Application of air stripping to powdered activated carbon adsorption of geosmin and 2-methylisoborneol

Sang-Min Park, Tae-Young Heo, Noh-Back Park, Kwang-Ju Na, Hang-Bae Jun and Jin-Young Jung

ABSTRACT

Removal of odor-causing compounds (OCCs) including geosmin and 2-methylisoborneol (2-MIB), well known to cause the musty and earthy odor in drinking water, was investigated using powdered activated carbon (PAC) adsorption and air stripping processes. Removal by air stripping was mainly affected by aeration flow rates with volumetric mass-transfer rates of 0.002–$0.005\,\text{min}^{-1}$. Aeration also proved efficient for marginal removal of geosmin and 2-MIB in conjunction with PAC adsorption. Removal efficiencies increased depending on both PAC dose and aeration time in the aerated PAC contactor. PAC adsorption with aeration reduced the required PAC dose and contact time for removal of these compounds, compared with PAC adsorption alone. Removal efficiency of geosmin above 93% was improved by simultaneous PAC adsorption and air stripping under the same conditions. 2-MIB was relatively less amenable to removal and removal efficiency was about 58% by PAC adsorption at a dose of $15\,\text{mg}\,\text{l}^{-1}$, 14% by air stripping at aeration flow rate of $15\,\text{l}\,\text{min}^{-1}$ with 60 min aeration and 74% by simultaneous PAC adsorption and air stripping, respectively. Aeration flow rate, contact time and PAC dose were the critical factors in PAC adsorption with aeration for OCC removal and optimum conditions are suggested.

Key words | air stripping, geosmin, odor causing compounds, PAC adsorption, 2-methylisoborneol

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NOMENCLATURE

a	Interfacial area for mass transfer per unit volume ($\text{m}^2\,\text{m}^{-3}$)
C	Bulk average solute concentration in the liquid ($\text{ng}\,\text{l}^{-1}$)
C_t	Concentration in liquid bulk phase at time t ($\text{ng}\,\text{l}^{-1}$)
C_0	Initial concentration ($\text{ng}\,\text{l}^{-1}$)
k_H	Henry's law constant
$K_\text{L}a$	Volumetric mass transfer coefficient ($1\,\text{min}^{-1}$)
k_G	Gas-phase mass transfer coefficient ($\text{m}\,\text{min}^{-1}$)
k_L	Liquid-phase mass transfer coefficient ($\text{m}\,\text{min}^{-1}$)
r_voc	Rate of mass transfer ($\text{ng}\,\text{l}^{-1}\,\text{min}^{-1}$)

ρ	Correlation coefficient
α	Parameter in nonlinear regression model

INTRODUCTION

Odor causing compounds (OCCs) contained in surface water sources result from algal blooms and cause operational difficulties in water treatment plants as well as aesthetic problems in drinking water. These problems generally occur after the rainy season between June and October in Korea. Typically, geosmin and 2-MIB have been the major OCCs found in water treatment plants and

their maximum concentration in source water reached 89 ng/L and 36 ng/L, respectively, during the last decade (Lim *et al.* 2007).

Powdered activated carbon (PAC) has been primarily used for treatment of OCCs and other trace organic pollutants in water treatment plants. The performance of the PAC contactor typically depends upon the kind of PAC, PAC dose, location of PAC addition, contact time and the presence of competing chemicals and oxidants. Ho & Newcombe (2005) also reported both high turbidity and higher alum dose might decrease the adsorption of 2-MIB. The inhibitory effect of natural organic matter (NOM) on the adsorption of OCCs in natural water has been well demonstrated by many researchers. NOM was found to have a great influence on the adsorption of OCCs, and especially low molecular weight NOMs were the major competitive compounds with OCCs (Newcombe *et al.* 2002a,b; Hepplewhite *et al.* 2004; Ho & Newcombe 2005).

