



## Removal of Particle-bound Water-soluble Ions from Cooking Fume Using Bio-solution Wet Scrubber

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### ABSTRACT

Wet scrubbers are one of the most important air-pollution control devices (APCDs) for the simultaneous removal of various acidic gases and particulates. This study was conducted on a lab-scale self-designed wet scrubber (WSB) system for the treatment of particle-bound water-soluble ions emitted from cooking fumes with/without adding bio-solution (namely, NOE-7F). The concentration and composition of eight particle-bound water-soluble ions in the three situations were determined. Three situations include (i) particle-bound water soluble ions in the cooking fume exhaust without applying WSB or NOE-7F treatment; (ii) treating particle-bound water soluble ions in the cooking fume exhaust with applying WSB without adding NOE-7F; and (iii) treating particle-bound water soluble ions in the cooking fume exhaust with applying WSB and adding NOE-7F\_50X/100X/200X. The particle-bound water-soluble ions samples were collected and then chemical analysis of the eight water soluble ionic species ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{NO}_2^-$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ , and  $\text{SO}_4^{2-}$ ) was conducted by ion chromatography. The result indicated that adding NOE-7F bio-solution by diluted 200 folds into wet scrubber water and forming blended circulation water has the good removal efficiencies and reaches removal efficiencies higher than 80% for both  $\text{Na}^+$  (86.6%) and  $\text{Cl}^-$  (85.9%). The addition of NOE-7F in the influent water had the enhanced effect on the particle-bound water-soluble ions removal and mainly promoted highly the hydrophilicity of particle-bound water-soluble ions in the water scrubber. The combination of both water scrubber and NOE-7F addition has a high potential for practical application.

**Keywords:** Bio-solution; Particle-bound water-soluble ions; Removal efficiencies; Wet scrubbers.

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### INTRODUCTION

Human activity-generated aerosols, including emissions from outdoor and indoor sources, are the dominant contributors of ambient particulate matter (PM) in urban environments (Geiss *et al.*, 2010; Hsieh and Chen, 2010; Cao *et al.*, 2011; Hussein *et al.*, 2011; Kim *et al.*, 2011; Peng *et al.*, 2011; Shakya *et al.*, 2010; Stone *et al.*, 2011). In fact, atmospheric PM is highly associated with certain water-soluble ions existed/formed in the environment. Recently, many atmospheric aerosol mass and inorganic water-soluble species content in the nano/micron size range

has received much attention (Tsai *et al.*, 2008). For example, Matsumoto and Okita (1998) described that the composition of atmospheric particulate matter is complex and generally includes sulfates ( $\text{SO}_4^{2-}$ ), nitrates ( $\text{NO}_3^-$ ), and carbonaceous materials. Shen *et al.* (2009) investigated chemical characteristics of submicron particles in winter in Xi'an. Their results showed that the mean  $\text{PM}_{10}$  mass concentration was  $149.7 \mu\text{g}/\text{m}^3$  and the water-soluble ions were dominant chemical species and occupied to 46% of  $\text{PM}_{10}$  mass. Moreover,  $\text{Na}^+$ ,  $\text{NH}_4^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$  and  $\text{NO}_3^-$  were the major species of ionic compounds, which accounted for 95.3% of total ions concentration and were potential to be produced from various gaseous pollutants during the particle conversion process.

Recently, for the photo etching and clean room environments, the concentrations and characteristics of major components in inorganic gases and fine particles

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were measured at the photo and etch clean room areas in a Taiwan semiconductor factory (Lin *et al.*, 2010). The average PM<sub>2.5</sub> mass concentration were 17.52 and 18.23  $\mu\text{g}/\text{m}^3$  at the photo and etch areas, respectively, with species of Na<sup>+</sup>, NH<sub>4</sub><sup>+</sup>, Cl<sup>-</sup> and SO<sub>4</sub><sup>2-</sup> had the highest concentrations in the PM<sub>2.5</sub> mass. And the inorganic species account for 56% and 62% of the particulate mass, respectively, at the photo and etch areas.

In the last few years, various investigations have been also carried out to quantify the cooking oil fumes emission from both indoor and outdoor ambient environments (He *et al.*, 2004). Those reports indicates that cooking emissions may contribute significantly to atmospheric organic/inorganic particles in urban environment (Cass, 1998; He *et al.*, 2004). See and Balasubramanian (2008) studied the chemical characteristics of fine particles emitted from different gas cooking methods. The PM<sub>2.5</sub> mass determined in their study revealed the following trend: background (15.4  $\mu\text{g}/\text{m}^3$ ) < steaming (72.3  $\mu\text{g}/\text{m}^3$ ) < boiling (91.6  $\mu\text{g}/\text{m}^3$ ) < stir-frying (120  $\mu\text{g}/\text{m}^3$ ) < pan-frying (130  $\mu\text{g}/\text{m}^3$ ) < deep-frying (209  $\mu\text{g}/\text{m}^3$ ).

See and Balasubramanian (2006) have carried out in a domestic kitchen using a scanning mobility particle sizer (SMPS) to investigate the size distribution of ultrafine particles emitted from cooking. In their study, five different cooking methods were studied, including steaming, boiling, stir-frying, pan-frying, and deep-frying. During the course of their experiments, the amount and type of food, and the heat setting on the gas stove were kept constant. Their results showed that deep-frying caused the largest increase (a 24-fold increase) in particle number concentration to  $6.0 \times 10^5$  1/cm<sup>3</sup> compared to a background concentration of  $2.5 \times 10^4$  1/cm<sup>3</sup> and contained the highest proportion of nanoparticles (90%). Such the increase was then followed by pan-frying ( $1.1 \times 10^5$  1/cm<sup>3</sup>, 78%), stir-frying ( $9.3 \times 10^4$  1/cm<sup>3</sup>, 69%), boiling ( $6.9 \times 10^4$  1/cm<sup>3</sup>, 62%), and steaming ( $5.4 \times 10^4$  1/cm<sup>3</sup>, 55%). In their study, it is implying that cooking with oil produced more particles than cooking with water. The above mentioned studies could provide comprehensive data on the physical characteristics of particles emitted from cooking.

