	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S10	ND	ND	962	124	ND	ND	ND	ND	ND	ND	31	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	ND	946	53	ND	ND	ND	ND	ND	ND	34	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	ND	858	51	ND	ND	ND	ND	ND	ND	30	ND	ND	ND	ND	ND	ND	ND	ND
May	S1	ND	5	12	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S2	ND	10	537	95	ND	ND	ND	ND	ND	ND	14	ND	ND	ND	ND	ND	ND	ND	ND
	S3	5	20	73	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S4	ND	7	120	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S5	ND	7.3	5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S6	ND	ND	71	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S7	7.4	ND	11	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S8	ND	ND	147	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	ND	98	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S10	ND	31	608	17	ND	ND	ND	ND	ND	4	16	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	14	344	27	ND	ND	ND	ND	ND	ND	15	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	ND	90	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Jun.	S1	ND	99	164	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S2	ND	66	278	9.7	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S3	ND	ND	29	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S4	ND	90	100	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S5	ND	70	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S6	ND	15	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S7	ND	24	52	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S8	ND	47	324	NQ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	7.8	30	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

	S10	ND	124	680	16	ND	ND	ND	ND	ND	3.5	12	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	38	12	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	46	173	23	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Jul.	S1	ND	100	29	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S2	ND	35	18	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S3	ND	153	56	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S4	ND	194	18	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S5	ND	19	3.6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S6	ND	19	4.0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S7	ND	ND	3.0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S8	ND	ND	11	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	ND	3.0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S10	ND	ND	NQ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	ND	6.5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	ND	8.0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Aug.	S1	ND	ND	NQ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S2	ND	ND	12	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S3	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S4	ND	ND	NQ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S7	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S8	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	ND	5.7	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S10	ND	ND	42	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	ND	15	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	ND	NQ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sep.	S1	ND	ND	24	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S2	ND	ND	5.6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S3	ND	ND	NQ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S4	ND	ND	79	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S5	ND	ND	20	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S6	ND	ND	11	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S7	ND	ND	0	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S8	ND	ND	NQ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	ND	2.6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S10	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	ND	NQ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	ND	31	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Nov.	S1	ND	ND	16	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S2	ND	ND	71	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S3	ND	ND	2.3	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S4	ND	ND	4.3	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S5	ND	ND	5.9	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S7	ND	ND	3.5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S8	ND	ND	2.9	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	ND	63	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S10	ND	ND	23	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	ND	9.6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

S12	ND	ND	36	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

[a]-: Not collected.

[b] ND: Below limit of detection.

[c] NQ: Below limit of quantification.

Table S8. Concentrations of LMTs in mussels collected from the southern coast of Korea from February to November 2023.

Month	Sites	Concentrations of LMTs in mussels (ng g^{-1} ww)																		
		YTX	hYTX	PTX2	PTX11	AZA1	AZA2	AZA3	AZA4	AZA5	OA	DTX1	DTX2	BTX1	BTX2	BTX3	BTX5	GYM	SPX	DA
Feb.	S1	ND[a]	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S2	ND	18	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S3	ND	15	NQ[b]	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S4	ND	15	NQ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S5	ND	ND	NQ	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S7	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S8	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S10	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	17	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Apr.	S1	ND	33	6.1	ND	ND	ND	ND	ND	ND	9.04	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S2	6	27	22	ND	ND	ND	ND	ND	ND	115	752	ND	ND	ND	ND	ND	ND	ND	ND
	S3	25	ND	4.7	ND	ND	ND	ND	ND	ND	8.2	148	ND	ND	ND	ND	ND	ND	ND	ND
	S4	ND	25	2.2	ND	ND	ND	ND	ND	ND	ND	38	ND	ND	ND	ND	ND	ND	ND	ND
	S5	146	16	4.6	ND	ND	ND	ND	ND	ND	6.9	82	ND	ND	ND	ND	ND	ND	ND	ND
	S6	ND	14	1.3	ND	ND	ND	ND	ND	ND	2.1	37	ND	ND	ND	ND	ND	ND	ND	ND
	S7	ND	15	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S8	ND	ND	5.1	ND	ND	ND	ND	ND	ND	9.5	24	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	ND	4.0	ND	ND	ND	ND	ND	ND	1.6	8.8	ND	ND	ND	ND	ND	ND	ND	ND
	S10	ND	ND	17	ND	ND	ND	ND	ND	ND	45	232	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	19	21	ND	ND	ND	ND	ND	ND	41	145	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	15	21	ND	ND	ND	ND	ND	ND	19	81	ND	ND	ND	ND	ND	ND	ND	ND
May	S1	NQ	20	ND	ND	ND	ND	ND	ND	ND	NQ	50	ND	ND	ND	ND	ND	ND	ND	ND
	S2	13	9.4	ND	ND	ND	ND	ND	ND	ND	21	227	ND	ND	ND	ND	ND	ND	ND	ND
	S3	47	32	ND	ND	ND	ND	ND	ND	ND	NQ	59	ND	ND	ND	ND	ND	ND	ND	ND
	S4	-[c]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	S5	66	24	ND	ND	ND	ND	ND	ND	ND	ND	36	ND	ND	ND	ND	ND	ND	ND	ND
	S6	16	6	ND	ND	ND	ND	ND	ND	ND	ND	22	ND	ND	ND	ND	ND	ND	ND	ND
	S7	29	6.5	ND	ND	ND	ND	ND	ND	ND	ND	6.9	ND	ND	ND	ND	ND	ND	ND	ND
	S8	ND	22	ND	ND	ND	ND	ND	ND	ND	2.8	29	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	4.6	ND	ND	ND	ND	ND	ND	ND	ND	11	ND	ND	ND	ND	ND	ND	ND	ND
	S10	ND	67	ND	ND	ND	ND	ND	ND	ND	34	147	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	55	ND	ND	ND	ND	ND	ND	ND	28	58	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	43	ND	ND	ND	ND	ND	ND	ND	16	66	ND	ND	ND	ND	ND	ND	ND	ND
Jun.	S1	ND	245	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S2	ND	226	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S3	ND	191	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S4	ND	414	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S5	ND	186	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S6	ND	15	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S7	ND	153	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S8	ND	84	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	151	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S10	ND	415	ND	ND	ND	ND	ND	ND	ND	44	98	ND	ND	ND	ND	ND	ND	ND	ND

