Microbial Growth in Shrimp Ponds as Influenced by Monosilicic and Polysilicic Acids

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Abstract
In order to increase shrimp production and minimize detrimental environmental impacts of aquaculture, the maintenance and regulation of the growth and composition of phytoplankton communities and nutritional balance are critical. Silicon (Si) is an essential nutrient for diatoms and other types of microorganisms, but the information about the Si impact on their growth is extremely scarce. Monosilicic and polysilicic acids were tested in several shrimp cultivation systems in Jiangsu Province, China. In pond waters, the concentrations of monosilicic and polysilicic acids were sharply reduced by 36-95% and 35-75%, accordingly, as compared with those in supply water sources. The microbial cell abundance was strongly dependent on monosilicic acid. In laboratory experiments, monosilicic acid added to pond water or probiotic solutions at 1- and 2-mM Si had a significant positive effect on cell abundance. Over three days, the concentrations of monosilicic acid decreased by 81 to 91% in pond water and by 11 to 24% in probiotic solution. In probiotic solutions, the degree of polymerization of silicic acid was more intensive than that in shrimp pond waters. The data obtained demonstrates the importance of systematic studies related to the functions of Si in shrimp aquaculture.

Keywords Bacteria · Microbial ecology · Monosilicic acid · Polysilicic acids · Silicon

1 Introduction
Shrimp farming production is one of the fastest-growing segments of the world agriculture with a forecast of the compound annual growth rate in the period 2017-2021 being 4.8 to 5.4% [1, 2]. Undoubtedly, shrimp farming management should be based on a systems approach including the application of different materials to provide high productivity and quality and minimize negative impact on the environment [3, 4]. To develop an efficient management strategy, understanding of the factors that maintain and control shrimp production is required. In the aquaculture system, the microbial community plays a significant role in providing additional feed, enhancing nutrient utilization efficiency, reducing anoxic conditions, and minimizing environmental impacts [5].

Silicon (Si) is the second most abundant element after oxygen on our planet. The role and functions of Si in plant physiology, veterinary, and medicine have been investigated for more than 200 years [6, 7]. Much Si-related research was conducted for plants and soil-plant system [8]. Over the last decade, Si has been recognized as an essential trace element in the metabolism of higher plants and animals [9, 10]. In plant biology and agriculture, Si has been declared a beneficial element being particularly important for the immune system induction in response to abiotic and biotic stresses [11]. Improved Si nutrition has a multi-effect on plant growth and cell functioning [12]. Silicon-mediated impacts like sugar formation, DNA stability, transport regulation (activated Fe, B, K, Ca transport and reduced that of Cd, Hg, As, Na) have been reported as a result of Si addition [13–15].

Several forms of Si are commonly presented in natural water: monosilicic acid, polysilicic acid (oligomers and polymers with large number of Si atoms), and organo-silicon compounds [16–18]. However, plants uptake Si only in the form of monosilicic acid [12]. Although polysilicic acid is soluble, it is not absorbed by plants [16].
In the aquatic system, Si is recognized as a key nutrient for diatoms and some sponges. It is also consumed by radiolarians, silicoflagellates, several species of chao- flagellates, and some picocyanobacteria [19]. Diatoms have silicified frustules and require a high level of Si in the form of monosilicic acid [20]. Diatom populations are responsible for ~50% of marine net primary production and provide the base of marine food chains [21]. The predominance of diatoms in shrimp ponds is highly desired because of nutritional properties. In the presence of diatoms, biochemical composition of shrimp is characterized by higher proteins, lipids, essential amino acids and unsaturated fatty acids [22, 23]. Silicon fertilization is a common approach to encourage diatom growth [24, 25].

Among serious problems faced by shrimp farming are infectious diseases and environmental deterioration. Probiotics are successfully used to overcome these challenges [26, 27]. Probiotics improve growth performance, stimulate immune responses, enhance disease resistance of shrimp, inhibit growth of pathogens as well as improve water quality parameters [28]. Probiotics usually include different bacteria, bacteriophages, microalgae, and yeast species [29, 30] There are monostrain, multispecies and multispecies probiotics [31, 32]. Information about the effect of Si on the metabolism of microorganisms other than diatoms and its impact on their growth is extremely scarce [33, 34].

Knowledge about the relationship between Si application rates and mono- and polysilicic acid concentrations in pond water, and how fast Si disappears from water as well as the relationship between mono- and polysilicic acid concentrations and microbial growth is critical to manage the microbial community. The aim of this study was to evaluate the concentrations of monosilicic and polysilicic acids in shrimp ponds and to determine the effect of monosilicic acid on microbial growth in pond water and in a probiotic solution.

2 Materials and Methods

2.1 Field Tests

Water samples were collected on 3 shrimp farms located in Jiangsu Province, China, in April. The first farm (near Huan Gangerzu Town; 32°30’26” N; 121°10’11” E) used greenhouse-enclosed raceways for intensive shrimp production. Fresh groundwater was directly pumped into separated ponds under a greenhouse, each individual pond was 6 × 50 m in size and 1 m depth. The shrimp age was 2 months. Water was sampled from well, 6 ponds, and a small creek filled with effluents from ponds.

