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REVIEW

Elimination of viruses from domestic wastewater: requirements and technologies

Chong-Miao Zhang[1] · Li-Mei Xu[1] · Peng-Cheng Xu[1] ·
Xiaochang C. Wang[1]

Abstract Domestic wastewater contains various pathogens, which, if not sufficiently eliminated, may enter the receiving water bodies and cause water-transmitted diseases. Among the waterborne pathogens, viruses may occur, survive and/or decay much differently from bacteria in water. In many cases, the diseases caused by viruses are more severe. Therefore, research efforts are mainly directed at the behavior of viruses in water environments, as well as the elimination of viruses from wastewater. In this paper, an overview of the occurrence of viruses in wastewater is presented, together with their categories, methods of detection and potential to cause waterborne diseases. As wastewater treatment plants are critical nodes for the influx and termination of virus transmission, the behavior of viruses at each stage of treatment is reviewed. Particular attention is paid to the unit operations, which play crucial roles in virus removals, such as coagulation and membrane filtration, and that for virus inactivation, such as chemical disinfection and UV irradiation. Future needs for the development of new technologies for virus elimination, source control, and finding more suitable indicators of viral pathogens are also highlighted.

Keywords Virus · Domestic wastewater · Removal · Inactivation

✉ Chong-Miao Zhang
  zhangchongmiao@163.com

✉ Xiaochang C. Wang
  xcwang@xauat.edu.cn

[1] Key Lab of Northwest Water Resource, Environment and
  Ecology, Ministry of Education, School of Environmental
  and Municipal Engineering, Xi'an University of Architecture
  and Technology, Xi'an 710055, China

Introduction

Pathogenic microorganisms that are harmful to human beings include bacteria, viruses and protozoan parasites. With their micro sizes, discrete distribution and low infective doses, viruses are considered to be the major source of infectious diseases, based on epidemiological studies (Xiao et al. 2013; Craun et al. 2010; Dziuban et al. 2006). Human and animal excreta often contain large numbers of virus particles, which may enter aquatic environments through effluent discharge, leachate from septic systems and runoff from agriculture areas. More than 150 types of enteric viruses have been found in domestic wastewater (Wong et al. 2012a), mainly including enteroviruses (EVs), rotaviruses (RVs), adenoviruses (AdVs), noroviruses (NVs), hepatitis A virus (HAV) and astroviruses (AVs). When human beings are exposed to these viruses through contaminated water or food, they will be under high risks of infectious diseases such as gastroenteritis, aseptic meningitis, poliomyelitis, myocarditis, conjunctivitis, hepatitis, respiratory diseases systemic neonatal infection and diabetes mellitus (WHO 2011; Swenson et al. 2003; Rajal et al. 2007). Aerosol may also be a transmission route of waterborne viruses in the process of domestic wastewater treatment and reuse such as blast aeration, water fountain, waterfall and spray irrigation (Carducci et al. 2000).

Although the hazardous effects of viruses on human health have been recognized for a long time, and there is no doubt that viruses should be eliminated from domestic wastewater before it is discharged to the environment, the ideal and most effective approach to control the risk of virus infection to an acceptable level is still a challenge for many environmental engineers. This is because almost all the guidelines and/or standards related to the microbiological quality of water deal only with bacteriological

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indicators such as total coliforms, fecal coliforms, fecal streptococci and *Escherichia coli*. In fact, there may not always be significant correlations between indicator bacteria and viruses in urban surface water and secondary effluents (Zhang et al. 2012). Moreover, the pathogenic bacteria in a given volume of water sample may not truly indicate a safe state regarding viruses. Therefore, special attention needs to be paid to the characteristic behavior of viruses in water, including their occurrence, survival, decay, and removal/inactivation in the whole process of domestic wastewater treatment.

Occurrence of viruses in domestic wastewater

Categories of viruses and related health hazards

Most waterborne viruses spread and transmit through fecaloral routes. Many viruses differ from each other in terms of their nucleic acids (DNA or RNA), genome size, and morphology, and cause different diseases, as can be summarized in Table 1.

