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Assessment and risk modeling of airborne enteric viruses emitted from wastewater reused for irrigation

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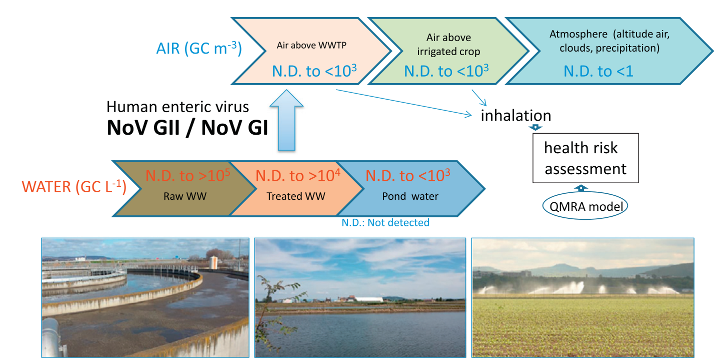
HIGHLIGHTS

- Enteric viruses were measured in water and in air near a WW treatment plant and fields irrigated with WW
- Noroviruses were the most abundant in raw water (>10e4 GC/L); low quantities of airborne viruses were detected (£10e3 GC/m^3)
- The health risk of inhaled norovirus was assessed using a Bayesian QMRA approach that included an atmospheric dispersion model
- The annual probability of infection at the 95th percentile is >10^-4 for strong wind speeds and a constant virus emission rate
- This probability decreases by 3 log when the distance to the emission source is doubled.

GRAPHICAL ABSTRACT



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ABSTRACT

Reclamation of wastewater (WW) for irrigation, after treatment represents a challenge that could alleviate pressure on water resources and address the increasing demand for agriculture. However, the risks to human health must be assessed, particularly those related to human enteric viruses that resist standard treatments in most wastewater treatment plants (WWTP). The risks associated with exposure to viral bioaerosols near WWTP and near agricultural plots irrigated with WW are poorly documented. The objectives of this study were to 1) better characterize human enteric viruses found in bioaerosols near a "standard WWTP" and over fields irrigated with treated WW and 2) propose a numeric model to assess the health risk to populations located close to the irrigated areas, with particular attention to norovirus, which is responsible for most viral gastroenteritis in France. Water and air samples were collected at various locations in the largest French WW-irrigated site near Clermont-Ferrand, at the WWTP entrance and after treatment, in the air above activated sludge basins, and above fields irrigated with WW. Various enteric viruses were found in the water samples collected both before and after treatment. Norovirus was the most abundant with >10e4 genome copies/l (GC/L) before treatment and ~10e3 GC/L after treatment. Low quantities (<10e3 GC/m^3) were detected in the air above active sludge pools and irrigated plots. Hepatitis E virus was detected in all sampled compartments. A quantitative microbial risk assessment (QMRA) approach, including a simplified atmospheric dispersion model, allowed assessment of norovirus

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infection risk. The Bayesian QMRA approach considered wind speed measurements over 21 years, and the variability and uncertainty of all measurements throughout the chain up to the risk. The probability of infection within one year for the most exposed WWTP employees was > 10e-4 for strong wind speed (≥3 m/s) and a constant emission rate of 8e3 GC/m^3/s. This probability decreases by 3 log when the distance to the emission source is doubled. This information can aid development of safe water reuse policies in terms of local setback distance and wind conditions for wastewater reuse.

1. Introduction

Reuse of treated wastewater (WW) is an essential component of integrated and sustainable water resources management, not only in water-scarce areas but also in water-abundant countries, in part because of global warming (GIEC, 2014, FAO, 2010), which causes major environmental, social and economic issues. WW reuse also allows reduce effluent pollution in rivers (Angelakis and Durham, 2008; Bixio et al., 2006; Drechsel and Evans, 2010). The following recommendations and guidelines on WW reuse were defined by the World Health Organization (WHO, Word Health Organization, 1989 revised in 2006) based on health risk considerations, and this practice (WW reuse) has been widely developed for agricultural irrigation in peri-urban areas in Israel (Brenner, 2012), Australia (Radcliffe, 2006), USA (Asano and Tchobanoglous, 1991), Spain and Italy (Lazarova et al., 2001). The benefits of irrigation with WW are multiple i.e., reduction of agricultural impact on the pollution of water bodies and improvement of crop yields due to nutrient delivery (Braddock and Downs, 2001; Keraita et al., 2012). However, drawbacks are linked with the presence in WW of toxic chemical compounds (Gros et al., 2010) and human pathogens such as the bacteria *Salmonella* (Ravva and Sarreal, 2014) and *Legionella*, (Shuval et al., 1988), helminth eggs (Pachepsky et al., 2011) and viruses (Barker, 2014), which have also been highlighted in various reports (see reviews by (Dungan, 2010; Gerba and Smith, 2005; Pachepsky et al., 2011; Rodriguez-Lazaro et al., 2012; Sidhu and Toze, 2009)). Even if WW reuse is wide spread in numerous countries and has demonstrated benefits for agriculture (Drechsel and Evans, 2010), in France, this practice is rather limited and is awaiting better risk characterization with respect to pathogens (Brissaud, 2008; Brissaud et al., 2008; Molle et al., 2012). In France, the decree regulating the practice of treated wastewater reuse for agriculture (MSS, Ministère de la Santé et des Sports, 2010, revised in 2014) is relatively restrictive for sprinkler irrigation (Loubier et al., 2013). The collective expertise appraisal performed by ANSES in 2012 (ANSES, 2012) pointed to a lack of knowledge on health risks, particularly due to the inhalation of pathogen bioaerosols.