	S11	ND	603	ND	ND	ND	ND	ND	ND	ND	9.9	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	227	ND	ND	ND	ND	ND	ND	ND	23	40	ND	ND	ND	ND	ND	ND	ND	ND
Jul.	S1	ND	217	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S2	ND	1600	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S3	ND	540	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S4	ND	997	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S5	ND	274	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S6	ND	176	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S7	ND	112	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S8	ND	109	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	80	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S10	ND	158	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	172	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	91	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Aug.	S1	ND	274	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S2	ND	656	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S3	ND	290	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S4	ND	118	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	S6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	S7	ND	38	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S8	ND	38	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	24	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S10	ND	115	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	92	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	68	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sep.	S1	ND	99	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S2	ND	243	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S3	ND	218	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S4	ND	96	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	S6	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	S7	ND	8	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S8	ND	36	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S9	ND	21	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S10	ND	103	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	30	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	8.5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Nov.	S1	ND	28	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S2	ND	30	12	ND	ND	ND	ND	ND	ND	ND	41	ND	ND	ND	ND	ND	ND	ND	ND
	S3	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	S4	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	S5	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	S6	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	24	ND	ND	ND	ND	ND	ND	ND	ND
	S7	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	S8	ND	ND	5.1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S9	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	S10	ND	25	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S11	ND	13	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	S12	ND	ND	ND	ND	ND	ND	ND	ND	ND	15	ND	ND	ND	ND	ND	ND	ND	ND	ND

[a] ND: Below limit of detection.
[b] NQ: Below limit of quantification.
[c] -: Not collected.

Table S9. Abundances (cells L^{-1}) of potential LMT-producing phytoplankton genera in the southern coast of Korea from February to November 2023.

