Asian Agricultural Research 2026, 18 (5): 26 – 30 DOI: 10.19601/j.cnki.issn1943 – 9903.2026.05.005

Research Advances Concerning the Effects of Cyanobacteria and Their Toxins in Agricultural Irrigation Water

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Abstract Cyanobacterial blooms have emerged as a significant issue in global freshwater ecosystems. Their presence in agricultural irrigation water sources poses potential risks to crop production, the quality and safety of agricultural products, and related aspects. This article provides a systematic analysis of the current research on cyanobacterial blooms in agricultural irrigation water, focusing on the occurrence and driving factors of cyanobacteria and their toxins in irrigation water bodies, the accumulation and toxic effects of cyanobacterial toxins in crops, the health risk assessment of agricultural products, and the beneficial utilization and management strategies of cyanobacterial resources in agriculture. According to existing research, microcystins (MCs) are among the most concerning cyanobacterial toxins. These toxins can accumulate in various crops, including lettuce, cucumbers, and rice, thereby posing potential health risks through dietary exposure. Furthermore, factors such as irrigation methods, crop species, and growth stages significantly influence the extent of toxin accumulation. This review seeks to provide a scientific foundation for the safe management of agricultural water use, the quality assurance of agricultural products, and the risk assessment and control of cyanobacterial blooms.

Key words Cyanobacteria, Cyanobacterial blooms, Irrigation water, Agricultural production

0 Introduction

Globally, the extensive eutrophication of freshwater ecosystems, combined with the ongoing trend of global warming, has resulted in a marked increase in the frequency, intensity, and duration of cyanobacterial blooms[1 – 2]. These blooms not only disrupt aquatic ecosystems but also present significant risks to human and animal health owing to the diverse cyanobacterial toxins they generate[3]. Agricultural irrigation constitutes a primary use of freshwater resources. The utilization of water bodies contaminated with cyanobacteria and their associated toxins for farmland irrigation establishes a potential transmission pathway encompassing the water source, soil, crops, and ultimately humans[4]. In recent years, the issue of cyanobacterial toxins in irrigation water has garnered considerable attention within the academic community. Previous studies have demonstrated that cyanobacterial toxins present in irrigation water can be absorbed by crops, accumulate within them, and induce phytotoxic effects, thereby posing risks to animal and human health through the food chain[5 – 6]. Consequently, systematically reviewing the research progress in this area and identifying critical scientific challenges is essential for developing effective irrigation management strategies. This article seeks to provide a comprehensive summary of global research advancements concerning cyanobacterial blooms in agricultural irrigation water. It reviews current studies from four perspectives: (i) the occurrence characteristics of cyanobacteria and their toxins in irrigation water bodies; (ii) the accumulation and toxicological mechanisms of cyanobacterial toxins in agricultural crops; (iii) the potential health risks posed to humans through exposure to these toxins via agricultural products; (iv) the beneficial applications of cyanobacteria in agriculture, alongside relevant countermeasures.

1 Occurrence characteristics of cyanobacterial blooms and cyanobacterial toxins in irrigation water bodies

1.1 Widespread existence across the world

The occurrence and detection of cyanobacterial blooms and their associated toxic compounds in agricultural irrigation water have emerged as a global concern. For example, elevated concentrations of microcystins (MCs) have been reported in various locations across Africa, ranging from small dams in Kenya[7] to the Crocodile (west) and Marico Catchment in South Africa[8], as well as irrigation rivers in Nigeria[9]. In Asia, cyanobacterial blooms frequently manifest in the irrigation waters of the Taihu Lake Basin, where MCs concentrations are notably high. In certain instances, these toxins coexist with heavy metals and other contaminants, potentially resulting in synergistic toxic effects that pose significant risks to the safety of agricultural products[10 – 11]. Furthermore, the occurrence of toxic cyanobacteria has been documented in the irrigation systems of Arequipa countryside in Peru[12], irrigation basins in Morocco[13], and irrigation reservoirs in Sri Lanka[14]. These findings indicate that the outbreak of cyanobacteria in agricultural irrigation water sources constitutes a global ecological threat.

1.2 Dominant cyanobacteria species and main toxin types

Among various water bodies used for irrigation, the most prevalent genus of cyanobacteria is *Microcystis*. Additionally, genera such as *Aphanizomenon*, *Anabaena* (now predominantly reclassified under *Dolichospermum*), and *Oscillatoria* are also commonly observed. For example, a study of the rural irrigation system in Arequipa, Peru, identified a total of 13 genera of cyanobacteria, including *Microcystis*, *Anabaena*, *Nodularia*, and *Oscillatoria*, among which 10 were considered to have potential toxin-producing capabili-

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Received: March 20, 2026 Accepted: May 6, 2026

Supported by Scientific Research Fund of Yunnan Provincial Department of Education (2023J0829); Kunming University Talent Program (YJL23003).

