

2012

## Chemical coagulation-based processes for trace organic contaminant removal: Current state and future potential

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### Recommended Citation

Alexander, Jonathan T.; Hai, Faisal I.; and Al-aboud, Turki M.: Chemical coagulation-based processes for trace organic contaminant removal: Current state and future potential 2012, 195-207.  
<https://ro.uow.edu.au/engpapers/5058>

# **Chemical coagulation-based processes for trace organic contaminant removal: Current state and future potential**

Revised version Submitted to

**Journal of Environmental Management**

July 2012

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1

2

3 **Abstract**

4 Trace organic contaminants have become an increasing cause of concern for governments  
5 and water authorities as they attempt to respond to the potential challenges posed by climate  
6 change by implementing sustainable water cycle management practices. The augmentation of  
7 potable water supplies through indirect potable water reuse is one such method currently  
8 being employed. Given the uncertainty surrounding the potential human health impacts of  
9 prolonged ingestion of trace organic contaminant, it is vital that effective and sustainable  
10 treatment methods are utilized. The purpose of this article is to provide a comprehensive  
11 literature review of the performance of chemical coagulation process in removing trace  
12 organic contaminant from water. This study evaluated the removal data collated from recent  
13 research relating to various trace organic contaminant during the coagulation process. It was  
14 observed that there is limited research data relating to the removal of trace organic  
15 contaminant using coagulation. The findings of this study suggest that there is a gap in the  
16 current research investigating the potential of new types of coagulants and exploring  
17 coagulation-based hybrid processes to remove trace organic contaminant from water. The  
18 data analyzed in this study regarding removal efficiency suggests that, even for the  
19 significantly hydrophobic compounds, hydrophobicity is not the sole factor governing  
20 removal of trace organic contaminant by coagulation. This has important implications in that  
21 the usual practice of screening coagulants based on turbidity (suspended solid) removal  
22 proves inadequate in case of trace organic contaminant removal.

23 **Keywords:** adsorption; coagulation; flocculation; hydrophobicity; micropollutants; trace  
24 organic contaminant

25

26 **Abbreviations:** AOPs, advanced oxidation processes; CAS, conventional activated sludge;  
27 CTC, chlortetracycline; DBP, dibutyl phthalate; DBPs, disinfection by-products; DEHP, di  
28 (2-ethylhexyl) phthalate; DEP, diethyl phthalate; EDCs, endocrine disrupting compounds;  
29 DHA, dissolved humic acid; GAC, granular activated carbon; HAA, haloacetic acid; MBRs,  
30 membrane bioreactors; MDMA, 3,4-methylene dioxy methamphetamine; NF, nanofiltration;  
31 NOM, natural organic matter; PACl, polyaluminium chloride; PAFCl, polyaluminium ferric  
32 chloride; PAH, polycyclic aromatic hydrocarbon; PFCl, polyferric chloride; PFS, polyferrous

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33 sulphate; PPCPs, pharmaceutical and personal care products; RO, reverse osmosis; THM,  
34 trihalomethane

35

## 36 **1. Introduction**

37 The term trace organic contaminant refers to contaminants present in water and wastewater at  
38 very low concentrations. Types of trace organic contaminant include endocrine disrupting  
39 compounds (EDCs), pharmaceutical and personal care products (PPCPs), and disinfection by-  
40 products (DBPs). PPCPs and EDCs, for example, can enter the water supply as a result of  
41 domestic and industrial usage. Certain trace organic contaminant have been shown to impose  
42 adverse impacts on human, wildlife and aquatic ecosystems (Ottinger et al., 2002; Purdom et  
43 al., 1994). **Table 1** lists toxicological effects of various trace organic contaminant on human  
44 and aquatic organisms as reported in the literature.

45

46 Trace organic contaminant have become an increasing cause of concern for governments and  
47 water authorities around the world as they attempt to implement sustainable water reuse  
48 practices. The presence of PPCPs in potable water is of concern given that the impact of  
49 prolonged low-level exposure on human health is not yet clearly understood (Daughton and  
50 Ternes, 1999). In order to address the problem of water scarcity and the potential impacts of  
51 climate change, indirect potable water reuse schemes are being implemented to augment the  
52 water supply (Radcliffe, 2006). Therefore it is vital that effective water treatment processes  
53 are employed to remove trace organic contaminant, and thus ensure that any potential human  
54 health risks are mitigated prior to consumption. PPCPs as a category of trace organic  
55 contaminant refer to a range of pharmaceutical and personal care products which can be  
56 present in natural waterways and wastewater due to a variety of waste sources, including  
57 household waste, hospital waste, and waste from pharmaceutical companies. PPCPs are

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58 classified according to their compound class (e.g. antibiotic, stimulant, musk) which refers to  
59 the intended purpose of the particular compound.

60

61 Chemical coagulation and flocculation in water/wastewater treatment involves the addition of  
62 chemicals to alter the physical state of dissolved and suspended solids and facilitate their  
63 removal by sedimentation (Duan and Gregory, 2003; Matilainen et al., 2010). Coagulants  
64 react with the suspended and colloidal particles in the water, causing them to bind together  
65 and thus allowing for their removal in the subsequent treatment processes (Lia et al., 2006).

66 The aggregation mechanisms through which particles and colloids are removed include a  
67 combination of charge neutralization, entrapment, adsorption and complexation with  
68 coagulant ions into insoluble masses (Duan and Gregory, 2003; Matilainen et al., 2010;  
69 Verma et al., 2012).

70

71 Coagulation treatment forms an integral part of the conventional water treatment scheme.  
72 Traditionally coagulation treatment has been employed in water treatment to decrease  
73 turbidity and color and to remove pathogens (Hai et al., 2007; Matilainen et al., 2010; Verma  
74 et al., 2012). The hydrophobic and high molar mass fractions of natural organic matter  
75 (NOM) can be efficiently removed by coagulation (Matilainen et al., 2010).  
76 Coagulation/flocculation/precipitation processes have been intensively used for decolorizing  
77 wastewater (Hai et al., 2007; Verma et al., 2012). Chemical coagulation is often applied to  
78 augment biological phosphorous removal in activated sludge processes (Nguyen et al., 2010).

79

80 Although coagulation, in combination with the other physicochemical water treatment  
81 processes of flocculation and sedimentation, has long been known to be effective for bulk

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82 natural organic matter removal from water, it has traditionally been found to be inefficient in  
83 removing trace organic contaminants (Choi, 2006; Dempsey and O'Melia, 1984; Huerta-  
84 Fontela et al., 2011; Kim et al., 2007b; Le-Minh et al., 2010; Snoeyink and Chen, 1985;  
85 Ternes, 2002; Vieno, 2007). Advanced water treatment processes such as adsorption (Bundy,  
86 2007; Choi, 2006; Ternes, 2002) and reverse osmosis/ nanofiltration processes have been  
87 found to be more effective in the removal of trace organic contaminant from water (Al-Rifai  
88 et al., 2011; Comerton et al., 2008; Nghiem et al., 2004; Nghiem et al., 2003).

89

90 **Table 2** summarizes the advantages and disadvantages of the available techniques for trace  
91 organic contaminant removal from water/wastewater. All methods listed here have some  
92 advantages as well as some drawbacks, and a universal standalone process applicable for  
93 majority of the trace organic contaminant is yet to be developed. In general, the advanced  
94 processes are more energy intensive and complex in operation than conventional treatment  
95 processes. Because chemical coagulation and flocculation is a cost-competitive, common  
96 method, it is logical to investigate ways to improve their performance of trace organic  
97 contaminant removal.

98

99 It is important to note that although the coagulation process has been shown to achieve  
100 insignificant removal of certain trace organic contaminant, the process of coagulation and the  
101 types of coagulants currently being used have not been designed for the purpose of trace  
102 organic contaminant removal. Therefore opportunities exist to optimize the coagulation  
103 process by selecting the most appropriate coagulants and potentially redesigning the  
104 coagulation process to maximize trace organic contaminant removal. If the coagulation  
105 process can be optimized, it may be possible to devise efficient, hybrid treatment processes.

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106 Several coagulation-based hybrid processes can be contemplated in this connection. For  
107 instance: coupling of coagulation process with membrane bioreactors (MBRs). MBRs have  
108 been shown to outperform conventional activated sludge (CAS) processes in terms of  
109 producing better quality effluent when considering water quality parameters such as total  
110 organic carbon and total nitrogen (Hai and Yamamoto, 2011; Leiknes, 2009; Visvanathan et  
111 al., 2000), however the superiority of MBR in terms of trace organic contaminant removal is  
112 yet to be demonstrated convincingly. Variation in removal of hydrophilic and persistent trace  
113 organic contaminant by MBR treatment has been reported (Clara et al., 2005; Kimura et al.,  
114 2005; Tadkaew et al., 2011). The sorption mechanism of coagulation, combined with the  
115 biodegradation mechanism of MBR, may be beneficial in terms of helping to mitigate the  
116 problems of membrane fouling (Hai and Yamamoto, 2011; Le-Clech et al., 2006) associated  
117 with MBR, and improving the overall trace organic contaminant removal efficiency (Leiknes,  
118 2009). This combination of coagulation and biological processes, for example, has been  
119 found to be effective in the treatment of textile dyeing wastewater (Zaisheng et al., 2009),  
120 while it has also been shown to be effective in removing certain trace organic contaminant  
121 (Serrano et al., 2010). Furthermore, because coagulation process is usually used for  
122 phosphate removal from wastewater (Yang et al., 2010), the phosphate removal and trace  
123 organic contaminant removal can potentially be combined in one step (Zhou, 2011).