Besides the investigation of air pollutants, the removing of air pollutants is important. In practice, wet scrubbers are effective at removing particulates due to the fact that they are quite excellent to remove large size particles by their main removal mechanisms for particulate matters, inertial impactions and direct interceptions. To our current knowledge, many factors (such as, the different scrubber type, gas velocity, the amounts of scrubbing solutions, and particle sizes distribution in the gas and so on) are highly associated with the removal efficiencies of WSB in practical field (Choi and Lee, 2007).

Recently, the new method related to the adding bio-solution into the WSB treatment process is with researchers' attention. For instance, by addition of a bio-solution called natural organic enzyme-7F (NOE-7F) could be a novel method to enhance the removal efficiencies in some air pollution control devices. Lin *et al.* (2005) indicated that NOE-7F is much friendlier to the

environment than artificial chemical diesel additives and it can be used to improve combustion efficiency, decrease pollutant emissions and resist, and stabilize emulsified diesel fuel in diesel generators. Especially, NOE-7F had a catalytic effect which elevated combustion efficiency and destroyed pollutants such as polycyclic aromatic hydrocarbons (PAHs) in the diesel engine. In a previous study, a bio-solution (NOE-7F) was also used to save energy (Lin *et al.*, 2006). Lin *et al.* (2006) demonstrated that NOE-7F was added first to water and then emulsified by adding surfactants to manufacture emulsified fuels. They indicated that the energy saving, reduction of particulate matter and total-PAH emissions by using E13 (13 wt% NOE-7F + 83 wt% premium diesel fuel), E16 and E19, respectively, were 3.38, 37, 34.9%; 5.87, 38.6, 49.3%; 4.75, 31.1 and 47.3%, compared with premium diesel fuel (Lin *et al.*, 2006). In fact, they validate that the NOE-7F had a catalytic effect which elevated the combustion efficiency and decreased pollutant emissions during the combustion process.

Recently, a novel method to enhance polychlorinated dibenzo-p-dioxins and dibenzofurans removal by adding bio-solution in EAF dust treatment plant was also studied by Lin *et al.* (2008). Their study shows that the addition of NOE-7F in the raw materials had the dechlorination effect on the PCDD/F removal and mainly inhibited highly chlorinated PCDD/F formation. The combination of both powder-activated carbon (PAC) injection and NOE-7F addition has a high potential for practical application.

Wet scrubbers have been continuously redeveloped into various types and combinations, including countercurrent contact spray towers, packed scrubbers, compacted scrubbers, ionizing wet scrubbers, and so on (Choi and Lee, 2007). Based on the excellent performance of WSB on removing the particulate matters, WSB should be also effective at removing particle-bound water-soluble ions, which would lead to the potential reductions of kitchen cooking emissions. However, no study focused on the particle-bound water-soluble ions removal by wet scrubber with adding bio-solution from cooking fume. In this study, therefore, different amounts of bio-solution (NOE-7F) were applied into the water scrubbing fluids (as cleaning fluids) and the concentrations of particle-bound water-soluble ions in the cooking fumes with or without the treatment of wet scrubber were measured, respectively, to investigate the removal efficiencies of particle-bound water-soluble ions under each situation. Three situations are designed and investigated in this study, including (i) particle-bound water soluble ions in the cooking fume exhaust without applying WSB or NOE-7F treatment; (ii) treating particle-bound water soluble ions in the cooking fume exhaust with applying WSB without adding NOE-7F; and (iii) treating particle-bound water soluble ions in the cooking fume exhaust with applying WSB and adding NOE-7F (using three different dilution ratios of 50X, 100X and 200X, respectively).

To get overall information on the environmental impact and health risk from oil fume emissions from the cooking processes related in citizen kitchens, a program (supported

by funds from the National Science Council in Taiwan) was initiated to determine the levels of cooking fumes emitted from citizen kitchens in Taiwan. Therefore, the main objective of this study was to investigate and compare the concentration and composition of particle-bound water-soluble ions removal by wet scrubber with or without adding the bio-solution (NOE-7F).

## MATERIALS AND METHODS

### Sampling Strategy

The whole study was conducted in a research laboratory that simulates a kitchen located in southern Taiwan. To evaluate the process performances that depend on with/without adding bio-solution for removing the eight particle-bound water-soluble ions ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{NO}_2^-$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ , and  $\text{SO}_4^{2-}$ ) from cooking fume, a lab-scale reactor of the water scrubbing process was operated at room temperature. The experimental setup for these experiments is shown in Fig. 1. Our lab-scale process operation system consists of (1) oil fume generator, (2) collected hood, (3) aluminum cylindrical pipe, (4) wet scrubbing tower, (5) droplet separation grids, (6) water/bio-solution tank, (7) circulating pump, (8) filter holder, (9) flow meter, (10) exhaust sampling pump.

This study was carried out during April 2009 in our laboratory in Department of Environmental Science and Engineering, National Pingtung University of Science and Technology (Pingtung, Taiwan). In this experiment, the oil

fume was generated from a small-scale electric oven (Fig. 1). Only one electric oven in our laboratory was used during the cooking experiments. This basic standard type of electric oven is also applied in our previous research papers and can obtain a good performance on testing the oil fume (Hsieh and Wang, 2010; Hsieh *et al.*, 2011). The input pork was heated and roasted at two high heating temperatures individually (i.e., 180°C and 220°C, for oven temperature sustainable), a steady gas flowrate, and a four-batch feeding pork amount. The two heating operational temperatures of 180 and 220°C are based on the basic design of most ovens sold in supermarkets or stores in Taiwan. In this study, a series of four batches feedings are performed without cooling during each a single run in this study. During the experiments, the oil fume gasflow followed the pathway (as shown in Fig. 1): passing the collected hood, passing the aluminum cylindrical pipe, introducing into the wet scrubbing tower, passing/contacting the droplet separation grids, entering the filter holder and finally venting by exhaust sampling pump.