The second shrimp farm (near Changsha City; 32°23’31” N; 121°18’09” E) had a system of open ponds (100 × 50 m each and 1.5 m depth), filled with unsalted water from a local canal. The shrimps were 2 months old. Water was sampled from the canal and 6 ponds.

The third shrimp farm (near Yangkou Town; 32°35’44” N, 120°59’09” E) took water directly from the Yellow Sea. Open ponds were 250 × 60 m each and 2 m depth. Farm has filtration system for cleaning the ocean water. Water was collected from 6 ponds, and a canal supplied water to the ponds. The shrimps were 1 month old. All three farms do not apply any bacterial-base products.

Samples were collected in triplicate in 100 mL plastic bottles early in the morning and were immediately transported to a laboratory to determine monosilicic acid, polysilicic acid, pH and microbial cell abundance.

The pH was analyzed on an Ion Meter PHS-3e (MRC, China). The concentration of monosilicic acid was determined using the modified molybdenum blue method [35] with a spectrophotometer V5800 XZBELEC (China). This method tests Si only in the form of monosilicic acid, without interference from phosphorus.

To analyze polysilicic acid, 2 g of NaOH was added to 20 mL of centrifuged water and kept in a refrigerator at +4 °C for 2 weeks [36]. During this time all polymers of silicic acid are transformed into monomers. After that monosilicic acid was determined as described above. The concentration of polysilicic acid was calculated by the following formula:

\[
\text{Si}_{\text{poly}} = \text{Si}_{\text{total}} - \text{Si}_{\text{mono}},
\]

where \(\text{Si}_{\text{total}}\) is the concentration of monosilicic acid determined after depolymerization;

\(\text{Si}_{\text{mono}}\) is the concentration of monosilicic acid determined before depolymerization.

Microbial abundance (cells mL\(^{-1}\)) was estimated on the day of sampling by binocular biological microscope (ML10, Guangzhou Mingmei, China) and by using the microscope lenses ×40, ×60 and ×100 according to the method proposed by Newell and Newell [37]. The same method was used to calculate the cell density in the laboratory experiment.

2.2 Laboratory Experiment

A laboratory experiment was conducted with collected farm water summarized samples and 3 commercial probiotics used in shrimp farming: dry probiotics “Ecopro” and “Ecopro Cold” (Ecomicrobials Co, USA) and liquid probiotic “HeJunMei” (Jiangsu Aijiafuru Soil Remediation Co, China). In dry and liquid probiotics, the amounts of bacteria and yeast spores were not less than 1 × 10\(^{12}\) and 1 × 10\(^{10}\) cells kg\(^{-1}\), respectively.

To activate dry probiotics, 1 g of probiotic was mixed with 1 L of sterilized distilled water (DW) and kept at +24 °C for 24 h. The liquid probiotic was diluted 1:10.
One liter of nutrient solution was prepared with $K_2HPO_4$ 3.125 g; $KH_2PO_4$ 3.125 g; $(NH_4)_2HPO_4$ 3.125 g; MgSO$_4$·7H$_2$O 0.25 g; FeSO$_4$·7H$_2$O 0.0125 g; MnSO$_4$·7H$_2$O 0.00875 g and sucrose 12.5 g [38]. Eighty (80) mL of this nutrient solution was added to each flask. Ten (10) mL of pond water collected on the day of sampling, probiotic solution or DW was added to the flasks. Considering that Farm 3 used sea water, NaCl (35 g L$^{-1}$) was added to flasks with pond water from Farm 3. Then 10 mL of DW or monosilicic acid solution at 10 and 20 mM Si was added to reach the Si concentrations of 0, 1 and 2 mM. Monosilicic acid solutions were prepared from concentrated monosilicic acid (Fisher Scientific, CAS-No 7699-41-4). The pH in each flask was adjusted to 7 by adding 0.1 M HCl or 0.1 M NaCl.

Flasks were kept in a climatic chamber at 24 ± 1 °C. The light/night regime was 12/12 h with light intensity 600 μmol photons m$^{-2}$ s$^{-1}$. Flasks were aerated twice a day for 1 h (morning and evening). After 3 days, the concentration of monosilicic acid and the density of microorganisms were determined using the method described above. Each treatment and each analysis were conducted in triplicate. All data obtained was subjected to a statistical analysis based on comparative methods using Duncan’s multiple range tests for mean separation at the 5% level of significance [39].

### 3 Results

The pH, concentration of mono- and poly-silicic acids, and density of microorganisms in tested solutions are presented in Table 1. Monosilicic acid in water supplied to shrimp ponds differed greatly among farms, from 49.3 to 517.0 μM Si, with a higher value in fresh underground water (Farm 1) and minimum value in coastal sea water (Farm 3). Although the maximum polysilicic acid also was in the fresh underground water, its proportion increased: Farm 1 < Farm 2 < Farm 3 and accounted for 3.1; 10.0; and 16.6%, respectively.