124

125 In order to achieve the goal of development of next generation coagulants, and also to assist  
126 in the development of hybrid treatment processes, it is important to know the efficiency of  
127 current coagulation processes and the efficacy of the particular coagulants currently being  
128 utilized. The aim of this study, therefore, is to evaluate in depth the extent to which the  
129 conventional coagulation treatment units are able to remove varieties of groups of trace

130 organic contaminant from water. An analysis of the data available in the literature will also be  
131 conducted in an effort to determine the most suitable types of coagulants, coagulant dosage,  
132 and associated parameters. It is expected that this study will assist efforts to develop high  
133 performance coagulants and efficient hybrid water treatment processes combining  
134 physicochemical and biological processes. This is particularly pertinent given the need to  
135 augment potable water supplies with water recycling schemes as a result of an increasing  
136 population and the potential adverse impacts of climate change. In-depth reviews on the  
137 coagulation process mechanisms in general (Duan and Gregory, 2003) and on its application  
138 in natural organic matter removal (Matilainen et al., 2010) or dye wastewater treatment (Hai  
139 et al., 2007; Verma et al., 2012) are available in the literature. However, a comprehensive  
140 literature review indicates that a critical review on the aspect of trace organic contaminant  
141 removal by coagulation process is lacking, and the current article aims to fill in this important  
142 gap.

143

## 144 **2. Removal of varieties of trace organic contaminants**

145

146 The efficiency of conventional water and wastewater treatment units in removing trace  
147 organic contaminant has been studied in a number of different forms ranging from bench-  
148 scale tests to operational water/wastewater treatment plants. The research conducted to date  
149 using the conventional coagulants, which were not specifically designed to remove trace  
150 organic contaminants, indicates that coagulation is an inefficient method of removing trace  
151 organic contaminants (Huerta-Fontela et al., 2011; Kim et al., 2007b; Le-Minh et al., 2010;  
152 Ternes, 2002; Vieno, 2007). The following is a comprehensive review of current research  
153 relating to the removal of various groups of trace organic contaminants. **Table 3** compiles the

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154 data related to removal of individual compounds sorted according to compound class, while  
155 **Table 4** presents a succinct summary of the data presented in **Table 3** to highlight the  
156 average removal according to compound class.

157

## 158 **2.1 Pharmaceuticals**

159 The removal efficiency of coagulation process in the removal of trace organic contaminant  
160 varies significantly, with complete removal observed only for a small number of compounds.  
161 For instance, one particular study showed that coagulation using aluminium sulphate  
162 ( $\text{Al}_2(\text{SO}_4)_3$ ), in combination with flocculation and sand filtration, was able to completely  
163 remove five out of the thirty-five trace organic contaminant (pharmaceuticals) detected in the  
164 raw water at a drinking water treatment plant (Huerta-Fontela et al., 2011). The five  
165 pharmaceuticals completely removed included chlordiazepoxide, zolpidem, bromazepam,  
166 clopidogrel and doxazosin. This study also noted removal efficiencies of around 80% for  
167 three other pharmaceutical compounds, namely warfarin, betaxolol and hydrochlorothiazide.  
168 The effective removal of the above mentioned eight compounds, with the exception of  
169 hydrochlorothiazide, may be the result of a removal phenomenon known as partitioning,  
170 given their relative hydrophobicity (Huerta-Fontela et al., 2011). However, the remainder of  
171 the trace organic contaminant tested in this study showed less than 50% removal during this  
172 treatment phase, indicating that coagulation, flocculation, and sand filtration are largely  
173 inefficient in removing those pharmaceuticals.

174

175 Certain antibiotics, which are a type of pharmaceutical compound, have been found to be  
176 removed reasonably effectively by coagulation (Choi et al., 2008). Choi et al (2008) reported  
177 that four of the seven tested tetracycline antibiotics showed removal efficiencies of between

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178 55% and 66%, from river water samples using polyaluminium chloride (PACl) coagulants.  
179 The effective removal of the tested tetracycline antibiotics in this case may be due to the  
180 effects of sweep coagulation in the river water samples, and charge neutralization in the  
181 synthetic water samples, respectively (Choi et al., 2008). The most poorly removed antibiotic  
182 seems to be sulfamethoxazole which has shown negligible removal using both ferric chloride  
183 (Stackelberg et al., 2007; Suarez et al., 2009) and ferric sulphate (Westerhoff et al., 2005).

184

185 Stimulants and psychoactive drugs are types of pharmaceuticals which include prescription  
186 medicines and illicit drugs, which may be used recreationally or abusively. The exact impact  
187 on human health as a result of ingestion of stimulants through water remains unclear (Huerta-  
188 Fontela, 2008). A particular study explored the removal of certain stimulatory drugs of abuse  
189 using chlorination, coagulation, flocculation, and sand filtration (Huerta-Fontela, 2008). The  
190 removal of the stimulants included in this study was generally poor with the exception of  
191 amphetamine which was completely removed during the conventional treatment processes  
192 (Huerta-Fontela, 2008). However, it should be noted that the direct contribution of  
193 coagulation to the overall removal of these compounds is uncertain as the removal data was  
194 only supplied for the entire conventional treatment phase.

195

## 196 **2.2 Musk fragrances**

197 Musk fragrances are personal care products which can be found in products such as  
198 detergents and cosmetics. Some selected musks were shown to be removed to a high degree  
199 when using coagulation and flocculation at an urban sewage treatment plant (Carballa et al.,  
200 2005), and as a pre-treatment method for hospital wastewater (Suarez et al., 2009). The musk  
201 compounds tonalide, galaxolide, and celestolide were removed from hospital wastewater by

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202 83%, 79%, and 78%, respectively during coagulation and flocculation, with the high degree  
203 of removal possibly attributed to the hydrophobic nature of these compounds (Suarez et al.,  
204 2009).

205

### 206 **2.3 Steroids/hormones**

207 Estrogenic compounds are another form of trace organic contaminant which have been found  
208 to be poorly removed using conventional water treatment units (Bodzek and Dudziak, 2006;  
209 Bundy, 2007; Le-Minh et al., 2010). Estrogens are female sex hormones which can be found  
210 in waterways as a result of human and animal waste. The impact of these trace organic  
211 contaminant on aquatic ecosystems and human health have become a growing cause of  
212 concern given the increased presence of estrogens in water as a result of the disposal of  
213 expired medications from hospitals, pharmaceuticals, and households (Bodzek and Dudziak,  
214 2006). Bodzek and Dudziak (2006) studied the potential of a hybrid treatment process  
215 combining coagulation and nanofiltration in removing natural and steroidal sex hormones.  
216 Polyaluminium chloride (PAX-18) was found to be the most suitable coagulant for this  
217 purpose, with removal efficiency of greater than 30% observed for estriol, diethylstilbestrol,  
218 and mestranol (Bodzek and Dudziak, 2006). Ferric sulphate as a coagulant however was  
219 shown to be less efficient in removing the estrogens used in this study, with the exception of  
220 estradiol where it produced similar removal to the polyaluminium chloride coagulant used  
221 (Bodzek and Dudziak, 2006), while aluminium sulphate has shown negligible removal of  
222 estrone (Le-Minh et al., 2010) and estradiol (Bundy, 2007; Le-Minh et al., 2010).

223

### 224 **2.4 Other EDCs**

225 Endocrine disrupting compounds (EDCs) refer to chemicals or compounds that interfere with  
226 the endocrine system of a human or animal. The EDCs, other than hormones, observed in the  
227 literature relating to coagulation as a removal method were phthalate plasticizers, herbicides,  
228 insecticides, pesticides, and polycyclic aromatic hydrocarbons (PAHs). The phthalate  
229 plasticizer compounds di (2-ethylhexyl) phthalate (DEHP), dibutyl phthalate (DBP), and  
230 diethyl phthalate (DEP) displayed the best removal efficiencies using coagulation and  
231 flocculation as part of a pilot-scale drinking water treatment plant, with 53%, 49%, and 46%  
232 removal, respectively (Choi, 2006). This may be explained by the removal of natural organic  
233 matter (NOM) onto which the phthalate plasticizer compounds with high octanol/water  
234 partition coefficients or hydrophobicity remained adsorbed (Choi, 2006). Insecticides have  
235 also been shown to be removed with varying degrees of success, with the compounds aldrin,  
236 heptachlor (Le-Minh et al., 2010), and diazinon (Stackelberg et al., 2007), removed by 49%,  
237 46%, and 33%, respectively. The remaining EDCs showed low removal efficiencies ranging  
238 between 24-33%, and consisted of a pesticide, herbicide, and two polycyclic aromatic  
239 hydrocarbons (PAHs) (Le-Minh et al., 2010; Stackelberg et al., 2007).

240

## 241 **2.5 Summary of compound group-specific removal performance**

242 It is interesting to note from **Table 3** and **4** that the musk fragrances investigated in various  
243 studies consistently showed significant removal by coagulation. Good removal (near 50%)  
244 was also obtained for phthalate plasticizers, but the amount of available data is not sufficient to  
245 draw a meaningful conclusion. Pharmaceuticals of different compound classes on an average  
246 received a removal of around 30%. However, given the great variations in physico-chemical  
247 properties of the pharmaceuticals, the removal of compounds even within the same  
248 therapeutic class was observed to vary significantly. For instance, out of the anti-

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249 inflammatory drugs listed in **Table 3**, only diclofenac consistently showed around 70%  
250 removal, which is significantly high compared to the average of 35( $\pm$ 23)% estimated for this  
251 compound class (**Table 4**). The average removal of the compound class “stimulants” was  
252 34( $\pm$ 34) % which may be attributed to the fact that the compounds within this class were  
253 often poles apart in terms of their removal by coagulation—for instance, while complete  
254 removal of amphetamine was observed, caffeine was barely removed (**Table 4**). It should be  
255 also noted that significant variation in removal of the same compound (e.g., caffeine) may be  
256 observed in different studies (Bundy, 2007; Huerta-Fontela, 2008; Westerhoff et al., 2005). It  
257 has been suggested that the classification of trace organic contaminant according to their  
258 intended use or origin can only be used to qualitatively predict the removal efficiencies of  
259 compounds of similar molecular structure, having similar molecular features or  
260 physicochemical properties (Hai et al., 2011; Tadkaew et al., 2011). Because certain  
261 molecular features and physicochemical properties of the trace organic contaminants as well  
262 as the operating parameters can govern their rate of removal during coagulation process  
263 (Lefebvre et al., 2010), Section 3 will analyze the data presented in **Table 3** and **4** from the  
264 point of view of the factors governing the performance of coagulation process.

