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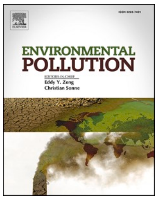

Unveiling the occurrence and ecological risks of triclosan in surface water through meta-analysis☆

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ABSTRACT

Triclosan, a widely used antimicrobial agent, is frequently detected in aquatic environments, prompting concerns about its toxic effects on aquatic species. Understanding its occurrence and ecological risks is crucial for mitigating triclosan contamination, formulating water quality criteria, and protecting aquatic organisms. This study systematically analyzed triclosan occurrence and ecological risks in surface water across China using the Risk Quotient methodology. A total of 139 and 134 data points were collected for triclosan concentrations and toxicities of aquatic organisms, respectively. Triclosan concentrations in surface water across China ranged from 0.06 to 612 ng/L. Higher triclosan levels were observed in Eastern China compared to Central and Western China, with the average concentration being 4.21- and 7.25-fold higher, respectively. Specifically, the Southeast Rivers Basin (132.98 ng/L) and Pearl River Basin (86.64 ng/L) exhibited maximum triclosan levels, 2.57–19.58 times higher than the other river basins. Further analysis revealed elevated triclosan concentrations in small rivers and surface water within residential areas, with values of 246.1 ng/L in Zhejiang, 86.64 ng/L in Guangdong, 67.58 ng/L in Jiangsu, and 127.99 ng/L in Beijing. Additionally, species sensitivity distribution curves indicated that algae was the most sensitive species to triclosan exposure, followed by invertebrates, while fish exhibited the highest tolerance. The Predicted No-Effect Concentration for the algae, invertebrates, fish, and combined aquatic species were determined to be 0.09, 2.95, 4.44, and 1.51 μg/L, respectively. The occurrence of triclosan in surface water across China did not pose widespread ecological risks. However, targeted monitoring and mitigation efforts are needed, especially in highly developed regions. This study provides crucial insights into the status of triclosan contaminations and risks in China and contributes valuable knowledge to global efforts aimed at safeguarding aquatic ecosystems.

1. Introduction

Triclosan is recognized as an emerging organic contaminant due to its endocrine-disrupting chemical effect (Planelló et al., 2020). Comprised of halogenated aromatic hydrocarbons and functional groups like phenol, ether, and polychlorinated biphenyls, triclosan exhibits broad-spectrum antimicrobial properties (Ghafouri et al., 2023; Wang et al., 2024c). Therefore, it is commonly used in pesticides, antiseptics, disinfectants, and personal care products like shampoo, toothpaste, soaps, and dishwashing liquids (Bilal et al., 2020; Ren et al., 2023). The wastewater generated from the production and consumption of products containing triclosan can be discharged into sewer systems and subsequently transported to downstream wastewater treatment plants (Liu et al., 2022; Wen et al., 2023). However, traditional wastewater treatment plants are ineffective in removing triclosan from wastewater (Wang et al., 2024b), with removal rates ranging from 17.3% to 95.6%, while the remaining triclosan will enter into water bodies (Wang et al., 2024c; Wang et al., 2023c).

Previously, studies have reported frequent detection of triclosan in surface water worldwide, with concentrations ranging from 1.4 to 40000 ng/L (Afolabi et al., 2023). The relatively strong lipophilicity of triclosan, reflected by its high octanol-water partition coefficient (log

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Kow = 4.76) (Miškelytė and Žaltauskaitė, 2023), along with its increasing environmental presence, facilitates its accessibility and entry into aquatic organisms. Consequently, it causes growth inhibition, reproductive impairment, and mortality across species, including algae, invertebrates, and fish (Do et al., 2024). For example, Gorenoglu et al. (2018) demonstrated that the median effective concentration (EC_{50}) in 72 h for triclosan's growth inhibition on algae *Raphidocelis subcapitata* was only 7.8 μg/L. Moreover, Samarakoon and Fujino (2024) discovered that exposure to triclosan concentrations ranging from 5 to 100, $\leq$10, and $\geq$50 μg/L within 48 h remarkably influenced the growth, reproduction, and population parameters of *Moina macrocopa* (invertebrate), respectively. Furthermore, the determined median lethal concentration (LC_{50}) of triclosan on fish species of *Oreochromis mossambicus*, *Anabas testudineus*, *Danio rerio*, *Gambusia affinis*, and *Pseudetroplus maculatus* was found to be 1.35, 1.76, 448, 700, and 750 mg/L, respectively (Neetha et al., 2023). These findings underscore the need for systematic risk assessments of triclosan in surface water to establish water quality criteria and protect aquatic ecosystems.

China, as a large country, has witnessed a significant increase in the production and consumption of triclosan owing to its economic development and population growth (Liu and Wong, 2013). Annually, around 66.1 tons of triclosan-containing wastewater are discharged into the environment, with 91% entering water bodies (Zeng et al., 2024). The COVID-19 pandemic further escalated the use of triclosan-based disinfectants, leading to significantly higher discharges and raising concerns about serious pollution (Sun et al., 2024). The United States and European Union banned triclosan in 2016, potentially reducing its concentration in water bodies (Adhikari et al., 2022), China has yet to implement similar regulations. Consequently, triclosan levels in Chinese waters may exceed those in countries with bans. For example, the Shijing River and the Yangtze River (Jiangsu section) reported maximum triclosan concentrations of 993.09 and 394.5 ng/L, respectively (Yu et al., 2024; Yuan et al., 2020), far exceeding levels in the United States (3.5–34.9 ng/L) (Afolabi et al., 2023). Given the severity of triclosan pollution in China, a comprehensive nationwide assessment of its occurrence and risks in surface water is crucial.

Despite numerous studies evaluating the ecological risk of triclosan in Chinese surface water, most have been limited to specific rivers like the Shahe, the middle Yangtze, and the Yellow Rivers, with few comprehensive assessments across China (Wang et al., 2022; Yu et al., 2023; Yuan et al., 2019). Moreover, Predicted No-Effect Concentration (PNEC) values often rely on a limited number of aquatic species, lacking a systematic collection of triclosan toxicity data (Liu et al., 2020; Yang et al., 2021). The collection of triclosan exposure concentrations and toxicity data on aquatic organisms lacks systematicity (Liu et al., 2022). Additionally, some studies focus only on acute toxicity data and base risk assessments on the maximum measured concentrations of triclosan (Lu et al., 2022; Yang et al., 2021). These limitations could bias the risk assessments, leading to inadequate water quality criteria formulas for protecting aquatic organisms.

Therefore, this study aims to comprehensively analyze triclosan occurrence in surface water across China and evaluate its ecological risk by systematically collecting the data, considering chronic toxicities, and incorporating the 50th and 95th percentiles of measured environmental concentrations. Data on triclosan concentrations from 2013 to 2024 and toxicity data (EC_{50} or LC_{50} as statistical endpoints) were gathered through systematic literature reviews following PRISMA guidelines. The occurrence of triclosan was then analyzed across various levels. Furthermore, the acute toxicity data were converted to chronic toxicity data, and species-sensitive distribution curves were constructed to obtain PNEC for combined aquatic organisms (fish, algae, and invertebrates). Finally, ecological risks were evaluated using the Risk Quotient methodology. This study provides useful insights for addressing triclosan contamination in China and offers guidance for environmental efforts in other developing countries.

