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REVIEW ARTICLE

Toxicity-oriented water quality engineering

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HIGHLIGHTS

- Toxicity-oriented water quality monitoring was proposed.
- Toxicity-oriented water quality engineering control was proposed.
- Future issues of the proposition were discussed.

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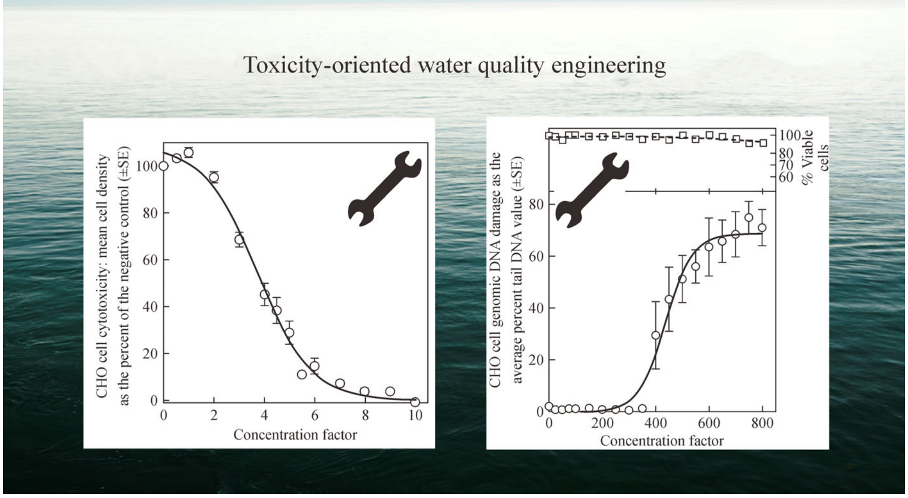
GRAPHIC ABSTRACT



ABSTRACT

The fundamental goal of water quality engineering is to ensure water safety to humans and the environment. Traditional water quality engineering consists of monitoring, evaluation, and control of key water quality parameters. This approach provides some vital insights into water quality, however, most of these parameters do not account for pollutant mixtures – a reality that terminal water users face, nor do most of these parameters have a direct connection with the human health safety of waters. This puts the real health-specific effects of targeted water pollutant monitoring and engineering control in question. To focus our attention to one of the original goals of water quality engineering – human health and environmental protection, we advocate here the toxicity-oriented water quality monitoring and control. This article presents some of our efforts towards such goal. Specifically, complementary to traditional water quality parameters, we evaluated the water toxicity using high sensitivity toxicological endpoints, and subsequently investigated the performance of some of the water treatment strategies in modulating the water toxicity. Moreover, we implemented the toxicity concept into existing water treatment design theory to facilitate toxicity-oriented water quality control designs. Suggestions for the next steps are also discussed. We hope our work will intrigue water quality scientists and engineers to improve and embrace the mixture water pollutant and toxicological evaluation and engineering control.

1 Introduction

Water quality engineering has come a long way since the mid-19th century. Researchers study water quality to not only monitor, but to impose necessary engineering controls to maintain or improve water quality, with the fundamental

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goal of ensuring water safety to humans and the environment.

