Phytoplankton Cell Density and Its Relationship with Nutrient Elements in the Taiyuan Fen River Reservoir Area (Postprint)

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Abstract

Nutrient elements in water bodies are crucial factors influencing aquatic ecosystems, determining the structure of different phytoplankton communities, and serving as important indicators for evaluating water quality and trophic status. An investigation and analysis of phytoplankton, various water environmental parameters, and nutrient elements were conducted at 9 sampling sites in the Taiyuan Fenhe River impoundment area. The survey revealed that: (1) Cyanobacteria and green algae were the dominant groups in this watershed, constituting a phytoplankton community dominated by Cyanophyta-Chlorophyta. The dominant species during both the normal water period and high water period were primarily Chroococcus minutus, Merismopedia tenuissima, Oscillatoria tenuis, and Microcystis aeruginosa from Cyanophyta, whose abundances accounted for 42.95% and 59.24% of the total algal cell counts during the normal and high water periods, respectively. Chlorophyll-a content exhibited significant variation with geographic location, being markedly higher in the middle and lower reaches compared to the upper reaches. (2) The water quality in the Taiyuan Fenhe River impoundment area had all reached a eutrophic state. Due to improper discharge of domestic waste and sewage along the Taiyuan Fenhe River impoundment area, indicators such as total nitrogen and total phosphorus in the Fenhe River were elevated, ultimately resulting in the entire water body being in a state of mild or moderate eutrophication. (3) Chlorophyll-a content showed significant positive correlations with water temperature, total nitrogen, and total phosphorus, and a very significant positive correlation with organic matter content, with total phosphorus having the most pronounced effect, indicating that phosphorus may be the limiting factor for phytoplankton growth in this region.

Full Text

Preamble

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Phytoplankton Cell Density and Its Relationship with Nutrient Elements in the Fenhe River Water Storage Area of Taiyuan

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Abstract

Nutrient elements in water bodies are critical factors influencing aquatic ecosystems, determining phytoplankton community structure and serving as important indicators for water quality and trophic status assessment. We investigated phytoplankton communities and various water environmental parameters at nine sampling sites in the Taiyuan Fenhe River water storage area. The results revealed that: (1) Cyanophyta and Chlorophyta constituted the dominant phytoplankton groups, with *Chroococcus minutus*, *Merismopedia tenuissima*, *Oscillatoria tenuis*, and *Microcystis aeruginosa* from Cyanophyta serving as the dominant species during both normal and wet seasons, accounting for 42.95% and 59.24% of total algal cell density, respectively. Chlorophyll-a content exhibited significant spatial and temporal variation (annual mean: 38.13 mg/L; range: 17.04–84.60 mg/L), with higher concentrations in the wet season than in the normal season, and significantly higher values in the middle and lower reaches compared to the upstream region. (2) Water quality in the study area reached eutrophic status. Due to domestic waste, sewage, and industrial discharge along the river, total nitrogen and phosphorus concentrations were elevated, resulting in mild to moderate eutrophication throughout the water body. (3) Correlation and principal component analyses showed that chlorophyll-a concentration was significantly positively correlated with water temperature, total phosphorus (TP), total nitrogen (TN), chemical oxygen demand (COD), and permanganate index (CODMn), with phosphorus identified as the primary limiting factor for phytoplankton growth in this region.

Keywords: Taiyuan Fenhe River water storage area; phytoplankton; nutrients; correlation analysis; principal component analysis

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Introduction

Phytoplankton are primary producers and important food organisms in aquatic ecosystems, serving as key bioindicators of water quality. Their species composition and abundance distribution represent essential ecological characteristics and primary research foci in aquatic ecosystems. With simple structures, phytoplankton are highly sensitive to environmental changes and can respond rapidly, accurately reflecting alterations in aquatic ecosystems. As important indicators of water environmental characteristics, phytoplankton have attracted worldwide research attention. Researchers can analyze water quality by measuring phytoplankton quantity and species composition. Numerous studies have investigated phytoplankton in rivers and lakes, analyzing water quality conditions.

The Fenhe River, the largest river in Shanxi Province and the second largest tributary of the Yellow River, originates from the Shui Mu Cave at Lou Mountain in the Guancen Mountains of Ningwu County and flows into the Yellow River at Wanrong County, covering a drainage area of approximately 40,000 km² (about one-quarter of Shanxi' s total area). As the core region for economic and social development in Shanxi, the Fenhe River basin has suffered severe ecological damage from prolonged overexploitation, significantly constraining sustainable development and affecting the province' s image. The rapid development of township enterprises in the middle and lower reaches, particularly coal washing and paper manufacturing, has exacerbated water pollution.