Among the pathogens detected in WW, viruses have the greatest infectivity. For norovirus, approximately 10-10e1 PFU/g (plaque forming units per gram) are sufficient to infect individuals and are often linked to consumption of contaminated foods or drinks. Infected humans can excrete large quantities of enteric viruses in the feces, i.e., up to 10e5–10e11 virus particles per gram of feces during the period of illness and for several weeks thereafter (Maunula et al., 2013; Rodriguez-Lazaro et al., 2012). Enteric viruses can be transmitted by direct fecal-oral contamination or indirect contamination via environmental surfaces and more generally via food (Iaconelli et al., 2015; Le Guyader et al., 2006; Uhrbrand et al., 2010) or drinking water (Gerba et al., 1996; Mara, 2011). Transmission via the air has also been reported by (Marks et al., 2000).

Viruses greatest concern in WW include norovirus, (NoV) (Barker, 2014; Redwan and Bagatadah, 2012), hepatitis A virus (HAV) (Arvanitidou et al., 2004), hepatitis E virus (HEV) (Masclaux et al., 2013), rotavirus (RV), (Aiello et al., 2013) and the group of enteroviruses (EV), including poliovirus, coxsackievirus and echovirus, adenovirus and astrovirus (Rodriguez-Lazaro et al., 2012). Norovirus infections could explain most of the viral adult gastroenteritis outbreaks in several developed countries (Ahmed et al., 2014; Baert et al., 2011; Belliot et al., 2010; Colas de la Noue et al., 2014) and in Europe (Lopman et al., 2003, Potier, 2012).

Enteric viruses are often found in significant amounts in WW (Anastasi et al., 2008; La Rosa et al., 2010; Lazarova et al., 2013; Lazarova et al., 1999; Sanchez-Monedero et al., 2008). These pathogens are not completely eliminated by common water treatments (Lazarova et al., 2013), thus exposing employees of wastewater treatment plants (WWTP) and populations near WWTP to viral infections (Aiello et al., 2013). Most are human enteric viruses that can survive for weeks or even months in water environments (Bertrand et al., 2012; Gerba et al., 1996). Viruses have also been found in the air near certain WWTP (Uhrbrand et al., 2011) mainly above tanks and in downwind positions at rates up to 10e3 most probable number (MPN)/L (Carducci et al., 2000). (Masclaux et al., 2014) found high amounts of adenovirus in > 97% of samples collected in the air above 37 Switzerland WWTPs (up to 10e5 GC/m^3). Viral particles can subsequently spread in the air (O'Hara and Rubin, 2005; Paez-Rubio et al., 2005; Teltsch and Katzenelson, 1978), soil (Santamaria and Toranzos, 2003), water and crops (Barker et al., 2013), but to date, notably few reports exist of virus surveys above areas irrigated with WW (Paez-Rubio et al., 2005; Teltsch and Katzenelson, 1978). Additionally, the fate of viruses in the atmosphere is still unclear. Selected studies have analyzed the effects of the main atmospheric factors on virus survival (Akers and Hatch, 1968; Casanova et al., 2010; Ijaz et al., 1994) and on their infectious potential in different environments (Gantzer et al., 1998; Harper, 1963). It is well established that solar radiation, particularly in the ultraviolet spectral range, can damage virus structures (Nuanualsuwan et al., 2008; Simonet and Gantzer, 2006) as well as high ozone concentrations (Lazarova et al., 2013; Tyrrell et al., 1995). More numerous references are available on virus survival in liquid media than in the air. Aerosols are generated from small water droplets (Molle et al., 2016), and studies of virus survival conducted in different media are also useful for prediction of the fate of virus in the environment. Thus, Bertrand et al., (2012) showed that high temperature is considered a major factor leading to virus inactivation. In contrast, certain viruses are strongly resistance to low temperature conditions outdoors. For example, HAV can survive in liquids for > 80 days at 25 °C (Bertrand et al., 2012; Pinto et al., 2010).

One difficulty in monitoring viruses in the air is that the process relies, first on sampling notably small particles (30 nm to ~1 μm in the case of aggregates) (Verreault et al., 2008). In addition, the method applied can damage the virus structure and lead to analytical issues. Methods for extracting viruses from solid matrices such as plant and soil produce now good results (Bosch et al., 2008; Bosch et al., 2011). However, it is more complicate to capture and characterize virus survival in the air. Various air sampling devices exist based on liquid or solid impaction and electrostatic properties (Zhao et al., 2011). Among these methods, cascade impactors allow determination of particle size distribution (Alonso et al., 2015; Kang et al., 2012; Zhao et al., 2011). All of these methods show large variability in their capture efficiency (Verreault et al., 2008; West and Kimber, 2015). No comparisons in natural environments have been performed using different air samplers to collect enteric viruses under the same conditions, and thus this topic still represents an important research component that must be investigated in additional depth.

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