PAC is usually added at the rapid mixing step in water treatment processes, however, this may reduce the rate of PAC adsorption by the blockage mechanisms of coagulant flocs. Cook *et al.* (2001) conducted experiments of geosmin and 2-MIB adsorption to predict PAC dose in four water sources and found high turbidity and NOM led to reduction of PAC adsorption capacity for OCCs. The PAC contactor is often configured prior to the rapid mixing tank to maximize the PAC adsorption capacity without inhibition of other chemicals such as chlorine, lime and coagulants. Kim & Bae (2007) suggested a baffled-channel PAC contactor to provide optimum velocity gradient through the channel without hydraulic short circuiting. They found OCC removal improved with increase in number of baffles, PAC dose and contact time. Therefore, the aeration system can be considered an alternative mixing method in a PAC contactor. Aeration can provide the PAC contactor with complete mixing and effective contact between adsorbent and the targeted pollutants. Aeration can increase mass transfer rate of the pollutants and also help the flexible design of the PAC contactor in a water treatment plant. Furthermore, removal of some OCCs may also be expected during the aeration period by air stripping, if OCCs have high Henry's law constants (k_H). Benzene (k_H: 0.23) and toluene (k_H: 0.27, Bielefeldt & Stensel 1999) having Henry's law constants greater than 0.20 are readily removed by stripping, while NH_3 (k_H: 0.00056, at 20°C) and SO_2 (k_H: 0.027) are marginally strippable (Metcalf & Eddy 2004). Geosmin and 2-MIB are known to be semi-volatile compounds whose dimensionless Henry's constants are 0.0028 and 0.0024 (or 6.66×10^{-5} and $5.76 \times 10^{-5} \, m^3 \, atm \, mol^{-1}$), respectively (Lalezary *et al.* 1984). Therefore, marginal removal of these OCCs may be expected during the aeration period in a PAC contactor.

In this paper, removal efficiencies of OCCs, especially geosmin and 2-MIB, were investigated by PAC adsorption with aeration in a water treatment process. The removal efficiencies of OCCs were compared between PAC adsorption, air stripping and a combination of both processes and the relationship of these processes was evaluated through nonlinear regression methods at different PAC doses and aeration flow rates.

MATERIAL AND METHODS

Water samples

Lake water and synthetic water samples were used for OCC removal experiments. Lake water samples were taken from the intake reservoir at a local water treatment plant during the outbreak of algal bloom when geosmin concentration was at maximum level throughout the year. Average concentration of geosmin in lake water samples was $8.9 \, ng \, l^{-1}$ as shown in Table 1. Turbidity of lake water was about 3.0 NTU and pH was in the range of 7.0–8.0. In the case of synthetic water samples, the concentration of geosmin and 2-MIB was adjusted to about 50 ng l by directly adding the undiluted standard solution (mixture of each 0.1 mg of geosmin and 2-MIB per 1.0 ml, Supelco Inc., USA)

Table 1 │ Characteristics of the raw water sample

Sample	Geosmin (ng l⁻¹)	2-MIB (ng l⁻¹)	DOC (mg l⁻¹)	UV₂₅₄ (cm⁻¹)	pH
Lake water	8.9	6.1	1.891	0.0594	7.3
Synthetic water	54.5	54.9	2.072	0.0534	7.0

to lake water. Table 1 shows other measured parameters of raw water samples used for experiments.

Air stripping

The aeration apparatus consisted of a cylindrical flexi glass column (working volume: 20 l, height: 1,750 mm, diameter: 130 mm) equipped with an air supplying device at the bottom. Compressed air was introduced through the porous diffuser into the bottom of the columns where head space opened to the atmosphere to prevent accumulation of OCCs in the air above the water surface of the column. Aeration flow rate was controlled in the range of 5–$20\,l\,min^{-1}$ using a gas flow-meter. After raw water had been equilibrated to an ambient temperature around $20 \pm 1°C$ for 24 hr, a standard solution of geosmin and 2-MIB was directly spiked to the synthetic water samples in the columns. During the 60 min aeration, samples were taken at regular intervals (15 min) and then were filtered through a $0.45\,\mu m$ membrane filter (cellulose acetate, Millipore HA, USA) for analyses. Geosmin and 2-MIB were monitored to evaluate the volumetric mass transfer coefficient ($K_L a$) and their removal efficiency.

PAC adsorption

A standard jar test apparatus and square jars (Phipps & Bird Co., USA) were used for PAC adsorption tests. Each jar was filled with 2 l of the raw or synthetic water and jar tests were conducted at room temperature ($20 \pm 1°C$). A domestic coconut-based PAC (Samchully Co., Korea) was used after passing it through a sieve #200 (0.075 mm) and its iodine number was $1,115\,mg\,g^{-1}$. PAC was added to the doses of 5, 10, 15, 25 and $30\,mg\,l^{-1}$, and the mixture was gently agitated at 15 rpm for 60 min to prevent settling of PAC and the possible losses of geosmin and 2-MIB by stripping. During the adsorption experiment, samples were periodically taken and were filtered through a membrane filter for analyses.

