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Occurrence and removal of multiple classes of antibiotics and antimicrobial agents in biological wastewater treatment processes

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ABSTRACT

Very little information on the occurrence and fate of multiple classes of antimicrobials in the aquatic environment is reported for the Southeast Asian region. This study provides the first and comprehensive data on the occurrence of ten different classes of antimicrobials in wastewater samples for Singapore. Among the investigated antimicrobials, 19 out of 21 target compounds were detected in 100% of the collected raw influent samples. Concentrations of the detected antimicrobials in raw influent varied from 23.8 to 43,740 ng/L. Removal of antimicrobials by conventional activated sludge (CAS) and membrane bioreactor (MBR) systems at a local wastewater treatment plant was evaluated. MBR exhibited better performance over CAS for most target antimicrobials. Beta-lactam, glycopeptide, and fluoroquinolone classes were largely eliminated by biological wastewater treatment processes, whereas trimethoprim and lincosamides appeared to be persistent. Effects of physicochemical properties and chemical structures of target antimicrobials on their removal efficiencies/mechanisms during wastewater treatment process were also discussed.

1. Introduction

In recent years, the occurrence of antimicrobials in the environment has been recognized as an emerging environmental problem due to their potential in causing undesirable ecosystem and human health (Díaz-Cruz and Barceló, 2005; Diaz-Cruz et al., 2008; Kummerer, 2009; Le-Minh et al., 2010; Richardson and Ternes, 2011; Luo et al., 2014). Antimicrobials, such as antibiotics, are one of the most important drugs to prevent and treat infectious diseases. In addition, a certain fraction of antibiotics is also used as feed additives to promote the growth rate of livestock and poultry animals (Kummerer, 2009; Le-Minh et al., 2010). It is reported that approximately 50–90 percent of antibiotics administrated by humans or animals are excreted via urine and feces as a mixture of parent and metabolite forms (Kummerer, 2009; Le-Minh et al., 2010). After administration, large amounts of antibiotics or their metabolites are released into municipal wastewater due to excessive consumption and disposal of unused antibiotics (Kummerer, 2009). Human and veterinary antibiotics can enter the aquatic environment via a number of routes, including (i) direct discharge of animal wastewater from poultry and meat processing, aquaculture as well as from household pets (Kummerer, 2009); discharge of treated wastewater effluents from wastewater treatment plants (WWTPs) (Le-Minh et al., 2010; Luo et al., 2014); (iii) sewer leaking/sewer overflow (Tran et al., 2014); (iv) surface runoff; and (v) infiltration from manure-amended agricultural lands (Cha and Cupples, 2009). Till now, the major concerns of the occurrence of antimicrobials in the environment are the development of antimicrobial resistance genes (ARG) and antimicrobial resistance bacteria (ARB), which reduce the therapeutic potential against human and animal bacteria pathogens (Kim and Aga, 2007; Rizzo et al., 2013; Blair et al., 2015b). Another concern of the occurrence of antimicrobials in the aquatic environment is possible toxicity to sensitive organisms (Richardson and Ternes, 2011).

The removal of antibiotics and antimicrobial agents in WWTPs was earlier reported in previous studies (Gobel et al., 2007; Radjenovic et al., 2007, 2009; Watkinson et al., 2007). For example, Gobel et al. (2007) investigated the removal of

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sulfonamides, macrolides and trimethoprim by different treatment technologies. They reported that the membrane bioreactor (MBR) system showed better removal efficiency than conventional activated sludge (CAS) system for most of the investigated compounds. In contrast, Radjenovic et al. (2009) found that no significant difference in removal efficiency between MBR and CAS systems was observed for several antibiotics, including erythromycin, sulfamethoxazole, and trimethoprim. It was also reported that removal efficiency of antibiotics in wastewater treatment process was not only dependent on treatment technologies employed at WWTPs, but also other factors, such as seasons and nature of antibiotics (Joss et al., 2006; Gobel et al., 2007; Kimura et al., 2007; Watkinson et al., 2007; Guerra et al., 2014).

Hitherto, the occurrence and fate of several classes of antimicrobials in different environmental compartments (wastewater, surface water, groundwater and soils) have been documented in some geographical regions of the world, such as North America, Europe, and Japan (Díaz-Cruz and Barceló, 2005; Karthikeyan and Meyer, 2006; Kobayashi et al., 2006; Gobel et al., 2007; Radjenovic et al., 2007, 2009; Kummerer, 2009; Garcia-Galan et al., 2010; Le-Minh et al., 2010; Blair et al., 2015a), while very little information on the occurrence and fate of antibiotics in the Southeast Asian region has been reported.

In addition, most of the previous studies only focused on a small number of antimicrobials as well as antimicrobial classes (Gobel et al., 2005, 2007; Gros et al., 2006b; Terzic et al., 2008; Cha and Cupples, 2009; Tong et al., 2009; Garcia-Galan et al., 2010; Behera et al., 2011). In another study, Cha et al. (2006) developed an analytical method for determination of the second generations of β-lactams, such as amoxicillin, ampicillin, and oxacillin. To the best of our knowledge, no or limited information on the occurrence and fate of new generations of β-lactam antibiotics (i.e. ceftazidime and meropenem) or other antibiotic classes, e.g. glycopeptide (vancomycin) and lincosamide (clindamycin), in the environment has been reported in the earlier studies, particularly for tropical regions.