2. Materials and methods

2.1. Systematic literature review of triclosan concentration in surface water across China

Following the PRISMA guidelines (Li et al., 2023), a systematic approach was conducted in January 2024 to identify peer-reviewed studies on triclosan concentration in surface water (i.e., rivers and lakes) across China. The search used the Scopus and Web of Science databases, with the search terms TITLE-ABS-KEY (triclosan) AND TITLE-ABS-KEY (China). The search scope was limited to research and conference articles published between 2013 and 2024. The exposure concentrations of triclosan in surface water collected from the various water bodies in China are detailed in Table S1.

2.2. Systematic literature review of triclosan toxicity data on aquatic organisms

A similar systematic approach was employed to search for peer-reviewed literature related to the toxicity data of triclosan on aquatic organisms. The search was also performed in January 2024 using the same databases as Section 2.1, with the search terms TITLE-ABS-KEY (triclosan) AND TITLE-ABS-KEY (aquatic organisms OR fish OR algae OR invertebrates). Notably, the research primarily focused on research and conference articles without a specific time constraint. This decision was made because current toxicity data for triclosan on aquatic organisms mainly stem from laboratory experiments (Arnot et al., 2018). Moreover, previous studies have shown no remarkable differences in species sensitivity distributions between native and non-native species (Wang et al., 2013; Zheng and Ni, 2024), suggesting that toxicity data from various geographic regions can be effectively utilized in ecological risk assessment of triclosan. Therefore, this study used aquatic organisms data not only from China but also from global sources. The collected toxicity data of triclosan on aquatic organisms were detailed in Table S2, encompassing various organisms (i.e., algae, invertebrates, and fish), endpoints (i.e., growth, biomass, mortality, survival rate, etc.), duration of triclosan exposure (i.e., 24, 48, 72 h, etc.), and statistic endpoints (i.e., EC_{50} and LC_{50}). The screening and selection results are presented in Fig. S1, with a detailed analysis provided in Text S1.

2.3. Occurrence of triclosan's environmental concentration in China

The measured environmental concentrations (MECs) of triclosan, sourced from published peer-reviewed articles (Section 2.1), were presented in various formats such as ranges from minimum to maximum values, median values, mean values, and individual data points, either as single or multiple combined values. To ensure consistency, average values were calculated for all analyses, with adjustments made for data below the detection limit by halving the limit, as outlined in previous studies (Lee et al., 2022; Yu et al., 2023). Subsequently, ranking all MECs by percentile and estimating the MEC 50th and 95th percentiles from the ranked MEC data offer a more comprehensive approach than relying solely on the maximum concentration of triclosan in surface water (Hamidin et al., 2008). The results at the 50th percentile offer valuable insights into the most probable risk profile. Meanwhile, the inclusion of the 95th percentile results for triclosan concentration allows for a thorough evaluation of conditions contributing to a more protective risk profile (Brown et al., 2020; Stanek et al., 2020). Additionally, this study investigated triclosan concentrations across China from three perspectives: 1) geographical divisions, including Eastern (Northeast China was included), Central, and Western China, as defined by the National Bureau of Statistics of China (https://www.stats.gov.cn); 2) main river basins; and 3) provinces and municipalities. The screening and selection results are presented in Fig. S1, with a detailed analysis provided in Text S1.

2.4. Determination of both acute and chronic toxicity values of equivalent

Following the guidelines outlined in the Technical Guideline for Deriving Water Quality Criteria for Freshwater Organisms issued by the Ministry of Economy and Environment of the People's Republic of China, the collected acute toxicity data in Table S2 underwent screening and filtering (MEE, 2022). Triclosan toxicity data for aquatic organisms is calculated using Eq. (1):

$$AVE_{i,K} = \sqrt[m]{ATV_{i,k,1} \times ATV_{i,k,2} \times \ldots \times ATV_{i,k,m}} \tag{1}$$

where AVE represents the acute toxicity value of equivalence (μg/L); ATV, i, k, and m represent the acute toxicity value (μg/L), the specific aquatic species, the type of acute toxicity effect, and the number of ATVs, respectively. Notably, the AVE adopted in this study was based on EC_{50} or LC_{50}, both of which were commonly utilized as statistical endpoints for acute toxicity data (MEE, 2022). Additionally, when numerous endpoints were available for the same species, the most sensitive toxicity data (lowest value) were selected according to the guidelines mentioned above. The exposure time of toxicity tests didn't influence the ultimate results of AVE, as AVE was solely related to species type and toxicity test endpoints according to Eq. (1). However, the toxicity data screening process requires consideration of exposure conditions, such as the exposure duration, in line with Technical Guidelines. This study strictly followed these guidelines, using the filtered data as the basis for chronic toxicity calculations.

As previously mentioned, the scarcity of chronic toxicology data for triclosan in aquatic organisms presents challenges in comprehensively understanding the actual environmental risks (Wimmerova et al., 2022). To address this, converting acute toxicity data into chronic equivalents is crucial for subsequent species sensitivity distribution construction. However, when dealing with chemicals for which comprehensive chronic toxicity data is available, it is unnecessary to convert between EC50/LC50 and EC_{10} for CVE calculations. Recent studies, including Wess et al. (2020) and Guo and Iwata (2017), have advocated adopting chronic toxicity data of Effective or Lethal Concentration at 10% (EC_{10} or LC_{10}) over traditional metrics like No Observed Effect Concentration (NOEC) and Lowest Observed Effect Concentration (LOEC) in species sensitivity distribution curve development. This preference also aligns with China's technical guideline standard (MEE, 2022). Moreover, a conversion relationship between AVE acute toxicity data (i.e., EC_{50} or LC_{50}) and CVE chronic toxicity data (i.e., EC_{10} or LC_{10}) proposed and utilized in previous research by Aurisano et al. (2019) and Oginah et al. (2023), has been well validated for triclosan toxicity data. This conversion relationship provides a valuable framework for estimating chronic toxicity from acute toxicity data, as depicted by Eq. (2):

$$\text{Log}_{10}\,\text{CVE} = 0.869 \times \text{Log}_{10}\,\text{AVE} - 0.508 \tag{2}$$

where Log_{10} represents logarithm to base 10, CVE (μg/L) and AVE (μg/L) represent equivalent chronic and acute toxicity data for aquatic organisms, respectively. Among these, CVE utilizes chronic toxicity data with EC_{10} or LC_{10} as statistical endpoints, while AVE utilizes acute toxicity data with EC_{50} or LC_{50} as statistical endpoints.

2.5. Species sensitivity distribution and 5% of the hazardous concentration

The species sensitivity distribution curve was commonly employed to assess the toxicity data of triclosan on aquatic organisms (Do et al., 2024). The construction of the species sensitivity distribution curve relied on the Log_{10} CVE values calculated in Section 2.4 alongside the corresponding fraction affected. For specific transformed data, please refer to Tables S3–6. The steps for handling aquatic organisms' toxicity data were detailed in Text S2.