PAC adsorption with aeration

The same experimental apparatus as for air stripping was used for the combination of PAC adsorption and air stripping. Air was supplied through a diffuser equipped at the bottom of the column and the average bubble size was about 2 mm in diameter. PAC was added to the column before starting the aeration, then aeration flow rate was maintained at $15\,l\,min^{-1}$. Samples for analyses were taken 30 and 60 min after spiking OCCs. One column was aerated without PAC addition, as a control, to evaluate and compare the OCC removal efficiencies by air stripping alone.

Analysis

Geosmin and 2-MIB were measured by gas chromatograph/mass spectrometry (Agilent 6890N GC/5973N MS, Hewlett Packard, USA) equipped with a solid-phase micro-extraction (SPME) apparatus to concentrate them up to the detection limit and GC column (HP-5MS, 30 m length, $250\,\mu m$ ID, and $0.25\,\mu m$ film depth). Dissolved organic carbon (DOC) in raw water was measured by total organic carbon (TOC) analyzer (Phoenix 8000, Dohrmann, USA). UV_{254} absorbance and other parameters were measured according to standard methods (APHA AWWA & WEF 1998).

RESULTS AND DISCUSSION

Volumetric mass transfer coefficient of geosmin and 2-MIB

OCCs, geosmin and 2-MIB, were found to be removed from synthetic water by air stripping, however, their removal efficiencies were as low as 8–22% as shown in Figure 1. Removal of these OCCs by air stripping might be affected by air flow rate and aeration time, which could explain why the effective contact of air bubbles with micro-pollutants played an important role to transfer them between liquid- and gas-phases. Therefore, the efficient mixing depending on physical conditions would be essential factors for mass transfer in the air stripping process. The mass transfer rate of geosmin and 2-MIB can be modeled by the following first order equation typically used for the mass transfer rate of volatile organic compounds (VOCs) (Roberts & Dänkliker 1983).

$$r_{voc} = \frac{dC}{dt} = -K_L a \cdot C \tag{1}$$
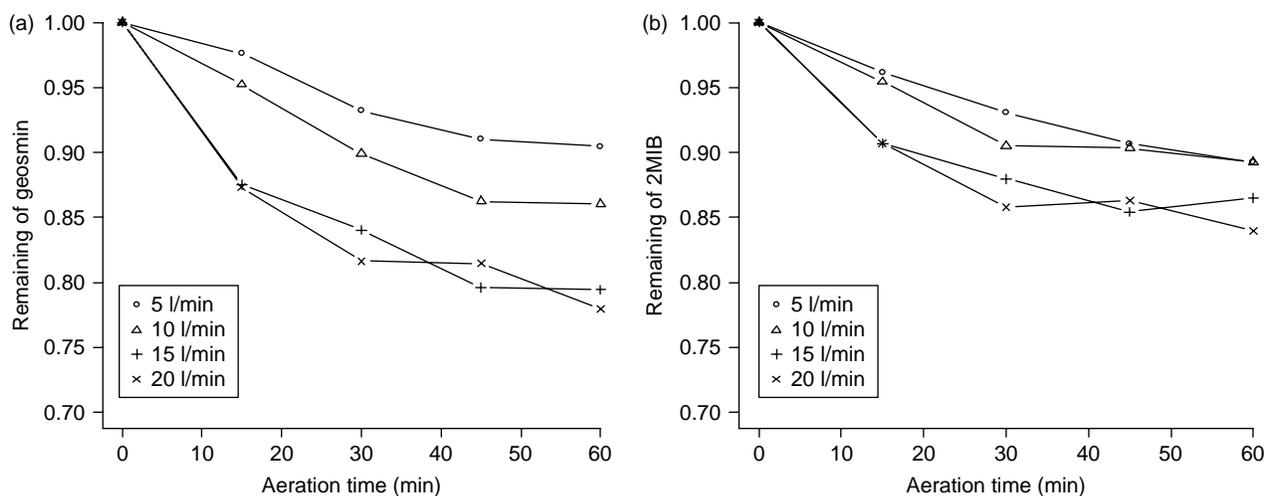
Figure 1 │ Remaining geosmin (a) and 2MIB (b) as a function of aeration time at different aeration flow rate with synthetic water samples.