The wet scrubbing tower consisted of a bio-solution blended basin and a scrubber rectangular column. The bio-solution blended basin was constructed from a 53 × 40 × 30 cm (i.e., Length × Width × Height) rectangular tank. The scrubber rectangular column was constructed from a 30 × 30 × 155 cm (i.e., Length × Width × Height) rectangular column. In this study, total volume of scrubbing water (25 liters) was introduced and circulated with pump during each designed run. In the wet scrubbing tower, multi-

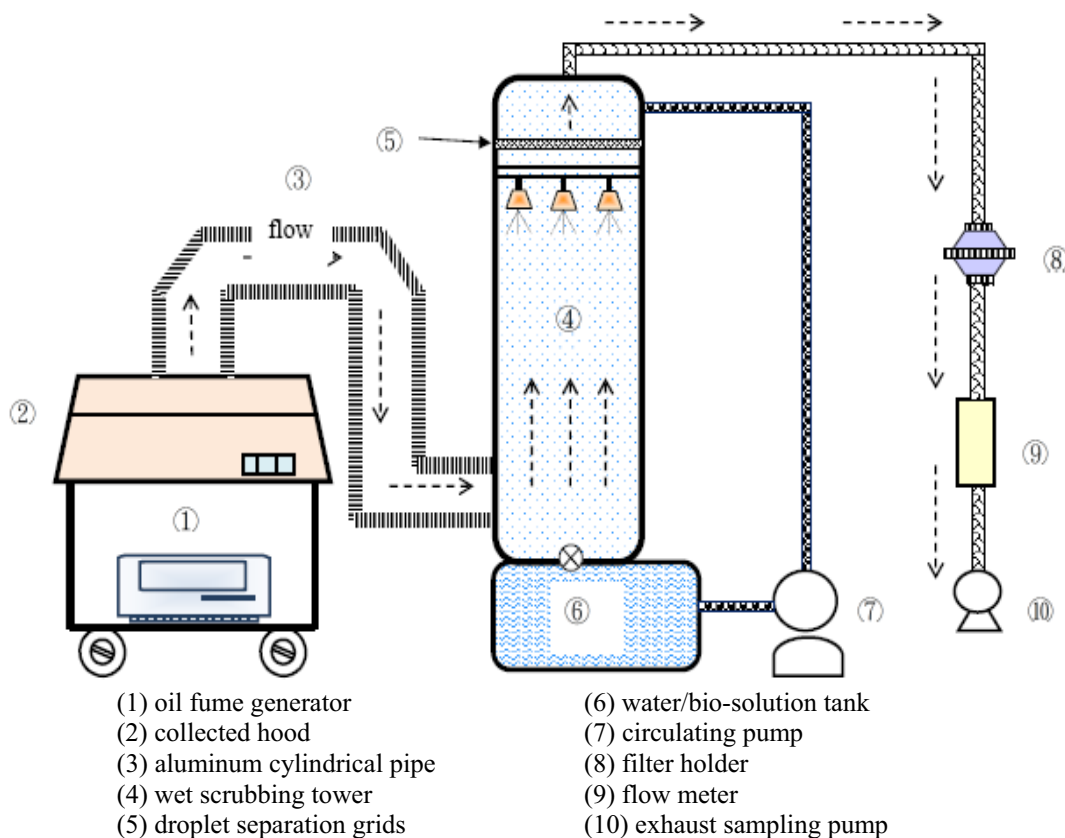


Fig. 1. Schematic diagram of experimental set-up.

sprayers were used with a high power spray pump (model: HY-20, HP: 1/2, Aquadyna Industries Inc.) with a water absorbing capacity 14 liters/min on average.

A PM collection holder equipped with quartz filters (51 mm in diameter) was used to collect aerosol samples (Fig. 1). The new filters were pre-heated at 450°C for 3 h to reduce the amount of organic vapors which were absorbed on these filters. All new filters were maintained in a condition of  $40 \pm 5\%$  RH and  $25 \pm 0.3^\circ\text{C}$  for over 24 h prior to weighing on a microbalance with an accuracy of 1  $\mu\text{g}$  before sampling. The exposed filters were unloaded from filter holders immediately after sampling and stored in a refrigerator at about 4°C until conducting chemical analysis to prevent the evaporation of volatile compounds.

### **The Addition of Bio-solution (NOE-7F)**

In this study, the bio-solution was named as natural organic enzyme-7F (NOE-7F). The process of producing NOE-7F is as follows. First, molasses, rice wine, acetic acid, water and an anti-oxidant enzyme were mixed together. Second, the mixture was domesticated by adding both lactic acid bacteria and yeast. Finally, the mixture was put through a separation and purification process. Based on the natural characteristics of NOE-7F, three dilutions were selected in this study, including NOE-7F\_50X, NOE-7F\_100X, and NOE-7F\_200X (dilution by 50, 100, and 200 times, respectively.)

A total of 30 samples were collected from the exit of WSB in applying different amounts of tap-water and NOE-7F, respectively. In this study, two heating-temperature operations (i.e., 180°C and 220°C) in oven were selected to evaluate the effect of different NOE-7F adding ratios on the process performances. Therefore, three samples were collected during the period without different amounts of tap-water or NOE-7F at each heating temperature. In the amount of 50X (dilution by 50 times), 100X (dilution by 100 times) and 200X (dilution by 200 times) of NOE-7F feeding, the numbers of sampling and analyses were all three. Three samples were collected and analyzed during the period while applying both tap-water and NOE-7F (50X, 100X, and 200X).

### **Water-soluble Ions Analysis**

Chemical analysis of the eight particle-bound water-soluble ions ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{NO}_2^-$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ , and  $\text{SO}_4^{2-}$ ) was conducted by ion chromatography (DIONEX DX-120) in Department of Environmental Science and Engineering, National Pingtung University of Science and Technology (Pingtung, Taiwan). The operational parameters of ion chromatography (IC) in this study as follows:

(i) Four anions, including  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$  and  $\text{NO}_2^-$  are analyzed.