Detection of viruses

Cell culture has been recognized as the standard method for the detection of infectious viruses that can propagate on the host cell lines and produce cytopathic effects (CPE) observable under a microscope. However, this method lacks the ability to detect nonculturable viruses (such as norovirus)

and cannot differentiate specific types of viruses in environmental samples. Also, labor-intensive and time-consuming are shortcomings that restrict the application of the cell culture method for virus detection. The advent of a series of molecular biological methods, such as polymerase chain reaction (PCR), nested-PCR, immunocapture PCR and realtime quantitative PCR (qPCR), largely solved the above problems and made it possible to detect and quantify specific viruses from environment samples based on high specificity and sensitivity. However, these methods lack the ability to characterize the infectiousness of viruses (Wong et al. 2012a; Xagoraraki et al. 2014). Thus, integrated technologies combining molecular biology and cell culture are the future development trends for virus detection.

Distribution of viruses in domestic wastewater

The concentration of viral pathogens originating from domestic wastewater can be as high as 10^6–10^8 copies/L. In a wastewater treatment plant (WWTP), virus numbers can be reduced gradually in each treatment unit, but a certain number of viruses may remain in the secondary effluent. Table 2 shows the distribution of viruses in the influent and effluent of typical wastewater treatment systems. In a study reported by Zhang and Wang (2012), the distribution of EVs in the secondary effluent was found to follow a log-normal relationship.

Seasonal variations in virus concentration have also been noticed in a number of studies. For example, Fong et al. (2005) reported that EVs and AdVs occurred more frequently in the winter, but Jiang et al. (2007) found the highest

Table 1 Characteristics of common waterborne enteric viruses

Virus	Genome	Genome size (kb)	Dimension (nm)	Major disease (s)	Infection dose (viral particles)
Enteroviruses	ssRNA	7.0–8.5	20–30		
Polioviruses (1–3)				Poliomyelitis, paralysis, meningitis, fever	100–500
Echoviruses (1–33)				Meningitis, respiratory disease, rash, fever, gastroenteritis	10–100
Coxsackieviruses (A1–22, 24)				Enteroviral vesicular pharyngitis, respiratory disease, meningitis, enteroviral vesicular stomatitis with exanthem (hand, foot and mouth disease)	10–100
Coxsackieviruses (B1–6)				Myocarditis, congenital heart anomalies, rash, fever, meningitis, respiratory disease, epidemic myalgia (pleurodynia)	10–100
New enteroviruses (68–73)				Meningitis, encephalitis, respiratory disease, rash, acute enteroviral haemorrhagic conjunctivitis, fever	1–100
Hepatitis A virus	ssRNA	7–8	27–32	Hepatitis	1–100
Adenoviruses	dsDNA	28–45	60–90	Conjunctivitis, respiratory disease, gastroenteritis	1–100
Rotaviruses	dsRNA	16–21	50–65	Gastroenteritis, diarrhoea	1–10
Norovirus	ssRNA	7–8	35–40	Diarrhea, fever, vomiting, gastroenteritis	10–100
Astrovirus	ssRNA	7–8	28	Gastroenteritis	1–100
Polyomavirus	dsDNA	5	35–40	Sarcoma, cancer	Unknown

Adapted from USEPA (2012), Wong et al. (2012a, b), Liang (2013) and Crittenden et al. (2012)

