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Review Article

Risk management of viral infectious diseases in wastewater reclamation and reuse: Review

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ABSTRACT

Inappropriate usage of reclaimed wastewater has caused outbreaks of viral infectious diseases worldwide. International and domestic guidelines for wastewater reuse stipulate that virus infection risks are to be regulated by the multiple-barrier system, in which a wastewater treatment process composed of sequential treatment units is designed based on the pre-determined virus removal efficiency of each unit. The objectives of this review were to calculate representative values of virus removal efficiency in wastewater treatment units based on published datasets, and to identify research topics that should be further addressed for improving implementation of the multiple-barrier system. The removal efficiencies of human noroviruses, rotaviruses and enteroviruses in membrane bioreactor (MBR) and conventional activated sludge (CAS) processes were obtained by a systematic review protocol and a meta-analysis approach. The $\log_{10}$ reduction (LR) of norovirus GII and enterovirus in MBR were 3.35 (95% confidence interval: 2.39, 4.30) and 2.71 (1.52, 3.89), respectively. The LR values of rotavirus, norovirus GI and GII in CAS processes were 0.87 (0.20, 1.53), 1.48 (0.96, 2.00) and 1.35 (0.52, 2.18), respectively. The systematic review process eliminated a substantial number of articles about virus removal in wastewater treatment because of the lack of information required for the meta-analysis. It is recommended that future publications should explicitly describe their treatment of left-censored datasets. Indicators, surrogates and methodologies appropriate for validating virus removal performance during daily operation of wastewater reclamation systems also need to be identified.

Contents

1. Introduction

Enteric viruses have caused infectious diseases owing to fecally-contaminated irrigation and environmental water. For example, a large outbreak of norovirus occurred in eastern Germany in 2012, which was likely caused by imported frozen strawberries from China (Bernard et al., 2014). Multiple genotypes of norovirus were found

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from tested strawberries and gastroenteritis patients, which supported the speculation that imported strawberries were cultivated with untreated wastewater (Mäde et al., 2013). Imported foodstuffs contaminated with pathogenic viruses originating from wastewater have also caused outbreaks in the other developed countries (Ethelberg et al., 2010; Pérez-Sautu et al., 2011; Terio et al., 2015), in particular when food products are imported from areas where water and sanitation systems are poorly installed and wastewater is directly used for irrigation. In the worst scenario, pathogens eradicated from developed countries can be imported from endemic areas via foodstuff, after which such neglected pathogens can cause outbreaks of infectious diseases in importing countries without any protective aids such as vaccination.

In the future, wastewater will have to be used as irrigation water in arid areas such as Australia, India, Pakistan, Vietnam, the northern part of China, and Middle Eastern countries including Israel (Hanjra et al., 2012). Wastewater is also becoming an important irrigation water source in the USA due to the heavy dependence of agricultural productions on fossil waters from three major over-exploited aquifers (Marston et al., 2015). The National Science Foundation/Mathematics and Physical Sciences Directorate (NSF/MPS) (2014) reported that one opportunity for transformative research can be found in ensuring a sustainable water supply for agriculture, including the expansion of supply through wastewater recycling. In these settings, enteric viruses require special attention because they are excreted to wastewater in larger numbers by infected individuals (up to 10^{12} viruses per gram feces) compared to other enteric pathogens (Drexier et al., 2011; Kirby et al., 2014), and they are typically so highly infectious that less than 10 particles is often enough to cause an infection in susceptible individuals (Thebault et al., 2013; Kirby et al., 2015). Removal of these viruses by wastewater treatment processes is required if treated wastewater is reclaimed; however, enteric viruses are more resistant than pathogenic bacteria to several water disinfection treatments such as filtration, chlorination, UV irradiation, and ozonation, due to the physicochemical properties of viral particles (WHO, 2011). These features highlight enteric viruses as the most important health issue for the safe use of reclaimed water (ATSE, 2013).

In this review article, current guidelines for designing wastewater reclamation and reuse systems from the viewpoint of virus risk management are overviewed, and the efficiency of virus removal from wastewater by currently employed wastewater treatment units are shown by the results of meta-analysis. The regulations for validating the virus removal efficiency of wastewater treatment processes during daily operation are then described in a separate section. Finally, the research areas that should be addressed in the future for better application of wastewater reclamation and reuse are identified from the viewpoint of virus risk management.