The Taiyuan Fenhe River water storage area extends from the north of Chaicun Bridge to the south of Xiangyun Bridge, with a total length of 22 km and a width of 500 m. This artificial compound channel is divided by a central wall into an eastern clear water channel and a western turbid water channel for flood discharge and irrigation, with sewage dark channels along both banks receiving municipal wastewater pipelines. Multiple rubber dams create storage zones, and sewage is transported to downstream treatment plants. This study systematically investigated phytoplankton community composition and environmental factors including permanganate index and total phosphorus, providing a theoretical basis for ecological evaluation and environmental monitoring of the Taiyuan Fenhe River water storage area.

Methods

1. Sampling Site Distribution and Sampling Time

Monthly sampling was conducted at nine sites in the Taiyuan Fenhe River water storage area from 2015 to 2016, selected based on natural conditions and geographic location: Chaicun Bridge (S1), Shengli Bridge (S2), Yingze Bridge (S3), Changfeng Bridge (S4), Nanneihuan Bridge (S5), Jifen Bridge (S6), Nanzhonghuan Bridge (S7), Jiuyuanshahe Bridge (S8), and the south side of Nanzhonghuan Bridge (S9) [Figure 1: see original paper].

2. Water Sample Collection and Identification

Phytoplankton sampling included both qualitative and quantitative collection. Qualitative samples were collected by towing a #25 plankton net in an "∞" pattern at 20–30 cm/s for 3 minutes, with samples fixed on-site with formaldehyde. Quantitative samples were collected using a water sampler, preserved with Lugol' s solution, and concentrated to 70–80 mL after sedimentation in 100 mL wide-mouth bottles. The supernatant was carefully removed, and the remaining sample was transferred to a 100 mL quantitative bottle for identification and counting using an Olympus BX51 microscope [13–15].

3. Determination of Physicochemical Indices

Transparency (SD) was measured using a Secchi disk. Dissolved oxygen (DO) was measured with a multi-parameter water quality analyzer (HQ40D, Hach, Loveland, USA). Chlorophyll-a (Chl-a) was determined by acetone extraction spectrophotometry. Total nitrogen (TN), total phosphorus (TP), ammonia nitrogen (NH -N), chemical oxygen demand (COD), and permanganate index (CODMn) were analyzed according to the "Water and Wastewater Monitoring Analysis Methods" and "Surface Water Environmental Quality Standards" (GB3838-2002) [16].

4. Data Analysis

Phytoplankton density calculation was performed using standard methods [17]. The **comprehensive trophic level index (TLI)** was calculated as:

$$TLI(\sum) = \sum_{j=1}^{m} W_j \cdot TLI(j)$$

where $TLI(j)$ represents the trophic state index for parameter j, W_j is the weight of parameter j, and m is the number of parameters. Using Chl-a as the reference parameter, the normalized weight was calculated as:

$$W_j = \frac{r_{ij}^2}{\sum_{j=1}^{m} r_{ij}^2}$$

where r_{ij} is the correlation coefficient between parameter j and Chl-a . Individual nutrient indices were calculated as:

$$TLI(Chl-a) = 10(2.5 + 1.086 \ln Chl-a)$$
$$TLI(TP) = 10(9.436 + 1.624 \ln TP)$$
$$TLI(TN) = 10(5.453 + 1.694 \ln TN)$$
$$TLI(SD) = 10(5.118 - 1.94 \ln SD)$$

$$TLI(CODMn) = 10(0.109 + 2.66 \ln CODMn)$$

The trophic status classification was: $TLI(\sum) < 30$ (oligotrophic), $30 \leq TLI(\sum) \leq 50$ (mesotrophic), $50 < TLI(\sum) \leq 60$ (mild eutrophic), $60 < TLI(\sum) \leq 70$ (moderate eutrophic), and $TLI(\sum) > 70$ (severe eutrophic) [19].

Correlation analysis and **principal component analysis (PCA)** were conducted using SPSS 19.0 and Origin 8.5 to examine relationships between Chl-a and environmental factors, identify key influencing factors, and establish regression equations.

Results

1. Spatial Distribution of Dominant Species

Investigations across different sampling sites revealed variations in dominant species between wet and normal seasons. Cyanophyta dominants included *Chroococcus minutus*, *Microcystis aeruginosa*, *Merismopedia tenuissima*, and *Oscillatoria tenuis*. Chlorophyta was dominated by *Chlorella vulgaris*, while Bacillariophyta was represented by *Synedra acus*. The wet season exhibited more diverse dominant species compared to the normal season .

2. Phytoplankton Abundance and Chlorophyll-a Characteristics

Phytoplankton abundance and composition are closely related to seasonal changes and nutrient availability. Cyanophyta and Chlorophyta were the predominant groups, comprising 54.89% and 33.49% of total species, respectively, followed by Bacillariophyta (5.15%) and Cryptophyta (1.47%). During summer and autumn, Cyanophyta and Chlorophyta accounted for 93.38% of the community, with Cyanophyta being more abundant in summer due to favorable light and temperature conditions essential for *Microcystis* bloom formation.