Table 2 Distribution of viruses in wastewater treatment

Virus	Influent (copies/L)	Secondary effluent (copies/L)	MBR effluent (copies/L)	After disinfection	References
Enteroviruses	$2.2 \times 10^3 – 7.9 \times 10^3$	6.8–250	1.5–53	36–67	Francy et al. (2012)
	$2.2 \times 10^2 – 2.9 \times 10^5$				Francy et al. (2012)
Adenoviruses	$10^6 – 10^7$		$10^3 – 10^4$	6.2–39	Kuo et al. (2010)
	$5.6 \times 10^2 – 1.7 \times 10^4$		1.2–120		Francy et al. (2012)
Rotavirus	$10^6 – 8.9 \times 10^6$	$9.3 \times 10^4 – 2 \times 10^5$	1.9–49		Zhou et al. (2015)
Noroviruses	$5.6 \times 10^2 – 8.3 \times 10^3$	6.9–250		36–67	Francy et al. (2012)
	$5.5 \times 10^5 – 6 \times 10^6$	$5.5 \times 10^4 – 7 \times 10^5$			Nordgren et al. (2009)
Astroviruses	$10^6 – 10^8$	10^5			Le Cann et al. (2004)

density of AdVs in the summer. Katayama et al. (2008) observed that NV genotype 1 and genotype 2 were both abundant in winter and less in summer, but the concentrations of EVs and AdVs did not vary too much all the year round during a 1-year monitoring of six WWTPs in Japan. The spatial and temporal distribution of virus in wastewater may be affected by many factors, such as its own nature, host excretion, microorganism predation, climate and so on.

Typical disease outbreaks due to waterborne viruses

Waterborne viruses can infect human beings with various diseases that may be fatal to sensitive populations such as infants, children, the elderly, and immunocompromised individuals. Many recently reported disease outbreaks are related to contaminated drinking and recreational waters (Okoh et al. 2010; Symonds et al. 2009), including the hand, foot and mouth disease in children due to EV71 and Coxsackievirus (Tu et al. 2007; Zhang et al. 2009). Enteroviruses including coxsackievirus and echovirus are causative agents in the outbreaks of a number of illnesses related to recreational water (Dziuban et al. 2006). Outbreaks of viral gastroenteritis are found to be caused by rotaviruses possibly due to polluted drinking water (Craun et al. 2010). NVs and Sapovirus, rather than EVs, RVs and AVs, are believed to be common causative agents in 68–90 % of gastroenteritis outbreaks (Greer et al. 2009).

Elimination of viruses in wastewater treatment processes

Wastewater treatment is typically conducted by the conventional activated sludge process, which is a train of unit operations including sedimentations (primary and secondary settlers), biological decomposition (aerobic, anoxic and/or anaerobic tanks or equivalent facilities), and disinfection (chlorination, ozonation, or UV irradiation). Filtration by sand filters or membranes may also be employed

for tertiary treatment especially when water reuse is to be practiced. In recent years, membrane bioreactors (MBRs) are increasingly commonly used for wastewater treatment. Generally, most of these unit operations, except for disinfection, are not designed for virus elimination but mainly for suspended solids (SS), organic substances, and nutrients removal. However, as viruses can be viewed as fine particles with colloidal characteristics (Cao et al. 2010; Wong et al. 2012b), they may easily be absorbed onto or enmeshed within suspended particles in wastewater (Xagoraraki et al. 2014; Templeton et al. 2008). Therefore, to a great extent, the elimination of viruses in the wastewater treatment process before the final stage of disinfection is usually accompanied by solid particle removal. Of course, as viruses are microorganisms by nature, they may also decay during the wastewater treatment process due to changes in environmental conditions including microbial antagonism (Hao et al. 2010).

Virus elimination by sedimentation and sand filtration

Kitajima et al. (2014) reported viruses removals of between 0.65 and 2.85-log for eleven virus types by the conventional activated sludge process before disinfection. Little information is available about the variation of virus numbers along the treatment train such as primary settler, activated sludge tank, and secondary settler. However, the authors noticed a decrease of EVs, RVs, and NVs from the WWTP effluent by 0.1 to 0.3-log just through a fine screen for the removal of coarse solid particles, and their further reduction by 1.4–1.7-log after the mixed liquor at the end of an anaerobic–anoxic–oxic unit was settled (Zhou et al. 2015). It is believed that the virus removal in these processes is mainly due to the separation of solid and activated sludge flocs from the liquid. Sand filtration usually can remove 10–98 % of viruses, but Shirasaki et al. (2010) reported that the NVs removal could be as high as 3-log when a coagulant was added prior to the sand filter.