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ties[12]. Toxin-producing benthic cyanobacteria, such as *Calothrix* and *Phormidium*, were detected in the irrigation water of the Nile River system in Egypt[15]. In the irrigation reservoirs of Sri Lanka, *Microcystis* was the predominant genus, with its biomass dominating eutrophic water bodies[14]. Similarly, in agricultural irrigation ponds in Maryland, USA, the potential toxin-producing genera *Microcystis* and *Aphanizomenon* were the dominant groups[16]. These data indicate that the dominant cyanobacteria present in the irrigation water exhibit relatively high diversity. Among the various cyanobacterial toxins identified in previous studies, MCs have been a primary focus of research due to their widespread occurrence and potent hepatotoxic effects[3,17]. Moreover, other toxins, such as the neurotoxin β-methylamino-L-alanine (BMAA)[18] and cylindrospermopsin (CYN)[19], have also been detected in irrigation water bodies. A study conducted in Egypt reported that the concentration of MCs in irrigation water in certain areas reached as high as 93.7 μg/L, significantly exceeding the World Health Organization's (WHO) recommended safety limit of 1 μg/L[20].

1.3 Main factors contributing to the outbreaks of cyanobacterial blooms The occurrence of cyanobacterial blooms in irrigation water results from the combined influence of multiple environmental factors. Among these, the excessive input of nitrogen and phosphorus nutrients into water bodies constitutes the primary driving factor. These nutrient inputs predominantly originate from agricultural non-point source pollution, including fertilizers and wastewater from livestock and poultry breeding, as well as urban domestic sewage[21-22]. Temperature and light serve as key physical factors in the development of cyanobacterial blooms. Elevated water temperatures and favorable light conditions significantly enhance the growth and dominance of cyanobacteria[23-24]. Furthermore, hydrological factors, including water level fluctuations resulting from the frequency of irrigation water diversion and drainage, as well as the stratification of water bodies, significantly influence the population dynamics of cyanobacteria. Prolonged water retention times and low flow rate environments generally facilitate the aggregation and proliferation of cyanobacteria[25-26]. In addition, environmental conditions such as elevated pH levels are recognized as important contributors to the development of cyanobacterial blooms[27].

2 Behaviors and effects of cyanobacterial toxins in the soil-crop system

2.1 Accumulation of cyanobacterial toxins in crops and their influencing factors Cyanobacterial toxins, such as microcystin, can enter crops primarily through irrigation water, leading to their accumulation within plant tissues. Various vegetables, including lettuce, spinach, Chinese chives, and radishes, as well as other leafy and root vegetables, have been reported to accumulate MCs[20,28]. Besides, cyanobacterial toxins have been detected in cereal grains such as rice and wheat, but the extent of accumulation is generally markedly different from that observed in vegetables[11,29]. The accumulation capacity of crops is influenced by multiple factors, including crop species, toxin concentration, duration of exposure, and irrigation methods. For instance, lettuce (*Lactuca sativa*) has been demonstrated to accumulate MCs more easily. When lettuce was irrigated with water containing MCs, the concentration of MCs in its leaves reached 0.79 mg/kg dry weight[30]. In field experiments conducted in the Taihu Lake region, the total concentration of MCs in rice grains irrigated with lake water containing MCs was measured at 5.2 μg/kg[11]. Moreover, significant variations in sensitivity and accumulation capacity of MCs have been observed among different varieties of the same crop, such as bush bean (*Phaseolus vulgaris*)[31]. These differences may be attributed to the distinct defense system activities and metabolic detoxification capabilities inherent to each variety.

The accumulation of cyanobacterial toxins in crops typically exhibits a pronounced concentration-dependent effect. Generally, higher concentrations of MCs in irrigation water correspond to greater accumulation of these toxins within crop tissues. Empirical studies have demonstrated that when MCs concentrations in irrigation water ranged from 1.3 to 93.7 μg/L, the toxin levels in the edible portions of vegetables were significantly and positively correlated with the concentration in the water source[20]. Further investigations involving cucumbers confirmed that, across an MCs concentration gradient of 1 - 1 000 μg/L, toxin accumulation in various plant organs increased proportionally with treatment concentration[32]. Additionally, MC-LR was detected in the edible parts of carrots even at relatively low exposure concentrations. However, as exposure levels increased, the rise in toxin accumulation tended to level off[28].