Month	Genus	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
Feb.	*Amphora*	890	ND[a]	850	480	ND	ND	ND	ND	470	400	440	890
	Asterionellopsis	450	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	450
	Chaetoceros	174660	78040	20430	19030	426960	6480	17260	15050	25270	14440	50780	174660
	Cosinodiscus	890	400	ND	ND	ND	ND	ND	ND	ND	ND	ND	890
	Dactyliosolen	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Detonula	ND	ND	ND	ND	ND	ND	ND	750	ND	ND	ND	ND
	Ditylum	450	400	ND	ND	ND	ND	ND	ND	ND	ND	ND	450
	Entomoneis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Leptocylindrus	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Licmphora	ND	400	ND	480	ND	400	780	ND	ND	800	ND	ND
	Navicular	ND	ND	ND	480	2810	400	ND	ND	1870	1200	ND	ND
	Melosira	ND	ND	ND	ND	ND	ND	ND	ND	ND	800	ND	ND
	Odontella	4010	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	4010
	Pleurosigma	ND	ND	ND	ND	ND	ND	ND	ND	940	ND	ND	ND
	Pseudo-nitzschia	10690	12870	80030	2850	58920	1210	780	750	2810	1600	1750	10690
	Skeletonema	857250	675800	435890	156960	16840	1620	10590	3010	ND	ND	4820	857250
	Thalassionema	3560	800	3410	950	ND	ND	390	ND	ND	800	440	3560
	Alexandrium	450	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	450
	Akashiwo	ND	800	ND	ND	ND	400	ND	380	470	ND	1310	ND
	Ceratium	ND	ND	ND	ND	ND	ND	ND	380	ND	ND	ND	ND
	Cochlodinium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Dinophysis	ND	400	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Gonyaulax	450	400	430	ND	ND	ND	390	ND	ND	ND	ND	450
	Gymnodinium	8020	8850	5530	480	6550	810	1180	750	ND	400	2190	8020
	Gyrodinium	9800	1610	3410	480	940	ND	780	1130	ND	ND	440	9800
	Karenia	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Oxytoxum	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Polykrikos	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Prorocentrum	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Protoperidinium	ND	ND	ND	ND	ND	ND	ND	380	ND	400	440	ND
	Scrippsiella	ND	ND	3410	480	470	ND	ND	ND	470	ND	ND	ND
	Dictyocha	ND	ND	ND	ND	ND	ND	ND	ND	ND	400	ND	ND
	Cryptomonas	7130	1610	ND	5710	11220	21050	22750	29350	18720	6420	106810	7130
	Achnanthes	ND	400	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Diploneis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Linglodinium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Apr.	*Amphora*	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Asterionellopsis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

	Chaetoceros	1660	31250	ND	ND	ND	7170	ND	ND	ND	23910	127300	1660
	Cosinodiscus	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Dactyliosolen	ND	ND	ND	4790	ND	ND	ND	ND	ND	ND	ND	ND
	Detonula	ND	930	ND	1990	ND	ND	ND	ND	ND	3540	ND	ND
	Ditylum	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Entomoneis	830	ND	ND	800	ND	420	410	ND	ND	890	ND	830
	Leptocylindrus	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Licmphora	420	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	420
	Navicular	3740	ND	ND	1600	1140	ND	ND	ND	430	440	ND	3740
	Melosira	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	3760	ND
	Odontella	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Pleurosigma	ND	ND	ND	400	ND	ND	ND	ND	ND	ND	ND	ND
	Pseudo-nitzschia	1660	1870	1280	1600	1140	1270	820	830	1730	2660	1880	1660
	Skeletonema	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Thalassionema	2910	ND	ND	7580	380	ND	ND	ND	430	3100	ND	2910
	Alexandrium	ND	470	ND	ND	3430	ND	ND	ND	430	ND	ND	ND
	Akashiwo	ND	ND	850	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Ceratium	ND	ND	ND	ND	ND	ND	ND	ND	860	2210	3000	ND
	Cochlodinium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Dinophysis	ND	470	ND	ND	760	ND	ND	ND	ND	ND	1500	ND
	Gonyaulax	420	470	ND	ND	ND	ND	410	ND	ND	ND	ND	420
	Gymnodinium	ND	3730	5540	ND	14120	3380	1640	1240	7780	17710	12020	ND
	Gyrodinium	2080	2800	6400	ND	1530	840	2450	410	ND	3100	ND	2080
	Karenia	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Oxytoxum	420	930	ND	ND	ND	ND	ND	ND	ND	ND	ND	420
	Polykrikos	ND	ND	ND	400	ND	ND	ND	ND	ND	ND	ND	ND
	Prorocentrum	ND	ND	ND	ND	ND	ND	ND	ND	430	ND	ND	ND
	Protoperidinium	ND	ND	ND	ND	760	ND	ND	ND	860	440	ND	ND
	Scrippsiella	ND	23320	2990	1200	7630	ND	ND	ND	3460	2210	1130	ND
	Dictyocha	ND	ND	430	400	ND	ND	ND	ND	ND	440	750	ND
	Cryptomonas	97770	35450	1710	6380	7630	83560	41710	43040	26360	68190	114910	97770
	Achnanthes	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Diploneis	ND	470	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Linglodinium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
May	*Amphora*	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Asterionellopsis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Chaetoceros	25050	6380	8370	15890	ND	76620	15450	18540	24350	32340	133860	25050
	Cosinodiscus	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Dactyliosolen	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Detonula	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	380	ND
	Ditylum	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Entomoneis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