(ii) Four cations, including  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Mg}^{2+}$ , and  $\text{Ca}^{2+}$  are analyzed.

(iii) Both anions and cations are shaking for 60 minutes during extraction process.

(iv) For anions analysis, the AS12A protection column, AS12A separation column, and ASRS-ULTRA II 4-mm

suppress column are used. (i.e., parameter settings were as follows: flow velocity: 1.5 mL/min; ineffect solvent: 2.7 mM  $\text{Na}_2\text{CO}_3/0.3$  mM  $\text{NaHCO}_3$ ; elapsed analyzing time: 13 min).

(v) For cations analysis, the CS12A protection column, CS12A separation column, and CSRS-ULTRA 4-mm suppress column are used. (i.e., parameter settings were as follows: flow velocity: 1.0 mL/min; ineffect solvent: 20mM MSA (Methanesulfonic Acid); elapsed analyzing time: 14 min).

In this study, blank and replicate analyses were also performed for 10% of all samples according to standard operating procedures. Standards were purchased from Merck (Merck KgaA, Darmstadt, Germany) and seven point calibration curves were prepared for each batch of samples. The r-values of calibration curves were all greater than 0.995. Method detection limits (MDL) of ionic species, in  $\mu\text{g}$  per milliliter, were  $\text{Na}^+$  0.091,  $\text{NO}_2^-$  0.083,  $\text{K}^+$  0.123,  $\text{Mg}^{2+}$  0.007,  $\text{Ca}^{2+}$  0.143,  $\text{Cl}^-$  0.044,  $\text{NO}_3^-$  0.077 and  $\text{SO}_4^{2-}$  0.046. Laboratory blanks were used to assess contamination. The blank concentrations of ionic species were less than corresponding MDLs. Concentrations of non-detects were taken as zero.

From the before treatment and the experience treatment outlet concentrations of  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{NO}_2^-$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ , and  $\text{SO}_4^{2-}$ , the removal efficiencies of particle-bound water soluble ions were calculated. In this study, all the processes were conducted at 25°C and atmospheric pressure conditions.

## **RESULTS AND DISCUSSION**

### **Concentrations of Particle-bound Water Soluble Ions in the Cooking Fume Exhaust without Applying WSB or NOE-7F Treatment**

Without applying WSB or adding NOE-7F, the different concentrations of eight particle-bound water-soluble ions ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{NO}_2^-$ ,  $\text{Mg}^{2+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ , and  $\text{SO}_4^{2-}$ ) are shown in Table 1. In condition of heating at 180°C, except for the concentration of  $\text{NO}_2^-$  was below the IC detection limitation, other three anions were discussed here in detail. The mean concentrations for  $\text{SO}_4^{2-}$ ,  $\text{Cl}^-$  and  $\text{NO}_3^-$  were 6.03  $\mu\text{g}/\text{Nm}^3$ , 5.59  $\mu\text{g}/\text{Nm}^3$  and 3.92  $\mu\text{g}/\text{Nm}^3$ , respectively, which account for 25.8%, 23.9% and 16.7% in total ions concentration. Moreover, the mean concentrations for four cations of  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  were 4.3  $\mu\text{g}/\text{Nm}^3$ , 1.69  $\mu\text{g}/\text{Nm}^3$ , 1.35  $\mu\text{g}/\text{Nm}^3$  and 0.54  $\mu\text{g}/\text{Nm}^3$ , respectively, which occupied to 18.4%, 7.2%, 5.7% and 2.3% in total ions concentration. Similarly, in condition of heating at 220°C, except for the concentration of  $\text{NO}_2^-$  was below the IC detection limitation, other three anions were also discussed here in detail. The mean concentrations for  $\text{SO}_4^{2-}$ ,  $\text{NO}_3^-$  and  $\text{Cl}^-$  were 5.28  $\mu\text{g}/\text{Nm}^3$ , 3.59  $\mu\text{g}/\text{Nm}^3$  and 2.16  $\mu\text{g}/\text{Nm}^3$ , respectively, which account for 32.4%, 22.1% and 13.3% in total ions concentration. Moreover, the mean concentrations for four cations of  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  were 2.17  $\mu\text{g}/\text{Nm}^3$ , 1.77  $\mu\text{g}/\text{Nm}^3$ , 0.85  $\mu\text{g}/\text{Nm}^3$  and 0.45  $\mu\text{g}/\text{Nm}^3$ , respectively, which occupied to 13.3%, 10.9%, 5.3% and 2.8% in total ions concentration.

**Table 1.** Particle-bound water-soluble ions concentrations in the cooking fumes without the treatment of wet scrubber.

Water-soluble ions (WSIs)	Sample A ( $\mu\text{g}/\text{Nm}^3$ )	Sample B ( $\mu\text{g}/\text{Nm}^3$ )	Sample C ( $\mu\text{g}/\text{Nm}^3$ )	Mean ( $\mu\text{g}/\text{Nm}^3$ )	S.D. ( $\mu\text{g}/\text{Nm}^3$ )
at 180°C					
Cl <sup>-</sup>	4.74	5.96	6.06	5.59	0.73
NO <sub>2</sub> <sup>-</sup>	ND	ND	ND	–	–
NO <sub>3</sub> <sup>-</sup>	3.05	3.76	4.95	3.92	0.96
SO <sub>4</sub> <sup>2-</sup>	6.84	5.08	6.18	6.03	0.89
Na <sup>+</sup>	3.50	4.89	4.51	4.30	0.72
K <sup>+</sup>	2.47	1.71	0.88	1.69	0.80
Mg <sup>2+</sup>	1.62	ND	ND	0.54	–
Ca <sup>2+</sup>	2.62	ND	1.41	1.35	0.86
Total WSIs	24.84	21.40	23.99	23.42	
at 220°C					
Cl <sup>-</sup>	2.17	3.19	1.11	2.16	1.04
NO <sub>2</sub> <sup>-</sup>	ND	ND	ND	–	–
NO <sub>3</sub> <sup>-</sup>	3.57	3.29	3.91	3.59	0.31
SO <sub>4</sub> <sup>2-</sup>	5.07	4.95	5.83	5.28	0.48
Na <sup>+</sup>	2.50	2.03	1.98	2.17	0.28
K <sup>+</sup>	2.80	1.70	0.81	1.77	1.00
Mg <sup>2+</sup>	1.35	ND	ND	0.45	–
Ca <sup>2+</sup>	1.55	ND	1.01	0.85	0.38
Total WSIs	19.01	15.16	14.65	16.27	