Water was pumped to shrimp pond daily on all farms. In ponds, the concentrations of monosilicic acid were

| Sample, pond # | pH        | Monosilicic acid Si, μM | Polysilicic acid μM | ×10$^5$ cells mL$^{-1}$ |
|----------------|-----------|-------------------------|---------------------|------------------------|
| **Farm 1**     |           |                         |                     |                        |
| Supply water   | 7.27 ± 0.11 | 517.0 ± 25.4 | 16.1 ± 0.3 | n/d                    |
| 1             | 7.36 ± 0.13 | 8.6 ± 0.4 | 5.4 ± 0.2 | 2.5 ± 0.2               |
| 2             | 7.50 ± 0.12 | 52.1 ± 2.4 | 8.6 ± 0.2 | 3.9 ± 0.2               |
| 3             | 8.44 ± 0.13 | 13.2 ± 1.3 | 4.3 ± 0.1 | 2.4 ± 0.1               |
| 4             | 7.36 ± 0.13 | 17.5 ± 1.5 | 3.9 ± 0.1 | 3.2 ± 0.2               |
| 5             | 7.58 ± 0.11 | 13.5 ± 1.4 | 8.6 ± 0.2 | 3.4 ± 0.3               |
| 6             | 8.25 ± 0.11 | 12.5 ± 0.5 | 9.3 ± 0.3 | 2.6 ± 0.1               |
| Average for ponds | 7.74     | 19.6 ± 2.1 | 6.7 ± 0.2 | 3.1                    |
| **Farm 2**     |           |                         |                     |                        |
| Supply water   | 8.43 ± 0.12 | 100.0 ± 15.4 | 10.0 ± 0.3 | 0.2 ± 0.1               |
| 1             | 8.65 ± 0.11 | 20.0 ± 1.1 | 3.5 ± 0.2 | 1.6 ± 0.2               |
| 2             | 8.58 ± 0.10 | 15.4 ± 1.2 | 4.3 ± 0.2 | 1.4 ± 0.2               |
| 3             | 8.55 ± 0.10 | 12.8 ± 1.0 | 5.0 ± 0.2 | 1.1 ± 0.3               |
| 4             | 8.65 ± 0.12 | 19.3 ± 1.3 | 4.3 ± 0.1 | 1.3 ± 0.2               |
| 5             | 8.53 ± 0.12 | 15.0 ± 1.2 | 5.4 ± 0.2 | 1.2 ± 0.2               |
| 6             | 8.43 ± 0.11 | 11.4 ± 1.1 | 6.4 ± 0.2 | 1.1 ± 0.1               |
| Average for ponds | 8.56     | 15.6 ± 1.4 | 4.8 ± 0.1 | 1.25                   |
| **Farm 3**     |           |                         |                     |                        |
| Supply water   | 8.32 ± 0.11 | 49.3 ± 3.5 | 8.2 ± 0.3 | 0.1 ± 0.1               |
| 1             | 8.46 ± 0.12 | 16.1 ± 1.3 | 3.6 ± 0.2 | 1.5 ± 0.2               |
| 2             | 8.34 ± 0.13 | 15.4 ± 1.3 | 3.6 ± 0.2 | 1.7 ± 0.2               |
| 3             | 8.38 ± 0.11 | 21.8 ± 1.4 | 4.6 ± 0.3 | 2.0 ± 0.2               |
| 4             | 8.42 ± 0.10 | 18.2 ± 1.2 | 5.3 ± 0.3 | 1.8 ± 0.3               |
| 5             | 8.43 ± 0.11 | 15.4 ± 1.1 | 4.3 ± 0.2 | 1.4 ± 0.2               |
| 6             | 8.37 ± 0.11 | 17.1 ± 1.3 | 3.9 ± 0.2 | 1.5 ± 0.2               |
| Average for ponds | 8.40     | 17.3 ± 1.2 | 4.2 ± 0.1 | 1.60                   |
remarkably lower as compared with incoming water: by 26.3 times (517.0 vs 19.6 μM Si), 6.4 times (100.0 vs 15.6 μM Si), and 2.8 times (49.3 vs 17.3 μM Si), respectively on Farm 1, Farm 2, and Farm 3. The concentrations of polysilicic acid decreased as well, but not as significantly.

The cell abundance in ponds of Farm 1 was higher than in others, probably due to more intensive farming system. However, the microbial densities differed, sometimes significantly, between ponds of each farm. For example, on Farm 1, the cell numbers ranged between 2.4 ± 0.1 and 3.9 ± 0.2 × 10^5 mL^-1, while on Farm 2 and Farm 3 the cell numbers ranged from 1.1 ± 0.1 to 1.6 ± 0.2 × 10^5 mL^-1 and from 1.4 ± 0.2 to 2.0 ± 0.2 × 10^5 mL^-1, respectively.