Therefore, the first objective of this study is to fill the existing gap by providing the first and comprehensive data on the occurrence of 21 commonly used antimicrobials belonging to 10 different classes in wastewater for the tropical region (Singapore), where weather conditions, land use, population size, population density, demographic pattern and usage patterns of antibiotics are different from those in North American and European countries. These differences may subsequently impact on the occurrence distribution and concentration of antimicrobials in the water environment.

The second objective was to investigate the removal of the target antimicrobials during biological wastewater treatment processes at a local WWTP. The removal efficiencies for target antimicrobials in dissolved phase by different wastewater treatment technologies, i.e. CAS and MBR, were also evaluated via an intensive sampling campaign. Meanwhile, insights into the relationship between the physicochemical properties (i.e. log K_{ow}, log D_{ow}, pK_a, and ionization state)/chemical structures of antimicrobials and their removal efficiencies/mechanisms were also taken into account.

2. Materials and methods

2.1. Target antimicrobials, chemical reagents and solvents

In this study, 21 antimicrobials belonging to ten different classes were investigated, including:

(i) β-lactam: ceftazidime [CFZ], meropenem [MER], and amoxicillin [AMX].
(ii) Fluoroquinolone: ciprofloxacin [CIPX].
(iii) Lincosamides: lincomycin [LIN] and clindamycin [CLI].
(iv) Macrolides: erythromycin [ERY], azithromycin [AZT], clarithromycin [CLAR], and tylosin [TYL].
(v) Sulfonamide antibiotics: sulfamethazine [SMZ] and sulfamethoxazole [SMX].
(vi) Reductase inhibitor: trimethoprim [TMP].
(vii) Tetracycline family: tetracycline [TET], minocycline [MIN], chlortetracycline [CTC], and oxytetracycline [OXY].
(viii) Glycopeptide: vancomycin [VCM].
(ix) Chloramphenicol [CAP].
(x) Antiseptic additives: triclosan [TCS] and triclocarban [TCC].

The physicochemical properties of the target antimicrobials are presented in Table A.1 (Supplementary Information). All the target antimicrobials as well as other chemical reagents/solvents are of high purity grade (>99%) and were purchased from Sigma–Aldrich (Sigma–Aldrich, Singapore). Fifteen ^{2}H and ^{13}C-isotope labeled internal/surrogate standards (ILISs) were purchased from Toronto Research Chemicals (Toronto, Canada), including ceftazidime-d_5 [CFZ-d_5], meropenem-d_6 [MER-d_6], ciprofloxacin-d_8 [CIPX-d_8], lincomycin-d_3 [LIN-d_3], clindamycin-d_3 [CLI-d_3], azithromycin-d_3 [AZT-d_3], clarithromycin-d_3 [CLAR-d_3], erythromycin-d_6 [ERY-d_6], sulfamethazine-d_4 [SMZ-d_4], sulfamethoxazole-d_4 [SMX-d_4], trimethoprim-d_3 [TMP-d_3], tetracycline-d_6 [TET-d_6], chloramphenicol-d_5 [CAP-d_5], triclosan-d_3 [TCS-d_3], and triclocarban-$^{13}C_6$ [TCC-$^{13}C_6$].

2.2. Wastewater treatment plant

To investigate the occurrence and removal of target antimicrobials during wastewater treatment processes, a routine sampling and monitoring campaign was conducted at a local wastewater treatment plant (WWTP). Detailed information on the investigated WWTP is provided elsewhere (Tran et al., 2015). Briefly, the investigated WWTP is constructed to treat wastewater mainly from municipal sources (approximately 90%), with a total design capacity of 361,000 m^3/d. The influent of the WWTP is treated in two concurrent liquid streams, i.e. South-works [Train-A] and North-works [Train-B], as illustrated in Fig. 1. Train-A is a conventional activated sludge system (CAS), which includes the following treatment units: primary settling tanks, Modified Ludzack–Ettinger (MLE) tanks (including anoxic tanks, followed by aerobic tanks with internal cycling) and secondary settling tanks. Train-B is a membrane bioreactor (MBR) system that consists of primary settling tanks, MLE tanks and microfiltration (MF) membrane unit.

The major difference between the two treatment trains is that Train-A uses conventional sedimentation for solid–liquid separation, whereas Train-B uses a MF membrane unit with a design flow rate of 23,000 m^3/d to retain the suspended solids (Tran et al., 2015). In addition, the operating parameters, such as mixed liquor suspended solid (MLSS), hydraulic retention time, and sludge retention time between CAS and MBR systems were also different. The main operating parameters of CAS (Train-A) and MBR (Train-B) are summarized in Table A.2 (Supplementary Information).

2.3. Sample collection

An intensive sampling campaign was carried out from April to May 2015 at five different sampling points (INFL, A1, A2, B1, and B2) as shown in Fig. 1. These sampling points were selected to evaluate the occurrence and change in antimicrobial concentrations at different treatment units on Train-A and Train-B. For example, the sampling point (INFL) was chosen to evaluate the characteristics of raw influent (raw wastewater) before entering the treatment