265

### 266 **3. Factors governing removal efficiency**

#### 267 **3.1 Coagulation process parameters**

268 The effectiveness of a coagulation unit may depend on several factors including coagulant  
269 type and dosage, mixing conditions, pH, alkalinity, temperature as well as the presence of  
270 divalent cations and concentrations of destabilizing anions (biocarbonate, chloride, sulphate  
271 etc.)(Duan and Gregory, 2003; Matilainen et al., 2010; Verma et al., 2012). In view of the  
272 availability of data, we will focus on the effect of type and dosage of coagulant and effect of  
273 pH, alkalinity and temperature of water.

274

### 275 *3.1.1 Effect of coagulant type and dosage*

276 The effect of coagulant type and dosage on trace organic contaminant removal has been  
277 reported in a few studies. The use of aluminium sulphate as a coagulant was proven to be  
278 highly effective in removing certain hydrophobic pharmaceutical compounds, namely  
279 chlordiazepoxide, zolpidem, bromazepam, clopidogrel, doxazosin, warfarin, and betaxolol  
280 (Huerta-Fontela et al., 2011), however the coagulant dose used in obtaining these results was  
281 not provided. Aluminium sulphate displayed poor removal efficiency (<5%) for both estrone  
282 and estradiol using a dosage of 78 mg/L (Bundy, 2007; Le-Minh et al., 2010). However it has  
283 been found to be reasonably effective in removing certain EDCs such as phthalate plasticizers  
284 at a dosage of 50 mg/L (Choi, 2006).

285

286 Ferric chloride was particularly effective in removing three musk compounds, namely  
287 tonalide, galaxolide, and celestolide, from hospital wastewater at a dosage of 25 mg/L  
288 (Suarez et al., 2009). The removal of these compounds does not seem to be improved by  
289 greatly increased dosages of ferric chloride, as another study has shown that 250 mg/L  
290 applied to an urban sewage treatment plant yielded similar removal efficiencies (Carballa et  
291 al., 2005). On the other hand, the removal of bisphenol A increased from 5% to 20% due to

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292 doubling the ferric chloride dose (Carballa et al., 2005). Because acidic compounds remain  
293 (partially) ionized in aqueous phase, comparatively higher coagulant dosage may be required  
294 for their removal. For instance, Zorita et al. (2009) achieved less than 25% removal of  
295 diclofenac by applying a ferric chloride dose of 70 mg/L as a tertiary treatment of sewage  
296 wastewater, while in another study Carballa et al. (2005) reported 70% removal applying a  
297 higher dose of 250 mg/L. Chang et al. (2004) reported negligible interactions between trace  
298 estrone, and iron oxyhydroxide particulates formed on addition of hydrolyzable ferric salts.  
299 An estrone concentration of 15 ng/L was used in this study. This scenario is quite different to  
300 that obtained with a significantly higher estrone concentration (~0.1 g/L) where a strong  
301 interaction between estrone and clay particles was observed (Lai et al., 2000), suggesting that  
302 organics in trace concentration are particularly difficult to remove by coagulation.

303

304 Verma et al. (2012) reported that pre-hydrolyzed coagulants such as polyaluminium chloride  
305 (PACl), polyaluminium ferric chloride (PAFCl), polyferrous sulphate (PFS) and polyferric  
306 chloride (PFCl) may achieve better removal of soluble dyes as compared to the hydrolyzing  
307 metal salts. A few similar examples of certain coagulants outperforming others in terms of  
308 trace organic contaminant removal can be found in the literature. For instance,  
309 polyaluminium chloride (PACl) was shown to outperform ferric sulphate in the removal of  
310 certain estrogen compounds using dosages of 5.4 mg/L and 12.2 mg/L, respectively, however  
311 removal efficiencies were not found to be greater than 40% for any of the estrogens tested  
312 (Bodzek and Dudziak, 2006). In another study, Carballa et al. (2003) observed that PACl  
313 achieved the highest removal of the studied musk fragrance compounds, while in the case of  
314 diazepam, ferric chloride displayed the best removal. Choi et al. (2008) also utilized PACl,  
315 with the best removal efficiencies in this study observed at a dosage of 40 mg/L, with

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316 reported removal efficiencies of above 50% for four of the seven antibiotics tested. While  
317 using PACl in dosages of above 2 mol/L, Wang et al. (2007) interestingly noted the absence  
318 of  $Al_{13}$  ( $AlO_4Al_{12}(OH)_{24}^{7+}$ ) species, which is reported to enhance NOM removal, whereas the  
319  $Al_{13}$  species were observed when a different coagulant (nano- $Al_{13}$ ) was used with the same  
320 level of dosage. The superiority of PAFCl over PFS and PACl for decoloration of  
321 petrochemical wastewater was demonstrated by Chen et al. (2010). They attributed the  
322 superior performance of PAFCl to the fact that PAFCl combines the coagulatory advantages  
323 of both aluminium and iron salts and is, hence, able to form more bulky flocs rapidly, leading  
324 to rapid sedimentation. Similarly, inorganic salts in combination with organic polyelectrolytes  
325 as coagulant aids or composite inorganic-organic coagulants (Matilainen et al., 2010) have  
326 been reported to be beneficial in some instances. However, systematic studies on comparison  
327 between the trace organic contaminant removal performance of various pre-hydrolyzed and  
328 hydrolyzable coagulants could not be identified in the literature. A lack of studies on the  
329 application of natural coagulants (e.g., polysaccharides, chitosan, guar gum etc.) (Verma et  
330 al., 2012) for trace organic contaminant removal is also evident. Based on turbidity removal,  
331 Zhou (2011) screened two cationic flocculants, one anionic flocculant and one coagulant  
332 from a list of 20 different polymers. However, the finally selected coagulants achieved  
333 negligible removal of the selected trace organic contaminant, indicating the limitation of  
334 using turbidity removal as a criterion for selecting/designing coagulants for trace organic  
335 contaminant removal.

336 It is worth-noting here that in addition to the type and dosage of coagulants that of the  
337 flocculants can be important in determining the removal efficiency of trace organic  
338 contaminants. However, in the literature the flocculation process has been was almost always  
339 discussed as part of a combined process with coagulation (e.g. mentioned as

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340 coagulation/flocculation), and specific details regarding the flocculation process such as  
341 dosage and types of flocculants used have been rarely provided. As a result, it was not  
342 possible to draw a meaningful conclusion relating to the impact of flocculant type and dosage  
343 on the removal of trace organic contaminants.

344

### 345 *3.1.2 Effect of pH, alkalinity and temperature*

346

347 Changes in coagulants species and/or charge of the target compound can result due to  
348 variation in pH of the liquid media (Yan et al., 2007; Yan et al., 2008; Zhao et al., 2008). In  
349 addition to governing the coagulant speciation, the media pH influences the extent of  
350 dissociation of the trace organic contaminants, and can, thereby, result in compound-specific  
351 removal performance during application of a certain type of coagulant. A simultaneous effect  
352 of coagulant species and the charge of the target compound can, therefore, be perceived.  
353 Zhao et al. (2008) explained this phenomenon with the example of the removal of  
354 trihalomethane (THM) and haloacetic acid (HAA) precursors with PACl. HAA precursors are  
355 mainly aromatic while the THM precursors contain more aliphatic moieties. At pH 5.5, the  
356 negatively-charged aliphatic THM precursors may be removed due to charge neutralization  
357 by the monomeric Al species that exists under that pH. However, because both the  $Al_{13}$  and  
358  $Al(OH)_3$  species exist at a higher pH (5.5—7.5), both charge neutralization precipitation and  
359 adsorption could be responsible for THM removal in that case. On the other hand, in the case  
360 of HAA precursors, self-aggregations of the aromatic and hydrophobic functional groups can  
361 occur under acidic pH, while adsorption onto flocs and subsequent removal through sweep  
362 flocculation may occur under alkaline pH. However, certain compounds may show negligible  
363 removal by coagulation over a wide range of pH. For instance, although Chang et al. (2004)

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364 observed a significant effect of pH on total organic carbon removal, no obvious change in  
365 estrone removal was observed for coagulation under different pH conditions (5—11.4).

366

367 Some coagulants, upon application, can cause pH change of water. The natural pH of ferric  
368 chloride, ferric sulphate as well as alum solution is acidic. Hence, certain basic compounds  
369 (e.g., lime or sodium hydroxide) need to be added to adjust the pH to neutral. This may lead  
370 to production of extra sludge. However, Westerhoff et al. (2005) reported that the application  
371 of a ferric sulphate coagulant at a low pH may be quite effective in removing ionic  
372 pharmaceuticals from water with a high amount of humic material. Vieno et al (2006),  
373 however, achieved moderate removal of the pharmaceutical compounds ibuprofen, diclofenac  
374 and bezafibrate by employing a ferric sulphate coagulant at a pH of 4.5. PACl coagulants are  
375 pre-neutralized, have smaller effect on the pH of water and therefore reduce the need of such  
376 pH correction. However, a higher dose of a coagulant may be required unless the natural pH  
377 of water is adjusted to a level suitable for the coagulant. Yan et al. (2008) noted that a higher  
378 dose of PACl was required for treating a highly alkaline river water. Optimum sweep  
379 coagulation refers to the point where significant interaction occurs between the colloidal  
380 particles and the precipitated polymeric hydroxides (Vieno et al., 2006). Choi et al. (2008)  
381 found that optimum sweep coagulation occurred in river water at a pH of 7.4 and PACl  
382 dosage of 60 mg/L, and at a pH of 6.8-8.3 and aluminium sulphate dosage of 20-50 mg/L.