where r_{voc} is rate of mass transfer $(ng\,l^{-1}\,min^{-1})$, C is bulk average solute concentration in the liquid $(ng\,l^{-1})$ and $K_L a$ is volumetric mass transfer coefficient $(1\,m^{-1})$. $K_L a$ in Equation (1) may be influenced by both liquid- and gas-phase resistances as follows:

$$\frac{1}{K_L a} = \frac{1}{k_L a} + \frac{1}{k_H \cdot k_G a} \tag{2}$$

where K_L and a is overall liquid mass transfer coefficient and interfacial area for mass transfer per unit volume. Terms k_L and k_G are liquid- and gas-phase mass transfer coefficient $(m\,min^{-1})$, respectively. The term k_H is Henry's law constant. In Equation (2), the liquid phase controls the mass transfer rate for compounds with k_H values greater than 0.05, while the gas phase controls it for compounds with k_H values less than 0.002 (Crittenden *et al.* 2005). The k_H values for geosmin and 2-MIB are 0.0028 and 0.0024, respectively. Therefore, both liquid- and gas-phase resistance may control the rate of mass transfer of geosmin and 2-MIB. The integrated form of Equation (1) can be summarized as follows:

$$\frac{C_t}{C_0} = \exp(-K_L a \cdot t) \tag{3}$$

where C_0 and C_t denote initial concentration $(ng\,l^{-1})$ and concentration in the liquid bulk phase at time t (min), respectively. The $K_L a$ value can be estimated from the experimental data, by air stripping of both geosmin and 2-MIB.

The remaining geosmin and 2-MIB as a function of time at different aeration flow rate in synthetic water samples are shown in Figure 1. For both geosmin and 2-MIB, removal efficiencies improved with increase in aeration flow rate, which might result from increase in physical turbulence and surface area of the air–water interface. However, the removal rate of these OCCs slightly declined after 30 minutes. Geosmin removal by air stripping was more effective than 2-MIB under the same operational conditions.
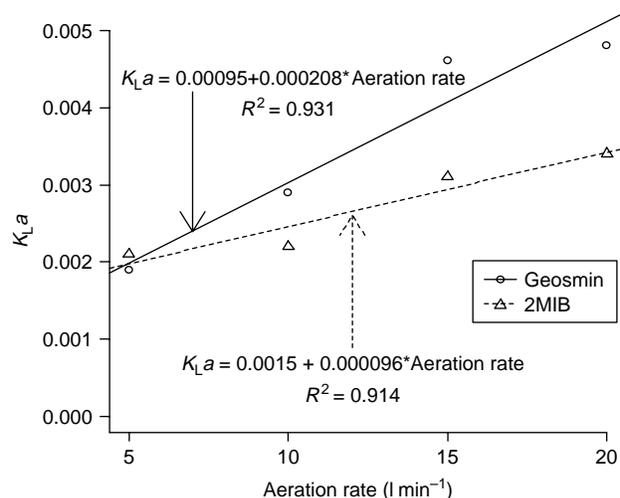
In order to show the effect of aeration flow rate, nonlinear regression on aeration time at different aeration flow rates was conducted. Table 2 shows the results of the nonlinear regression on geosmin and 2-MIB removal. The range of correlation coefficients (ρ) between observed values and predicted values from the nonlinear regression model was found to be very high. Increase in 'estimates' of each aeration rate on geosmin and 2-MIB in Table 2 is directly related to improvement in removal efficiency of geosmin and 2-MIB. These results shows the effect of aeration flow rate on OCC removal increased as aeration flow rate increased. The 'estimates' of aeration flow rate on geosmin in Table 2 increased rapidly at aeration flow rate up to $15\,l\,min^{-1}$, while those values showed a relatively slow increase between 15 and $20\,l\,min^{-1}$. The 'estimates' of aeration flow rate on 2-MIB gradually increased in all ranges of aeration flow rates. Removal efficiency of geosmin was much larger than that of 2-MIB with increase in

Table 2 | Nonlinear regression outputs for geosmin and 2-MIB by air stripping

Aeration flow rate	Estimates	Standard error	t-value	P-value	ρ
Geosmin:					
$5\,l\,min^{-1}$	0.001893	0.000132	14.36	0.000137	0.9731
$10\,l\,min^{-1}$	0.002928	0.000212	13.31	0.000183	0.9710
$15\,l\,min^{-1}$	0.004743	0.000585	8.112	0.00126	0.9168
$20\,l\,min^{-1}$	0.004898	0.000631	7.757	0.00149	0.9249
2-MIB:					
$5\,l\,min^{-1}$	0.002076	0.000105	19.76	<0.0001	0.9886
$10\,l\,min^{-1}$	0.002255	0.000252	8.96	0.000866	0.9348
$15\,l\,min^{-1}$	0.003183	0.000487	6.54	0.00283	0.8826
$20\,l\,min^{-1}$	0.003494	0.000484	7.224	0.00195	0.9040