Without applying WSB or adding NOE-7F, the mean concentration of total particle-bound water-soluble ions in the cooking fume exhaust were 23.4 and 16.3  $\mu\text{g}/\text{Nm}^3$  ( $n = 3$ ) at 180 and 220°C, respectively (Table 1). The ratio of total WSIs at 180°C to the level at 220°C ranged from 1.31 to 1.64 and averaged 1.44, which indicated the abundance of particle-bound water-soluble ions at low heating temperature (180°C) during the cooking.

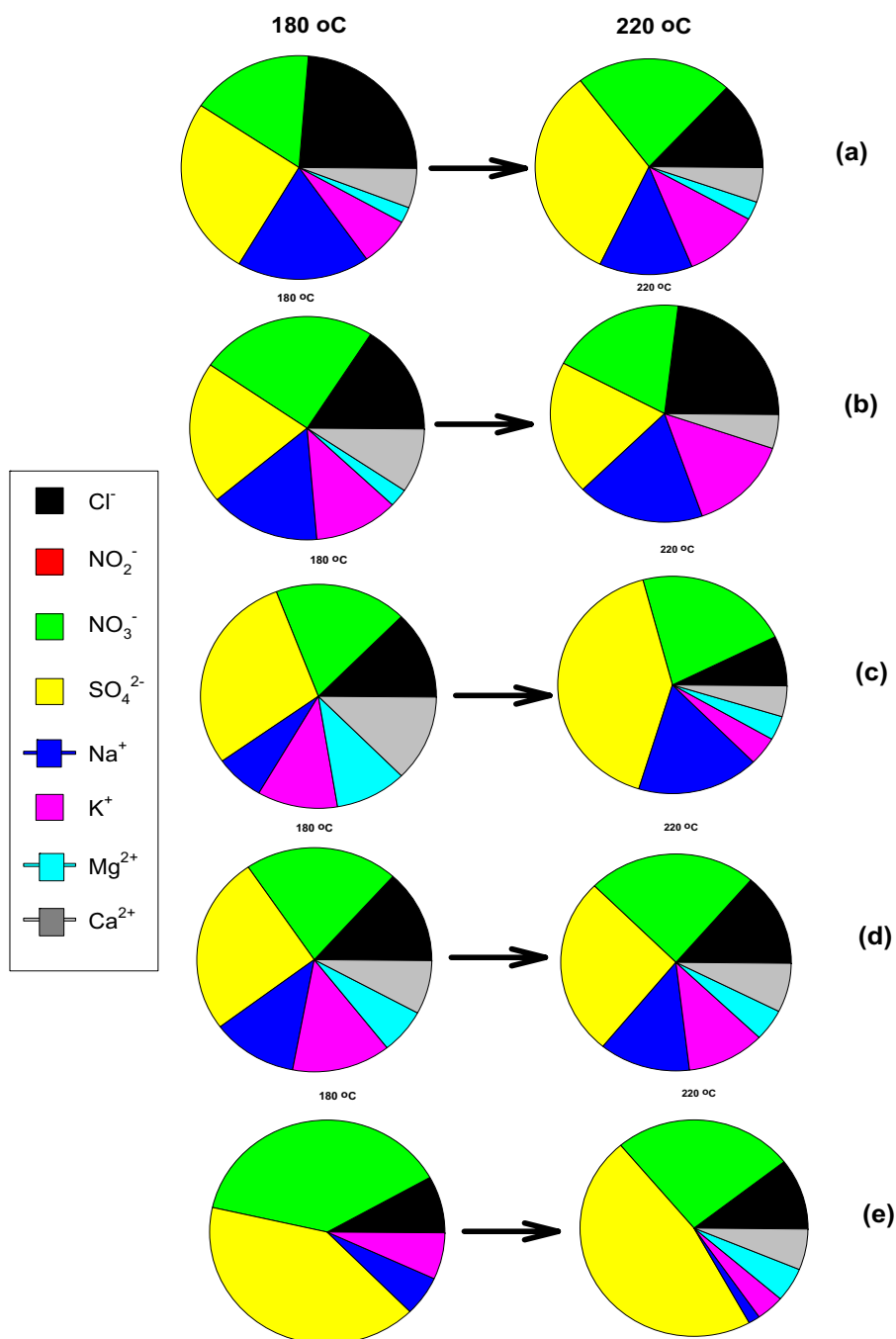
For comparison of the distribution of composition percentage (%) at different treatment, Fig. 2 indicates the change of mean composition percentage (%) between at 180°C and at 220°C. Without any treatment, the mean composition percentages (%) at 180°C were calculated for the distribution and exhibited the following decreasing order: SO<sub>4</sub><sup>2-</sup> > Cl<sup>-</sup> > Na<sup>+</sup> > NO<sub>3</sub><sup>-</sup> > K<sup>+</sup> > Ca<sup>2+</sup> > Mg<sup>2+</sup> > NO<sub>2</sub><sup>-</sup> (N.D.) (Fig. 2(a) left). At 220°C, the mean composition percentage (%) was similarly exhibited the following decreasing order: SO<sub>4</sub><sup>2-</sup> > NO<sub>3</sub><sup>-</sup> > Na<sup>+</sup> > Cl<sup>-</sup> > K<sup>+</sup> > Ca<sup>2+</sup> > Mg<sup>2+</sup> > NO<sub>2</sub><sup>-</sup> (N.D.) (Fig. 2(a) right). Obviously, without applying WSB or NOE-7F treatment, the most abundant water soluble ion at both 180 and 220°C is SO<sub>4</sub><sup>2-</sup>. Additionally, NO<sub>3</sub><sup>-</sup> and Cl<sup>-</sup> are abundant at both 180 and 220°C.

