ARTICLE IN PRESS

Bioresource Technology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

Review

Assimilable organic carbon (AOC) variation in reclaimed water: Insight on biological stability evaluation and control for sustainable water reuse

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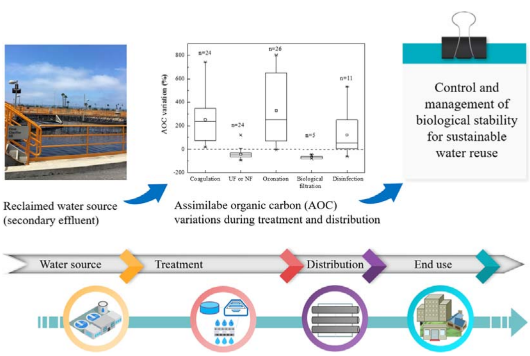
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Assimilable organic carbon (AOC)
Biological stability
Microbial regrowth
Reclaimed water
Sustainable water reuse

ABSTRACT

This review highlights the importance of conducting biological stability evaluation due to water reuse progression. Specifically, assimilable organic carbon (AOC) has been identified as a practical indicator for microbial occurrence and regrowth which ultimately influence biological stability. Newly modified AOC bioassays aimed for reclaimed water are introduced. Since elevated AOC levels are often detected after tertiary treatment, the review emphasizes that actions can be taken to either limit AOC levels prior to disinfection or conduct post-treatment (e.g. biological filtration) as a supplement to chemical oxidation based approaches (e.g. ozonation and chlorine disinfection). During subsequent distribution and storage, microbial community and possible microbial regrowth caused by complex interactions are discussed. It is suggested that microbial surveillance, AOC threshold values, real-time field applications and surrogate parameters could provide additional information. This review can be used to formulate regulatory plans and strategies, and to aid in deriving relevant control, management and operational guidance.

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https://doi.org/10.1016/j.biortech.2018.01.111
Received 11 December 2017; Received in revised form 20 January 2018; Accepted 22 January 2018
0960-8524/

Please cite this article as: Chen, Z., Bioresource Technology (2018), https://doi.org/10.1016/j.biortech.2018.01.111

1. Introduction

Nowadays, water reuse is being increasingly considered as an important aspect to alleviate water-related challenges such as water scarcity and water environment contamination (Verstraete et al., 2009). With the continuous exploitation and development of water reuse applications, it is vital to guarantee the reclaimed water stability for long-term sustainable water reuse (Luo et al., 2014; Tran et al., 2015). Many studies have observed apparent microbial regrowth situations during water reuse practices, including open storage tanks (Ajibode et al., 2013), distribution systems (Jjemba et al., 2010; Thayanukul et al., 2013), and end uses, such as urban replenishment ponds, agricultural irrigation and industrial cooling systems (Alley, 2007). Excessive microbial regrowth in reclaimed water can cause nuisances, such as deterioration of odor and color, biofouling of membranes, clogging of facilities and corrosion of distribution pipes (Shan et al., 2005; Ghunmi et al., 2010). More importantly, the presence of some opportunistic pathogens can bring about health risks and public misgivings (Narasimhan et al., 2005). This could hinder the further expansion of water reuse market to a large extent. For instance, *Legionella* reportedly can survive in cooling water and ornamental water features using reclaimed water, which is likely to cause pneumonia symptoms or other health related diseases (Fykse et al., 2016).

Therefore, biological stability is one of the key issues to be evaluated in water reuse management in order to prevent microbial regrowth and reclaimed water quality deterioration (Ryu et al., 2005; Thayanukul et al., 2013). It is defined as the concept of maintaining microbial water quality from production up to consumption (ISO, 2017). It is further explained as the inability of water or a material in contact with water to support microbial growth in the absence of a disinfectant (van der Wielen and van der Kooij, 2010). Achieving and maintaining biological stability not only implies producing biologically stable water after treatment but also ensures that storage, distribution and end use processes not to generate or promote uncontrollable changes in microbial concentrations (Prest et al., 2016). Given the possibility of opportunistic pathogen regrowth in reclaimed water, microbial community and bioavailability of organic carbon can also be taken into account (Cheng et al., 2016).