Figure 2 | Dependence of volumetric mass transfer coefficient on aeration flow rate.

aeration flow rate during the aeration of 60 min. Since 'estimates' at aeration flow rate of $15\,l\,min^{-1}$ on geosmin and 2-MIB were about 0.004 743 and 0.003 183 min^{-1} (*P*-value < 0.05), aeration flow rate is statistically significant at 5% significant level. Therefore, aeration flow rate is a crucial factor to remove geosmin and 2-MIB from the raw water by air stripping, as shown in Table 2.

Roberts & Dänkliker (1983) showed that the K_La value depended significantly on the power input to the reactor. Velocity gradient also increased at higher aeration rate (Metcalf & Eddy 2004). Similarly, higher aeration flow rate in this study could match higher power input in Roberts' research and also supplied more surface area at the air–water interface, which was followed by more effective contact of air bubbles with micro-pollutants. Accordingly, volumetric mass transfer coefficient, K_La, depends significantly upon the aeration rate as shown in Figure 2. K_La values and aeration flow rate may be related; for geosmin $0.95 \times 10^{-3} + 2.08 \times 10^{-4} \times$ (aeration flow rate) with R^2 of 0.931. Removal efficiencies of OCCs also improved with increase in the ratio of the supplied air volume to unit volume of reactor ($l\,l^{-1}$), corresponding to each aeration flow rate. The removal portion of geosmin at ratios above $15\,l\,l^{-1}$ was larger than that of 2-MIB, as shown in Figure 3. This results were consistent with the results from nonlinear regression, which 'Estimates' a value for geosmin, which was higher than 2-MIB, as shown in Table 2. Removal efficiency of geosmin at air volume to reactor volume ratio of $60\,l\,l^{-1}$ (corresponding to 60 min aeration at a flow rate

of $20\,l\,min^{-1}$) was about 22%, while that of 2-MIB was as relatively low as 16% (Figure 3).

PAC adsorption of geosmin and 2-MIB

Based on the adsorption isotherm result showing *n* values in the range of 0.8–2.0, geosmin and 2-MIB were readily adsorbed on PAC in both lake water and synthetic water samples. Figure 4(a) shows the removal of geosmin and 2-MIB by adsorption from raw water as a function of PAC dose. The average concentrations of geosmin and 2-MIB were 8.9 and 6.1 $ng\,l^{-1}$, respectively, in raw water samples taken during the recent outbreak of odor problem.
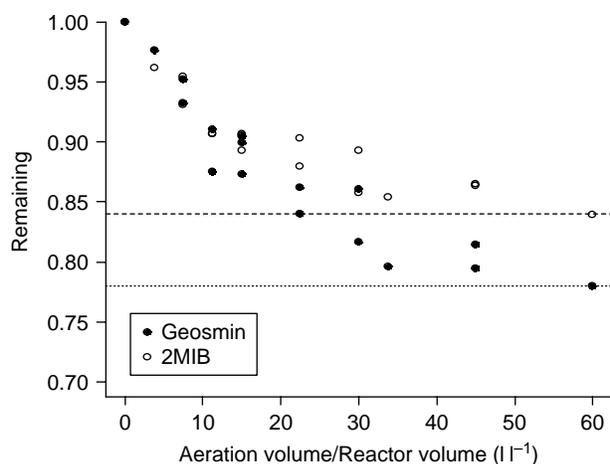
Figure 3 | Geosmin and 2-MIB remaining as a function of total aeration volume with synthetic water samples. Dashed line: 2-MIB; dotted line: geosmin.