The numbers of microbial cells and soluble forms of Si in the laboratory test are presented in Table 2. The concentration of monosilicic acid in the laboratory test is presented in Table 2. The low density of microbial cell in all tested samples is related with fact that all farms do not apply any microbial-based product. The farm #3 also wave special filtration system for minimization of the biological pollution from ocean. Supplementation of monosilicic acid significantly increased the microbial density, up to 60 and 33% in pond water and probiotic solution, respectively.

Over 3 days, the concentration of monosilicic acid decreased in all microorganism-containing solutions in comparison with the corresponding sterile solutions. Remarkable reductions in monosilicic acid were detected in all pond water samples, whereas probiotic solutions demonstrated much smaller changes.

Initial silicic acid contained NaOH to prevent polymerization; therefore, there no polymers. Since in the experiment the pH was 7, the polysilicic acid formation proceeded in both sterile and nonsterile solutions. The process of polymerization was more intense in pond water and especially in probiotic solutions. The polysilicic acid concentration reached up to 230 ± 21 mg L^-1 Si in liquid probiotic as compared to 10.5 ± 0.3 mg L^-1 Si in the corresponding sterile solution.

Table 2. Abundance of microbial cells and silicic acid concentration after 3-day incubation, laboratory experiment

| Condition          | ×10^5 cells mL^-1 | Cell increase, % | Monosilicic acid Si, μM | Polysilicic acid Si, μM |
|--------------------|-------------------|------------------|--------------------------|-------------------------|
| Sterile solution   |                   |                  |                          |                         |
| Control            | n/d               | –                | 1.5 ± 0.3                | 0.1 ± 0.1               |
| Si, 1 mM           | n/d               | –                | 994.5 ± 0.7              | 0.3 ± 0.1               |
| Si, 2 mM           | n/d               | –                | 1983.5 ± 1.5             | 10.5 ± 0.3              |
| Farm 1             |                   |                  |                          |                         |
| Control            | 2.1 ± 0.1         | –                | 1.4 ± 0.2                | 0.2 ± 0.1               |
| Si, 1 mM           | 2.5 ± 0.1         | 19.0             | 151.4 ± 13.1             | 15.3 ± 0.7              |
| Si, 2 mM           | 2.9 ± 0.2         | 38.1             | 202.3 ± 15.3             | 47.5 ± 0.9              |
| Farm 2             |                   |                  |                          |                         |
| Control            | 2.0 ± 0.1         | –                | 1.2 ± 0.2                | 0.3 ± 0.1               |
| Si, 1 mM           | 2.4 ± 0.1         | 20.0             | 142.3 ± 10.1             | 27.4 ± 0.9              |
| Si, 2 mM           | 2.7 ± 0.1         | 35.0             | 183.3 ± 10.3             | 48.5 ± 1.4              |
| Farm 3             |                   |                  |                          |                         |
| Control            | 1.5 ± 0.1         | –                | 1.1 ± 0.1                | 0.2 ± 0.1               |
| Si, 1 mM           | 1.9 ± 0.2         | 26.7             | 186.4 ± 11.2             | 18.4 ± 0.5              |
| Si, 2 mM           | 2.4 ± 0.2         | 60.0             | 254.2 ± 16.8             | 57.5 ± 0.8              |
| Ecopro             |                   |                  |                          |                         |
| Control            | 1.3 ± 0.1         | –                | 0.3 ± 0.1                | 0.1 ± 0.1               |
| Si, 1 mM           | 1.4 ± 0.1         | 7.7              | 755 ± 45                 | 92 ± 12                 |
| Si, 2 mM           | 1.6 ± 0.2         | 23.1             | 1618 ± 120               | 133 ± 21                |
| Ecopro Cold        |                   |                  |                          |                         |
| Control            | 1.2 ± 0.1         | –                | 0.2 ± 0.1                | 0.1 ± 0.1               |
| Si, 1 mM           | 1.4 ± 0.1         | 16.6             | 816 ± 27                 | 25 ± 1.5                |
| Si, 2 mM           | 1.6 ± 0.1         | 33.3             | 1633 ± 127               | 150 ± 15                |
| HeJunMei           |                   |                  |                          |                         |
| Control            | 1.4 ± 0.1         | –                | 0.4 ± 0.1                | 0.1 ± 0.1               |
| Si, 1 mM           | 1.6 ± 0.2         | 14.3             | 833 ± 32                 | 167 ± 14                |
| Si, 2 mM           | 1.8 ± 0.2         | 28.6             | 1770 ± 125               | 230 ± 21                |

n/d not detected
4 Discussion

In the experiment, the concentrations of dissolved Si (DSi) (monosilicic acid + polysilicic acid) in supply water sources were 533.1 μmol (groundwater, Farm 1), 110.0 μmol (fresh water canal, Farm 2) and 57.53 μmol (sea water, Farm 3). This data is consistent with reported DSi concentrations in groundwater [40], surface terrestrial waters [41], and ocean water [42, 43].