#### **Concentrations of Particle-bound Water Soluble Ions in the Cooking Fume Exhaust with Applying WSB without Adding NOE-7F**

By applying WSB without adding NOE-7F, the different concentrations of eight particle-bound water-soluble ions (Na<sup>+</sup>, K<sup>+</sup>, NO<sub>2</sub><sup>-</sup>, Mg<sup>2+</sup>, Ca<sup>2+</sup>, Cl<sup>-</sup>, NO<sub>3</sub><sup>-</sup>, and SO<sub>4</sub><sup>2-</sup>) are shown in Table 2. In condition of heating at 180°C, except for the concentration of NO<sub>2</sub><sup>-</sup> was below the IC detection limitation, other three anions were discussed here in detail. The mean concentrations for NO<sub>3</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup> and Cl<sup>-</sup> were 3.92  $\mu\text{g}/\text{Nm}^3$ , 3.30  $\mu\text{g}/\text{Nm}^3$  and 2.58  $\mu\text{g}/\text{Nm}^3$ , respectively,

which account for 24.4%, 20.5% and 16.0% in total ions concentration. Moreover, the mean concentrations for four cations of Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>2+</sup> and Mg<sup>2+</sup> were 2.46  $\mu\text{g}/\text{Nm}^3$ , 1.89  $\mu\text{g}/\text{Nm}^3$ , 1.51  $\mu\text{g}/\text{Nm}^3$  and 0.43  $\mu\text{g}/\text{Nm}^3$ , respectively, which occupied to 15.3%, 11.7%, 9.4% and 2.6% in total ions concentration. In condition of heating at 220°C, except for the concentration of NO<sub>2</sub><sup>-</sup> was ND. The mean concentrations for Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup> and NO<sub>3</sub><sup>-</sup> were 4.13  $\mu\text{g}/\text{Nm}^3$ , 3.53  $\mu\text{g}/\text{Nm}^3$  and 3.38  $\mu\text{g}/\text{Nm}^3$ , respectively, which account for 23.3%, 19.9% and 19.0% in total ions concentration. In addition, the mean concentrations for three cations of Na<sup>+</sup>, K<sup>+</sup> and Ca<sup>2+</sup>, except for Mg<sup>2+</sup> (ND), were 3.22  $\mu\text{g}/\text{Nm}^3$ , 2.59  $\mu\text{g}/\text{Nm}^3$  and 0.91  $\mu\text{g}/\text{Nm}^3$ , respectively, which occupied to 18.1%, 14.6% and 5.1% in total ions concentration. This result reveals that three water soluble ions of SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup> and Cl<sup>-</sup> are dominant at both 180 and 220°C when the cooking fume exhaust was treated with applying WSB without adding NOE-7F.

By applying WSB without adding NOE-7F, the mean concentration of total particle-bound water-soluble ions in the cooking fume exhaust were 16.1 and 17.8  $\mu\text{g}/\text{Nm}^3$  ( $n = 3$ ) at 180°C and 220°C, respectively (Table 2). The ratio of total WSIs at 180°C to the level at 220°C ranged from 0.74 to 1.24 and averaged 0.91, which showed the abundance of particle-bound water-soluble ions at high heating temperature (220°C) during the cooking. Unlike the trend in the case of without applying WSB or adding NOE-7F as mentioned before, such trend is reversed by applying WSB without adding NOE-7F. This change could be associated with the effect of water scrubbing in this system. In fact, the real mechanism related to the WSB could be associated with the conversion of gas phase into liquid phase in the system. In this stage, this phenomenon is still complicated and is not fully understand.



**Fig. 2.** The variation of mean composition percentages at different conditions: (a) without any treatment (b) water scrubbing only; (c) water scrubbing with adding the bio-solution (NOE-7F\_50X); (d) water scrubbing with adding the bio-solution (NOE-7F\_100X); (e) water scrubbing with adding the bio-solution (NOE-7F\_200X).

Fig. 2(b) indicates that when the water scrubbing was only used, the mean composition percentages (%) at 180°C were calculated for the distribution and exhibited the following decreasing order:  $\text{NO}_3^- > \text{SO}_4^{2-} > \text{Cl}^- > \text{Na}^+ > \text{K}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{NO}_2^-$  (N.D.) (Fig. 2(b) left). At 220°C, the mean composition percentages (%) was dissimilarly exhibited the following decreasing order:  $\text{Cl}^- > \text{SO}_4^{2-} > \text{NO}_3^- > \text{Na}^+ > \text{K}^+ > \text{Ca}^{2+} > \text{Mg}^{2+} > \text{NO}_2^-$  (= N.D.) (Fig. 2(b) right). It was supposed that the shifts of mean composition percentages for the particle-bound water-soluble ions in wet scrubbers

were fairly associated with whether particulate matters could be removed or not. In fact, the particle-bound water-soluble ions concentrations were decreased in the wet scrubbers that experienced oily droplets capture and condensation, which should be intimately related to the practical decrease of particle-bound water-soluble ions. Therefore, in certain cases of experimental runs in this study, where the oily-droplet fumes levels in the gas increased, the reductions of particle-bound water-soluble ions were also observed through wet scrubbing systems.

**Table 2.** Particle-bound water-soluble ions concentrations in the cooking fumes with the treatment of water scrubbing without adding the bio-solution (NOE-7F).