At a PAC dose of $20\,\mathrm{mg\,l^{-1}}$, 85% and 70% of geosmin and 2-MIB could be removed by PAC adsorption within 60 min, respectively. They were considerably higher than the removal efficiencies of air stripping only. Removal of geosmin and 2-MIB by PAC adsorption from synthetic water samples whose initial concentrations were about 47.2 and $46.8\,\mathrm{ng\,l^{-1}}$ respectively, were also investigated at different doses as shown in Figure 4(b). Up to a PAC dose of $10\,\mathrm{mg\,l^{-1}}$, removal efficiencies of OCCs increased rapidly, however, their removal rates decreased slightly at a PAC dose over $15\,\mathrm{mg\,l^{-1}}$. At a PAC dose of $20\,\mathrm{mg\,l^{-1}}$, removal efficiencies of geosmin and 2-MIB can be achieved up to 81 and 66% within 60 min, respectively. This difference in removal efficiencies of OCCs, irrespective of initial concentrations, might be due to adsorption capacity on PAC. These results are comparable with the PAC doses and contact time for removal of geosmin and 2-MIB reported by Cook *et al.* (2001). They explained this difference in the adsorption of the two compounds as possibly due to the difference in their structure, solubility and molecular weight. In this study, geosmin is more amenable to adsorption on PAC than 2-MIB, similar to the results from the air stripping process. Besides the competitive effects by NOM, factors affecting the effectiveness of PAC adsorption including carbon type, initial adsorbates concentration and contact time have been focused on the optimization of OCC

removal by several researchers (Lalezary *et al.* 1986; Gillogly *et al.* 1999; Graham *et al.* 2000). They concluded that geosmin and 2-MIB were independent of the initial concentration in PAC adsorption but significantly dependent on PAC dose. Comparing the removal trends between synthetic and lake water samples, geosmin and 2-MIB were independent of initial concentrations, on the basis of percent age removal as shown Figure 4. However, they were considerably dependent on PAC dose.

There has been little research on how the combination of PAC adsorption with air stripping, affects OCC removal. Therefore, removal characteristics of geosmin and 2-MIB removal were also investigated in an aerated PAC contactor in this study.

PAC adsorption and air stripping of Geosmin and 2-MIB

Figure 5 shows the removal of geosmin and 2-MIB by PAC adsorption only, within 60 min and by a combination of air stripping with PAC adsorption at different aeration times of 30 and 60 min. 'PAC' in Figure 5 gives the same results from performance of PAC adsorption for 60 min without aeration as described previously. $30\,\mathrm{mg\,l^{-1}}$ of PAC was required for geosmin removal to the level below $5-10\,\mathrm{ng\,l^{-1}}$, which was the threshold concentration for aqueous odor reported by Whelton & Dietrich (2004). However, 15 mg/L of PAC dose
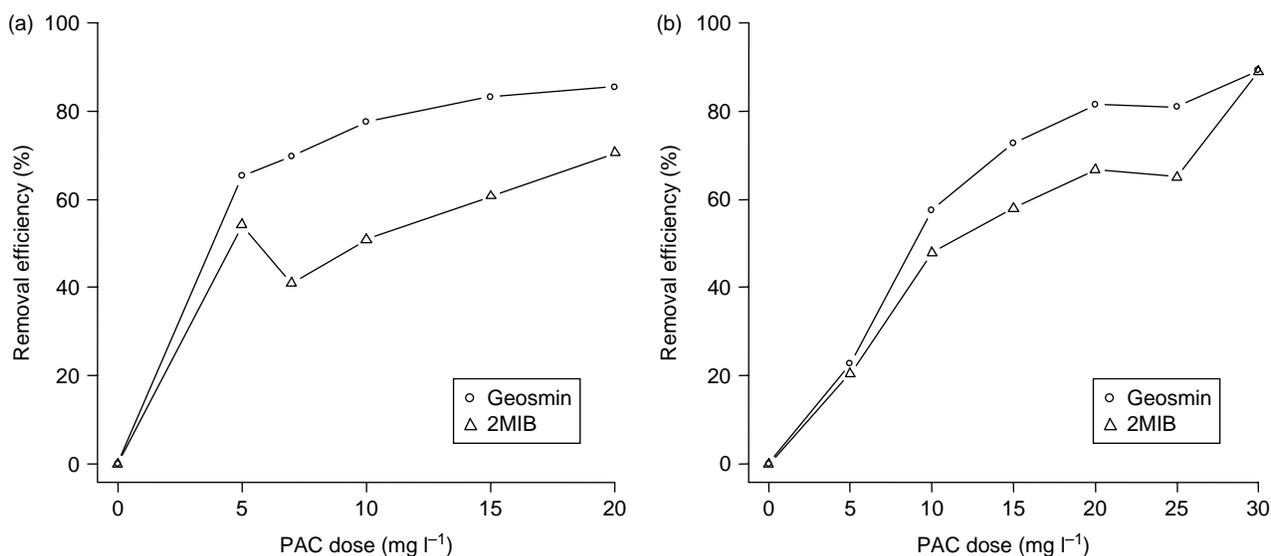