In tested shrimp ponds, DSi ranged from 14.0 to 60.7 μM Si on Farm 1, from 17.8 to 23.5 μM Si on Farm 2 and from 19.7 to 26.4 μM Si on Farm 3 which corresponds to the available data. For example, DSi in low salinity shrimp ponds in Alabama ranges between 3.4 and 196 μM Si with an average of 37.0 μM [44]. It is important to note that we observed very fast reductions in pond water Si, in spite of daily water exchange. The monosilicic acid concentration decreased more than the polysilicic acid (Table 3). It is well known that higher plants take up Si only in the form of monosilicic acid. Perhaps algae, being phototrophic organisms like higher plants, have the same mode of Si uptake. With decreasing monosilicic acid, equilibrium between soluble forms of Si shifts, resulting in acceleration of depolymerization, which is typical for the systems with low concentrations of monosilicic acid, in turn leading to decreasing polysilicic acid [18].

The correlation coefficients between soluble forms of Si and cell abundance evidence that the number of microorganisms in ponds correlates positively with monosilicic acid (R = 0.80-0.84) (Table 4). However, the content of polysilicic acid is reduced in pond water as well. But it is not available strong correlation between cell abundance and polysilicic acid. For farm #1 and 3 was found the positive low-level correlation and for farm #2 was observed negative correlation. It is available several hypotheses, which can explain different correlations. Considering that concentration of polysilicic acid content depend on numerous factors (monosilicic acid concentration, pH, content of colloids, number of microorganisms, concentration of such elements as Ca, Al, Fe and other) [16–18]. The obtained data showed that polysilicic acid concentration in solutions has less influence on microbial population and probably other factors in the tested water system may have effect on stability and formation of the polysilicic acid. Secondary, the different microorganisms require different level of Si nutrition [19, 45]. Consequently, on farm #2 the microbial association can be different that on water in farm #1 and #3. The confirmation of the suggested hypothesis of the mechanisms which affect on the polysilicic acid concentration in the aqua-system require additional specific investigations. However, our current investigations have demonstrated that unlike polysilicic acid, monosilicic acid is an essential factor in the regulation of microbial growth in the shrimp pond.

The laboratory experiment has shown that monosilicic acid affected beneficially microbial population in pond water and probiotics solution (Table 2). In pond water, Si may be consumed mainly by different algae species, including diatoms. The tested probiotics contained only bacteria having less need for Si, though additional Si benefitted their growth as well. The increase in polysilicic acid with the addition of monosilicic acid could be the result of polymerization (Table 2). Monosilicic acid can be physically adsorbed on the cell wall leading to initiation of the polymerization process [46]. The formation of Si-based polymers was higher in probiotic solutions. Although a significance of this process in shrimp cultivation is unknown, Si polymers generally possess high adsorption properties to organic and inorganic molecules [47, 48]. Thus, new formed silica-gel

| Pond, # | Reduction, % |
|---------|--------------|
|         | Monosilicic acid | Polysilicic acid | Monosilicic acid | Polysilicic acid |
| Farm 1  |
| 1       | 98.3          | 66.4          | 80.0          | 65.0          |
| 2       | 89.9          | 46.6          | 84.6          | 60.0          |
| 3       | 97.4          | 73.3          | 87.2          | 50.0          |
| 4       | 96.6          | 75.8          | 80.7          | 57.0          |
| 5       | 97.5          | 46.6          | 85.0          | 46.0          |
| 6       | 97.6          | 42.2          | 88.6          | 36.0          |
| Average | 96.2          | 58.4          | 84.4          | 52.0          |

| Farm 2  |
| 1       | 67.3          | 63.4          |
| 2       | 68.8          | 56.1          |
| 3       | 55.8          | 43.9          |
| 4       | 63.1          | 35.4          |
| 5       | 68.8          | 47.6          |
| 6       | 65.3          | 52.4          |
| Average | 64.9          | 48.8          |

| Farm 3  |
| 1       | 67.3          | 63.4          |
| 2       | 68.8          | 56.1          |
| 3       | 55.8          | 43.9          |
| 4       | 63.1          | 35.4          |
| 5       | 68.8          | 47.6          |
| 6       | 65.3          | 52.4          |
| Average | 64.9          | 48.8          |

Table 3 Reductions of monosilicic and polysilicic acids in pond water in comparison with those in the corresponding supply water, %

Table 4 Correlation coefficients (R) between cell abundance and soluble forms of Si in pond water

| Farm # | Monosilicic acid | Polysilicic acid |
|--------|------------------|------------------|
| 1      | 0.80             | 0.41             |
| 2      | 0.83             | −0.87            |
| 3      | 0.84             | 0.52             |

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(polymerized silicic acid) may adsorb organic compounds and nutrients promoting attraction of microorganisms and floc formation. This hypothesis requires further confirmation (Table 5).