The duration of exposure to cyanobacterial toxins and the developmental stage of crops significantly influence the capacity of crops to accumulate these toxins. For example, studies demonstrated that carrots and radishes exposed to MCs from the seed germination stage exhibited the highest concentrations of MCs in their roots at maturity. In contrast, when exposure commenced only during the growth phase, the accumulation of cyanobacterial toxins was markedly reduced[28]. Research on rice seedlings indicated that after 7 d of MCs exposure, the toxin concentration in various plant organs reached its maximum level[29]. In certain instances, crops initially exposed to cyanobacterial toxins and subsequently irrigated with clean water for a recovery period exhibit a reduction in cyanobacterial toxin levels. For example, following exposure, rice seedlings transferred to clean water for a 7 d recovery period demonstrated a decrease in MCs concentrations across various plant organs[29]. Similarly, studies on strawberries revealed that after 60 d of exposure to MCs followed by 30 d of irrigation with clean water, the concentrations of MCs in the rhizosphere matrix, root system, leaves, and fruits were significantly reduced[33].

The irrigation method constitutes a primary factor affecting the accumulation of MCs in crops. Two prevalent agricultural irrigation techniques are sprinkler irrigation and drip irrigation. Sprinkler irrigation involves the direct application of water containing cyanobacteria onto the aerial parts of crops. Codd *et al.* [34] demonstrated that when lettuce was irrigated with water containing cyanobacteria via sprinkling, both cyanobacteria and MCs were retained in the edible portions of the lettuce. Conversely, drip irrigation delivers water directly to the root zone, thereby minimizing direct contamination of the aerial parts of crops. Nonetheless, drip irrigation does not entirely prevent the uptake of toxins by crops. Studies demonstrated that under drip irrigation conditions, the root system of strawberries continuously absorbed MCs and transported them to the leaves and fruits[35-36]. These findings also indicate that the soil's capacity to adsorb and degrade MCs is limited. Given that different irrigation methods influence the accumulation of cyanobacterial toxins, subsequent investigations examined the spatial arrangement of drip irrigation systems. The results revealed that when drip irrigation pipes were positioned close to the base of the plant stems, toxins rapidly reached the root zone and were absorbed by the crops. By contrast, when the pipes were located farther from the stem base, the soil's adsorption capacity and the degradative activity of rhizosphere microorganisms on MCs may be more effectively functioned[37].

2.2 Phytotoxic effects of cyanobacterial toxins Cyanobacterial toxins exhibit various phytotoxic effects on crops, with mechanisms that include the inhibition of growth and development, impairment of photosynthesis, induction of oxidative stress, and modulation of gene expression and metabolic processes. High concentrations of MCs have been shown to significantly reduce seed germination rates, inhibit root elongation in seedlings, and decrease plant height and biomass[32,38]. For example, exposure of cucumber seedlings to 10 μg/L of MCs resulted in growth inhibition, while higher concentrations (≥100 μg/L) caused some plants to fail to bear fruit[32]. MCs act as potent inhibitors of protein phosphatases 1 and 2A (PP1 and PP2A), enzymes that play critical regulatory roles in plant photosynthesis. Study once demonstrated that the net photosynthetic rate, chlorophyll content, and chlorophyll fluorescence parameters of bush bean and tomato leaves treated with MCs significantly decreased, suggesting potential damage to the photosynthetic elements of these plants[39-40]. Exposure to MCs typically induces membrane lipid peroxidation, as evidenced by increased malondialdehyde (MDA) content, and compromises cell membrane integrity due to the generation of reactive oxygen species (ROS). In response to oxidative stress, plants activate antioxidant defense mechanisms, including enzymes such as superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), and glutathione S-transferase (GST), resulting in elevated enzymatic activities[35,41]. At the molecular level, MCs stress influences gene expression in plants. For example, MCs treatment upregulated genes involved in abscisic acid (ABA) biosynthesis (*OsNCED*) in rice while downregulating genes associated with auxin (IAA) synthesis (*OsYUCCA*), thereby elucidating the observed growth inhibition[42].