A logistic model embedded within the National Ecological Environment Criteria Calculation Software was then employed to fit the transformed Log_{10} CVE toxicity data of triclosan (Tables S3–6), which has been recognized as the optimal model for characterizing its toxicity on aquatic organisms (Khatikarn et al., 2018; Liu et al., 2022). HC_5 (hazardous concentration of 5% species), indicating that 95% of species remained unaffected by triclosan exposure, was derived from the species sensitivity distribution curves.

The PNEC of triclosan was calculated using Eq. (3):

$$\text{PNEC} = \frac{HC_5}{AF} \tag{3}$$

where AF means assessment factor, with values between 1 and 5, reflecting the uncertainty of the data; HC_5 and PNEC represent the hazardous concentrations of 5% species (μg/L) and Predicted No-effect concentrations (μg/L), respectively. In this study, AF was set as 3 for algae, invertebrates, and fish individually and 2 for all aquatic organisms considered collectively, including algae, invertebrates and fish. Notably, the specific choice of AF was determined according to the guidelines set forth by China's technical guideline standards (MEE, 2022). This equation was commonly used for benchmark extrapolation and allows for the determination of long-term or short-term water quality criteria for aquatic organisms (Liu et al., 2022; Zhang et al., 2020). Additionally, regarding the species sensitivity distribution used to derive the PNEC for combined aquatic species, the only difference between sole and combined species was that the combined species rankings included all collected aquatic species, such as algae, invertebrates, and fish), while the sole species ranking applied to only one species.

2.6. Ecological risk assessment

To evaluate the ecological risk of triclosan in surface water, the widely recognized Risk Quotient (*RQ*) methodology was employed (Gu et al., 2022; Ren et al., 2021). The *RQ* serves as a critical indicator of ecological risk levels associated with triclosan exposure (Wang et al., 2024a). The *RQ* was calculated using Eq. (4).

$$RQ = \frac{\text{MEC}}{\text{PNEC}} \tag{4}$$

where MEC (ng/L) and PNEC (ng/L) represent the measured environmental concentration of triclosan in surface water and Predicted No-Effect Concentration, respectively. Additionally, *RQ* values were categorized into four degrees: $RQ < 0.01$ indicates no ecological risk; $0.01 \leq RQ < 0.1$ indicates low risk; $0.1 \leq RQ < 1$ indicates moderate risk, warranting further monitoring; and $RQ > 1$ indicates high risk, requiring risk reduction measures.

3. Results and discussion

3.1. Triclosan occurrence in surface water across China

3.1.1. Triclosan occurrence in surface water across China's geographical divisions

The violin plots in Fig. 1 reveal triclosan concentrations across China's geographical divisions, with Eastern China exhibiting the highest average value (74.16 ng/L), 4.21-fold and 7.25-fold higher than Central (17.61 ng/L) and Western China (10.23 ng/L), respectively ($p = 0.0023$–0.016). Specifically, triclosan concentration in Eastern China ranged from 0.12 to 612 ng/L, while Central and Western China exhibited concentrations ranging from 0.06 to 248.5 ng/L and 7.2 to 18.3 ng/L, respectively. This disparity can primarily be attributed to the region's varying economic growth rates, with Eastern China experiencing the highest economic growth followed by Central and Western China (Wang et al., 2023b), resulting in increased population density and, consequently, more triclosan-containing wastewater generation (Strokal et al., 2021; Strokal et al., 2023). This detailed relationship

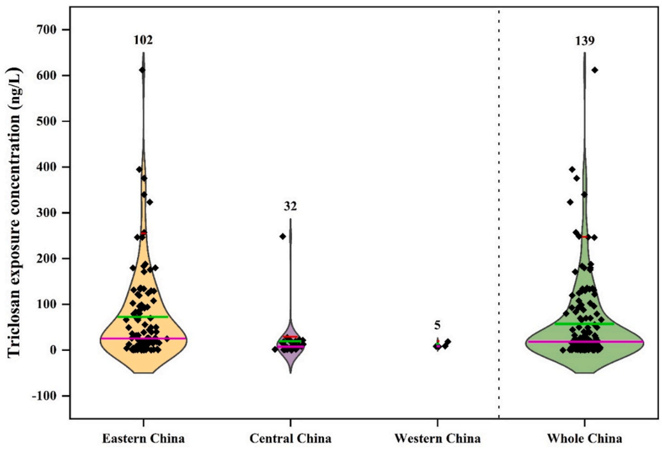

Fig. 1. Violin plots of triclosan concentration in surface water across China's geographical divisions, including Eastern China, Central China, Western China, and the entire country (Whole China). The green (middle), purple (bottom), and red (top) lines within the violin plots represent the mean, median (50th percentile), and 95th percentile of triclosan concentrations in surface water, respectively. The black diamond denotes the concentration distribution of triclosan in surface water. The labels above the violin plot indicate the number of collected data points for triclosan concentrations in the surface water of China. Note: The portions appearing below zero do not imply actual negative values, rather, they indicate a lower density of data within this region. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

between economic development, population density, and triclosan-containing wastewater generation was provided in Text S3. However, when considering the entire dataset from China, the mean triclosan exposure concentration, based on 139 collected data points from surface water, was 58.84 ng/L, with values ranging from 0.06 to 612 ng/L (Fig. 1). Notably, the 50th and 95th percentiles concentrations of triclosan across different geographical divisions of China are detailed in Text S4.

3.1.2. Triclosan occurrence in surface water across China's river basins

Triclosan concentrations were recorded across 6 out of 9 main river basins in China (Fig. 2). The Southeast Rivers Basin and Pearl River Basin had significantly higher levels, 1.78 to 4.85 times greater than others, with significant differences compared to the Yangtze River Basin ($p = 0.017$–0.019). The Southeast Rivers Basin had the highest average concentration (132.98 ng/L), followed by the Pearl River Basin (86.64 ng/L). In contrast, the Yellow, Hai-Luan, and Liao River Basins had lower concentrations of 47.66, 43.12, and 27.4 ng/L, respectively, with the Yangtze River Basin at the lowest (23.66 ng/L) (Fig. 2). However, even for the same river basin, the triclosan concentrations varied substantially in different branches or lakes. For example, in the Southeast Rivers Basin, the Qiantang River recorded the highest at 246.1 ng/L, 12.40-fold higher than the Jiulong River. In the Pearl River Basin, the Liuxi River recorded 219.82 ng/L, 2.17–12.92 times higher than other water bodies (Fig. 2). Similarly, in the Yangtze River Basin, concentrations ranged from 126.16 ng/L in the upper reaches to the lowest in the Xiangjiang River (Fig. 2). The North Canal River in the Hai-Luan River Basin, had the highest triclosan concentration (127.99 ng/L), 4.90–18.85 times higher than the remaining water bodies (Fig. 2). These variations suggest that triclosan levels are influenced by regional or local factors promoting further analysis of its distribution across different provinces and municipalities in China.