383

384 The detrimental effect of lower temperature (for instance, 1°C as compared to 25 °C) over  
385 turbidity or color removal efficiency of coagulants is well known (Duan and Gregory, 2003;  
386 Matilainen et al., 2010; Verma et al., 2012). However, only a handful of studies have  
387 specifically studied the effect of temperature in case of trace organic contaminant removal by

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388 coagulation process. By conducting investigations under two different temperatures (12° and  
389 25° C), Carballa et al. (2003) reported negligible difference in removal of galaxolide, tonalide  
390 and diclofenac.

391

### 392 **3.2 Effect of physico-chemical properties of trace organic contaminants**

393 Various physico-chemical properties of the target trace organic contaminant may exert  
394 profound effects on the efficiency of the coagulation process. Differences have been noted  
395 between the removal of acidic and neutral trace organic contaminant, with the latter showing  
396 higher removal efficiencies in a study on the removal of PPCPs from municipal wastewater  
397 using coagulation and flocculation (Carballa et al., 2003). Lipophilic compounds, like musks,  
398 are mainly absorbed on the lipid fractions of the sludge, while acidic compounds, like  
399 diclofenac, are mainly adsorbed due to electrostatic interactions (Carballa et al., 2005). The  
400 partition coefficient, Log D, is a physicochemical parameter that measures the  
401 hydrophobicity of a compound at a given pH. It has been suggested that the sorption of trace  
402 organic contaminants to activated sludge is related to the hydrophobicity of a compound, and  
403 thus the Log D value of a compound at a given pH (Wells, 2006). A study using a laboratory  
404 scale MBR system found that significantly hydrophobic (Log D > 3.2) trace organic  
405 compounds were removed with a high degree of efficiency (Tadkaew et al., 2011). The  
406 relationship between hydrophobicity and removal efficiency has also been shown in the case  
407 of the coagulation process. For instance, a study relating to the removal of pesticides from  
408 surface water using coagulation and flocculation found that the main mechanism governing  
409 the removal of these trace organic contaminant was sorption onto the natural material in the  
410 river water (Thuy et al., 2008). Trace organic contaminant can also partition into the  
411 hydrophobic domain in colloidal organic matter. Rebhun (1998) utilized dissolved humic acid

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412 (DHA) to remove hydrophobic contaminants (polycyclic aromatic hydrocarbons, PAHs) from  
413 water by complexation–flocculation process. Dissolved humic acid was added to the  
414 contaminated water and allowed to interact (bind) with the dissolved contaminants to form  
415 DHA–contaminant complexes (complexation stage). A flocculant was then added, resulting  
416 in precipitation and flocculation of the DHA and the associated contaminant. Similarly,  
417 hydrophobic partitioning has been noted as a potential reason for the effective removal of  
418 certain pharmaceutical compounds (Huerta-Fontela et al., 2011), and certain musk  
419 compounds (Suarez et al., 2009). This is consistent with another study exploring the removal  
420 of EDCs and PPCPs by coagulation, where it was found that neutral compounds with higher  
421 hydrophobicity displayed better removal efficiencies (Westerhoff et al., 2005). These  
422 findings relating to the removal of these neutral, hydrophobic musk compounds are consistent  
423 with another study where a ferric chloride coagulant was directly added into conventional  
424 activated sludge (CAS) reactors (Serrano et al., 2010).

425

426 Reports in contrary to the above examples demonstrating a correlation between  
427 hydrophobicity (Log D) and/or charge of a compound and its removal by coagulation process  
428 do, however, exist. A poor correlation between Log D and adsorption was found when  
429 hydrophobic partitioning was less relevant, i.e., when the solutes were small, hydrophilic  
430 and/or charged/polar (de Ridder et al., 2010). However, Carballa et al. (2003) noted  
431 differences in removal efficiencies even between neutral compounds. They observed that  
432 while the tested musk fragrances (galaxolide and tonalide) showed removal efficiencies  
433 between 50-70%, certain pharmaceuticals (diazepam and carbamazepine) showed very low  
434 removal despite being neutral compounds. The neutral pharmaceutical compounds diazepam  
435 and carbamazepine have been consistently shown to be poorly removed. Coagulation has

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436 been found to have no impact on the removal of diazepam (Huerta-Fontela et al., 2011;  
437 Suarez et al., 2009), and very little impact on the removal of carbamazepine (Suarez et al.,  
438 2009; Ternes, 2002; Vieno et al., 2006; Vieno, 2007). On the other hand,  
439 hydrochlorothiazide, despite having relatively smaller Log D than carbamazepine and  
440 diazepam, has been reported to be significantly removed by coagulation using alum (Huerta-  
441 Fontela et al., 2011). In contrast, hormones (estrogens and progesterone), which possess  
442 significantly high Log D (Tadkaew et al., 2011) have been consistently shown to be poorly  
443 removed by coagulation treatment (**Table 3**).

444

445 **Figure 1** plots the Log D values (at a pH of 7) of trace organic contaminant listed in **Table 3**  
446 against their removal efficiency data. The information displayed in **Figure 1** suggests that  
447 there is no discernable link between hydrophobicity (Log D) and removal efficiency for the  
448 compounds in these studies. The most common pH values utilized for the coagulation phase  
449 of the studies reviewed in this paper were around 5 and 7. Accordingly, the graph was re-  
450 plotted (not shown) with Log D values at a pH of 5; however, a similar trend was observed.  
451 Therefore, based on the literature reviewed here, hydrophobicity appears not to be the sole  
452 factor governing the removal of trace organic contaminant using coagulation, even when the  
453 compound is significantly hydrophobic (Log D > 3.2). To remove the target trace organic  
454 contaminants from a particular wastewater, coagulants are commonly selected according to  
455 turbidity (suspended solids) removal from that wastewater, since it is usually expected that  
456 hydrophobic organics may partition onto settled solid particles and be removed (Zhou, 2011).  
457 However, the observation made through **Figure 1** suggests that coagulant selection based on  
458 only turbidity (suspended solids) removal may not be always effective. Information on no  
459 alternative suitable indicator could be found in the literature.

460

461 The extent of adsorption can be related to the structures of the target compounds. Yu et al.  
462 (2002) reported on the effect of dye structure on the interaction between a selected set of  
463 organic flocculant and dye. They observed that the process of dye flocculation is controlled  
464 by both charge and hydrophobic interactions. However, there has rarely been any specific  
465 study with the coagulant—trace organic contaminant combination from this aspect.  
466 Haberhauer et al. (2000) reported increased adsorption due to replacement of the methyl  
467 group of the phenoxy ring of a phenoxyalkanoic herbicide by a chlorine (dichlorprop) and  
468 additional increase due to the substitution of the propionic moiety by an acetic acid moiety  
469 (2,4-D). They attributed this to the effect of such structural change on the volume and  
470 polarity of the investigated compounds.

471

#### 472 **4. Coagulation-based combined/hybrid processes**

473

474 Use of advanced water treatment processes in conjunction with coagulation process have  
475 often been found to improve the overall removal efficiency of trace organic contaminant in  
476 both laboratory investigations and operational drinking water treatment plants (Bundy, 2007;  
477 Choi, 2006; Huerta-Fontela, 2008; Lefebvre et al., 2010; Ternes, 2002). A few such examples  
478 are given below.

479

##### 480 **4.1 Combination with activated carbon adsorption**

481 A properly designed coagulation-flocculation unit can efficiently remove suspended solids  
482 and can thereby enhance the performance of a subsequent activated carbon adsorption unit by  
483 reducing competitive adsorption (Hai et al., 2007). For instance, in the case of dye effluent

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484 treatment, coagulation followed by adsorption was reported to produce effluent of reuse  
485 standard, while reducing the coagulant consumption by 50%, hence lowering the volume of  
486 sludge formed, in comparison to coagulation only (Papic et al., 2004). Treatment methods  
487 employing coagulation and flocculation followed by filtration with granular activated carbon  
488 (GAC) have been reported to be very effective in removing certain trace organic contaminant  
489 during drinking water treatment (Bundy, 2007; Choi, 2006; Ternes, 2002). GAC post-  
490 treatment has been found to significantly enhance the removal efficiency to almost complete  
491 removal of caffeine, trifloxacin mesylate and estradiol (Bundy, 2007), carbamazepine,  
492 bezafibrate and diclofenac (Ternes, 2002), cocaine, 3,4-Methylene dioxy methamphetamine  
493 (MDMA) and benzoylecgonine (Huerta-Fontela, 2008). GAC following coagulation has also  
494 been reported to be reasonably effective in removing certain tetracycline antibiotics (Choi et  
495 al., 2008). Tomaszewska et al. (2004) investigated the removal efficiency of humic acid and  
496 phenol by coagulation and adsorption (powdered activated carbon, PAC) and revealed that in  
497 comparison to coagulation alone, the integrated adsorption-coagulation system is effective in  
498 removing phenol. Zhang et al. (2011) reported an enhanced phenol removal in a process  
499 involving combined application of the common coagulant aluminum chloride and manganese  
500 dioxide formed in situ. Nanotechnology has appeared as a very promising new way to  
501 remove organics from water (Matilainen et al., 2010). Nanomaterials have exceptional  
502 adsorption properties and they are able to entrap diverse organic molecules, including those  
503 in trace concentrations (Joseph et al., 2011; Upadhyayula et al., 2009). Analysis of the mode  
504 of action of such adsorbents may be beneficial while carrying out fundamental research on  
505 development of high performance coagulants.