Water quality engineering has undergone shifts in parameter coverage throughout its development. Traditional water quality engineering consists of monitoring, evaluation, and control of key water pollution parameters (Crittenden et al., 2012; Metcalf & Eddy Inc., 2013). It is a useful approach in that it provides partial insights into the extent of water environment pollution. Additionally, it is relatively efficient to control these selected individual parameters, such as benzene, polychlorinated biphenyls, given the difficulty to evaluate all possible water-relevant parameters. However, this poses a problem because of a lack of simultaneous consideration of multiple pollutants, or toxicants, that occur in the water environments all at once. In other words, pollutant mixtures were not considered. It is known that antagonizing and synergistic effects exist among mixtures of toxicants (Timbrell, 1999; Pals et al., 2016), meaning that their individual toxicological potency sum do not necessarily reflect the scenario in which the same individual toxicants are mixed together – precisely what happens in the real environments. Many studies address the negative biological response separately that arise from each chemical toxicant and attempt to connect the toxic responses with corresponding chemical analyses (Plewa et al., 2004; Jeong et al., 2015; Plewa et al., 2017). However, these studies are limited in the types of actual toxicants in water samples and therefore cannot reveal the overall toxicity of the water that most often contains multiple toxicants. This conundrum puts the real effects of targeted pollutant monitoring, evaluation, and engineering control methodology in question. Long realizing the limitations of individualized parameter monitoring and control, researchers proposed and developed the combined parameters that has been proven to be effective and efficient in many scenarios, e.g. total organic carbon. However, these parameters are not directly indicative of water safety – an important part of the original intention to investigate water quality. Researchers and practitioners recognized this limitation and proposed combined parameters to address health concerns in wastewater scenarios because only wastewaters were deemed toxic enough (Blatchley et al., 1997). It was not long before people started to realize the need for toxicity measurement in drinking waters because the disinfection of drinking water in public facilities primarily employs chemical disinfectants that can convert naturally occurring and synthetic substances in the raw water into unintended chemical disinfection byproducts (DBPs) (Rook, 1974; Crittenden et al., 2012). The DBPs that are unintentionally generated pose a chronic health risk and are regulated by many environmental agencies worldwide as the DBPs may possess long-term human health implications such as the induction of spontaneous abortions in humans (Waller et al., 1998; Waller et al., 2001). Nevertheless, the toxicity-based approach was only used for the evaluation of individual DBP chemicals, and the overall effect of DBP mixtures are mostly predicted based on a linear addition model (Yeatts et al., 2010). This brings the question back to the original conundrum about the real human health protection effects of targeted individual pollutants control. While most water quality control facilities, such as properly designed and managed drinking water facilities produce clean water that contain much fewer known contaminants than the influents, considering the number of people who rely upon this water, it is however still prudent and crucial to show the potential composite mixture effects of contaminants that may impair the public health, and that the treatment processes can sufficiently control these negative impacts from trace contaminants that may not be known or measurable (Tang et al., 2014; Li and Mitch, 2018). It therefore is clear that a more broad-spectrum toxicity-oriented water engineering approach, encompassing but is not limited to, water quality monitoring and water quality control, is the technological and conceptual gap to fill. To refocus our attention to our original goal of human health protection through better water quality engineering, we advocate here the toxicity-oriented monitoring and engineering control methodology. The toxicity-oriented water quality monitoring and control is hoped to collectively consider a broader range of contaminants' negative health impacts simultaneously compared to the traditional approach (Li and Mitch, 2018), and thus reveals a different set of biological impacts that the traditional approach may have missed.

2 Toxicity-oriented water quality monitoring

Chemical-based water quality monitoring has been shown to at times leave much of the observed total water toxicity unexplained (Pressman et al., 2010; Tang et al., 2014), which calls for toxicity-oriented water quality monitoring (Li and Mitch, 2018; Neale and Escher, 2019). In recent years, we, along with colleagues from various institutions that believe in the same direction, have progressively developed and deployed tools for reliable broad-spectrum composite water toxicity monitoring. A lot of success has been received. These tools mainly encompass *in vivo* bioassays, such as the rodent bioassay, the marine polychaeta bioassay (Pressman et al., 2010; Yang and Zhang, 2013; Yang et al., 2015); *in vitro* bioassays, such as the bacteria mutagenicity bioassay, the yeast estrogenic bioassay, the mammalian cell cytotoxicity bioassay (Wagner et al., 2012; Jia et al., 2015; Dong et al., 2019). Taking the case of reuse of municipal secondary effluents as an example, which is gaining popularity due to reasonable compliance with the regulated individual water quality parameters. To ensure safety of such waters, we demonstrated toxicologically that these secondary effluents, with or without the common impacts from the elevated halogen content from seawater intrusion, did in fact express lower toxicity than many other reuse water alternatives, such as agricultural wastewater and shower gray water, other two common candidates for water reuse (Fig. 1). As another example, chloramination of wastewaters for disinfection purposes is a common practice to reduce the microbial risks in wastewater discharges. This method is more economical than chlorination due to less chlorine dosage, and is thus adopted by many wastewater utilities (Metcalf & Eddy Inc., 2013). By conducting targeted organic DBP analyses, previous research established the superiority of chloramination technology over chlorination as the former consistently generated less regulated DBPs, such as trihalomethanes and haloacetic acids, two groups of important regulated DBPs (Goslan et al., 2009; Bougeard et al., 2010). This discovery led to the adoption of chloramination over chlorination by water utilities to comply with the DBP limits.