3.1.3. Triclosan occurrence in surface water across China's provinces and municipalities

The collected dataset revealed that Zhejiang, Beijing, Guangdong, and Jiangsu recorded significantly higher triclosan concentrations at 246.1, 127.99, 86.64, and 67.58 ng/L, respectively, which were 1.23–164.07 times higher than in other provinces and municipalities, with Henan showing the lowest at 1.5 ng/L (Fig. S2). All four provinces and municipalities were in Eastern China, consistent with the higher triclosan concentrations observed in Eastern China compared to Central and Western China.

Triclosan concentrations were generally higher in smaller rivers compared to larger ones. For example, the Liuxi River (Guangdong) recorded the highest average triclosan concentration at 219.82 ng/L, while the larger Dongjiang River (Guangdong) had just 17.02 ng/L (Fig. 3). Similarly, East Lake (Hubei) recorded 28.07 ng/L, compared to Liangzi Lake's (Hubei) 9.97 ng/L (Fig. 3). This trend was linked to the smaller watershed areas of the Liuxi River and East Lake compared to the Dongjiang River and Liangzi River (2300 *versus* 35340 and 128.74 *versus* 2085 km^2, respectively). Smaller rivers typically have slower flow velocities and longer retention times, leading to higher triclosan

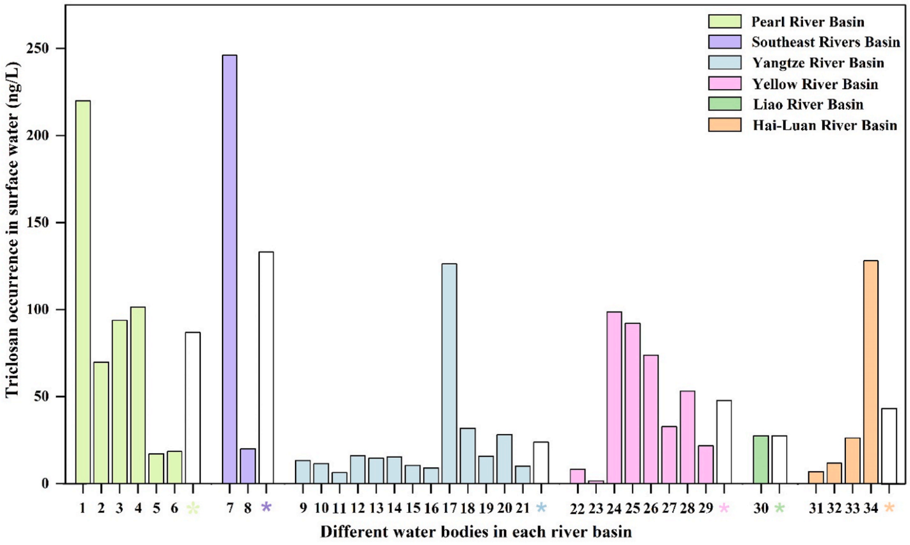

Fig. 2. Triclosan occurrence in surface water across the main river basins in China. Note: The column marked with an asterisk represents the average concentration of triclosan in each river basin. The numbers within each river basin represent the different water bodies. Please refer to Text S5 in the Supplementary Materials for the specific names of water bodies within each river basin across China.

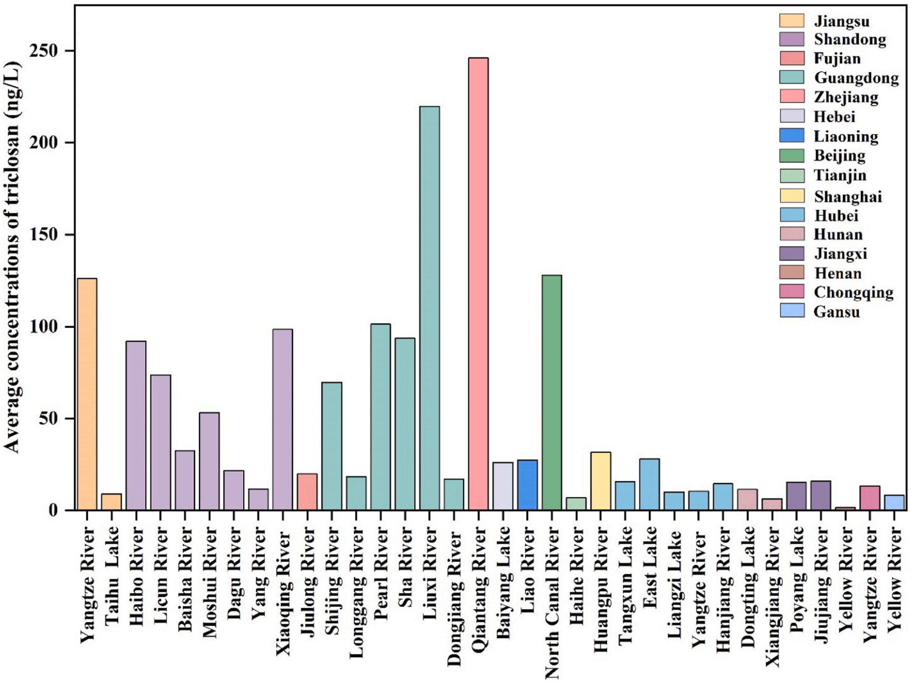

Fig. 3. The average concentration of triclosan across various water bodies in different provinces and municipalities across China. Note: Rivers such as the Yangtze River and the Yellow River may traverse several provinces in China, and rivers were labeled according to the location of the sampling points within the respective provinces. The columns of different colors represent water bodies in the different provinces and municipalities, while columns of the same colors denote water bodies within the same provinces and municipalities. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

concentrations (Thomaidi et al., 2017; Wang et al., 2022). However, exceptions exist, such as the Xiaoqing River (Shandong) with 98.54 ng/L, significantly higher than its tributary, the Yang River, at 11.61 ng/L (Fig. 3). Similarly, Dongting Lake (Hunan) showed 11.44 ng/L, 1.83-times higher than the Xiangjiang River's 6.25 ng/L (Fig. 3). These discrepancies often stem from the proximity of sampling points to wastewater treatment plant effluent (Chen et al., 2018; Wang et al., 2014), highlighting the need to consider discharge outlets in triclosan assessments.

Economic activities and anthropogenic factors also influence triclosan levels. For example, East Lake in urban Hubei exhibited much higher concentrations (28.07 ng/L) compared to non-urbanized water bodies (9.97–15.7 ng/L). Similarly, Jiujiang River (Jiangxi), which is an urban area, had slightly higher triclosan levels than Poyang Lake (15.95 *versus* 15.27 ng/L). The elevated concentrations in urban rivers can be attributed to the direct discharge of domestic wastewater from nearby residential districts (Wang et al., 2017). Moreover, rivers in eastern provinces and municipalities, such as the Qiantang, North Canal, Yangtze, and Huangpu Rivers exhibit triclosan levels 1.13–18.6 times higher than those in Central and Western regions, reflecting the impact of economic development and population density (please refer to Text S3 for more information) (Strokal et al., 2021; Strokal et al., 2023). Notably, water protection efforts also played a crucial role. Taihu Lake (Jiangsu) and the Yellow River (Henan), both critical drinking water sources, exhibited low triclosan levels (9 ng/L and 1.5 ng/L, respectively), likely due to the implementation of stringent protection measures (Li et al., 2022; Wang et al., 2023a; Zhang et al., 2022).