Virus elimination by stabilization processes

It should be noted that by sedimentation and filtration virus are only transported to the separated sediments and sludge but not inactivated. Stabilization processes of sludge, such as dehydration, liming, composting, heat treatment and mesophile anaerobic digestion, are available for viral reduction. Mechanical dehydration and desiccation can eliminate 1-log viruses by rupturing the virus capsid and releasing nucleic acid (Monpoeho et al. 2004). Liming process combined with a high pH can diminish enterovirus titers by at least 4-log. During the composting process both temperature and antagonistic organisms co-operate in viral inactivation (Dumontet et al. 1999). Temperatures of 55–70 °C during treatment is sufficiently high to eliminate 3–4-log virus. Heat treatment clearly has, by far, the highest inactivation efficiency. Mesophile anaerobic digestion showed the low disinfecting power with 1-log reduction for viruses (Monpoeho et al. 2004; Guzmán et al. 2007).

Virus elimination by membrane filtration

When the secondary effluent is further treated by membrane filtration, the basic mechanism of virus elimination can be considered as size exclusion. With a nominal cutoff in the order of 10^{-2} μm, the ultrafiltration (UF) membrane is thought to be sufficient for physical elimination of most viruses. The formation of a cake layer on the membrane surface can further improve the virus removal efficiency (Shirasaki et al. 2008). Moreover, lowering the trans-membrane pressure (TMP) can also bring about higher virus removal by UF filtration (Arkhangelsky et al. 2007). UF membranes with slightly negative charge tend to be more efficient for virus elimination than those with neutral charge (Antony et al. 2012). Lovins et al. (2002) reported that UF could achieve up to 5-log virus removal.

Because a viral particle is often smaller than the nominal pore size of most microfiltration (MF) membranes, MF alone may only achieve less than 1-log virus removal. However, a coagulation-MF system achieved a 4-log reduction of viruses (Zhu et al. 2005).

Virus elimination by MBR

An MBR is an integration of activated sludge process and membrane filtration. The virus removal by the MBR can be attributed to four mechanisms, namely attachment to mixed solids particles, interception by the membrane, interception by the membrane cake layer and inactivation by predation and enzymatic breakdown (Chaudhry et al. 2015).

The reported removal of viruses by MBRs ranges between 3.0-log and higher than 6.0-log for domestic wastewater treatment. In a study reported by Simmons et al. (2011), the removals of AdVs, EVs and NVs by MBR without disinfection were 6.3, 6.8, and 4.8-log, respectively. In contrast, in a study reported by da Silva et al. (2007), the removals NV genogroup I and NV genogroup II by MBR were up to 5.5 and 5.2-log, respectively. Furthermore, Katayama et al. (2008) found that the virus removal by MBR ranged between 3.4 and 6.3-log. However, viruses such EVs, RVs and NVs are still at a detectable level in the MBR filtrate before final disinfection (Zhou et al. 2015).

The operating condition of MBRs may also affect the removal of viruses. Wu et al. (2010) reported that MBRs with a longer hydraulic retention time (HRT) and shorter solids retention time (SRT) could achieve higher virus removal. However, Shang et al. (2005) pointed out that a longer SRT or lower MLSS would benefit the removal of bacteriophage.

Virus elimination by chemical disinfection

The action models of the different disinfection methods on viral particles are shown in Fig. 1. Chemical disinfectants (chlorine, chlorine dioxide, chloramine and ozone) do more damage viral capsid than nucleic acid, whereas UV irradiation mainly affects nucleic acid. Under enough high dosage of chemical disinfectants or UV irradiation, viral capsid and nucleic acid will be destroyed.