Phytoplankton abundance ranged from 4.52–67.27 $\times$ 10 cells/L in the normal season (mean: 36.03 $\times$ 10 cells/L) and 16.85–89.19 $\times$ 10 cells/L in the wet season (mean: 50.24 $\times$ 10 cells/L). Cyanophyta dominated abundance in both seasons (35.36% in normal season, 59.24% in wet season), followed by Chlorophyta and Bacillariophyta. Higher wet season abundance was attributed to increased rainfall and nutrient input.

Chlorophyll-a concentrations varied significantly from 17.04 to 84.60 mg/L (mean: 38.13 mg/L), with higher values in the wet season ((79.56 $\pm$ 4.36) mg/L) than the normal season ((24.32 $\pm$ 3.15) mg/L). Spatially, middle and lower reaches showed significantly higher concentrations than upstream areas, correlating with elevated nutrient levels that stimulated phytoplankton growth [Figure 2: see original paper].

3. Comprehensive Trophic Status Index

All nine sampling sites exhibited eutrophic conditions. Sites S1-S6 showed mild eutrophasia, while S7-S9 reached moderate eutrophasia during the wet season. This pattern likely resulted from municipal sewage discharge and industrial wastewater along the river, particularly affecting downstream sites .

4. Correlation Analysis Between Chlorophyll-a and Environmental Factors

Correlation analysis revealed significant positive relationships between chlorophyll-a and water temperature ($r = 0.12$, $p < 0.05$), TP ($r = 0.58$, $p < 0.01$), TN ($r = 0.42$, $p < 0.01$), COD ($r = 0.68$, $p < 0.05$), and CODMn ($r = 0.82$, $p < 0.01$) [TABLE:5, FIGURE:3]. The stronger correlation with phosphorus suggests it may be the limiting nutrient. The N:P ratios of 24.91 (wet season) and 28.27 (normal season), combined with TN exceedances, indicate phosphorus limitation in the study area.

5. Principal Component Analysis

PCA extracted three principal components explaining 87.489% of variance. PC1 (59.182% variance) was dominated by water temperature, COD, CODMn, and Chl-a, representing factors associated with phytoplankton abundance. PC2 (16.580% variance) was primarily influenced by TN and ammonia nitrogen, representing nitrogen sources. PC3 (11.726% variance) was dominated by transparency (negative loading) [TABLE:6, TABLE:7].

The PCA score plot [Figure 4: see original paper] revealed four distinct zones: Zone 1 (S5, S7, S8) with high cell density, temperature, and ammonia; Zone 2 with high dissolved oxygen and moderate density; Zone 3 with high transparency and low density; and Zone 4 with low density and high dissolved oxygen. This classification provides an intuitive framework for understanding relationships between sampling sites and environmental parameters.

Discussion

Under typical conditions, wet seasons feature higher temperatures and nutrient concentrations that favor algal growth. Although Cyanophyta and Bacillariophyta were abundant, species composition varied among sites. Midstream sites (S4-S6) showed fewer algal species, likely due to concentrated industrial and domestic wastewater discharge. The predominance of Cyanophyta (particularly *C. minutus* and *M. tenuissima*) and Chlorophyta throughout the year, with *M. aeruginosa* appearing downstream, indicates high bloom risk.

Eutrophication, driven by rapid socioeconomic development, population growth, and uncontrolled waste discharge, represents a severe global environmental issue.

The Taiyuan Fenhe River water storage area, traversing the entire city, receives substantial domestic and industrial waste, resulting in elevated TN and TP concentrations and mild to moderate eutrophasia. This has caused ecological degradation and requires urgent implementation of total pollutant load control measures, including point source regulation, cleaner production, and enhanced municipal wastewater treatment.

Environmental factors and nutrients critically influence aquatic ecosystems and phytoplankton community structure. Temperature directly affects physicochemical processes and nutrient cycling. In the Taiyuan Fenhe River area, summer warming accelerates nutrient cycling and phytoplankton metabolism, increasing cell density, while winter cooling reduces it. Chlorophyll-a, essential for photosynthesis, serves as a comprehensive indicator of phytoplankton biomass and water quality, with its concentration reflecting the combined effects of temperature, nutrients, and organic matter.

Phosphorus is a crucial nutrient for algal growth, promoting phytoplankton proliferation within certain concentration ranges. High N:P ratios (>16) typically indicate phosphorus limitation. In this study, N:P ratios of 24.91–28.27 combined with TN exceedance confirm phosphorus as the primary limiting factor. COD and CODMn, important indicators of organic pollution, showed extremely significant positive correlations with chlorophyll-a, indicating that organic matter from domestic sewage and aquaculture promotes algal growth while algae themselves produce organic matter through photosynthesis.

PCA effectively reduced dimensionality while retaining critical information, with the first three components explaining 87.489% of variance. This approach provides a robust theoretical basis for identifying key environmental controls on phytoplankton and supports development of targeted management strategies for this ecologically and economically vital water resource.

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Note: Figure translations are in progress. See original paper for figures.