Additionally, seasonal variations of triclosan in China's surface water bodies were further explored, with most research focusing on the summer (wet season, high flow) and winter (dry season, low flow) (Fig. S3). Generally, triclosan levels in winter, spring or autumn were 1.3–9.0 times higher than in summer, as observed in rivers like Xiaoqing, Liuxi, and Yangtze Rivers, etc. This was attributed to slower microbial and photodegradation during winter due to lower temperatures and reduced UV intensity (Zheng et al., 2020), along with decreased precipitation (Wang et al., 2022; Yu et al., 2023), which concentrated triclosan in surface water. Conversely, in some areas like Sha River, and Hanjiang River, triclosan levels were higher in summer, possibly due to increased use of triclosan-containing products (Lu et al., 2021; Wu et al., 2015). Moreover, in certain protected reservoirs like Liuxi, triclosan levels remained stable across seasons, likely due to lower levels of human activity (Peng et al., 2017).

3.2. *Triclosan toxicity to aquatic organisms*

The summarized calculation results of triclosan toxicity data on aquatic organisms were presented in Fig. 4. In total, 65 aquatic species (corresponding to 134 toxicity data points) for triclosan on aquatic organisms were collected following PRISMA guidelines, comprising 18 for algae, 29 for invertebrates, and 18 for fish (Fig. 4). The toxicities of triclosan to various aquatic organisms, including algae, invertebrates, and fish exhibited considerable variability. For algae, the concentration ranged from 0.5 to 1637 μg/L, as illustrated in Fig. 4. *Anabaena flos-aquae* was identified as the most sensitive species to short-term exposure to triclosan, with an AVE value of only 0.5 μg/L. This finding is consistent with a previous study that concluded *Anabaena flos-aquae* to be the most sensitive algae species to triclosan (Liu et al., 2022). In contrast, the most tolerant algae species was *Chlamydomonas reinhardtii* (1637 μg/L), which was 3274 times higher than the sensitivity of *Anabaena flos-aquae* (Fig. 4). This phenomenon was likely due to structural similarities between *Anabaena flos-aquae* (a type of cyanobacterium) and targeted organisms (bacteria), allowing triclosan to exert its toxicity on *Anabaena flos-aquae* by targeting the signaling pathway of fatty acid biosynthesis, similar to its mechanism of action in bacteria (Mo et al., 2023).

The toxicity of triclosan on invertebrates ranged from 40 to 3650 μg/L (Fig. 4). Among these AVE values, *Crassostrea gigas* exhibited the lowest value of 40 μg/L, indicating its high sensitivity to triclosan

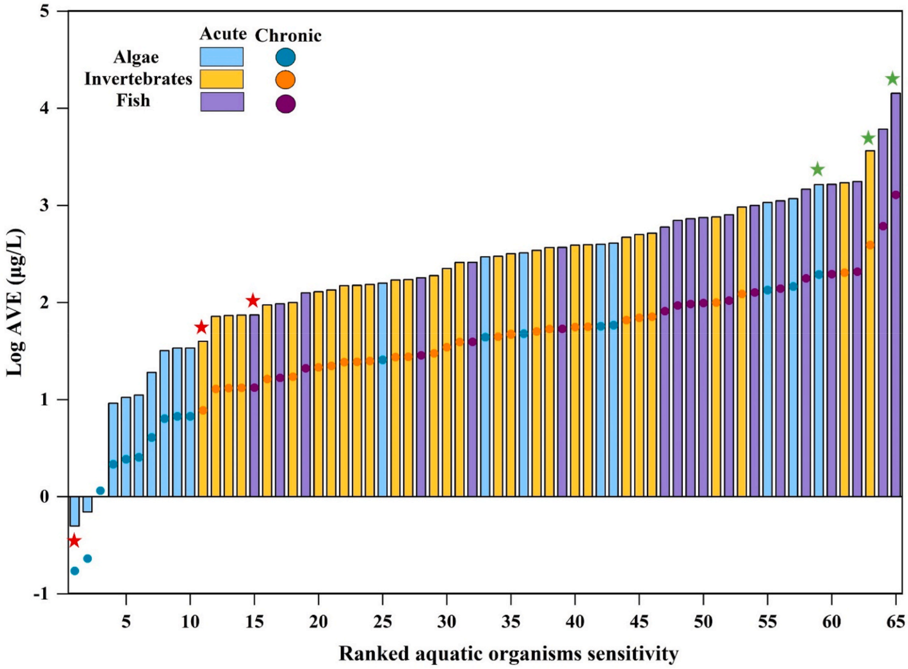

Fig. 4. Equivalent toxicity data values of triclosan in aquatic organisms (i.e., algae, invertebrates, and fish). Note: AVE represents the toxicity value of equivalence (μg/L). Please refer to Table S3 for the specific names of the aquatic organisms ranked according to their sensitivity, from the most sensitive to the most tolerant (1–65). Red and green stars at the top of the columns indicate the most sensitive and most tolerant aquatic species (i.e., algae, invertebrates, and fish), respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

exposure (Fig. 4). A similar conclusion was reached, indicating that *Crassostrea gigas* was less capable of tolerating the toxicity induced by triclosan exposure (Maynou et al., 2021). Conversely, *Caenorhabdities elegans* demonstrated the highest AVE value of 3650 μg/L, suggesting its high tolerance to triclosan exposure (Fig. 4). The triclosan tolerance disparity between *Crassostrea gigas* and *Caenorhabdities elegans* may be due to the latter's high capacity for resilience to the fluctuations caused by triclosan exposure. This resilience could be attributed to an increase in available cellular energy, which in turn may inhibit the execution of apoptosis processes (Zhang et al., 2024).

Triclosan toxicity in fish varied significantly, ranging from 74.6 to 14307.61 μg/L, as shown in Fig. 4. Among the 18 species recorded, *Danio rerio* was the most sensitive, with a concentration of 74.6 μg/L (survival rate as endpoints). Other endpoints, including mortality, reproductive effects, and heart-beat, were observed at triclosan concentrations ranging from 565.51 to 1121.73 μg/L (Table S2). This finding aligns with Neetha et al. (2023), who also identified *Danio rerio* as the most sensitive fish to triclosan, but contrasts with Liu et al. (2022), who found *Misgurnus anguillicaudatus* to be the most sensitive. The discrepancy likely stems from the broader review of triclosan toxicity data in this study, which included *Danio rerio*, unlike Liu et al. (2022). Conversely, *Clarias gariepinus* was the least sensitive fish species, with acute toxicity data of 14307.41 μg/L (Fig. 4), likely due to its behavioral adaptations such as mucous deposition, surfacing, air gulping, and erratic swimming, which help it avoid exposure to triclosan (Jimoh and Sogbanmu, 2021; Priyatha and Chitra, 2018).