Chlorination

When chlorine is used for disinfection, the effective agent to inactive viruses is hypochlorous acid, which can damage the genome- and protein-mediated functions (Wigginton and Kohn 2012). Chlorine dose (C) and contact time (t) or
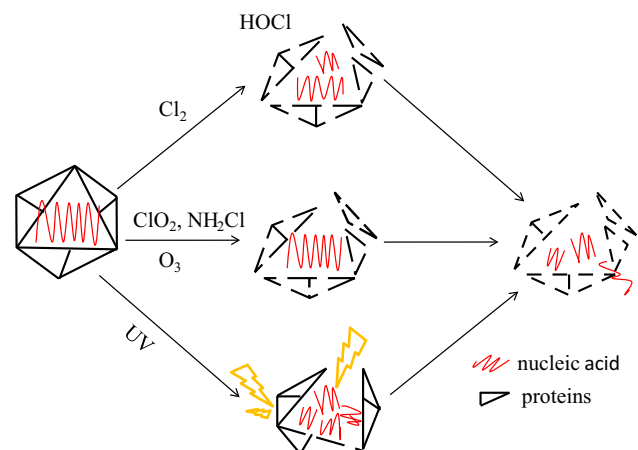

Fig. 1 Action models of the different disinfection methods on viral particles. Adapted from Wigginton et al. (2012), Wigginton and Kohn (2012) and Mayer et al. (2015)

Table 3 UV doses required for 3-log inactivation of viruses

Virus	UV dose (mJ/cm^2)	References
Coxsackievirus	20–27	Shin et al. (2005) and Gerba et al. (2002)
Hepatitis A virus	12–20	Battigelli et al. (1993)
Echovirus	16–25	Gerba et al. (2002) and Malley (2004)
Poliovirus	14–24	Shin et al. (2005)
Adenovirus type 2, 15, 40, 41	125–167	Hijnen et al. (2008)
Calicivirus	16–31	Hijnen et al. (2008)
Rotavirus	23–44	Malley (2004)

their product, Ct value, usually governs the virus inactivation result. The typical initial chlorine dose is 5–20 mg/L and the contact time is 30–60 min for the disinfection of secondary effluent. Li et al. (2011) reported that no residual infectious rotaviruses could be detected when chlorine dose was higher than 10 mg/L with a contact time of 60 min, i.e., a Ct value higher than 600 mg min/L. Tree et al. (2003) indicated that with chlorine doses of 16 and 8 mg/L, and contact time of 30 min, a reduction in indigenous enteroviruses of 1.2 and 0.35-log, respectively, could be achieved. In contrast, the inactivation of polioviruses could reach 1.76 and 1.0-log, respectively. As the Ct values, in this case, were between 240 and 480 mg min/L, an increase of chlorine dose or extension of contact time may be required to achieve a higher virus removal.

Chlorine dioxide and chloramine are also alternative disinfectants, and in these cases, viruses be inactivated primarily due to damage of viral capsid (Wigginton and Kohn 2012). Chlorine dioxide is thought to be more effective for disinfection than chlorine while chloramine is a less effective disinfectant (Huang et al. 1997).

The chlorination effect may be strongly affected by the existence of various nitrogen forms and organic substances residual in the secondary effluent. The formation of disinfection by-products (DBPs) is also a factor that restricts its application.

Ozonation

As shown in Fig. 1, ozone, as a very strong oxidant, is firstly effective in destroying viruses by attacking the viral protein material (Wigginton and Kohn 2012).

Ozone can react with water to produce radicals which then further destroy viral nucleic acids. Compared with chlorine, ozone has a higher efficiency but needs higher operation cost and with no continuous disinfection effect. The typical initial ozone dose is 3–10 mg/L and the contact time is 10 min, which result in Ct values between 30 and 100 mg min/L, much lower than chlorination (Paraskeva and Graham 2002). However, Burns et al. (2007) reported that a 6-log virus inactivation could be achieved at a residual Ct value as low as 0.5 mg min/L by ozonation. Similar results were obtained

by Sigmon et al. (2015) who achieved a 4-log virus inactivation at Ct = 1 mg min/L by ozonation.