Figure 4 │ Removal efficiencies of geosmin and 2-MIB as a function of PAC dose, (a) lake water; (b) synthetic water samples.
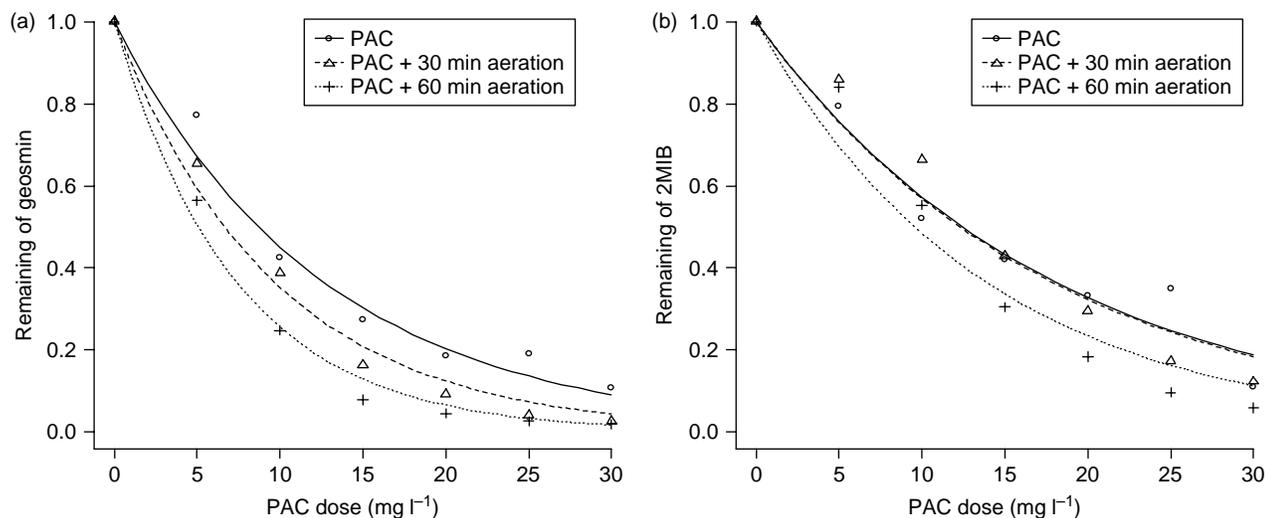
Figure 5 │ Effects of aeration on removal of (a) geosmin and (b) 2MIB at aeration flow rate of 15 l min^{-1} with PAC adsorption.

with aeration was enough to remove a similar amount of geosmin within 30–60 min. OCC removal in aerated PAC contactors was found to be considerably affected by contact time as well as PAC doses. Air stripping for 60 min at an aeration rate of 15 l^{-1} min exhibited the largest removal of both geosmin and 2-MIB in the PAC contactors. Removal efficiencies of geosmin and 2-MIB were about 96 and 84% respectively, at a PAC dose of 20 mg l^{-1} for an aeration time of 60 min. The additional portion of the geosmin and 2-MIB removed by air stripping is about 15% by simple calculation from the results in Figure 5. Improvement in the removal of geosmin for 60 min aeration was not apparent, compared to that for 30 min aeration at PAC doses above 20 mg l^{-1}. Therefore, 30 min aeration time could be suggested for the rational removal of geosmin with PAC adsorption, which coincides with the typical hydraulic residence time for a PAC contactor in local water treatment plants. In order to reduce the 2-MIB concentration to a level below 10 ng l^{-1}, optimal aeration time should be extended up to 60 min in a PAC adsorption contactor, as shown in Figure 5(b). This result indicated that 2-MIB was more dependent on contact time and less amenable to removal than geosmin in an aerated PAC contactor. Increase in 2-MIB removal by air stripping during PAC adsorption was also similar to that of geosmin. These results showed that aeration could obviously improve the removal efficiencies of both geosmin and 2-MIB in PAC contactors.