	Leptocylindrus	24240	ND	1200	12620	ND	ND	ND	ND	ND	ND	ND	24240
	Licmphora	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Navicular	810	ND	ND	470	ND	ND	ND	ND	420	ND	ND	810
	Melosira	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Odontella	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Pleurosigma	ND	ND	ND	ND	ND	ND	ND	440	ND	ND	ND	ND
	Pseudo-nitzschia	1592390	36140	334730	1126080	120180	13150	17720	64450	1260	116430	368870	1592390
	Skeletonema	15350	ND	ND	ND	ND	ND	6360	ND	ND	ND	ND	15350
	Thalassionema	11310	1280	800	22430	1500	ND	450	1770	ND	1520	ND	11310
	Alexandrium	400	16580	400	ND	ND	ND	ND	ND	ND	ND	ND	400
	Akashiwo	810	ND	ND	1400	2250	ND	ND	ND	ND	ND	380	810
	Ceratium	ND	430	ND	ND	1500	ND	ND	880	2520	1520	380	ND
	Cochlodinium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Dinophysis	400	14460	400	ND	750	ND	ND	ND	420	380	ND	400
	Gonyaulax	400	2550	400	1400	380	380	ND	ND	ND	380	380	400
	Gymnodinium	27480	571460	33470	56070	42060	3760	3640	4410	3360	12560	3040	27480
	Gyrodinium	18590	4250	7970	1870	4510	750	2730	3530	840	2280	4560	18590
	Karenia	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Oxytoxum	400	850	ND	ND	1500	ND	ND	ND	420	ND	ND	400
	Polykrikos	ND	ND	400	ND	ND	ND	ND	ND	ND	ND	6460	ND
	Prorocentrum	810	161570	ND	3740	3760	750	450	ND	420	1140	380	810
	Protoperidinium	ND	2130	400	ND	1500	ND	2270	ND	ND	1140	1900	ND
	Scrippsiella	810	42520	9560	9350	9010	2630	2730	14130	ND	3040	2280	810
	Dictyocha	1210	430	400	1400	ND	ND	ND	ND	ND	ND	ND	1210
	Cryptomonas	23440	182830	38260	35040	28540	93150	90880	65340	52910	123660	61610	23440
	Achnanthes	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Diploneis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Linglodinium	ND	850	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Jun.	*Amphora*	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Asterionellopsis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Chaetoceros	14050	3140	212790	40030	25710	110400	19130	22550	12530	49530	72740	14050
	Cosinodiscus	ND	ND	ND	ND	ND	ND	420	ND	ND	490	ND	ND
	Dactyliosolen	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Detonula	1760	ND	ND	4730	ND	ND	ND	ND	ND	ND	ND	1760
	Ditylum	440	ND	800	ND	ND	ND	ND	ND	ND	ND	ND	440
	Entomoneis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Leptocylindrus	1320	ND	ND	3440	3430	12520	6650	1730	1570	1940	2200	1320
	Licmphora	440	390	ND	ND	ND	ND	1660	ND	ND	ND	ND	440
	Navicular	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Melosira	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Odontella	ND	ND	400	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Pleurosigma	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

	Pseudo-nitzschia	7020	ND	3210	33570	36430	ND	4160	62450	780	2910	2200	7020
	Skeletonema	ND	ND	27300	7750	6430	ND	1660	ND	ND	ND	ND	ND
	Thalassionema	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Alexandrium	ND	5100	ND	ND	860	ND	1660	2170	ND	ND	ND	ND
	Akashiwo	880	16460	ND	ND	ND	2320	ND	ND	ND	ND	ND	880
	Ceratium	1760	1570	ND	ND	430	ND	1250	34260	19190	970	1320	1760
	Cochlodinium	3070	91720	ND	ND	ND	460	420	ND	ND	ND	ND	3070
	Dinophysis	440	1570	800	860	ND	ND	420	430	1960	ND	ND	440
	Gonyaulax	2190	1180	ND	430	1710	460	ND	870	ND	ND	ND	2190
	Gymnodinium	28090	4700	3210	10760	10710	8350	15800	20820	7830	22340	44080	28090
	Gyrodinium	7900	780	ND	6890	2140	930	2500	13880	3130	4860	57310	7900
	Karenia	ND	ND	ND	ND	ND	ND	ND	ND	390	490	ND	ND
	Oxytoxum	2190	780	ND	ND	ND	ND	1250	ND	5880	ND	ND	2190
	Polykrikos	440	1960	ND	ND	ND	ND	420	1730	390	ND	ND	440
	Prorocentrum	61890	285360	14450	7750	8570	224520	4580	3040	4310	490	29540	61890
	Protoperidinium	14050	6270	1200	1290	860	2780	1660	870	1570	ND	2200	14050
	Scrippsiella	10530	16460	800	2580	6860	5570	4160	4340	1960	6800	6610	10530
	Dictyocha	1320	390	800	860	2140	ND	ND	ND	1180	490	440	1320
	Cryptomonas	175570	109750	92340	18080	34280	50100	4990	38160	407330	51470	127840	175570
	Achnanthes	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Diploneis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Linglodinium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Jul.	*Amphora*	800	ND	ND	ND	ND	380	ND	ND	ND	ND	ND	800
	Asterionellopsis	ND	ND	ND	ND	ND	380	840	440	ND	ND	1230	ND
	Chaetoceros	789130	410650	51600	188180	11980	112500	31340	ND	24380	8130	283850	789130
	Cosinodiscus	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Dactyliosolen	ND	1180	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Detonula	4780	2360	2650	15680	8990	ND	5010	ND	ND	1360	1640	4780
	Ditylum	400	ND	ND	ND	ND	ND	840	ND	ND	ND	410	400
	Entomoneis	ND	ND	ND	ND	ND	380	ND	ND	ND	ND	ND	ND
	Leptocylindrus	7960	5520	10590	6270	7280	123560	8360	870	2520	ND	34510	7960
	Licmphora	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Navicular	ND	ND	ND	780	ND	ND	ND	ND	ND	ND	ND	ND
	Melosira	ND	390	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Odontella	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Pleurosigma	1990	790	ND	1960	ND	380	ND	ND	ND	ND	ND	1990
	Pseudo-nitzschia	31850	41380	15880	35280	108270	526290	20890	ND	16820	24840	99000	31850
	Skeletonema	59720	92220	11030	697830	ND	15250	7520	2752300	5744140	20330	87090	59720
	Thalassionema	ND	ND	ND	ND	ND	1530	1250	ND	5890	ND	ND	ND
	Alexandrium	800	ND	ND	ND	430	ND	ND	ND	1260	ND	410	800
	Akashiwo	1590	1180	ND	2350	ND	ND	420	ND	ND	ND	ND	1590
	Ceratium	ND	ND	ND	ND	ND	ND	ND	ND	ND	11290	ND	ND