Additionally, the chronic toxicity data of triclosan on aquatic organisms were also revealed in Fig. 4 (different colors of solid circles), with concentrations ranging from 0.17 to 1268.20 μg/L. Notably, among the collected toxicity data for 65 aquatic species, acute toxicity data were consistently 2.94 to 11.28 times higher than the chronic toxicity data (Fig. 4). This finding aligns with previous studies indicating that PNEC derived from the chronic toxicity data are sufficient to establish water quality criteria formulas that adequately protect aquatic organisms, compared to acute toxicity data (Wess et al., 2020; Wimmerova et al., 2022). Therefore, the subsequent species sensitivity distribution curves were constructed through chronic toxicity data.

3.3. Species sensitivity distribution curves for triclosan

The collected acute toxicity data of triclosan for aquatic organisms were transformed into CVE (see Section 2.4) for the construction of species sensitivity distribution curves. The log-logistic model was then employed to fit the transformed chronic toxicity data, yielding HC_5 values of 0.27 μg/L for algae, 8.84 μg/L for invertebrates, and 13.31 μg/L for fish (Fig. 5A–C). Accordingly, the corresponding PNEC was calculated as 0.09 μg/L for algae, 2.95 μg/L for invertebrates, and 4.44 μg/L for fish. These findings indicate that algae exhibited the highest sensitivity to triclosan, followed by invertebrates, with fish demonstrating the highest tolerance among collected aquatic species exposed to triclosan. This phenomenon may be explained by an earlier study, which suggests that species sensitivity to triclosan exposure correlates with the ratio of surface and volume, where smaller organisms often display heightened sensitivity (Liu et al., 2022). Additionally, for the combined aquatic organisms, encompassing algae, invertebrates, and fish, the HC_5 value was 3.02 μg/L, with the corresponding PNEC value for the combined aquatic organism being 1.51 μg/L (Fig. 5D). It is noteworthy that the root mean square error (RMSE) values from the fitted species sensitivity distribution curves were 0.063, 0.031, 0.048, and 0.026 for the algae, invertebrates, fish, and combined aquatic organisms, respectively (Fig. 5). These near-zero RMSE values demonstrate a strong fit to the toxicity data of aquatic organisms (Wang et al., 2024a). The calculated PNEC values of 0.09, 2.95, 4.44, and 1.51 μg/L provided important references for the ecological risk assessment of triclosan in surface water.

Remarkably, the PNEC value calculated in our study differs significantly from those reported by Liu et al. (2022) and Wang et al. (2013), with values of 250, and 2000 ng/L, respectively. The significant difference between the two studies' results was due to their use of relatively few species, with only 15 and 9 species, respectively. In contrast, our study conducted a systematic and comprehensive literature review following the PRISMA guidelines, incorporating toxicity data for up to

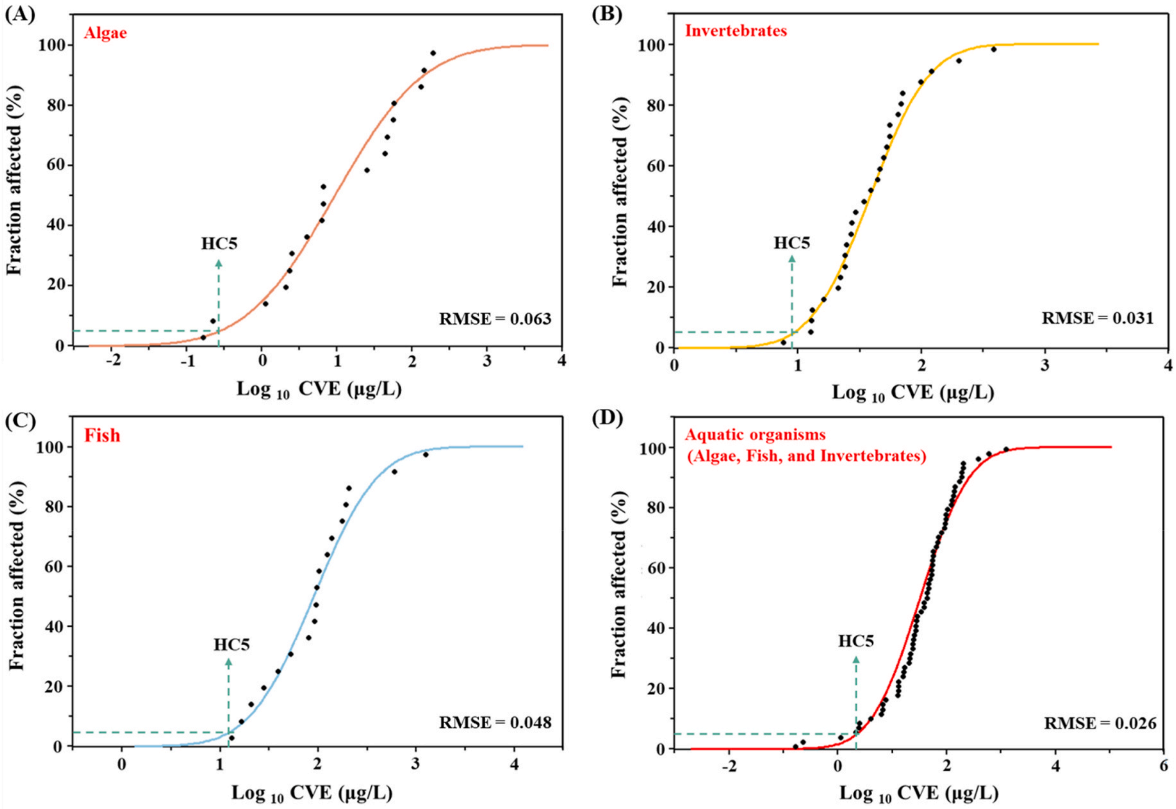

Fig. 5. Species sensitivity distribution curves of triclosan. (A) Transformed chronic toxicity data specifically from algae; (B) Transformed chronic toxicity data specifically from invertebrates; (C) Transformed chronic toxicity data specifically from fish; (D) Transformed chronic toxicity data from the combined aquatic organisms, such as algae, invertebrates, and fish. Note: CVE, HC5, and RMSE represent equivalent chronic toxicity data for aquatic organisms, hazardous concentration at 5% species, and root mean square error, respectively.

65 species. Additionally, our research evaluated a broader range of toxicity endpoints, such as reproduction, photosynthesis, biomass, immobilization, survival rate, development, growth, population, mortality, heartbeat, etc. This expanded scope of endpoints in our research provides a more comprehensive assessment of species sensitivity. These discrepancies highlight the impact of selecting an adequate number of aquatic species and a diverse set of toxicity endpoints in deriving PNEC values. Notably, the works of Liu et al. (2022) and Wang et al. (2013) provided some preliminary and important data on triclosan's hazards, our findings underscore the critical importance of these factors in future research and accurate risk assessment of emerging pollution in aquatic ecosystems aiming to protect aquatic organisms.