506

#### 507 **4.2 Combination with nanofiltration/ reverse osmosis**

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508 Combination of coagulation, flocculation, and membrane filtration has been described as an  
509 efficient and reliable treatment option for surface waters with high NOM concentrations  
510 (Leiknes, 2009). The use of coagulation prior to nanofiltration (NF) may help to streamline  
511 the transport properties of NF by removing almost all of the NOM in the water (Bodzek and  
512 Dudziak, 2006) so that trace organic contaminants can be efficiently removed by NF. Muller  
513 and Uhi (2009) reported that a single-tank coagulation—ultrafiltration process removed high  
514 molecular weight organics (preferentially humics) from raw water and subsequently  
515 improved the adsorption of the trace compound cis-1,2-dichloroetheneon onto granular  
516 activated carbon.

517

#### 518 **4.3 Combination with advanced oxidation processes (AOPs)**

519 Because high concentrations of suspended or colloidal solids in the wastewater may impede  
520 the advanced oxidation processes, sufficient prior removal of these materials by a  
521 physicochemical treatment such as coagulation is required (Ciardelli and Ranieri, 2001; Hai  
522 et al., 2007). Ozonation, when employed as a treatment process following conventional water  
523 treatment, has been reported to be very effective in removing trace organic contaminant  
524 (Huerta-Fontela, 2008; Ternes, 2002). Similarly to GAC, ozonation has been shown to  
525 effectively remove carbamazepine, bezafibrate, diclofenac (Ternes, 2002), and caffeine  
526 (Huerta-Fontela, 2008). A hybrid coagulation-membrane reactor may be placed subsequent to  
527 an advanced oxidation process in order to remove soluble degradation products (Hai et al.,  
528 2007). Chemical coagulation following Fenton treatment has been found to reduce floc  
529 settling time, enhance decoloration, and reduce soluble iron in effluent (Hai et al., 2007).  
530 Combining coagulation process with related techniques such as Fenton's reagent may also be



531 beneficial for trace organic contaminant removal too. However, no such studies could be  
532 identified in the literature.

533

534 Removal of trace organic contaminant can be enhanced by utilizing oxidizing agents such as  
535 ferrate (hexavalent Fe) which also have coagulating effect (Lee et al., 2009; Lim and Kim,  
536 2009; Yang et al., 2011). A small dose of ferrate as a pretreatment could enhance the removal  
537 rate of humic acid by traditional coagulants (Lim and Kim, 2009). By using Fe (VI)  
538 oxidation-coagulation Lee et al. (2009) achieved 95% removal of diclofenac which compares  
539 favourably with the removal efficiency achieved by common coagulants (Carballa et al.,  
540 2005). Simultaneous removal of trace organic contaminant and phosphate in secondary  
541 treated effluent was achieved by using Fe (VI) (Lee et al., 2009). At a stoichiometric ratio of  
542 10:1 (Fe(VI):triclosan), complete removal of triclosan was achieved by Yang et al.(Yang et  
543 al., 2011).

544

#### 545 **4.4 Combination with biological reactors**

546 It is very interesting to note that among the compounds listed in Table 3 a few compounds  
547 which have been reported to be poorly removed in conventional activated sludge (CAS)  
548 process or membrane bioreactor (MBR), have been observed to be significantly removed by  
549 coagulation process. For instance, the persistence towards MBR treatment and variable  
550 removal of diclofenac (Hai et al., 2011; Hai et al., 2011; Tadkaew et al., 2011) and  
551 hydrochlorothiazide (Sipma et al., 2010) are well known. However, these compounds were  
552 well removed by coagulation (Table 4). On the other hand, some of the hydrophobic  
553 compounds (Log D> 3.2), such as hormones, which are routinely reported to be significantly  
554 removed by MBR treatment (Hai et al., 2011; Tadkaew et al., 2011), were poorly removed by

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555 coagulation treatment (Table 3). Given the complementary nature of the two treatment  
556 processes, it is likely that simultaneous addition of coagulants into MBR in analogy to  
557 simultaneous addition of activated carbon (Li et al., 2011) would result in enhanced removal  
558 of trace organic contaminant as compared to their standalone applications. Serrano et al.  
559 (2010) conducted a preliminary study on direct addition of a coagulant into a CAS reactor for  
560 trace organic contaminant removal. On the other hand, the effect of direct addition of  
561 coagulant (inorganic or organic or both) into MBR on phosphorous removal by MBR  
562 treatment has been explored in a few studies (Nguyen et al., 2010; Song et al., 2008).  
563 However, the aspect of trace organic contaminant removal in such systems appears to have  
564 not been explored.

565

## 566 **5. Future scope of research**

567

568 This review highlights the potential for further optimization of the available coagulation  
569 techniques to formulate coagulation-based combined processes to enhance the removal of  
570 trace organic contaminant. The discussion provided here also emphasizes the need for more  
571 fundamental research on the mechanisms of trace organic contaminant removal by various  
572 coagulants so as to facilitate the development of high performance new generation coagulants.  
573 The effects of the properties of coagulants and target trace organic contaminant (e.g,  
574 hydrophobicity, charge, polarizability and presence of specific functional groups) as well as  
575 of operational parameters on the trace organic contaminant removal remain poorly studied  
576 although their important role is quite apparent.

577

578 The impact of the data collected from the literature reviewed in this study is limited by the  
579 amount of research which has been conducted to date focusing on this specific topic. This  
580 may be attributed to the relatively recent increase in the scale of water recycling schemes for  
581 the augmentation of potable water supplies, and the associated increasing concern regarding  
582 the presence of trace organic contaminant. Another reason for the lack of focus on  
583 coagulation is that it is generally considered to be an inefficient method of removing trace  
584 organic contaminant, and as a result there seems to be a stronger focus on advanced methods  
585 of water treatment which have shown to, or are considered to have the potential to be, more  
586 efficient methods of removing trace organic contaminant from water. In addition to the  
587 limited amount of research in this specific area, the data specifically relating to coagulation  
588 was often insufficient to draw meaningful conclusions regarding the effects of coagulant type,  
589 dosage and operational parameters. The pH of the water during the coagulation treatment  
590 stage was not frequently reported and thus it was not always possible to determine the effects  
591 of pH on the removal efficiency.

592

593 Among the available chemical coagulation and flocculation technologies, pre-hydrolyzed  
594 coagulants such as PACl, PFCI, PFS and PAFCl are often considered superior to the  
595 hydrolyzing metal salts in terms of turbidity and color removal over a wide pH range and  
596 requiring smaller dosage. However, the effectiveness of most of the pre-hydrolyzed  
597 coagulants for trace organic contaminant removal is yet to be explored. The use of natural  
598 coagulants (e.g., polysaccharides, chitosan, guar gum etc.) as coagulant aids to enhance trace  
599 organic contaminant removal is another important topic which remains unexplored. Natural  
600 coagulants are non-toxic, biodegradable and environmentally friendly and, therefore, are  
601 particularly promising considering simultaneous application of coagulants into bioreactor.

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602

603 There does not seem to have been any research to date which has focused specifically on the  
604 application of new composite coagulants to water treatment for the removal of trace organic  
605 contaminant. This represents an important gap in the current research and it is therefore  
606 indispensable that future research focus on this area. Given that traditional coagulants have  
607 not been designed for the purpose of removing trace organic contaminant, by studying the  
608 performance of new types of coagulants under different operating conditions, there is the  
609 potential to identify coagulants which may be more effective in removing trace organic  
610 contaminant. Research in this area may assist in the evaluation of the merit of efficient hybrid  
611 treatment processes combining conventional physicochemical water treatment processes such  
612 as coagulation, with biological processes such as MBR, for the removal of trace organic  
613 contaminant.

614

## 615 **6. Conclusion**

616 A comprehensive review of the current literature pertaining to the removal of trace organic  
617 contaminant from drinking water and wastewater using coagulation process has been  
618 furnished here. The analysis of the data collected from the literature reviewed in this study  
619 largely reaffirms the consensus which has been reached to date, that trace organic  
620 contaminant tend to be poorly removed by coagulation treatment. The literature does  
621 however show that certain musk fragrances and pharmaceutical compounds can be  
622 effectively removed using coagulation. An analysis of the removal data for all compounds  
623 covered in this review was carried out according to their relative hydrophobicity (Log D).  
624 This analysis showed that although hydrophobicity can explain the high removal of certain  
625 compounds, there was no discernable correlation between Log D and removal, suggesting

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626 that hydrophobicity is not the sole factor governing removal by coagulation, even for  
627 significantly hydrophobic compounds. This implies that the usual method of coagulant  
628 selection based on turbidity/suspended solids removal may not be always effective.. Pre-  
629 coagulation has been found to enhance the trace organic contaminant removal performance of  
630 the advanced treatment processes such as ozonation, GAC adsorption and nanofiltration. The  
631 research to date has largely focused on traditional coagulants such as ferric and aluminium  
632 coagulants which were not designed for the purpose of removing trace organic contaminant.  
633 Therefore there is the potential to investigate the efficiency of new generation high  
634 performance coagulants in removing trace organic contaminant.

635

#### 636 **Acknowledgement**

637 The University Research Committee (URC) small grant 2012 of University of Wollongong,  
638 Australia awarded to the corresponding author (Dr. Faisal I. Hai) is acknowledged with  
639 thanks for providing funding to carry out research in the related area. Luong N. Nguyen is  
640 thanked for his assistance in some of the baseline analyses.