However, we discovered that chloramination of de facto reuse impacted waters, especially in coastal regions where high halogen occurrence is a real possibility, could induce higher toxicity that stemmed from the halogens, the extracted organics, and the disinfectant, compared to chlorination (Fig. 2) (Dong et al., 2017a; Dong et al., 2017b). This toxicological observation is in agreement with other studies that identified new, more toxic DBPs in chloraminated waters that contained organic matter than their chlorinated counterparts (Joo and Mitch, 2007; Postigo et al., 2016). Regardless of the differences in waters that we used and those by research that promoted chloramination technology, had the more health-specific toxicological evaluation approach been adopted over a targeted specific contaminants evaluation approach, the suggestion of a more health-oriented disinfection technology may have been different. The benefit of the toxicological approach becomes more apparent given that new technologies will give rise to the detection of many new potential contaminants over time, a lot of which have already been included in the wholistic toxicological testing methodology.

3 Toxicity-oriented water quality control

Realizing the more direct health-relevant potential of the toxicity-oriented water quality monitoring approach, along with other colleagues (Wu et al., 2010; Yang et al., 2015; Li et al., 2017a; Li et al., 2017b; Zhang et al., 2017) we further explored improving the water safety through toxicity reduction. First, we consistently demonstrated the potential of certain treatment technologies in reducing water toxicity that stems from the organic components, or a combination of organic and inorganic components (Fig. 2) (Dong et al., 2016; Dong et al., 2017a; Dong et al., 2017b; Dong et al., 2018; Massalha et al., 2018; Dong et al., 2019). Specifically, quantitative biological assessments of composite toxicity levels were conducted as a function of water treatment strategies and treatment levels. For both genotoxicity and cytotoxicity toward mammalian cells, two of the most tested and compared against toxicological endpoints with great resolving power, utilizing the selected water treatment techniques we targeted at and managed to reduce the toxicity of waters of very diverse water quality. These included swine farm wastewaters, municipal secondary effluents with or without seawater intrusion, passive stabilization pond fishery wastewaters, agricultural wastewaters, shower gray waters etc. (Fig. 2). Each technology had its advantages and disadvantages but, in many cases, we were able to show modulation of waters'

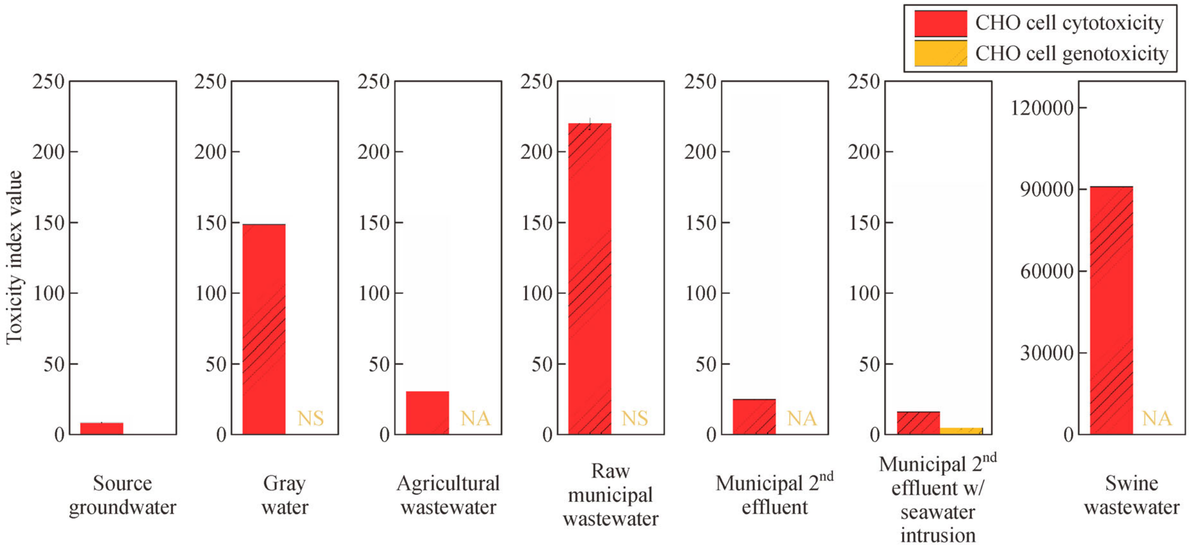

Fig. 1 Examples of the proposed toxicity-oriented water quality monitoring on the selected wide variety of waters that we investigated. We evaluated the cytotoxicity and genotoxicity to the Chinese Hamster Ovary (CHO) cells. Error bars represent the standard error of the mean. NS, no significant difference from the negative control; NA, not available; 2nd effluent, secondary effluent.