Additionally, several factors introduced uncertainty into the calculation of PNECs in this study, primarily related to the quantity and quality of the collected data. Currently, it remains uncertain whether the limited aquatic chronic toxicity data adequately represent the comprehensive effects of triclosan exposure on all aquatic organisms within ecosystems, despite using a wide range of toxicity endpoints to construct species sensitivity distribution curves that aim to mimic real-world conditions. Meanwhile, toxicity effects of different chemicals (i.e., clotrimazole, per-and polyfluoroalkyl substances, octocrylene) (Navarro et al., 2020; Peng et al., 2018) may also cause the uncertainty of PNEC values. Exposure to multiple chemicals in surface water was frequently assessed as isolated events, with insufficient attention given to the combined toxicity effects of simultaneous exposure. This oversight may result in an underestimation of the toxic impacts of triclosan. A previous study indicated that individual chemicals (i.e., methylparaben, triclosan, carbamazepine, venlafaxine) were unlikely to pose acute toxicity to aquatic organisms (i.e., *Crassostrea gigas*, *Pseudokirchneriella subcapitata*, and *Daphnia magna*). However, the study observed significant combined effects when these chemicals were present together, even though the toxicity of each substance on its own was low (Pittinger and Pecquet, 2018). Unfortunately, there are limited studies exploring the toxicity effects of chemical mixtures on aquatic organisms. Future research needs to address this gap and strengthen our understanding in this area.

3.4. Ecological risk assessment of triclosan in surface water of China

The ecological risk assessment of triclosan in the surface water of China, based on the MEC 50th and 95th percentiles, is illustrated in Fig. 6. Across different geographical divisions, *RQ* values were below 0.01 in Central and Western China, based on the MEC 50th percentile, suggesting no ecological risks posed by triclosan in these areas (Fig. 6A). However, in Eastern China and across the entire country, *RQ* values based on the MEC 50th percentile fell between 0.01 and 0.1, signifying low ecological risks, with Eastern China being the primary contributor to triclosan pollution in surface water (Fig. 6A). When considering the MEC 95th percentile, low ecological risks were observed in Central and Western China, with *RQ* values within the range of 0.01–0.1 (Fig. 6A). However, in Eastern China and as well as the entire country, moderate ecological risks were recorded, with *RQ* values of 0.17 and 0.16, respectively (Fig. 6A). This highlights the need for enhanced monitoring efforts, particularly in water bodies in Eastern China, in future research endeavors.

The ecological risk assessment results of the main river basins in China are depicted in Fig. 6B, with details of the MEC 50th and 95th percentiles provided in Fig. S4 and Text S6. According to the MEC 50th percentile, only the Southeast Rivers Basin and Pearl River Basin exhibited low ecological risks, while the other river basins showed no risks associated with triclosan. When considering the MEC 95th

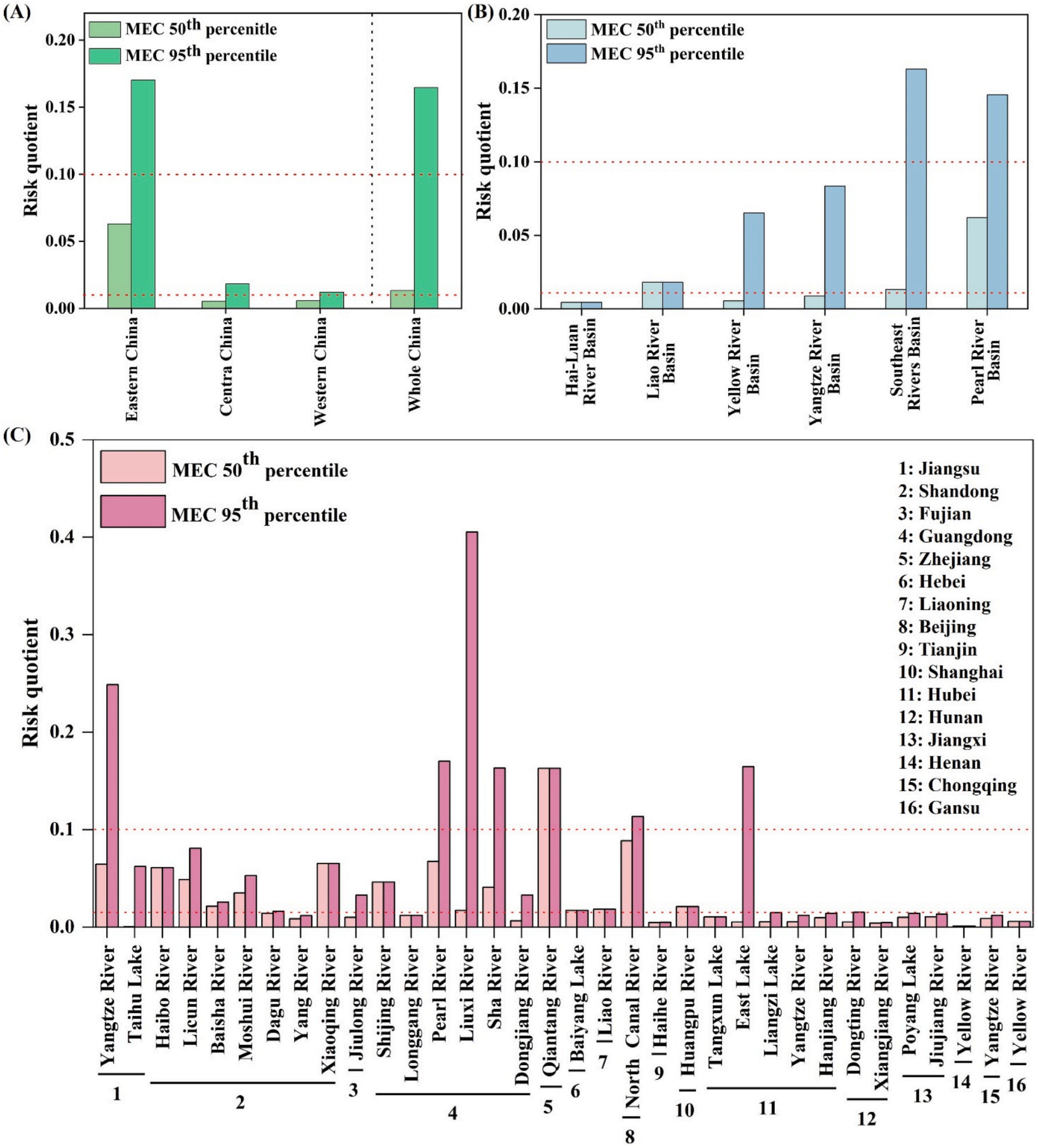

Fig. 6. Risk quotients of triclosan in surface water of China based on MEC 50th and 95th percentiles. (A) Risk quotients of triclosan in surface water across different geographical divisions of China, including Eastern, Central, and Western China; (B) Risk quotients of triclosan in surface water across the main river basins of China; (C) Risk quotients of triclosan characterized for surface water across different provinces and municipalities of China. Note: The MEC 50th and 95th percentiles represent the 50th and 95th percentiles of the collected measured environmental concentration of triclosan in surface water, respectively. Both the upper and lower red dashed lines in each figure represent "no risk" and "low risk," respectively. Surface water samples withdrawn from these rivers were recorded in corresponding provinces or municipalities. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

percentile, the Southeast Rivers Basin and Pearl River Basin exhibited moderate risk levels, with *RQ* values of 0.16 and 0.15, respectively. Following these, the Yangtze River Basin, Yellow River Basin, and Liao River Basin demonstrated low ecological risks, while no risk was recorded for the Hai-Luan River Basin concerning triclosan exposure. These findings emphasize the necessity for heightened monitoring efforts in future research, particularly in the Southeast River Basin and Pearl River Basin, to address the identified ecological risks effectively.