	Cochlodinium	ND	ND	1760	780	ND	ND	ND	ND	ND	ND	ND	ND
	Dinophysis	ND	ND	ND	ND	ND	ND	420	ND	ND	ND	410	ND
	Gonyaulax	ND	390	440	2350	860	760	1670	2610	4200	ND	3290	ND
	Gymnodinium	220570	190740	70130	31360	27390	18310	54310	3480	5040	26200	8220	220570
	Gyrodinium	27870	20490	7940	11760	7700	ND	8360	5230	ND	ND	ND	27870
	Karenia	ND	ND	ND	390	1710	380	ND	ND	ND	ND	ND	ND
	Oxytoxum	ND	ND	ND	ND	ND	ND	420	ND	ND	ND	ND	ND
	Polykrikos	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	400
	Prorocentrum	144130	40590	ND	1180	ND	1530	18800	870	ND	ND	5750	144130
	Protoperidinium	7960	6310	1320	8230	1710	1530	2510	ND	ND	ND	9860	7960
	Scrippsiella	105510	25220	7060	7840	5140	2670	76040	3480	10090	900	11500	105510
	Dictyocha	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Cryptomonas	16720	10640	27790	78410	20540	139200	287450	123680	193380	20330	18070	16720
	Achnanthes	400	ND	440	ND	ND	760	840	ND	ND	ND	ND	400
	Diploneis	ND	ND	ND	ND	ND	380	420	ND	ND	ND	ND	ND
	Linglodinium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Aug.	*Amphora*	ND	ND	ND	ND	410	ND	ND	ND	ND	ND	ND	ND
	Asterionellopsis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Chaetoceros	117310	41140	5170	ND	65940	216970	368880	ND	192150	43300	14240	117310
	Cosinodiscus	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Dactyliosolen	ND	ND	ND	ND	ND	ND	4330	ND	ND	ND	ND	ND
	Detonula	1170	820	2160	ND	ND	4550	ND	ND	3760	2160	ND	1170
	Ditylum	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Entomoneis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Leptocylindrus	132960	ND	3880	21190	16480	3030	38970	62140	505430	12990	ND	132960
	Licmphora	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Navicular	ND	ND	ND	ND	ND	ND	ND	730	ND	ND	ND	ND
	Melosira	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Odontella	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Pleurosigma	2350	1230	ND	780	410	ND	ND	ND	ND	430	ND	2350
	Pseudo-nitzschia	774270	444290	1487010	1459740	766500	427110	62780	43860	138680	2600	1260	774270
	Skeletonema	656960	102840	61200	5085550	76650	ND	382730	321660	213030	12990	8380	656960
	Thalassionema	11730	ND	3880	14910	30500	ND	59750	18280	292400	1730	840	11730
	Alexandrium	390	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	390
	Akashiwo	7820	1230	ND	ND	ND	ND	430	ND	ND	ND	ND	7820
	Ceratium	ND	ND	ND	390	ND	ND	ND	ND	ND	ND	ND	ND
	Cochlodinium	170890	262050	ND	ND	ND	ND	ND	ND	ND	ND	ND	170890
	Dinophysis	ND	410	ND	ND	ND	ND	ND	ND	420	ND	ND	ND
	Gonyaulax	ND	410	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Gymnodinium	14080	133700	20690	64350	18540	9860	11690	29240	8350	24250	12570	14080
	Gyrodinium	5470	7400	6030	6280	820	1520	2600	13160	3760	8660	7540	5470
	Karenia	ND	410	430	1570	ND	380	ND	370	ND	430	ND	ND