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### Figure caption

**Figure 1:** Plot of removal efficiency and Log D (at pH 7) of the compounds listed in Table 3 showing no apparent relationship between hydrophobicity and removal by coagulation treatment. A similar trend was observed when the graph was re-plotted with the Log D values at a pH of 5. Log D data were obtained from SciFinder database (<https://scifinder.cas.org/scifinder/view/scifinder/scifinderExplore.jsf>)

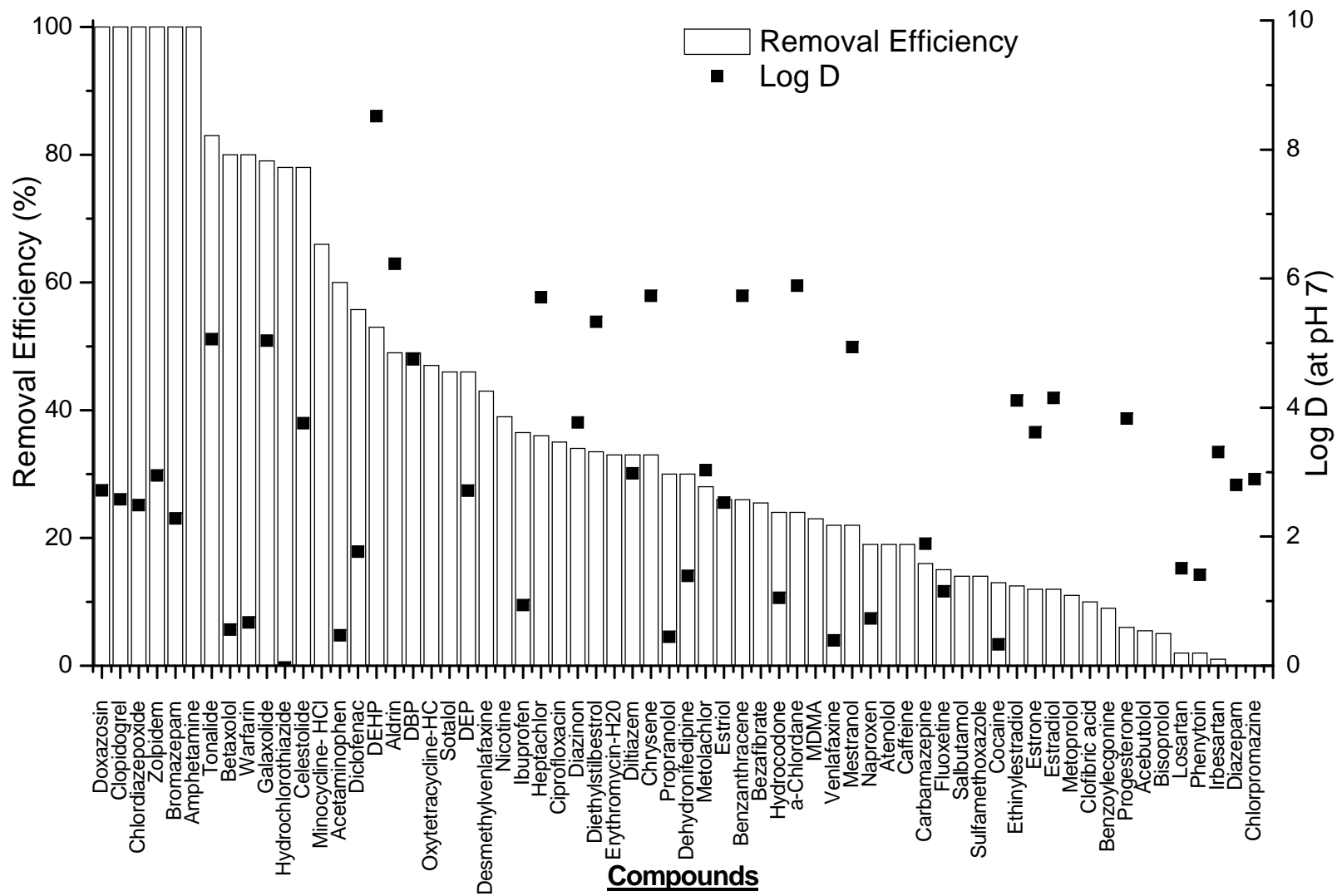


Figure 1

**Table 1:** Toxicological effect of trace organics in water on human and aquatic organisms as reported in selected studies (modified after Pal et al. (2010))

| Compound type            | Compounds causing risks  | Concentration of exposure | Type of risks involved   | Reference                      |
|--------------------------|--|---------------------------|--|--------------------------------|
| Hormone/ steroid         | Ethinylestradiol, zearalonol, 17 $\beta$ trenbolone and melengestrol acetate | < 1-68 ng/ L              | Different levels of hepatic gene expression in freshwater fish fathead minnows.  | (Kolok et al., 2007)           |
| Hormone/ steroid         | 17 $\alpha$ -ethinylestradiol  | 5- 50 ng/ L               | Modulation of brain and inter-renal steroidogenic acute regulatory protein and cytochrome P-450 mediated cholesterol side chain cleavage expressions of juvenile salmon were modulated with time and concentration | (Lyssimachou and Arukwe, 2007) |
| Disinfection by-products | Chloroform, BDCM, dibromochloromethane and bromoform                         | 20-160 $\mu$ g /L         | Reductions in mean birth weight; increases in gestational duration and a reduced risk of preterm delivery of human baby  | (Wright et al., 2004)          |
| Musk fragrances          | Nitro- and polycyclic musks  | 0.09-2.56 $\mu$ M         | Inhibit the activity of multidrug efflux transporters responsible for multixenobiotic resistance (MXR) in gills of the marine mussel <i>Mytilus californianus</i>  | (Luckenbach and Epel, 2005)    |
| Pharmaceutical           | Diclofenac   | 0.5 -50 $\mu$ g/ L        | Affect tissues of gills and kidney of freshwater fish brown trout  | (Hoeger et al., 2005)          |
| Pharmaceutical           | Ibuprofen, diclofenac  | 0.01 $\mu$ g/ L           | Risk to aquatic environment with chronic toxic effect (such as inhibited polyp regeneration and reduced reproduction)  | (Carlsson et al., 2006)        |
| Pharmaceutical           | Mixture of 13 <sup>a</sup> pharmaceuticals                                   | 10 -1000 ng/ L            | Inhibited growth of human embryonic kidney cells HEK293 with the highest effect observed as a 30% decrease in cell proliferation compared to control   | (Pomati et al., 2006)          |
| Pharmaceutical           | Diltiazem, acetaminophen and sulfamethoxazole                                | 8.2 – 271.3 $\mu$ g/ L    | Diltiazem proved to be most toxic with a lethal conc. of 8.2 mg/L for freshwater invertebrate <i>Daphnia magna</i>   | (Kim et al. 2007a)             |
| Pharmaceutical           | Chloramphenicol, florfenicol and thiamphenicol                               | 1.3 – 158 mg/ L           | Inhibited growth of freshwater <i>Chlorella pyrenoidosa</i> and marine <i>Isochrysis galbana</i> and <i>Tetraselmis chui</i>   | (Lai et al., 2009)             |

<sup>a</sup>atenolol, bezafibrate, carbamazepine, cyclophosphamide, ciprofloxacin, furosemide, hydrochlorothiazide, ibuprofen, lincomycin, ofloxacin, ranitidine, salbutamol, and sulfamethoxazole

**Table 2:** Available technologies for trace organics removal from water and wastewater

| Process                         | Advantages  | Disadvantages  | Reference  |
|---------------------------------|---|--|--|
| Chemical coagulation            | An economical conventional treatment process widely used for turbidity and color removal  | Produces large quantity of sludge; the available coagulants were not developed aiming at trace organics removal, therefore, removes only selected groups of trace organics   | (Duan and Gregory, 2003; Huerta-Fontela et al., 2011; Lefebvre et al., 2010; Matilainen et al., 2010; Verma et al., 2012; Vieno, 2007) |
| Electrocoagulation              | Potential of achieving both adsorption and degradation and removal of both soluble and insoluble organics   | Inherent limitations are secondary pollution (from chlorinated organics, heavy metals) and high cost (electricity); compound-specific removal has been reported by the few available references regarding trace organics removal | (Barrera-Díaz et al., 2011; Martins et al., 2011)  |
| Activated carbon adsorption     | Well-established tertiary treatment option; removal of wide variety of trace organics   | Competitive adsorption leads to early breakthrough of several groups of compounds; difficult regeneration and costly disposal of potentially hazardous spent adsorbent   | (Grover et al., 2011; Nguyen et al., 2011; Ternes, 2002)   |
| Nanofiltration/ Reverse osmosis | Good removal of a large range of trace organics via size exclusion and electrostatic repulsion  | A considerable degree of complexity associated with the separation process; production of concentrated sludge; adsorption to membrane surface and subsequent diffusion of the hydrophobic organics through the membrane          | (Alturki et al., 2010; Bellona et al., 2004; Nghiem et al., 2004)  |
| Advanced oxidation processes    | Degradation of various trace organics by generation of a large number of highly reactive free radicals, surpassing the conventional oxidants by far in efficiency | Pretreatment almost always necessary to remove suspended solids, radical scavengers and competing ions; formation of toxic by-products; expensive, and very few full scale plants  | (Belgiorno et al., 2007; Rojas et al., 2011; Tuhkanen and Marinoso, 2010)  |
| Membrane bioreactor (MBR)       | Excellent removal of significantly hydrophobic trace organics in a single-step compact biological process   | Inefficient removal of hydrophilic and persistent trace organics requiring a polishing step  | (Cirja et al., 2008; Li et al., 2011; Tadkaew et al., 2011)  |