As is well known, diatoms require high level of DSi for growth [49–51]. Minimum DSi required for diatom growth was shown to be 0.1 mg L⁻¹ (3.57 μM Si) [52]. Early research reported that the monosilicic acid concentrations of 8.1-81.0 μM Si benefit the cultivation of diatoms [53]. Soluble Si at 714 μM stimulated respiration of diatoms [54]. As recently shown, suitable Si concentration in a growth medium for diatoms amounts to 470 μM as Na₂SiO₃·5H₂O [55]. Optimal Si concentrations for diatoms depend on the species, as well as the content of other elements. For example, Adams and Bugbee [56] found that the maximum dry mass density of diatoms (Chaetoceros gracilis) was observed at the Si concentrations of 200-400 μM and 600-800 μM, respectively in highly salted water (400 mM Na) and low salted water (50 mM Na).

Other phytoplanktonic algae that do not need so much Si can replace diatoms [45]. Among undesirable algae species, blue-green algae are of particular concern. Blooms of blue-green algae cause a lack of dissolved oxygen, off-flavors problems, and toxin formation, thus deteriorating water quality and declining shrimp productivity [57]. Evidently, the abundance of silicic acid is an essential requirement to achieve desirable diatom domination in algal communities. However, no systematic studies have been conducted showing the Si limitation and influence of its addition on shrimp production.

The obtained data has demonstrated that all tested shrimp ponds were characterized by extremely low concentrations of monosilicic acid, while the supply waters originally were high in DSi. Monosilicic acid applied to shrimp pond water or probiotic solution significantly increased the microbial cell abundance. It is important to distinguish monomeric and polymeric forms of DSi, because these substances affect microbial population in aquaculture in different ways.

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**Authors’ Contributions** Dr. Ruiping Zhang participate in sample collection, analysis and manuscript writing, Dr. Elena Bocharnikova is participated in the analysis, laboratory test and manuscript writing, Prof. Vladimir Matichenkov is participated in the sample collection, laboratory experiments and manuscript preparation.

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**Data Availability** All data availability statement is present within the text of the manuscript.

**Code Availability** Not available.

**Declarations**

**Ethics Approval** This article does not contain any studies with human participants or animals performed by any of the authors.

**Consent to Participate** All authors are agreed to be listed as authors in current version of manuscript.

**Consent for Publication** All authors are agreed for publication of this manuscript in the Applied Microbiology and Biotechnology.

**Conflict of Interest** There is no conflict of interest.

**References**

1. Anderson J, Valderrama D, Jory D (2016) Shrimp production review. Global Aquaculture Alliance: Presentation Global Aquaculture Production Data and Analysis, p 1–50

2. Anderson JL, Valderrama D, Jory D (2019) Shrimp production review. Global Aquaculture Alliance: Presentation Global Aquaculture Production Data and Analysis. https://www.aquaculturealliance.org/advocate/goal-2019-global-shrimp-production-review/. Accessed 4 Nov 2019

3. Ray AJ, Lotz JM (2017) Comparing salinities of 10, 20, and 30% in intensive, commercial-scale biofloc shrimp (Litopenaeus