3 Health risk assessment of cyanobacteria and their toxins in irrigation water

Cyanobacterial toxins present in irrigation water can enter the food chain through contaminated agricultural products, thereby posing potential health risks. Studies have quantitatively assessed the health risks associated with vegetables containing cyanobacterial toxins, primarily MCs. For instance, a field sampling investigation conducted in China revealed that the MCs content in over 60% of vegetable samples represented a moderate to high risk to human health[43]. Similarly, research in Egypt involving the sampling and analysis of vegetables such as potatoes and spinach irrigated with cyanobacteria-contaminated water demonstrated that the estimated daily intake (EDI) of MCs significantly exceeded the WHO's recommended tolerable daily intake (TDI) of 0.04 μg/kg bw/d[20]. Similar risks have been documented in studies conducted in Nigeria[44] and Sri Lanka[45], where children, owing to their lower body weight, generally face greater risks than adults. In addition to surface water used for irrigation containing cyanobacteria and their associated toxins, certain levels of cyanobacterial toxins have also been detected in some groundwater sources utilized for irrigation[46]. Currently, the WHO has established a guideline value for MCs in drinking water (1 μg/L), but a definitive safety threshold for MCs in irrigation water has yet to be determined. Researchers have advocated for the prompt development of regulatory standards for cyanobacterial toxins in irrigation water to safeguard food safety[6,22].

4 Application of cyanobacteria in agricultural production

Despite the challenges associated with cyanobacteria and their toxins, these organisms hold significant potential for application in agricultural production. For example, nitrogen-fixing cyanobacteria such as *Nostoc* and *Anabaena* can serve as biological fertilizers, enhancing the nitrogen content of paddy field soils, reducing reliance on chemical nitrogen fertilizers, and improving nitrogen use efficiency[47]. Additionally, the polysaccharides secreted by cyanobacteria contribute to soil particle aggregation, thereby improving soil structure, stabilizing the soil surface, and preventing erosion[48-49]. In the context of saline-alkali land remediation, cyanobacteria have been demonstrated to decrease soil sodium ion concentration and electrical conductivity, mitigating salt stress damage to crops[50-51]. Furthermore, extracts from cyanobacteria, including *Spirulina* and *Nostoc*, are rich in bioactive compounds. Seed soaking or irrigation with these extracts has been shown to significantly enhance growth performance, root development, and yield in crops such as wheat[52] and corn[53] under drought stress conditions. This is likely related to the regulation of plant physiological processes[54]. Given the potential hazards posed by cyanobacteria and their toxins, it is imperative to increase monitoring of cyanobacterial toxins when utilizing cyanobacteria and their extracts in agricultural applications. Such measures will enable the effective exploitation of cyanobacterial resources while minimizing associated health risks to humans.

5 Management and countermeasures of cyanobacteria in farmland irrigation water

Currently, to mitigate the risks associated with cyanobacterial blooms in irrigation water, some have proposed various countermeasures. From the standpoint of agricultural management practices, optimizing irrigation techniques represents a direct approach to risk reduction. As previously noted, the implementation of drip irrigation systems and the strategic placement of drippers can substantially decrease the accumulation of toxins in the edible portions of crops[37]. Furthermore, selecting and cultivating crop varieties with low MCs accumulation capabilities[31], as well as conducting a period of "purification" irrigation using clean water prior to harvest, have been shown to effectively reduce toxin levels in edible tissues[28,33]. These strategies offer practical and operationally feasible methods to diminish the health risks posed by cyanobacteria in irrigation water in agricultural production.

6 Conclusions and prospects

This review, drawing upon existing literature, elucidates the complex challenges that cyanobacterial blooms pose to global agricultural irrigation systems. The presence of cyanobacteria in irrigation water represents a significant and widespread risk. Cyanobacterial blooms and their associated toxins, particularly MCs, are prevalent in irrigation water sources across numerous regions worldwide. Crops have the capacity to absorb these toxins from irrigation water and accumulate them within their tissues, thereby threatening the yield, quality, and safety of agricultural products as well as human health. Preliminary assessments have identified the health risks associated with the consumption of agricultural products contaminated with cyanobacteria and their toxins. Concurrently, practical production strategies, including the optimization of irrigation methods and the development of crop varieties with low toxin accumulation capacity, offer viable approaches to mitigate these risks.

It is imperative to establish safety standards for irrigation water and undertake comprehensive toxicological and exposure assessment studies to develop a scientific foundation for determining safety thresholds for cyanobacterial toxins in irrigation water. Currently, the majority of research emphasizes short-term, high-concentration acute exposures. Future investigations should focus on the long-term and chronic response mechanisms, as well as the accumulation patterns of crops exposed to environmentally relevant low concentrations of toxins throughout their growth cycles.

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