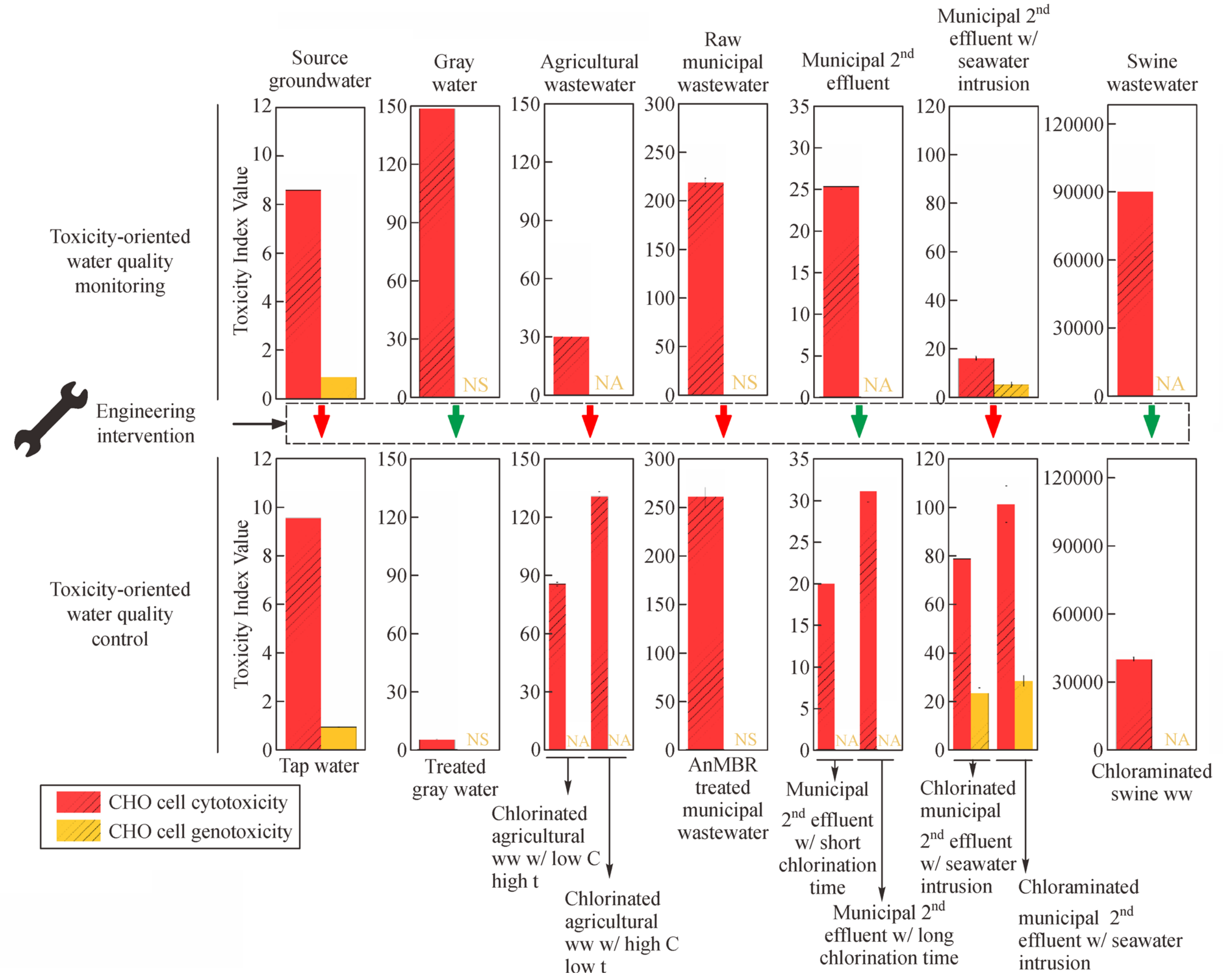

Fig. 2 Demonstration of the proposed toxicity-oriented water quality control effort on the selected wide variety of waters that we investigated. We evaluated the cytotoxicity and genotoxicity to the Chinese Hamster Ovary (CHO) cells. Red (increased toxicity after intervention) and green (decreased toxicity after intervention) arrows in the dashed box show modulation of toxicity post various engineering treatments. Error bars stand for the standard error of the mean. NS, no significant difference from the negative control; NA, not available; AnMBR, Anaerobic Membrane Bioreactor; 2nd effluent, secondary effluent.

overall toxicity and explored the mechanisms behind. For example, swine wastewaters are used as fertilizers in many parts of the world due to dense nutritional content. The microbial safety of these fertilizers thus has to be guaranteed to ensure human health safety. Chlorine is an economical way to fulfill such a purpose. It was believed that in the presence of wastewater organic matter, toxic DBPs that are formed from reactions between these organic matter and chlorine can negatively impact the wastewater's overall toxicity (Metcalf & Eddy Inc., 2013). However, using the wholistic toxicological approach rather than the targeted DBP detection approach, we discovered that the overall toxicity of the wastewater may in fact be lowered using appropriate chlorine addition methods, despite the formation of many regulated DBPs (Fig. 2) (Dong et al., 2016). We discovered that the governing toxicity driving factor in such wastewater was the dissolved ammonia rather than the organics. Ammonia could combine with chlorine to form chloramines so that ammonia becomes not freely available. This highly health-relevant phenomenon with ammonia would never have been captured by the very narrowly-focusing common monitoring scheme of traditional water quality parameters. Possible water toxicity modulation mechanisms were also explored. For instance, the toxicity of four sources of treated municipal wastewaters was reduced by ozonation because of a reduced aromaticity (indicated by fluorescence and SUVA) (Massalha et al., 2018).