To date, there is no unified method to quantify the biological stability of reclaimed water (Garner et al., 2016). It is generally noticed that concentrations of available organic and inorganic nutrients are major factors governing the extent of bacterial growth (Shan et al., 2005; Thayanukul et al., 2013, 2016). Organic carbon is considered as the dominant growth limiting compound for bacteria and biological stability is thusly often evaluated by biodegradable dissolved organic carbon (BDOC) and/or assimilable organic carbon (AOC) concentrations (Escobar et al., 2001; Prest et al., 2016). Moreover, some studies claimed that additional information on microbial community using advanced techniques, such as flow cytometry, adenosine triphosphate (ATP) and pyrosequencing can be complementary to conventional parameters to account for bacterial dynamics in storage and distribution (Lautenschlager et al., 2013; Prest et al., 2014). Nevertheless, AOC can be considered as the first evaluation of biological stability that can provide indications for optimization and control of treatment processes. Since AOC can still influence biological stability at μg/L levels, there is a significant need to analyze the impacts of different treatment technologies on this indicator.

Consequently, this study aims to give an overview of existing biological stability indicators and add emphasis on AOC for assessment. Given distinct differences between reclaimed water and drinking water, a necessity to adopt the AOC bioassay that is specially targeted for reclaimed water is highlighted. Afterwards, the study evaluates how this indicator is influenced by different advanced water reuse treatment processes comprehensively, followed by a deep discussion on challenges and potential needs for biological stability control and management. Better insight into biological stability control of reclaimed water can produce more reliable risk assessment and help to guarantee sustainable water reuse.

2. AOC for biological stability evaluation of reclaimed water

2.1. Typical approaches for biological stability evaluation

A number of methods were reportedly used for biological stability evaluation. One approach is to quantify indigenous bacterial biomass (colony-forming units, CFU), such as bacterial growth potential (BGP) and biofilm formation rate (BFR) (Sathasivan and Ohgaki, 1999). Another alternative approach is to quantify changes of nutrients present in water, such as AOC, BDOC and microbially available phosphorus (MAP) (Wang et al., 2014a, b; Zhang et al., 2016). The comparisons and characteristics of different methods are listed in Table 1. Notably, AOC displays a better correlation with bacterial growth compared to BDOC (Escobar et al., 2001). It is defined as the fraction of labile dissolved organic carbon (DOC), namely the low molecular weight organic carbon contents, e.g. sugars, carboxylic acids and amino acids, that is more easily utilized and converted to cell mass by heterotrophic bacteria than the other types of organic carbon (Liu et al., 2015). Thus, AOC bioassay is widely adopted to give an indication of bacterial regrowth potential (Escobar et al., 2001; Zhao et al., 2013). However, since AOC measurements could not directly reflect microbial composition, not to mention the biological instability caused by autotrophic bacteria growth (e.g. denitrifying and ammonium oxidizing bacteria), some recent studies also call for the identification of microbial community changes in distribution systems (Lautenschlager et al., 2013; Prest et al., 2014).

2.2. Measurement of AOC for biological stability evaluation

2.2.1. Typical AOC levels of drinking water and reclaimed water

Dissolved organic matter (DOM) present in reclaimed water can be apparently distinct from that of drinking water in terms of DOC, dissolved organic nitrogen (DON) and AOC (Hu et al., 2016). Reclaimed water, even tertiary treated, usually contains higher amount of DOM in regard to soluble microbial products, synthetic organic compounds, etc. with greater fluctuations (Ma et al., 2013; Diamantis et al., 2014; Farooq et al., 2015; Verstraete et al., 2016; Bustamante and Liao, 2017). Specifically, AOC concentrations in most treated drinking water (after coagulation and/or ozonation processes) are less than 500 μg/L, and over 80% of drinking water samples have AOC levels below 200 μg/L (Fig. 1). Afterwards, AOC levels are slightly decreased due to bacterial growth in pipelines (Liu et al., 2002).

Comparatively, AOC levels in reclaimed water could be 5–10 times higher than that of drinking water. Weinrich et al. (2010) conducted a survey of 21 water reclamation plants (WRP) in the U.S. and found an AOC level of reclaimed water from 45 to 3200 μg/L with a median value of 450 μg/L. Besides, Thayanukul et al. (2013) investigated 6 WRPs in Japan and claimed that AOC levels of secondary effluent and tertiary effluent from various processes were 66–138 μg/L and 36–446 μg/L (median: 316 μg/L) respectively. In addition, based on 5 WRPs in China, Zhao et al. (2014a, 2014b) concluded that AOC levels of secondary effluent and tertiary effluent from various processes were 57–8150 μg/L (median: 223 μg/L) and 22–3036 μg/L (median: 870 μg/L) respectively. As can be seen from Fig. 1, AOC levels in tertiary effluent were much higher than that of secondary effluent. Significant variations of AOC levels existed due to the adoption of different treatment approaches. It is important to conduct further analyses since high AOC amount in reclaimed water has high potential to provide an environment for the rapid regrowth of certain microorganisms and affects biological stability (Thomure et al., 2014).

2.2.2. AOC bioassay for reclaimed water

The conventional AOC bioassay was developed originally in