	Oxytoxum	ND	ND	ND	ND	ND	ND	ND	ND	420	430	ND	ND
	Polykrikos	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Prorocentrum	ND	410	ND	ND	ND	45140	20780	1460	1670	ND	5030	ND
	Protoperidinium	2350	1650	5170	17270	8240	2280	870	40570	420	1730	840	2350
	Scrippsiella	12900	99960	3450	31390	28850	4550	2600	51170	ND	870	10890	12900
	Dictyocha	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Cryptomonas	6260	2470	1720	3920	ND	5310	1300	3660	ND	6060	5030	6260
	Achnanthes	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Diploneis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Linglodinium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Sep.	*Amphora*	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Asterionellopsis	10790	18150	198700	ND	20490	35370	ND	760	ND	ND	ND	10790
	Chaetoceros	95300	30570	114630	ND	56740	134420	ND	34260	39340	32830	15440	95300
	Cosinodiscus	ND	ND	ND	420	ND	ND	ND	ND	ND	ND	ND	ND
	Dactyliosolen	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Detonula	ND	ND	57320	ND	790	1330	ND	ND	ND	ND	ND	ND
	Ditylum	1350	960	76420	ND	390	ND	ND	ND	ND	ND	ND	1350
	Entomoneis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Leptocylindrus	5390	2870	133740	5050	8670	ND	ND	4570	870	1770	ND	5390
	Licmphora	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Navicular	ND	480	ND	840	ND	ND	2220	2280	72130	1770	ND	ND
	Melosira	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Odontella	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Pleurosigma	ND	480	380	ND	ND	440	ND	380	440	ND	ND	ND
	Pseudo-nitzschia	613140	515810	1834150	517550	537470	1269910	19540	36540	72130	37270	860	613140
	Skeletonema	115080	329550	802440	10100	33100	54830	ND	167480	21860	53690	ND	115080
	Thalassionema	16180	1910	ND	ND	10640	3540	5330	92120	102730	7100	ND	16180
	Alexandrium	ND	480	380	ND	4730	ND	ND	ND	ND	ND	430	ND
	Akashiwo	ND	ND	380	840	2360	ND	ND	ND	ND	ND	ND	ND
	Ceratium	1350	ND	ND	420	61860	ND	ND	ND	ND	ND	ND	1350
	Cochlodinium	3600	ND	ND	ND	2760	ND	ND	ND	ND	ND	ND	3600
	Dinophysis	ND	ND	ND	420	ND	ND	ND	ND	ND	ND	ND	ND
	Gonyaulax	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	860	ND
	Gymnodinium	6290	8600	8790	27350	17730	2650	1330	15990	2190	6210	10290	6290
	Gyrodinium	4500	6210	6110	2950	5910	2650	1780	9520	870	1330	4720	4500
	Karenia	ND	ND	ND	ND	ND	ND	ND	ND	ND	440	ND	ND
	Oxytoxum	900	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	900
	Polykrikos	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Prorocentrum	2700	ND	1530	420	390	880	890	2280	ND	ND	8150	2700
	Protoperidinium	2250	1910	3820	840	4730	5310	4440	1520	ND	ND	1290	2250
	Scrippsiella	450	4300	760	2100	3150	7070	14210	15990	870	890	3860	450
	Dictyocha	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