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### Table 5

| Solution      | Si, 1 mM |                  | Si, 2 mM |                  |
|---------------|----------|------------------|----------|------------------|
|               | Monosilic acid | Polysilicic acid | Monosilic acid | Polysilicic acid |
| Farm 1        | -84.8    | +5000            | -89.8    | +352             |
| Farm 2        | -85.7    | +9033            | -90.8    | +362             |
| Farm 3        | -81.2    | +6033            | -87.2    | +447             |
| Ecopro        | -24.1    | +30,567          | -18.4    | +2090            |
| Ecopro Cold   | -17.9    | +2823            | -17.7    | +1328            |
| HeJunMei      | -16.2    | +55,566          | -10.7    | +2090            |
vannamei) production systems. Aquaculture 476:29–36. https://doi.org/10.1016/j.aquaculture.2017.03.047
4. Sarkar AK, Islam MN, Ansary FH (2019) Some aspects of shrimp farming systems and shrimp production management: Bangladesh perspective. J Biodivers Conserv Bioresearch Manag 5(2):93–100 https://www.researchgate.net/doi/10.2492/Ferbom.v512.i449
5. Dene S, Beev G, Staykov Y, Moutafchieva R (2009) Microbial ecology of the gastrointestinal tract of fish and the potential application of probiotics and prebiotics in fish farming aquaculture. Int Aquat Res 1:1–29. https://doi.org/10.1749/3.745.s0.0105.tb00390.x
6. Chepeleva E, Kozyr K, Zuharev D, Kudriashov A, Kretov E, Vasilieva M, ... Sergeevichev D (2018) Blood plasma cytokines releasing after implantation of self-expanding nitinol stents modified with silicon in experimental animals. AIP Conf Proc 2051(1):020048 https://doi.org/10.1063/1.5083291
7. Szacawa E, Dudek K, Bederska-Lojewska D, Liseicka U, Bednarek D, Pieszka M (2019) The effect of silicon dioxide nanoparticles as feed additive on health condition and immunological parameters of calves. Anim Biol 21(2):140
8. Snyder GH, Matichenkov VV, Datnoff LE (2016) Silicon. In: Pilbeam DJ (ed) Barker AV. Handbook of plant nutrition, CRC Press, pp 567–584
9. Michalak I, Chojnacka K (2018) Fluoride and silicon as essential and toxic trace elements. In: Chojnacka K, Saeed A (eds) Recent advances in trace elements. John Wiley & Sons, pp 207–218
10. Peris-Felipe FJ, Benavent-Gil Y, Hernández-Apaolaza L (2020) Silicon beneficial effects on yield, fruit quality and shelf-life of strawberries grown in different culture substrates under different iron status. Plant Physiol Biochem 152:23–31. https://doi.org/10.1016/j.plaphy.2020.04.026
11. Guerriero G, Hausman JF, Legay S (2016) Silicon and the plant extracellular matrix. Front Plant Sci 7:463. https://doi.org/10.3389/fpls.2016.00463
12. Ma JF, Miyake Y, Takahashi E (2001) Silicon as a beneficial element for crop plants. In: Datnoff LE, Snyder GH, Korndorfer GH (eds) Silicon in agriculture. Elsevier, pp 17–39
13. Adrees M, Ali S, Rizwan M, Zia-ur-Rehman M, Ibrahim M, Abbas F, Farid M, Qayyum M, Irshad M (2015) Mechanisms of silicon-mediated alleviation of heavy metal toxicity in plants: a review. Ecotox Environ Safe 119:186–197. https://doi.org/10.1016/j.ecoenv.2015.05.011
14. Bochkarikova EA, Pakhnenko EP, Matichenkov VV, Matychenkov IV (2014) The effect of optimization of silicon nutrition on the stability of barley DNA. Moscow Univ Soil Sci Bull 69(2):84–87. https://doi.org/10.3103/S1017687414020033
15. Hernandez-Apaolaza L (2014) Can silicon partially alleviate micronutrient deficiency in plants? A review. Planta 240(3):447–458. https://doi.org/10.1007/s00218-014-2119-x
16. Bochkarikova EA, Matichenkov VV (2012) Influence of plant associations on the silicon cycle in the soil-plant ecosystem. Appl Ecol Environ Res 10(4):547–560
17. Dietzel M (2002) Interaction of polyolysilicate and monosilicic acid with mineral surfaces. In: Stober I, Bucher K (eds) Water-rock interaction. Springer, Dordrecht, pp 207–235
18. Iler RK (1979) The chemistry of silica. Wiley, New York
19. Tréguer P, De La Rocha CL (2013) The world ocean silica cycle. Annu Rev Mar Sci 5:477–501. https://doi.org/10.1146/annurev-marine-121211-172346
20. Leynaert A, Longhiuiri SN, Claquin P, Chauvaud L, Raguenneau O (2009) No limit? The multiphasic uptake of silicic acid by benthic diatoms. Limnol Oceanogr 54(2):571–576
21. Nelson DM, Tréguer P, Brzezinski MA, Leynaert A, Quégoulin B (1995) Production and dissolution of biogenic silica in the ocean: revised global estimates, comparison with regional data and relationship to biogenic sedimentation. Glob Biogeochem Cycles 9(3):359–372
22. Brito LO, dos Santos IGS, de Abreu JL, de Araújo MT, Severi W, Gálvez AO (2016) Effect of the addition of diatoms (Navicula spp.) and rotifers (Brachionus plicatilis) on water quality and growth of the Litopenaeus vannamei postlarvae reared in a biofloc system. Aquac Res 47:3990–3997. https://doi.org/10.1111/are.12849
23. de Abreu JL, Brito LO, de Lima PC, Silva SM, Severi W, Gálvez AO (2019) Effects of addition of Navicula sp. (diatom) in different densities to postlarvae of shrimp Litopenaeus vannamei reared in a BFT system: growth, survival, productivity and fatty acid profile. Aquaculture 50(8):2231–2239. https://doi.org/10.1111/are.14104
24. Llario F, Rodilla M, Escrivá J, Falco S, Sebastiá-Frasquet MT (2019) Phytoplankton evolution during the creation of a biofloc system for shrimp culture. Int J Environ Sci Te 16(1):211–222. https://doi.org/10.1007/s13762-018-1655-5
25. Martins TG, Odebrecht C, Jensen LV, D’Oca MG, Wasielewsky JW (2016) The contribution of diatoms to bioflocs lipid content and the performance of juvenile Litopenaeus vannamei (Boone, 1931) in a BFT culture system. Aquac Res 47(4):1315–1326. https://doi.org/10.1111/are.12592
26. Lakshmi B, Viswanath B, Sai Gopal DV (2013) Probiotics as antiviral agents in shrimp aquaculture. J Pathog 424123. https://doi.org/10.1155/2013/424123
27. van Hai N, Fotedar R (2010) A review of probiotics in shrimp aquaculture. J Appl Aquac 22(3):251–266. https://doi.org/10.1080/10454438.2010.500597
28. Hoseinifar SH, Sun YZ, Wang A, Zhou Z (2018) Probiotics as means of diseases control in aquaculture, a review of current knowledge and future perspectives. Front Microbiol 9:2429. https://doi.org/10.3389/fmicb.2018.02429
29. Llewellyn MS, Boutin S, Hoseinifar SH, Derome N (2014) Tel-eost microbiomes: the state of the art in their characterization, manipulation and importance in aquaculture and fisheries. Front Microbiol 5:207. https://doi.org/10.3389/fmicb.2014.00207
30. Wang A, Ran C, Wang Y, Zhang Z, Ding Q, Yang Y, Olsen R, Ringo E, Bindelle J, Zhou Z (2019) Use of probiotics in aquaculture of China—a review of the past decade. Fish Shellfish Immun 86:734–755. https://doi.org/10.1016/j.fsi.2018.12.026
31. Das S, Mondal K, Haque S (2017) A review on application of probiotic, prebiotic and synbiotic for sustainable development of aquaculture. J Entomol 5(2):422–429
32. Van Doan H, Hoseinifar SH, Dawood MA, Chitmanat C, Matic M, Curic D, Djakic N, Petrovic J, Stojanovic R, Ajašov I, Djuranovic D, Golubovic M, Steering Committee of the International Society Comparative Aquaculture (2018) Microbiomes: the state of the art in their characterization, manipulation and importance in aquaculture and fisheries. Front Microbiol 9:2429. https://doi.org/10.3389/fmicb.2018.02429
33. Hurst CJ, Crawford RL, Garland JL, Lipson DA (2007) Manual of environmental microbiology. ASM Press, Washington
34. Wainwright M, Al-Wajeek K, Grayston SJ (1997) Effect of silicic acid and other silicon compounds on fungal growth in oligotrophic and nutrient-rich media. Mycol Res 101(8):933–938. https://doi.org/10.1017/S0953755297003360
35. Mullin JB, Riley JP (1935) The colorimetric determination of silicate with special reference to sea and natural waters. Anal Chem Acta 12:162–176. https://doi.org/10.1016/0003-2670(00)87825-3
36. Matichenkov VV, Ammosova YM, Bochkarikova EA (1997) The method for determining plant-available silicon in soil. Agrochem [Rus] 1:76–84
37. Newell GE, Newell RC (2006) Marine plankton (a practical guide to ecology, methodology, and taxonomy). Oxford University Press, London
Vitullo D, Di Pietro A, Romano A, Lanzotti V, Lima G (2012) Role of new bacterial surfactants in the antifungal interaction between bacillus amyloliquefaciens and fusarium oxysporum. Plant Pathol 61(4):689–699. https://doi.org/10.1111/j.1365-3059.2011.02561.x