**Table 3** Summary of available data regarding trace organics removal by coagulation/flocculation

| Category        | Compound Class    | Compound           | Removal (%) | Coagulant Type  | Coagulant Dose | pH      | Reference                                       |
|-----------------|-------------------|--------------------|-------------|---|----------------|---------|---|
| Pharmaceuticals | Analgesic         | Hydrocodone        | 24          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>                     | 78 mg/L        | 6.8     | (Westerhoff et al., 2005)                       |
|                 | Analgesic         | Acetaminophen      | 60          | FeCl <sub>3</sub>   | 20-45 mg/L     | 4.5-5.5 | (Stackelberg et al., 2007)                      |
|                 | Anti-inflammatory | Diclofenac         | 8-77        | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>                     | 94 mg/L        | 4.5-4.9 | (Vieno et al., 2006; Vieno, 2007)               |
|                 | Anti-inflammatory | Diclofenac         | 11          | FeCl <sub>3</sub>   | 25 mg/L        | 7.9-8.5 | (Suarez et al., 2009; Ternes, 2002)             |
|                 | Anti-inflammatory | Diclofenac         | >65         | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> , FeCl <sub>3</sub> | 50 mg/L        | --      | (Carballa et al., 2005)                         |
|                 | Anti-inflammatory | Diclofenac         | <25         | FeCl <sub>3</sub>   | 0.07 mg/L      | --      | (Zorita et al., 2009)                           |
|                 | Anti-inflammatory | Diclofenac         | 70          | PACl  | 200 mg/L       | --      | (Carballa et al., 2003)                         |
|                 | Anti-inflammatory | Naproxen           | 10          | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>                     | 94 mg/L        | 4.9     | (Vieno, 2007)                                   |
|                 | Anti-inflammatory | Naproxen           | 5           | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>                     | --             | --      | (Boyd, 2003)                                    |
|                 | Anti-inflammatory | Naproxen           | 42          | FeCl <sub>3</sub>   | 25 mg/L        | 7.9-8.5 | (Suarez et al., 2009)                           |
|                 | Anti-inflammatory | Naproxen           | 20          | FeCl <sub>3</sub>   | 50 mg/L        | --      | (Carballa et al., 2005)                         |
|                 | Anti-inflammatory | Naproxen           | <25         | FeCl <sub>3</sub>   | 0.07 mg/L      | --      | (Zorita et al., 2009)                           |
|                 | Anti-inflammatory | Ibuprofen          | 23          | FeCl <sub>3</sub>   | 25 mg/L        | 7.9-8.5 | (Suarez et al., 2009)                           |
|                 | Anti-inflammatory | Ibuprofen          | 50          | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>                     | 140 µmol/L     | 4.5     | (Vieno et al., 2006)                            |
|                 | Anti-inflammatory | Ibuprofen          | <25         | FeCl <sub>3</sub>   | 0.07 mg/L      | --      | (Zorita et al., 2009)                           |
|                 | Antibiotic        | Sulfamethoxazole   | 0-33        | FeCl <sub>3</sub>   | 20-45 mg/L     | 4.5-5.5 | (Stackelberg et al., 2007; Suarez et al., 2009) |
|                 | Antibiotic        | Sulfamethoxazole   | < 10        | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>                     | 140 µmol/L     | 4.5     | (Vieno et al., 2006)                            |
|                 | Antibiotic        | Ciprofloxacin      | 35          | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub>                     | 94 mg/L        | 4.9     | (Vieno, 2007)                                   |
|                 | Antibiotic        | Oxytetracycline-HC | 47          | PACl  | 40 mg/L        | 7.4     | (Choi et al., 2008)                             |



**Table 3** Summary of available data regarding trace organics removal by coagulation/flocculation

| Category        | Compound Class | Compound                           | Removal (%) | Coagulant Type                                  | Coagulant Dose | pH      | Reference                     |
|-----------------|----------------|------------------------------------|-------------|---|----------------|---------|-------------------------------|
| Pharmaceuticals | Antibiotic     | Minocycline- HCl                   | 66          | PACl  | 40 mg/L        | 7.4     | (Choi et al., 2008)           |
|                 | Antibiotic     | DXC                                | 39          | PACl  | 40 mg/L        | 7.4     | (Choi et al., 2008)           |
|                 | Antibiotic     | Meclocycline-sulfosalicylate (MCC) | 57          | PACl  | 40 mg/L        | 7.4     | (Choi et al., 2008)           |
|                 | Antibiotic     | Chlortetracycline (CTC)            | 55          | PACl  | 40 mg/L        | 7.4     | (Choi et al., 2008)           |
|                 | Antibiotic     | Democlocycline-HCl (DMC)           | 65          | PACl  | 40 mg/L        | 7.4     | (Choi et al., 2008)           |
|                 | Antibiotic     | Tetracycline (TC)                  | 49          | PACl  | 40 mg/L        | 7.4     | (Choi et al., 2008)           |
|                 | Antibiotic     | Trivofloxacin mesylate             | 0           | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 25 mg/L        | 8       | (Bundy, 2007)                 |
|                 | Antibiotic     | Erythromycin-H2O                   | 33          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 78 mg/L        | 6.8     | (Westerhoff et al., 2005)     |
|                 | Beta-blocker   | Doxazosin                          | 100         | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011) |
|                 | Beta-blocker   | Betaxolol                          | 80          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011) |
|                 | Beta-blocker   | Sotalol                            | 46          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011) |
|                 | Beta-blocker   | Propranolol                        | 30          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011) |
|                 | Beta-blocker   | Bisoprolol                         | 5           | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011) |
|                 | Beta-blocker   | Atenolol                           | 19          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011) |
|                 | Beta-blocker   | Acebutolol                         | 3           | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011) |
|                 | Beta-blocker   | Acebutolol                         | 8           | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 94 mg/L        | 4.9     | (Vieno, 2007)                 |
|                 | Beta-blocker   | Metoprolol                         | 11          | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 94 mg/L        | 4.9     | (Vieno, 2007)                 |

**Table 3** Summary of available data regarding trace organics removal by coagulation/flocculation

| Category        | Compound Class | Compound             | Removal (%) | Coagulant Type                                  | Coagulant Dose | pH      | Reference                           |
|-----------------|----------------|----------------------|-------------|---|----------------|---------|-------------------------------------|
| Pharmaceuticals | Cardiac        | Clopidogrel          | 100         | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)       |
|                 | Cardiac        | Hydrochlorothiazide  | 78          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)       |
|                 | Cardiac        | Diltiazem            | 33          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)       |
|                 | Cardiac        | Warfarin             | 80          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)       |
|                 | Cardiac        | Dehydronifedipine    | 30          | FeCl <sub>3</sub>                               | 20-45 mg/L     | 4.5-5.5 | (Stackelberg et al., 2007)          |
|                 | Psychiatric    | Chlordiazepoxide     | 100         | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)       |
|                 | Psychiatric    | Zolpidem             | 100         | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)       |
|                 | Psychiatric    | Bromazepam           | 100         | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)       |
|                 | Psychiatric    | Venlafaxine          | 22          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)       |
|                 | Psychiatric    | Phenytoin            | 2           | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)       |
|                 | Psychiatric    | Diazepam             | 0           | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)       |
|                 | Psychiatric    | Diazepam             | 0           | FeCl <sub>3</sub>                               | 25 mg/L        | 7.9-8.5 | (Suarez et al., 2009)               |
|                 | Psychiatric    | Desmethylvenlafaxine | 43          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)       |
|                 | Psychiatric    | Chlorpromazine       | 0           | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)       |
|                 | Psychiatric    | Carbamazepine        | 15          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)       |
|                 | Psychiatric    | Carbamazepine        | 30          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)       |
|                 | Psychiatric    | Carbamazepine        | 7           | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 94 mg/L        | 4.5-4.9 | (Vieno et al., 2006; Vieno, 2007)   |
|                 | Psychiatric    | Carbamazepine        | 12          | FeCl <sub>3</sub>                               | 25 mg/L        | 7-8.5   | (Suarez et al., 2009; Ternes, 2002) |

**Table 3** Summary of available data regarding trace organics removal by coagulation/flocculation

| Category        | Compound Class      | Compound        | Removal (%) | Coagulant Type                                  | Coagulant Dose | pH      | Reference  |
|-----------------|---------------------|-----------------|-------------|---|----------------|---------|--|
|                 | Psychiatric         | Fluoxetine      | 15          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 78 mg/L        | 6.8     | (Westerhoff et al., 2005)                                    |
|                 | Stimulant           | Caffeine        | 0-38        | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 25-78 mg/L     | 6.8-8   | (Bundy, 2007; Huerta-Fontela, 2008; Westerhoff et al., 2005) |
|                 | Stimulant           | Cocaine         | 13          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | --      | (Huerta-Fontela, 2008)                                       |
| Pharmaceuticals | Stimulant           | Benzoylcegonine | 9           | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | --      | (Huerta-Fontela, 2008)                                       |
|                 | Stimulant           | Amphetamine     | 100         | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | --      | (Huerta-Fontela, 2008)                                       |
|                 | Stimulant           | MDMA            | 23          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | --      | (Huerta-Fontela, 2008)                                       |
|                 | Stimulant           | Nicotine        | 39          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | --      | (Huerta-Fontela, 2008)                                       |
|                 | Pulmonary drug      | Losartan        | 2           | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)                                |
|                 | Pulmonary drug      | Irbesartan      | 1           | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)                                |
|                 | Pulmonary drug      | Salbutamol      | 14          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | --             | 7.4-8.5 | (Huerta-Fontela et al., 2011)                                |
|                 | Hypolipidemic agent | Bezafibrate     | 15          | FeCl <sub>3</sub>                               | 40 mg/L        | 7.5     | (Ternes, 2002)   |
|                 | Hypolipidemic agent | Bezafibrate     | 36          | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 140 μmol/L     | 4.5     | (Vieno et al., 2006)   |
|                 |                     | Tonalide        | 83          | FeCl <sub>3</sub>                               | 25 mg/L        | 7.9-8.5 | (Suarez et al., 2009)  |