In addition to these technological efforts that aimed at minimization of toxicity with existing technologies and to provide insights into the forcing factor behind the observed toxicity so that the toxicity could be better controlled, we also integrated the toxicity-management thinking into the engineering design process to truly enable toxicity-oriented water engineering designs that minimize water toxicity from the design phase. For instance, integrating toxicity into the Ct water disinfection concept that originally aimed to keep pathogens in check, we demonstrated in an easy to implement fashion how agricultural water safety (as partially reflected via toxicity) could be modulated using the Ct concept on top of the appropriate pathogen inactivation (Dong et al., 2018). We found that for a given Ct value that is required to inactivate pathogens, low disinfectant exposure concentration over long contact time produced significantly lower toxicity than high disinfectant exposure concentration over short contact time. This information can be parlayed into a general engineering design where several separate disinfectant injection ports emitting low concentration of disinfectants along a long water contact path is the preferable way to reduce water toxicity compared to the traditional single injection port at a high disinfectant dosage. These highly practical water toxicity control design theories not only provide new insights and perspectives to the theory that facilitated the design of many disinfection systems at water works, but balance microbial control vs. toxicity minimization. These theories have been proposed to hydroponics farmers who increasingly rely heavily on the reuse of low toxicity water.

Our approach has also been used to guide the engineering of government-funded next-generation potable water reuse system, the priority of which is long-term human health safety of people tasked with important missions overseas. As can be seen, the toxicity-oriented water quality engineering has just begun and is hopeful to attract attention and applications.