Figure 6 shows the removal efficiencies of geosmin and 2-MIB by both PAC adsorption and air stripping for 60 min at an aeration rate of 15 l min^{-1}, according to PAC doses. Geosmin is generally removed much faster than 2-MIB by air stripping (Figure 3), PAC adsorption (Figure 4), and air stripping with PAC adsorption (Figure 6). And removal efficiencies above 90% for both geosmin and 2-MIB could be achieved by 60 min aeration at 15 l min^{-1} with a PAC dose of 25 mg l^{-1}.
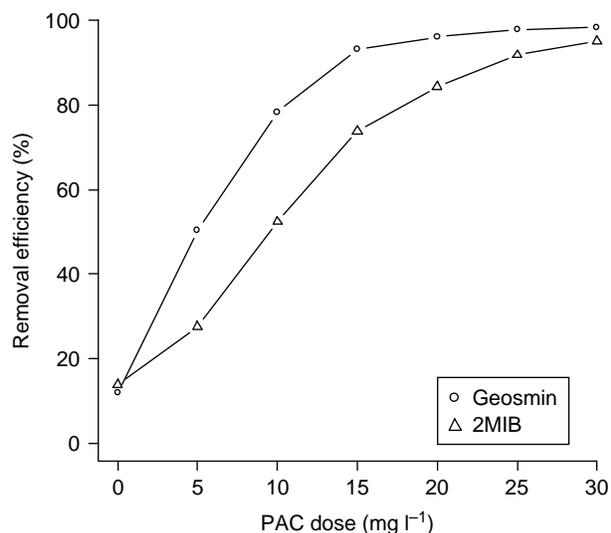

Figure 6 │ Removal of geosmin and 2MIB by 60 min aeration with PAC adsorption.

Table 3 | Nonlinear regression outputs for geosmin and 2-MIB by PAC dose

Type	Estimates	Standard error	*t*-value	*P*-value	ρ
Geosmin:					
PAC only (60 min)	0.0796	0.00496	16.04	<0.0001	0.9901
PAC + 30 min aeration	0.1043	0.00603	17.30	<0.0001	0.9959
PAC + 60 min aeration	0.1363	0.00739	18.44	<0.0001	0.9967
2-MIB:					
PAC only (60 min)	0.0557	0.00411	13.55	0.00016	0.9801
PAC + 30 min aeration	0.0564	0.00501	11.26	0.00011	0.9867
PAC + 60 min aeration	0.0726	0.00744	9.76	0.00095	0.9857

Nonlinear regression for removal of geosmin and 2-MIB by simultaneous air stripping and PAC adsorption was also conducted to analyze the effectiveness of aeration in the PAC adsorption process (Table 3).

'Estimate' values in Table 3 means the extent of the effect by PAC doses on OCC removal. Also, increase in 'Estimate' values indicates that removal of geosmin and 2-MIB increased with aeration flow rate and contact time in the PAC contactors. These results could strongly prove that aeration helped to enhance the removal of geosmin and 2-MIB from the synthetic raw water and to reduce the PAC dose for optimal removal. Aeration might also help adequate mixing of PAC in the PAC contactors, by enhancing mass transfer and preventing PAC from settling. PAC contactors for water treatment are generally designed as plug flow types to minimize short circuiting with baffles (Kim & Bae 2007). However, various types of PAC contactor can be considered by applying aeration systems in water treatment plants.

In conclusion, the main mechanism of OCC removal in the aerated PAC contactor might be adsorption, and aeration could improve removal efficiency. Aeration in the adsorption process was found to remove OCCs additionally due to the air stripping process. Therefore, aeration with mixing in a PAC contactor can reduce contact time and the required PAC consumption, for OCC removal in water treatment plants.

CONCLUSIONS

Air stripping was an effective process for marginal removal of geosmin and 2-MIB in conjunction with PAC, owing to improved removal efficiencies and reduced hydraulic retention time as well as PAC doses. Their removal efficiencies vary depending on PAC dose, aeration flow rate and aeration time. More than 93% of geosmin was removed by both adsorption at PAC dose of $15 \, \text{mg} \, \text{l}^{-1}$ and 60 min aeration at $15 \, \text{l} \, \text{min}^{-1}$. Removal efficiency of geosmin by PAC adsorption alone under the same conditions was about 73%, and that by air stripping alone was about 20%. 2-MIB removal efficiencies by PAC adsorption, by air stripping, and by the combination of PAC adsorption and air stripping were about 58, 14 and 74%, respectively, at a PAC dose of $15 \, \text{mg} \, \text{l}^{-1}$ and at an aeration flow rate of $15 \, \text{l} \, \text{min}^{-1}$ for 60 min aeration. Geosmin was much more amenable to removal by PAC adsorption, air stripping and simultaneous adsorption and air stripping than 2-MIB removal. Desirable geosmin removal occurred at a PAC dose of $15 \, \text{mg} \, \text{l}^{-1}$ and an aeration flow rate of $15 \, \text{l} \, \text{min}^{-1}$ for 30 min aeration.

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