**Table 3** Summary of available data regarding trace organics removal by coagulation/flocculation

| Category        | Compound Class | Compound         | Removal (%) | Coagulant Type                                  | Coagulant Dose | pH                         | Reference                              |
|-----------------|----------------|------------------|-------------|---|----------------|----------------------------|--|
| Musk fragrances |                | Tonalide         | 71          | PACl  | 17.5 % w/w     | --                         | (Carballa et al., 2005)                |
|                 |                | Tonalide         | 70          | PACl  | 200 mg/L       | --                         | Carballa, Omil et al. 2003)            |
|                 |                | Tonalide         | 90          | FeCl <sub>3</sub>                               | 75 mg/L        | --                         | (Serrano et al., 2010)                 |
|                 |                | Galaxolide       | 79          | FeCl <sub>3</sub>                               | 25 mg/L        | 7.9-8.5                    | (Suarez et al., 2009)                  |
|                 |                | Galaxolide       | 63          | PACl  | 17.5 % w/w     | --                         | (Carballa et al., 2005)                |
| Musk fragrances |                | Galaxolide       | 65          | PACl  | 200 mg/L       | --                         | (Carballa et al., 2003)                |
|                 |                | Galaxolide       | 90          | FeCl <sub>3</sub>                               | 75 mg/L        | --                         | (Serrano et al., 2010)                 |
|                 |                | Celestolide      | 78          | FeCl <sub>3</sub>                               | 25 mg/L        | 7.9-8.5                    | (Suarez et al., 2009)                  |
| Hormone         | Estrogen       | Estrone          | 12          | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 12.2 mg/L      | 6.8-7.2                    | (Bodzek and Dudziak, 2006)             |
|                 | Estrogen       | Estrone          | 18          | PACl  | 5.4 mg/L       | 6.8-7.2                    | (Bodzek and Dudziak, 2006)             |
|                 | Estrogen       | Estrone          | 5           | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 78 mg/L        | 6.8                        | (Westerhoff et al., 2005)              |
|                 | Estrogen       | Estradiol        | 17          | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 12.2 mg/L      | 6.8-7.2                    | (Bodzek and Dudziak, 2006)             |
|                 | Estrogen       | Estradiol        | 16          | PACl  | 5.4 mg/L       | 6.8-7.2                    | (Bodzek and Dudziak, 2006)             |
|                 | Estrogen       | Estradiol        | 0-2         | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 25-78 mg/L     | 6.8-8                      | (Bundy, 2007; Westerhoff et al., 2005) |
|                 | Estrogen       | Estriol          | 21          | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 12.2 mg/L      | 6.8-7.2                    | (Bodzek and Dudziak, 2006)             |
|                 | Estrogen       | Estriol          | 31          | PACl  | 5.4 mg/L       | 6.8-7.2                    | (Bodzek and Dudziak, 2006)             |
|                 | Estrogen       | Ethinylestradiol | 4           | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 12.2 mg/L      | 6.8-7.2                    | (Bodzek and Dudziak, 2006)             |
|                 | Estrogen       | Ethinylestradiol | 21          | PACl  | 5.4 mg/L       | 6.8-7.2                    | (Bodzek and Dudziak, 2006)             |
|                 | Estrogen       | Mestranol        | 10          | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 12.2 mg/L      | 6.8-7.2                    | (Bodzek and Dudziak, 2006)             |
| Estrogen        | Mestranol      | 34               | PACl        | 5.4 mg/L  | 6.8-7.2        | (Bodzek and Dudziak, 2006) |  |

**Table 3** Summary of available data regarding trace organics removal by coagulation/flocculation

| Category                              | Compound Class | Compound           | Removal (%) | Coagulant Type                                  | Coagulant Dose | pH      | Reference                  |
|---------------------------------------|----------------|--------------------|-------------|---|----------------|---------|----------------------------|
|                                       | Estrogen       | Diethylstilbestrol | 27          | Fe <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 12.2 mg/L      | 6.8-7.2 | (Bodzek and Dudziak, 2006) |
|                                       | Estrogen       | Diethylstilbestrol | 40          | PACl  | 5.4 mg/L       | 6.8-7.2 | (Bodzek and Dudziak, 2006) |
|                                       | Progesterone   | Progestogen        | 6           | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 78 mg/L        | 6.8     | (Westerhoff et al., 2005)  |
| Pesticide                             | Herbicide      | Metolachlor        | 28          | FeCl <sub>3</sub>                               | 20-45mg/L      | 4.5-5.5 | (Stackelberg et al., 2007) |
|                                       | Herbicide      | Clofibric acid     | 10          | FeCl <sub>3</sub>                               | 40 mg/L        | 7.5     | (Ternes, 2002)             |
|                                       | Insecticide    | Diazinon           | 34          | FeCl <sub>3</sub>                               | 20-45mg/L      | 4.5-5.5 | (Stackelberg et al., 2007) |
|                                       | Insecticide    | Heptachlor         | 36          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 78 mg/L        | 6.8     | (Westerhoff et al., 2005)  |
| Pesticide                             | Insecticide    | Aldrin             | 49          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 78 mg/L        | 6.8     | (Westerhoff et al., 2005)  |
|                                       | Pesticide      | a-Chlordane        | 24          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 78 mg/L        | 6.8     | (Westerhoff et al., 2005)  |
| Polycyclic Aromatic Hydrocarbon (PAH) |                | Chrysene           | 33          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 78 mg/L        | 6.8     | (Westerhoff et al., 2005)  |
|                                       |                | Benanthracene      | 26          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 78 mg/L        | 6.8     | (Westerhoff et al., 2005)  |
| Phthalate plasticizer                 |                | DEHP               | 53          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 50 mg/L        | 8.2-8.5 | (Choi, 2006)               |
|                                       |                | DBP                | 49          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 50 mg/L        | 8.2-8.5 | (Choi, 2006)               |
|                                       |                | DEP                | 46          | Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> | 50 mg/L        | 8.2-8.5 | (Choi, 2006)               |



**Table 4:** Average removal efficiency according to trace organic compound class

| Category                                     | Compound Class               | Average Removal (%) | Standard Deviation | N  | Compounds showing over 50 % removal in this category                   | Reference   |
|--|------------------------------|---------------------|--------------------|----|--|---|
| <b>Pharmaceuticals</b>                       | Analgesic/ Anti-inflammatory | 35                  | 23                 | 15 | Acetaminophen, diclofenac  | (Boyd, 2003; Stackelberg et al., 2007; Suarez et al., 2009; Ternes, 2002; Vieno et al., 2006; Vieno, 2007; Westerhoff et al., 2005) |
|  | Antibiotic                   | 39                  | 22                 | 12 | Minocycline-HCl, meclocycline-sulfosalicylate, CTC, democlocycline-HCl | (Choi et al., 2008; Stackelberg et al., 2007; Suarez et al., 2009; Vieno et al., 2006; Vieno, 2007; Westerhoff et al., 2005)        |
|  | Beta-blocker                 | 34                  | 25                 | 9  | Doxazosin, betaxolol   | (Huerta-Fontela et al., 2011; Vieno, 2007)  |
|  | Cardiac                      | 64                  | 24                 | 5  | Clopidogrel, hydrochlorothiazide, warfarin                             | (Huerta-Fontela et al., 2011; Stackelberg et al., 2007)   |
|  | Psychiatric                  | 32                  | 39                 | 14 | Chlordiazepoxide, zolpidem, bromazepam                                 | (Huerta-Fontela et al., 2011; Suarez et al., 2009; Ternes, 2002; Vieno et al., 2006; Vieno, 2007; Westerhoff et al., 2005)          |
|  | Stimulant                    | 34                  | 34                 | 6  | Amphetamine  | (Bundy, 2007; Huerta-Fontela, 2008; Westerhoff et al., 2005)  |
|  | Pulmonary drug               | 6                   | 7                  | 3  | --   | (Huerta-Fontela et al., 2011)   |
|  | Hypolipidemic agent          | 26                  | 15                 | 2  | --   | (Ternes, 2002; Vieno et al., 2006)  |
| <b>Musk fragrance</b>                        |                              | <b>77</b>           | <b>10</b>          | 9  | Tonalide, galaxolide, celestolide                                      | (Suarez et al., 2009)   |
| <b>Hormone</b>                               |                              | 19                  | 12                 | 15 | --   | (Bodzek and Dudziak, 2006; Boyd, 2003; Westerhoff et al., 2005)   |
| <b>Pesticide</b>                             |                              | 30                  | 13                 | 6  | --   | (Stackelberg et al., 2007; Ternes, 2002; Westerhoff et al., 2005)   |
| <b>Polycyclic Aromatic Hydrocarbon (PAH)</b> |                              | 30                  | 5                  | 2  | --   | (Westerhoff et al., 2005)   |
| <b>Phthalate plasticizers</b>                |                              | 49                  | 4                  | 3  | DEHP   | (Choi, 2006)  |

Jonathan T. Alexander, Faisal I. Hai, Turki M. Al-aboud. Chemical coagulation-based processes for trace organic contaminant removal: Current state and future potential *Journal of Environmental Management*, Volume 111, 30 November 2012, Pages 195–207. <http://dx.doi.org/10.1016/j.jenvman.2012.07.023>