2. Guidelines for designing wastewater reclamation and reuse systems from the viewpoint of virus risk management

The World Health Organization (WHO) published four volumes of guidelines for the safe use of wastewater, excreta, and greywater in 2006. Policy and regulatory aspects are compiled in volume 1, where WHO employs 10^{-6} disability adjusted life year loss per person per year (DALY loss pppy) as a tolerable additional disease burden (WHO, 2006), which is equivalent to rotavirus disease and infection risks of approximately 10^{-4} and 10^{-3} per person per year, respectively (Mara, 2008). These values of tolerable additional disease burden can be used to calculate the acceptable level of pathogen concentration in water if the dose-response relationship is available for the pathogen of interest; however, the WHO suggests guideline users set performance targets for wastewater treatment processes in place of the acceptable pathogen concentrations in treated wastewater. The performance target is a value of removal efficiency expressed in common logarithm of the ratio of pathogen concentration in untreated wastewater to that in treated wastewater. For example, the WHO guideline describes that the health-based target (10^{-6} DALY loss pppy) for viral pathogens can be achieved by a total virus reduction of 2–3 $\log_{10}$ in reclaimed wastewater for restricted irrigation (the irrigation of all crops except salad crops and vegetables that may be eaten uncooked), while a 6–7 $\log_{10}$ pathogen reduction is needed for unrestricted irrigation (including the irrigation of salad crops and vegetables that may be eaten uncooked) and localized irrigation (e.g., drip irrigation). The total pathogen reduction in $\log_{10}$ units is obtained by a combination of wastewater treatment including disinfection, natural die-off and health protection measures such as washing produce prior to consumption. The combination of wastewater treatment units is called the multiple-barrier system, consisting of multiple steps where the pathogen removal efficiency (pathogen removal credit) of each step has already been evaluated and determined as a credited $\log_{10}$ reduction (LR) value (Fig. 1). WHO (2006) recommends guideline users measure reduction/inactivation of adenoviruses, reoviruses, enteroviruses, and hepatitis A virus to validate the efficacy of each treatment when the treatment system starts operation. The WHO (2006) guidelines also suggest that each country should establish national criteria and procedures that suit its epidemiological, social, and economic needs.

The United States Environmental Protection Agency (USEPA) (2012) guideline explicitly notes that setting a tolerable virus concentration in reclaimed wastewater (virus limit) is not recommended for the following reasons: 1) viruses are well reduced by appropriate wastewater treatments, 2) identification and enumeration of viruses is time- and labor-consuming, 3) detection of infectious viruses in water is further labor- and time-consuming, 4) molecular-based virus detection does not always indicate the presence of infectious viruses, and 5) waterborne viral infections due to reclaimed water have not been documented. Instead of setting a virus limit, the control of viral infectious diseases caused by contaminated reclaimed wastewater is to be achieved by the multiple-barrier system, which coincides with the WHO guideline. Based on the USEPA guidelines for water reuse, several U.S. state governments have set performance targets for virus removal in wastewater reclamation. In the Groundwater Replenishment Reuse Project (GRRP) of the state of California, where the most stringent and intimate regulations related to recycled water have been established, a 12 LR of viruses along with a 10 LR of both *Giardia* cysts and *Cryptosporidium* oocysts in the wastewater is required when treated wastewater is used for groundwater recharge intended for indirect potable reuse (California State Water Resources Control Board, 2015). The reductions should be accomplished by three or more successive treatment process units, each of which can reduce 1–6 $\log_{10}$ of viruses. In the state of Texas, where direct potable reuse (DPR) of reclaimed water is being implemented, 12, 10, and 10 LRs of viruses, *Cryptosporidium*, and *Giardia*, respectively, are recommended as a baseline for DPR when untreated wastewater is used as a source (Texas Water Development Board, 2015). These required LR values were developed based on the general approach presented in "Potable Reuse: State of the Science Report and Equivalency Criteria for Treatment Trains", which was prepared as part of the Water Reuse Research Foundation Project 11-02 (WRRF Project 11-02) (Texas Water Development Board, 2015). The general approach for determining the required pathogen LR used available data obtained from literatures and calculated drinking water concentrations needed to meet a health goal in the USEPA Surface Water Treatment Rule (SWTR), which is a risk of 1 infection per 10,000 exposed individuals per year (Texas Water Development Board, 2015). On another front, Texas Commission on Environmental Quality (TCEQ) has established minimum (or baseline) LR and/or inactivation targets for the DPR, which are 8, 5.5, and 6 LRs of viruses, *Cryptosporidium*, and *Giardia*, respectively, when wastewater treatment plant effluent is used as a source, although these baseline LR targets are considered a starting point for the TCEQ approval process and may be revised based on data collected from the wastewater effluent in question (Texas Water Development Board, 2015).