	Cryptomonas	ND	ND	ND	35340	ND	3980	5330	389780	17490	71880	168090	ND
	Achnanthes	ND	ND	ND	ND	ND	ND	ND	ND	440	ND	ND	ND
	Diploneis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Linglodinium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Nov.	*Amphora*	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Asterionellopsis	ND	ND	1740	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Chaetoceros	3610	2230	92420	2110	ND	106270	2190	1210	ND	ND	830	3610
	Cosinodiscus	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	420	ND
	Dactyliosolen	ND	ND	ND	ND	ND	ND	ND	ND	ND	850	830	ND
	Detonula	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Ditylum	ND	ND	1300	ND	ND	370	ND	ND	ND	ND	ND	ND
	Entomoneis	900	ND	ND	ND	ND	ND	ND	ND	ND	420	ND	900
	Leptocylindrus	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	16630	ND
	Licmphora	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Navicular	ND	ND	430	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Melosira	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Odontella	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Pleurosigma	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Pseudo-nitzschia	2710	11580	62480	850	1840	14910	1310	1210	ND	420	830	2710
	Skeletonema	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Thalassionema	1350	ND	5210	ND	370	750	ND	400	ND	ND	420	1350
	Alexandrium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Akashiwo	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Ceratium	9480	89520	ND	10150	370	ND	ND	ND	ND	ND	ND	9480
	Cochlodinium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Dinophysis	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Gonyaulax	450	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	450
	Gymnodinium	1350	5790	430	420	ND	1860	2630	2020	1680	2970	ND	1350
	Gyrodinium	450	1780	870	420	ND	ND	880	810	ND	420	420	450
	Karenia	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Oxytoxum	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Polykrikos	ND	ND	ND	ND	ND	ND	ND	400	ND	ND	ND	ND
	Prorocentrum	ND	ND	ND	ND	ND	ND	880	400	ND	ND	420	ND
	Protoperidinium	ND	890	430	ND	ND	750	ND	400	ND	850	1250	ND
	Scrippsiella	ND	ND	ND	ND	ND	ND	440	ND	ND	ND	ND	ND
	Dictyocha	ND	ND	ND	ND	ND	ND	440	400	ND	ND	420	ND
	Cryptomonas	24840	26720	29500	192020	175490	5970	55640	286340	276760	8900	16630	24840
	Achnanthes	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
	Diploneis	450	ND	430	ND	ND	370	ND	ND	ND	ND	420	450
	Linglodinium	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

[a] ND: Not detected.

Supplementary Figures

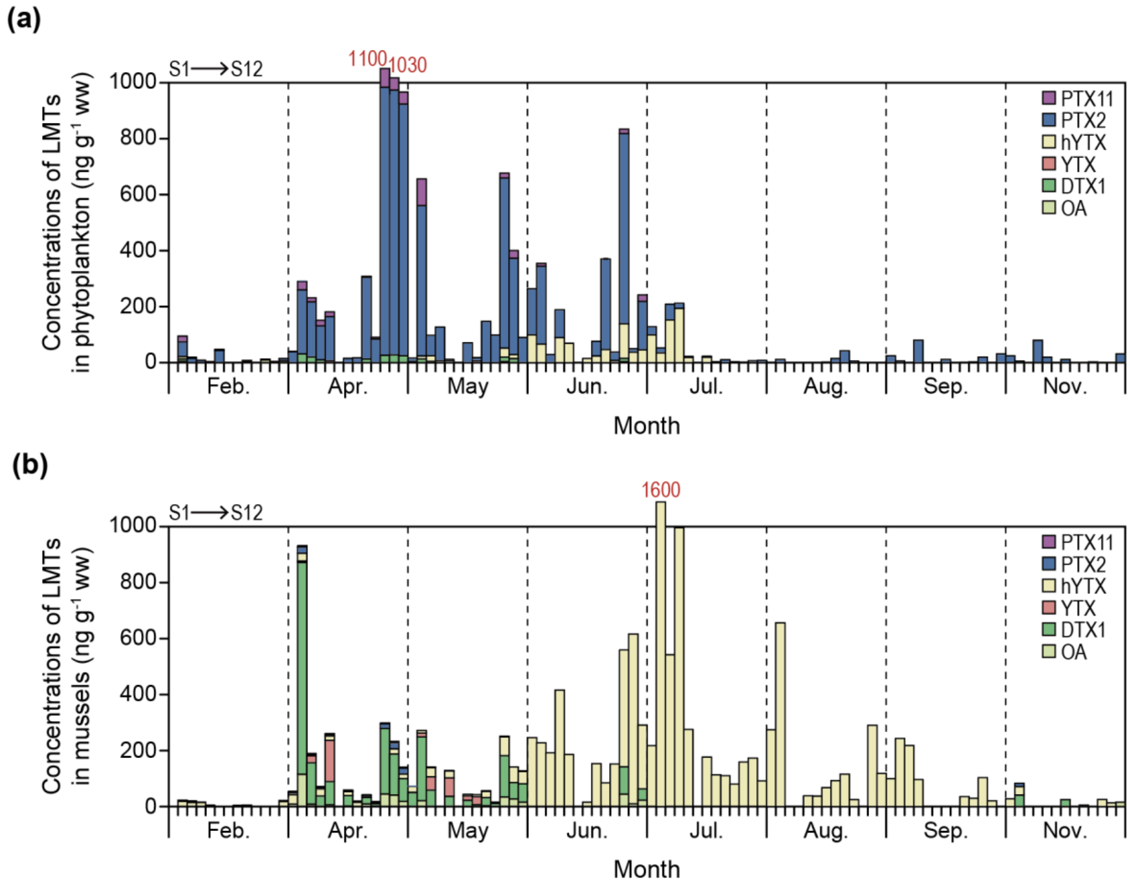

Fig. S1. Monthly variations in the concentrations and compositions of lipophilic marine toxins in **(a)** phytoplankton and **(b)** mussels collected from 12 stations of the southern coast of Korea during 2023.