The ecological risk assessment results of the water bodies in different provinces and municipalities are demonstrated in Fig. 6C, with details of the MEC 50th and 95th percentiles provided in Fig. S5 and Text S7. Only the Qiantang River in Zhejiang ($RQ = 0.16$) showed a moderate ecological risk exposure to triclosan, according to the MEC 50th percentile (Fig. 6C). Moreover, 58.8% of reported rivers exhibited low risks, with *RQ* values ranging from 1.01×10^{-2} to 8.85×10^{-2}, while 38.2% of rivers showed no risks, with *RQ* values between 9.93×10^{-4} to 8.54×10^{-3} (Fig. 6C). The moderate ecological risks identified in the Qiantang River may be attributed to the limited available data received (only 1 data point in this study), and the sampling point may be close to the effluent of wastewater treatment plants, resulting in higher triclosan concentration and ultimately resulting in moderate ecological risks. The *RQ* values based on the MEC 50th percentile provide a more realistic assessment, offering practical insights for water resource management (Guo and Iwata, 2017; Stanek et al., 2020). This aids in formulating targeted management strategies and measures to address current risks and challenges. Additionally, based on the MEC 95th percentiles, 20.6% of rivers exhibited moderate ecological risks ($RQ = 0.11$ to 0.41), followed by 67.6% of rivers showed low ecological risks ($RQ = 1.04 \times 10^{-2}$ to 8.08×10^{-2}), and 11.8% of rivers showed no risks (RQ below 0.01). Specifically, the rivers showing moderate ecological risks include the Yangtze River in Jiangsu, Pearl River, Liuxi River, Sha River in Guangdong, Qiantang River in Zhejiang, North Canal River in Beijing, and East Lake in Hubei. This highlights the need for preventive measures and sustainable water resource management practices to mitigate potential risks and ensure the long-term health of aquatic ecosystems.

3.5. Implications of this study

This study unveiled a remarkable variation in triclosan concentration in the surface water of China, spanning from 0.06 to 612 ng/L, with the majority of recorded water bodies assessed as having low ecological risks. These findings indicate that, overall, triclosan pollution in China has not led to severe ecological hazards. The Southeast Rivers Basin and Pearl River Basin exhibited the highest average triclosan concentration at 132.98 and 96.64 ng/L, respectively, corresponding to moderate ecological risks (RQ within 0.1–1) based on the MEC 95th percentile. Currently, the Chinese government emphasizes the unified planning and management of river basins, making these basins focal points of attention (He et al., 2020). Notably, significant variations in triclosan concentration and ecological risks were observed within specific river basins, indicating that regional or local factors, as well as anthropogenic factors, may be primary contributors to triclosan concentration and the associated ecological risks. Further analysis revealed that triclosan ecological risks are mainly observed in the smaller rivers and those situated in residential areas, particularly in provinces and municipalities with highly developed economies; hence, control measures need to be implemented in the water bodies of these areas (Thomaidi et al., 2017). For example, long-term monitoring of triclosan concentration in these water bodies is crucial to promptly understand fluctuations in triclosan levels. Additionally, for wastewater treatment plants located near urban rivers, it is advisable to enhance the removal efficiency of triclosan to reduce the likelihood of its release into aquatic environments, possibly through optimization of existing activated sludge technologies or advanced membrane-based methods (Jabłońska-Trypuć, 2023).

Additionally, this study evaluated the ecological risk of triclosan by systematically reviewing the literature and analyzing established species sensitivity distribution curves of multiple aquatic organisms to derive the PNEC. Notably, these data were derived from the chronic toxicity of aquatic organisms, addressing the limitations of using acute toxicity data by avoiding the underestimation of potential ecological risks (Liu et al., 2022). Meanwhile, the results of this study can provide robust evidence for the ecological risk assessment of triclosan globally. One important point to emphasize is the prioritization of chronic data for aquatic organisms, with the ranking of $\mathrm{MATC} > \mathrm{EC}_{20} > \mathrm{EC}_{10} = \mathrm{NOEC} > \mathrm{LOEC} > \mathrm{EC}_{50} > \mathrm{LC}_{50}$ (Yan et al., 2023). This highlights the need for more chronic toxicity tests (i.e., MATC, EC_{20}) to better protect freshwater organisms. The current study mainly focused on the toxicity of triclosan to aquatic organisms. It is also worthwhile to note that the transformation product of triclosan, i.e., methyl-triclosan, has been shown to be more persistent and can accumulate at higher levels in aquatic organisms than triclosan itself (Liang et al., 2022; Wang et al., 2024c). Therefore, it is recommended to conduct targeted monitoring studies to assess methyl-triclosan levels in surface water and its potential toxicity to aquatic organisms. Meanwhile, the impact of triclosan extends beyond aquatic systems, as it can also affect terrestrial ecosystems. Triclosan has been detected in soils and plants, where it may influence microbial communities and plant growth. This highlights the need for an integrated approach to assess the environmental and health impacts of triclosan and its transformation products across different ecosystems. Moreover, triclosan and its transformation products may accumulate in the human body through the food chain, necessitating a comprehensive analysis to evaluate their potential impact on human health.

4. Conclusions

This study provides the first comprehensive systematic analysis of triclosan occurrence and ecological risks in surface water across China. It revealed that triclosan concentrations were highest in Eastern China, surpassing those in Central and Western China by 4.21-fold and 7.25-fold, respectively. The Southeast Rivers Basin and Pearl River Basin had triclosan concentrations 2.57 to 19.58 times higher than other basins. Zhejiang, Guangdong, Beijing, and Jiangsu reported the highest triclosan levels, likely due to their advanced economic development and high population density. Species sensitivity distribution curves indicated that algae were the most sensitive to triclosan, followed by invertebrates, while fish showed the highest tolerance, with PNEC values of 0.09, 2.95, and 4.44 μg/L, respectively. The PNEC for combined aquatic organisms was determined to be 1.51 μg/L. Despite the widespread occurrence of triclosan, it has not caused significant ecological risks across China. However, special attention should be given to small rivers and surface waters in residential areas, particularly in economically developed regions.

CRediT authorship contribution statement

Zhenyao Wang: Writing – review & editing, Writing – original draft, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Xuan Li:** Writing – review & editing, Supervision, Methodology, Data curation. **Yi Li:** Writing – review & editing, Methodology. **Huan Liu:** Writing – review & editing. **Carol Sze Ki Lin:** Writing – review & editing. **Jing Sun:** Writing – review & editing, Validation, Supervision, Funding acquisition. **Qilin Wang:** Writing – review & editing, Validation, Supervision, Funding acquisition.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envpol.2024.124901.

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