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A review of monitoring technologies for real-time management of cyanobacteria: Recent advances and future direction

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ABSTRACT

The frequency and intensity of potentially toxic cyanobacterial blooms in water sources are increasing. Currently, the water industry relies on laboratory analysis of cyanobacteria that can take two-five days; there is therefore a need to improve response time. Online fluorometric probes (also called "fluorescence probes" in some publications) are available for the rapid detection of cyanobacteria cells via measurement of specific pigmentation; however, water quality interferences with probe measurements in natural environments hinder their wider application. This review aims to investigate the sources of interference and bias, and assess the applicability of these probes for measurement of water supplies. Reported laboratory and field validation of these probes showed that their readings were sufficiently accurate. Correction procedures have been investigated for the identified sources of interferences but require field validation. Fluorometric probes can help with decision making during plant operation and have the potential to be applied as a management technique; however, probe users should be fully aware of the sources of interferences when interpreting the in situ probe measurements.

Contents

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1. Introduction

The effects of global climate change appear to enhance the development of potentially toxic cyanobacterial blooms in surface water sources worldwide [1]. Some cyanobacteria species are producers of a variety of potent toxins and/or taste and odor (T&O) compounds [2–4]. Geosmin and 2-methylisoborneol (MIB) are the most well-known T&O compounds associated with cyanobacterial blooms that produce unpleasant odors [3,5], while microcystins are the most commonly detected cyanotoxins. Several other cyanotoxins have been identified including nodularins, anatoxins, cylindrospermopsin and saxitoxins with toxic effects including hepatotoxicity, neurotoxicity, cytotoxicity, genotoxicity and dermatotoxicity [6–8] and reported human health effects of gastroenteritis, liver damage and cancer [7,9–11]. The increasing frequency and intensity of cyanobacterial blooms is therefore causing several problems, including: (1) repeated widespread poisoning of animals, fish, other aquatic living beings and humans by cyanotoxins; (2) toxic cell accumulation in water treatment processes and toxin breakthrough into drinking water that has led to instances of advisories against drinking the tap water in some communities; (3) breakthrough of unpleasant cyanobacterial T&O compounds to finished water leading to customer dissatisfaction; (4) human health effects after recreational exposure to nontoxic cyanobacterial cells; and (5) human exposure to cyanotoxins by consumption of plants irrigated with cyanotoxin contaminated surface water or recycled water from sewage[3–6,11–14].

Due to the harmful effects of toxic cyanobacteria, water authorities across the globe have adopted management strategies to improve the handling of bloom events [15,16]. The main components of these strategies are the identification of threshold levels that define alert levels and specific interventions. Several water authorities have issued management guidelines based on World Health Organisation (WHO) thresholds [17–20]. The WHO have proposed two cyanobacteria alert levels for the management of drinking water sources, which are 2,000 and 100,000 cells/mL, labeled WHO Alert Level 1 and 2, respectively, and a drinking water guideline of 1 µg/L for microcystins [2]. The ability to promptly and accurately monitor cyanobacteria, as well as associated toxins and T&O compounds, in order to correctly identify the exceedance of an alert threshold, is thus a key factor in the implementation of a successful risk management strategy for recreational activities, drinking water production and water reuse[16,19,21–23].

Cyanobacterial biomass and community composition is highly inconstant in space and time; therefore its characterization requires an analytical approach that captures this variability [24]. A number of technologies are promoted for cyanobacteria monitoring. These methods can be classified into two main categories, (1) methods detecting cyanobacteria cells without molecular extraction, for example microscopic enumeration, and (2) those detecting their specific molecules (pigments) once extracted, such as quantitative polymerase chain reaction (qPCR). However, the best available technologies are not capable of achieving accurate, repeatable results in real time [25–27]. For example, the microscopic enumeration method cannot provide in situ results and requires highly qualified personnel, while change in cell biovolume due to preservation by Lugol's Iodine solution can introduce measurement bias [21,28]. Real time qPCR is a promising technique but again requires skilled personnel and is not yet available as an "off the shelf" technology [29–31]. In contrast, currently available fluorometric probes (also called "fluorescence probes" in some publications) can theoretically provide an in situ estimation of cyanobacteria cell density.

Cyanobacteria possess chlorophyll a (Chl*a*), as well as phycocyanin (PC) and phycoerythrin (PE) which are photochemically active pigments [26,32–38]. Cyanobacteria are photoautotrophs with two photosystems (PS), labelled PSI and PSII, located in their thylakoid membrane. PSI, PSII and the Terminal Emitter Pigments receive light energy, fix CO_2 and provide energy for the cell [39]. Phycobilisomes form the light harvesting complex of cyanobacteria; PC is the phycobilisome pigment of blue-green cyanobacteria while PE is specific to red cyanobacteria which are mainly found in marine environment [21,33,40]. While PC and PE are highly fluorescent and are responsible for the majority of the light emission by cyanobacteria, the majority of cyanobacterial Chl*a* is located in PSI and is very efficient at trapping energy [41]. The photoemission of light energy by pigments (Fig. 1) is the process used to develop in situ fluorescence monitoring equipment [41]. Moreover, fluorescence technology has become far more advanced in recent years with specific light-emitting diodes (LED) and optical filters, offering the opportunity to significantly improve upon existing fluorescent probe technology [21,43–48]. However, recent widespread development and application of in situ fluorometric probes by both scientists and water utilities have led to recognition of major issues associated with the undertaking of these measurements, particularly around interferences and how these differ between the range of available probes and bias associated with probes [21,23,41,43–45]. There is a need to quantify these interferences and identify suitable correction technologies.

This review aims to: (1) investigate the attributes of the available submersible or flow-through real-time measurement techniques with a focus on fluorometric probes; (2) determine the difficulties associated with these probe technologies that lead to poor accuracy and repeatability; and, (3) assess the applicability of these probes for the measurement of cyanobacteria to a degree of accuracy that is suitable for identifying whether a cell population is exceeding trigger action levels. Analysing the performance of different in situ instruments with peer-reviewed publications of their application in natural field conditions and/or within water treatment plants is the focus of this paper. To the best of our knowledge, this article provides the first systematic review of the performance of available fluorometric probes for cyanobacterial in situ monitoring while identifying the sources of interferences involved with in situ fluorescence measurements.

2. Available real-time monitoring technologies

All real-time management technologies employed for cyanobacterial management are based on fluorescence. This is because of the fluorescent pigment in the cyanobacterial cell. Each of the fluorescent pigments present in cyanobacterial or algal cells has an excitation spectrum and an emission spectrum [37,38]. The excitation spectrum describes the wavelengths where energy is absorbed to cause fluorescence of the pigment molecules. Specifically, photons of light energy are absorbed by loosely-bound electrons, causing them to jump to higher energy levels. Since fluorescence is a type of luminescence, this is followed by the emission of a lower energy photon that occurs with a time delay as the electrons return to a lower energy state. As energy is inversely proportional to

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