4 Conclusions and future needs for toxicity-oriented water quality engineering

In this article, instead of promoting any specific technology or toxicity testing endpoints we summarized our recent overall progress in toxicity-oriented water quality monitoring and control. We developed and deployed multi-endpoint tools for reliable broad-spectrum composite water toxicity monitoring. Additionally, we improved water safety through toxicity reduction and consistently demonstrated and optimized the potential of treatment technologies in reducing water toxicity. However, as with most novel means and perspectives, we still have a long way perfecting this approach and bringing this idea to full potential. For instance, one area that demands attention is the mixture method's ability to "be representative of the real environment". Improvements are constantly made and refined to extract and recover as much toxicants as possible to represent real environments (Richardson, 2011; Stalter et al., 2016; Han and Zhang, 2018). Currently for highly toxic waters the organic and inorganic fractions can be evaluated simultaneously, however, for dilute waters such as municipal drinking waters, extraction and concentration processes have to be employed due to low sensitivity of the testing methods. It should probably be restated that the idea is to cover as wide range of potentially toxic water components as possible, rather than to encompass all possible water components, which is virtually impossible. Therefore, our proposition should not be construed as full-spectrum testing of toxicological profiles of all components in the water simultaneously but rather a toxicity-targeted engineering monitoring and control thinking that aims to combat a much broader (compared to the traditional approach) range of chemicals all at once, and to incorporate toxicity reduction into the engineering design phase as practically and economically as possible. Once this proposition received wide recognition and adoption, we believe that it is just a matter of time to discover ways to negotiate problems such as increasing the sensitivity of the testing methods, or improving the comprehensiveness of the extracted samples, or a combination of both.

Additionally, toxicity testing has been the subject to debate for decades about its real-world impact. How to demonstrate that what is flagged by the toxicity assay is expected to be seen in the real population? This is analogous to the "be representative of the real environment" mentioned above. Moreover, different testing organisms/substances may respond differently to the same toxicants. Currently, numerous *in vitro*, *in vivo*, and *in chemico* toxicological testing endpoints exist with varying strengths and weaknesses (Timbrell, 1999). This makes the selection of various testing organisms/substances under heavy debate and research – beneficial for the long-term development of our proposition. Other problems also exist such as the selection of appropriate toxicity testing duration, which depends on the intention of the research such as an acute or chronic testing – another area that attracts criticism and debate (Timbrell, 1999). Low dosage of toxicants delivered to the recipient over extended periods of time does not in all cases equate high dosage of toxicants exposure for short durations, which is the experimental condition that most toxicological studies fall under due to experimental and/or practical reasons. However, the type of toxicant exposure scenarios specific to many human health toxicological concerns are usually best represented by low dosage and long exposure duration. Better balancing of real environmental conditions vs. practical research limitations calls for our attention.

Possible but understandable resistance from the water science and technology community is expected. Researchers and practitioners in our community are generally conservative in adopting new concepts or technologies to solve the water problems or improve water quality, as most of the current parameters and design concepts are in general adequate for environmental compliance purposes. However, given the potential long-term benefits of toxicity-oriented water quality monitoring and control, maybe it is time to embrace novel concepts that have the potential to advance our field – improving water quality to benefit human health, because sole speculations about new methods and techniques will not improve water quality, or benefit human health.

Despite all problems, as new ideas and technologies emerge, we believe there are ways to plow through. For instance, for the problem of "How to demonstrate that what is flagged by the toxicity assay is expected to be seen in the real population?", take drinking water as an example, we propose to explore possible correlations between the selected toxicological endpoints and the real epidemiological data, while previous research only established the correlations between DBP occurrence and the selected toxicological endpoints, and that between DBP occurrence and the epidemiological data (Jeong et al., 2012). As another example to work on the "be representative of the real environment" problem, it may not be necessary to adopt every seemingly endless new tools (endpoints) as soon as they arise, but rather to spend effort into improving the currently available methods while comparing it with other new metrics. For instance, for many surface waters that show relatively high heavy metal content, attempts can be made to add the equivalent concentration of these heavy metal pollutants into the extract – at least we may be one step closer to the goal. It should however be noted that many other limiting factors are at play, for example cost of doing an epidemiological data. But so long as problems are identified, solutions may just be time-dependent.

We advocate here water quality engineering that adopts more comprehensive measurement parameters that reflect mixture scenarios, specifically the health-relevant toxicity because safeguarding health was one of the most important original goals of water quality engineering. This entails integration of the toxicity-management thinking into the engineering design phase to truly allow for toxicity-oriented water engineering designs that factors in water toxicity minimization. We need to be more cautious and warier of the past and future water quality engineering designs and suggestions that are based on the analyses of limited contaminants rather than the real mixtures without direct connection with the health impact. As of now, steps should be taken to incorporate toxicological approaches and augment them with traditional water quality analyses and risk assessments. We believe this is the future direction.

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