Ultraviolet disinfection

Ultraviolet (UV) disinfection is regarded as an effective and competitive solution for the disinfection of secondary effluent, due to its merits of no chemical agents addition, non-corrosive, simple installation, easy operation, and no formation of disinfection by-products. However, the disinfection effect may be significantly hindered by turbid and colored substances residual in the secondary effluent. The mechanism of UV disinfection is that the ultraviolet light causes the damage of viral genome and protein (Fig. 1), including damaging the phosphodiester bond, cross-links to other molecules (DNA–DNA and Protein–DNA) and forming pyrimidine dimmers, thereby preventing the viruses from replicating and losing injection functions (Wigginton and Kohn 2012).

Table 3 summarizes the required UV doses to achieve 3-log inactivation of viruses. In a range of the UV dose from 14 to 27 mJ/cm^2, 3-log inactivation can be achieved for EVs including poliovirus, coxsackievirus and echovirus (Shin et al. 2005; Malley 2004; Gerba et al. 2002). In the European standards for drinking water (NSF International 2009), a UV dose of 40 mJ/cm^2 is required to ensure 4-log virus inactivation. However, Malley (2004) pointed out that this dose would not be sufficient to ensure 4-log inactivation for all viruses in the secondary effluent. AdVs are known to be highly resistant to UV irradiation, and may need three times higher UV doses, namely 120 mJ/cm^2, to achieve 3-log inactivation, and 200 mJ/cm^2 or even higher to meet the 4-log virus removal requirement (Nwachuku et al. 2005; Gerba et al. 2002).

Comparison of processes

The log removal/inactivation of viruses by different wastewater treatment processes are summarized in Table 4. For primary treatment, because only coarse solid particles can be removed by mechanical screening and the grit chamber, the associated virus removal is usually no more

Table 4 Log removal/inactivation of viruses by different treatment processes

Process	Removal/inactivation (log)	References
Primary treatment		
Grit chamber	0–0.3	Prakashi and Chaudhuri (1982)
Fine screen	0.1–0.2	Zhou et al. (2015)
Secondary treatment		
Activated sludge	0.7–2.9	Katayama et al. (2008) and Hewitt et al. (2011)
Trickling filter	0–0.82	Prakashi and Chaudhuri (1982)
MBR	3.4–6.8	Katayama et al. (2008) and Simmons et al. (2011)
Tertiary/advanced treatment		
Chemical coagulation-alum, iron salts	1–2.86	Zhu et al. (2005)
Microfiltration (0.1 μm)	0.2–5.1	Madaeni et al. (1995) and Zheng and Liu (2006)
Ultrafiltration (0.01 μm)	>3.0	Lovins et al. (2002) and Jacangelo et al. (2005)
Nanofiltration (0.001 μm)	>5.4	Lovins et al. (2002)
Reverse osmosis (0.0001 μm)	>6.5	Adham et al. (1998)
Disinfection		
Chlorination	0.81–2.8	Francy et al. (2012) and Tree et al. (2003)
Ozonation	0.24–>6	Francy et al. (2012)
UV radiation	1.43–6	Owens et al. (2000) and NRC (2012)

than 0.3-log. The conventional secondary biological processes such as activated sludge tanks and biological filters can cause substantial reduction of viruses up to 3-log. Nevertheless, the enmeshment of viruses in activated sludge flocs seems to be more effective than the attachment of viruses on to the biofilms of the filter media. As for the tertiary and/or advanced treatment, chemical coagulation using alum or iron salts usually aims at removing the residual suspended and colloidal particles, and can simultaneously result in less than 3-log virus removal. The efficiency of virus removal by membrane filtration apparently depends on membrane cutoffs, which ranges from 0.2-log for microfiltration to >6.5-log for reverse osmosis. The reason for the higher virus removal by MBR than the conventional activated sludge process is also believed to be due to the membrane cutoff.