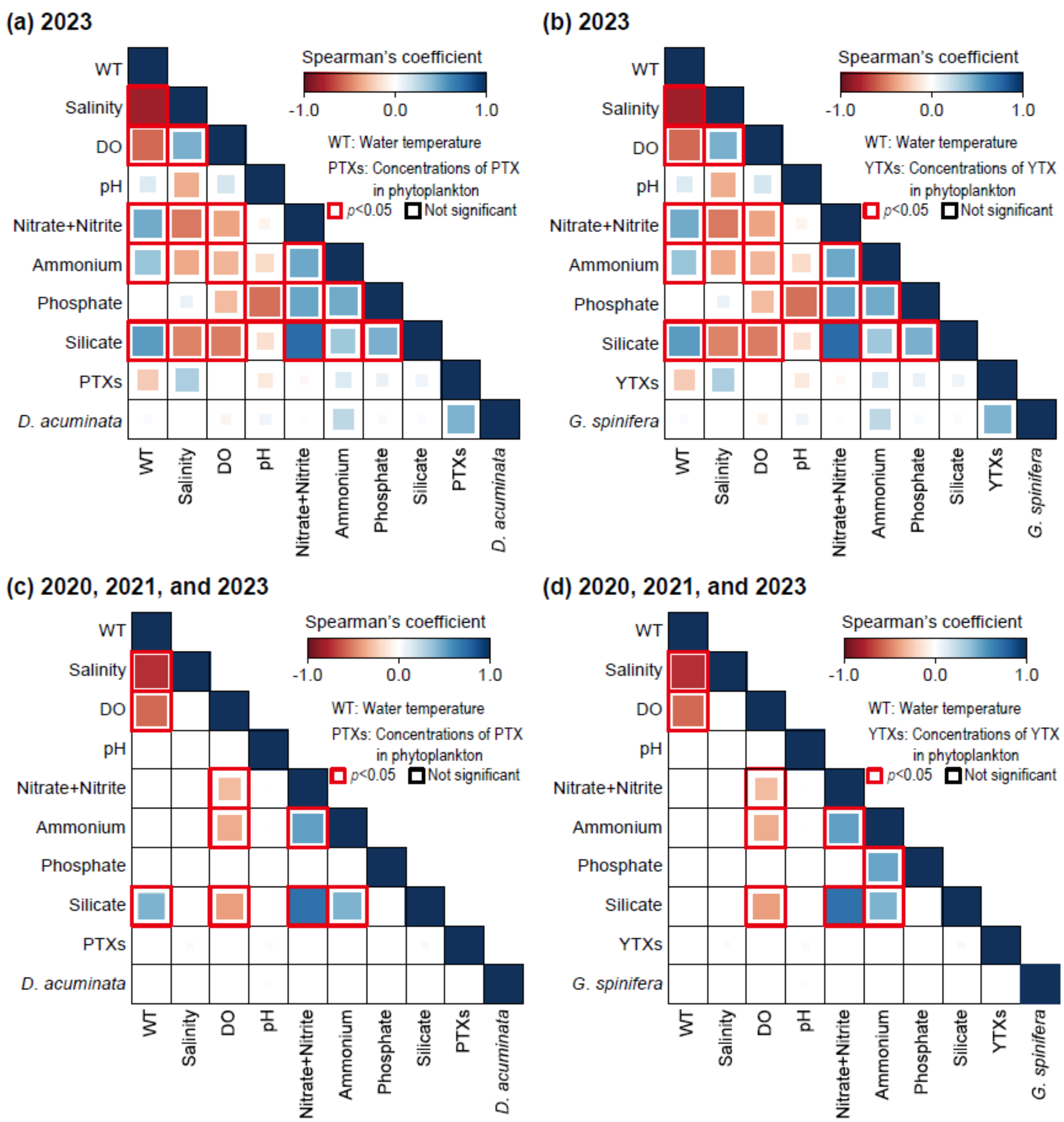

Fig. S2. Spearman's correlation heatmaps among environmental variables, toxin concentrations, and causative species: **(a)** PTXs and *D. acuminata* (2023), **(b)** YTXs and *G. spinifera* (2023), **(c)** PTXs and *D. acuminata* (2020–2023), and **(d)** YTXs and *G. spinifera* (2020–2023). Significant correlations ($p < 0.05$) are highlighted with red outlines.