Duncan DB (1957) Multiple range tests for correlated and heteroscedastic means. Biometrics 13(2):164–176. https://doi.org/10.2307/2527799

Khan A, Umar R, Khan HH (2015) Significance of silica in identifying the processes affecting groundwater chemistry in parts of Kali watershed, central ganga plain, India. Appl Water Sci 5(1):65–72. https://doi.org/10.1007/s13201-014-0164-z

Zhang Q, Tao Z, Gao Q, Ma Z (2015) A review of the biogeochemical cycles of dissolved silicon in rivers. Adv Earth Science 30(1):50–59

Wei Q, Yao Q, Wang B, Wang H, Yu Z (2015) Long-term variation of nutrients in the southern Yellow Sea. Cont Shelf Res 111:184–196. https://doi.org/10.1016/j.csr.2015.08.003

Zhao W, Jiao N, Zhao Z (2000) Distribution and variation of the nutrient in the Yantai Sisihili bay cultivated water. Mar Sci 24(4):31–34

Prapaiwong N, Boyd CE (2014) Trace elements in waters of inland, low-salinity shrimp ponds in Alabama. Aquac Res 45(2):327–333. https://doi.org/10.1111/j.1365-2109.2012.03230.x

Boyd CE (2014) Silicon, diatoms in aquaculture. Global Aquaculture Advocate May/June, 38–39

Matichenkov VV, Korenevsky AA, Beveridge TJ (2001) Adsorption of soluble silicon compounds by Pseudomonas Aeruginosa. In: proc. 11th annual V. M. Goldschmidt Conference. Hot Springs, Virginia, p 3831

Parida SK, Dash S, Patel S, Mishra BK (2006) Adsorption of organic molecules on silica surface. Adv Colloid Interf Sci 121(1-3):77–110

Xia ZZ, Chen CJ, Kiplagat JK, Wang RZ, Hu QJ (2008) Adsorption equilibrium of water on silica gel. J Chem Eng Data 53(10):2462–2465. https://doi.org/10.1021/je800019a

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