Disinfection is usually the final step of wastewater treatment aiming at inactivating pathogenic microorganisms including viruses. Either chlorination, ozonation or UV irradiation can provide a sufficient barrier to prevent the viruses from entering the environment with the discharged effluent. Nonetheless, ozone and UV seem to be more effective than chlorine. With its advantages of high viral inactivation efficiency and no disinfection/oxidation by-product generation, UV irradiation is considered to be a clean disinfection technology. However, similar to ozone, UV cannot provide residual disinfection functions as chlorine does. Therefore, the use of two disinfectants should be recommended to make sure the redundancy of microbial protection (USEPA 2006).

Future perspectives

Although virus elimination can be achieved by careful selection of conventional treatment processes and/or optimized combinations of several processes to provide multibarriers, there are still needs for the development of new technologies for better virus elimination. As discussed in the above sections, in most of the physical and biological processes, the elimination of viruses from water is, in fact, to transfer the viruses from the liquid phase to the solid phase such as sludge or sediments. There still exists the risk of virus contamination through other pathways. Therefore, research interests are still much concentrated on virus inactivation. With the development of the UV-based advanced oxidation processes (AOPs), such as UV–H_2O_2, UV–Cl_2, UV–O_3 and UV–TiO_2, the capabilities of the highly reactive radicals generated by photolysis to inactivate viruses have drawn wide attentions (Bounty et al. 2012; Rattanakul et al. 2014; Gehr et al. 2003; Lee et al. 2008). In addition, solar radiation has also shown its advantages of cleanness, low operation cost and sufficient effect of virus inactivation for small-scale treatments. This may also be the direction of applicable technology development.

The viral waterborne pathogens mainly result from human and animal feces, biological laboratory, hospitals and sewage sludge. Therefore, virus source control should be strengthened. For example, the wastewater from specific locations (such as hospitals, livestock farms and laboratory) should not be discharged into the domestic sewer

system before it is sufficiently disinfected. Sewage sludge and feces must undergo stabilization processes before agricultural use.

To safeguard water quality, guidelines have been put forward by international organizations and governmental agencies in some countries (WHO 2003; USEPA 2006, 2012) on the target of virus removal and/or inactivation. However, lack of proper virus indicators still hinders a rational control of virus contamination. The conventional fecal indicators such as total coliforms, fecal coliforms, fecal streptococci and *E. coli* have been used for a long time to indicate pathogenic contamination of water. However, it is noticed that there is not always a significant correlation between fecal indicator bacteria and viruses in water (Zhang et al. 2012). For this reason, many researchers have been trying to find alternative indicators for viral pathogens, such as coliphages and *Bacteroides fragilis*, which have similarities to waterborne viruses and often occur in wastewater with high numbers (Maier et al. 2009). However, bacteriophage is also questioned by some researchers because certain viruses such as EVs were detected when bacteriophage was below the detection limit (Hot et al. 2003). It is also suggested to use AdVs, EVs and polyomavirus (PyV) directly as potential indicators of waterborne pathogens (Hamza et al. 2011; Harwood et al. 2009). The way to identify or develop more suitable indicators of viral contamination may continuously be a hot topic for future studies. This is closely related to more stringent environmental legislation for the control of waterborne pathogens pollution.

Conclusions

Domestic wastewater is the main source of viral waterborne pathogens, which, if not sufficiently eliminated, may enter receiving water bodies and cause water-transmitted diseases. Therefore, technique for eliminating viruses through wastewater treatment is an important topic for protecting human health. In the process of a conventional secondary treatment, viruses can be removed by up to 3-log through an attachment onto solid particles and/or enmeshment into activated sludge flocs. The tertiary treatment by coagulation and/or membrane filtration can be more effective for virus elimination. All these are mainly due to the transfer of viruses from the liquid phase to the solid phase but not virus inactivation, which is performed by chemical disinfection using chlorine, ozone or UV irradiation usually as the final stage of wastewater treatment. From the viewpoint of effluent quality control, the treatment train has provided multi-barriers for preventing viruses from entering receiving water bodies. However,

viruses may still remain in the effluent even after membrane filtration, and proper disinfection is indispensable.

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