Water-soluble ions (WSIs)	Sample A ( $\mu\text{g}/\text{Nm}^3$ )	Sample B ( $\mu\text{g}/\text{Nm}^3$ )	Sample C ( $\mu\text{g}/\text{Nm}^3$ )	Mean ( $\mu\text{g}/\text{Nm}^3$ )	S.D. ( $\mu\text{g}/\text{Nm}^3$ )
at 180°C					
Cl <sup>-</sup>	3.09	2.58	2.08	2.58	0.51
NO <sub>2</sub> <sup>-</sup>	ND	ND	ND	–	–
NO <sub>3</sub> <sup>-</sup>	2.95	4.26	4.54	3.92	0.85
SO <sub>4</sub> <sup>2-</sup>	3.52	3.17	3.22	3.30	0.19
Na <sup>+</sup>	3.88	1.81	1.70	2.46	1.23
K <sup>+</sup>	2.75	1.52	1.40	1.89	0.75
Mg <sup>2+</sup>	ND	1.28	ND	0.43	–
Ca <sup>2+</sup>	1.67	1.57	1.30	1.51	0.19
Total WSIs	17.86	16.19	14.24	16.09	
at 220°C					
Cl <sup>-</sup>	3.89	4.45	4.06	4.13	0.29
NO <sub>2</sub> <sup>-</sup>	ND	ND	ND	–	–
NO <sub>3</sub> <sup>-</sup>	2.55	3.16	4.42	3.38	0.95
SO <sub>4</sub> <sup>2-</sup>	3.25	3.76	3.57	3.53	0.26
Na <sup>+</sup>	2.66	3.69	3.31	3.22	0.52
K <sup>+</sup>	2.03	2.86	2.89	2.59	0.49
Mg <sup>2+</sup>	ND	ND	ND	–	–
Ca <sup>2+</sup>	ND	1.67	1.06	0.91	0.43
Total WSIs	14.38	19.59	19.31	17.76	

Fig. 3(a) presents the removal efficiencies at the condition of using water scrubbing only, which indicated the significance of removal efficiencies on particle-bound water-soluble ions were only observed for Cl<sup>-</sup> (52.7%), SO<sub>4</sub><sup>2-</sup> (44.7%) and Na<sup>+</sup> (38.2%) ions at 180°C and for SO<sub>4</sub><sup>2-</sup> (32.8%) ions at 220°C, respectively. Except for Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup> and Na<sup>+</sup> ions, other ions was found no satisfied removal efficiencies. Nevertheless, it was difficult to calculate the removal efficiencies for NO<sub>2</sub><sup>-</sup>, because the concentrations of NO<sub>2</sub><sup>-</sup> were ND in all runs during such runs. Actually, wet scrubbers are not suitable to reduce NO<sub>x</sub> levels, because NO, which generally accounted for more than 90% of the NO<sub>x</sub> from the incinerators, is almost insoluble in water (Choi and Lee, 2007)

#### **Concentrations of Particle-bound Water Soluble Ions in the Cooking Fume Exhaust with Applying WSB and Adding NOE-7F**

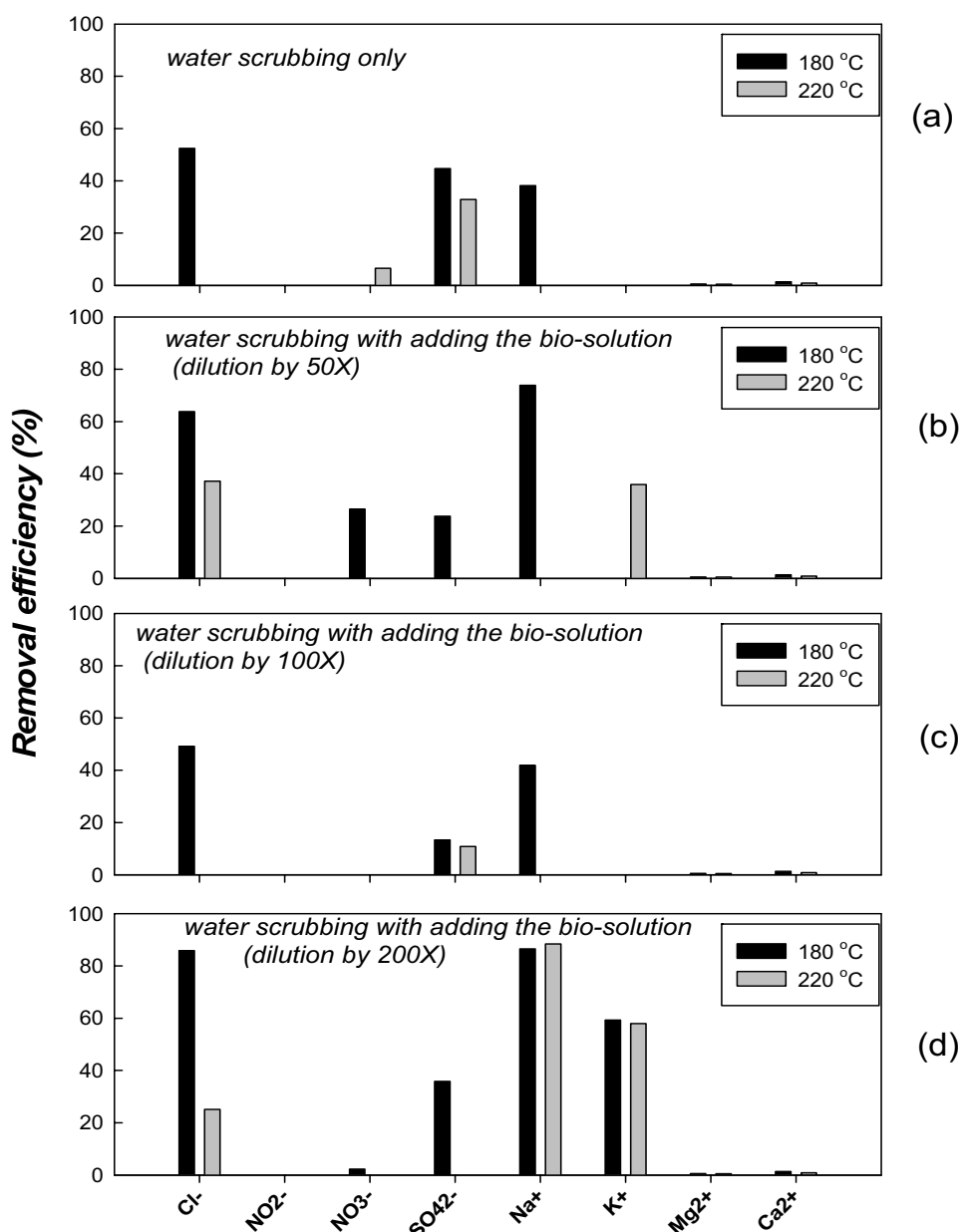
Our research attempts to evaluate the effectiveness of the different dilution ratios about NOE-7F when the cooking fume exhaust was treated with applying WSB. Three dilutions were selected, including NOE-7F\_50X, NOE-7F\_100X, and NOE-7F\_200X (dilution by 50, 100, and 200 times, respectively.) The results of three cases are shown in Tables 3–5 and a summary of the results as follows:

(i) By applying WSB with adding NOE-7F\_50X (dilution by 50 times), the mean concentration of total particle-bound water-soluble ions in the cooking fume exhaust were 15.7 and 19.7  $\mu\text{g}/\text{Nm}^3$  ( $n = 3$ ) at 180 and 220°C, respectively (Table 3). The ratio of total WSIs at 180°C to the level at 220°C ranged from 0.68 to 0.87 and averaged 0.80.

(ii) By applying WSB with adding NOE-7F\_100X (dilution by 100 times), the mean concentration of total particle-bound water-soluble ions in the cooking fume exhaust were 20.3 and 17.7  $\mu\text{g}/\text{Nm}^3$  ( $n = 3$ ) at 180 and 220°C, respectively (Table 4). The ratio of total WSIs at 180°C to the level at 220°C ranged from 1.05 to 1.24 and averaged 1.15.

(iii) By applying WSB with adding NOE-7F\_200X (dilution by 200 times), the mean concentration of total particle-bound water-soluble ions in the cooking fume exhaust were 9.4 and 14.5  $\mu\text{g}/\text{Nm}^3$  ( $n = 3$ ) at 180 and 220°C, respectively (Table 4). The ratio of total WSIs at 180°C to the level at 220°C ranged from 0.48 to 0.91 and averaged 0.65. These results implied that the three different dilution ratios of NOE-7F could affect the hydrophilicity of particle-bound water-soluble ions in the water scrubber and produce a change in the ratio of total WSIs at 180°C to the level at 220°C. It is suggests that the addition of NOE-7F in the influent water had the enhanced effect on the particle-bound water-soluble ions removal and mainly promoted highly the hydrophilicity of particle-bound water-soluble ions in the water scrubber.

Fig. 2(c) presents that when the water scrubbing with adding the bio-solution NOE-7F\_50X (dilution by 50 times) was only used, the mean composition percentages (%) at 180°C were calculated for the distribution and exhibited the following decreasing order; SO<sub>4</sub><sup>2-</sup> > NO<sub>3</sub><sup>-</sup> > Cl<sup>-</sup> > Ca<sup>2+</sup> > K<sup>+</sup> > Mg<sup>2+</sup> > Na<sup>+</sup> > NO<sub>2</sub><sup>-</sup> (= N.D.). (Fig. 2(c) left). At 220°C, the mean composition percentages (%) was dissimilarly exhibited the following decreasing order: SO<sub>4</sub><sup>2-</sup> > NO<sub>3</sub><sup>-</sup> > Na<sup>+</sup> > Cl<sup>-</sup> > Ca<sup>2+</sup> > K<sup>+</sup> > Mg<sup>2+</sup> > NO<sub>2</sub><sup>-</sup> (= N.D.) (Fig. 2(c) right). Fig. 2(d) shows that when the water scrubbing with adding the bio-solution NOE-7F\_100X



**Fig. 3.** The removal efficiency at different conditions: (a) water scrubbing only; (b) water scrubbing with adding the bio-solution (NOE-7F\_50X); (c) water scrubbing with adding the bio-solution (NOE-7F\_100X); (d) water scrubbing with adding the bio-solution (NOE-7F\_200X).

(dilution by 100 times) was only used, the mean composition percentages (%) at 180 °C were calculated for the distribution and exhibited the following decreasing order; SO<sub>4</sub><sup>2-</sup> > NO<sub>3</sub><sup>-</sup> > K<sup>+</sup> > Cl<sup>-</sup> > Na<sup>+</sup> > Ca<sup>2+</sup> > Mg<sup>2+</sup> > NO<sub>2</sub><sup>-</sup> (= N.D.). (Fig. 2 (d) left). At 220 °C, the mean composition percentages (%) was dissimilarly exhibited the following decreasing order: SO<sub>4</sub><sup>2-</sup> > NO<sub>3</sub><sup>-</sup> > Cl<sup>-</sup> > Na<sup>+</sup> > K<sup>+</sup> > Mg<sup>2+</sup> > NO<sub>2</sub><sup>-</sup> (= N.D.) (Fig. 2(d) right). Fig. 2(e) shows that when the water scrubbing with adding the bio-solution NOE-7F\_200X (dilution by 200 times) was only used, the mean composition percentages (%) at 180 °C were calculated for the distribution and exhibited the following decreasing order; SO<sub>4</sub><sup>2-</sup> > NO<sub>3</sub><sup>-</sup> > Cl<sup>-</sup> > K<sup>+</sup> > Na<sup>+</sup> > Mg<sup>2+</sup>, Ca<sup>2+</sup>, NO<sub>2</sub><sup>-</sup> (= N.D.). At 220 °C, the mean composition

percentages (%) was dissimilarly exhibited the following decreasing order: SO<sub>4</sub><sup>2-</sup> > NO<sub>3</sub><sup>-</sup> > Cl<sup>-</sup> > Ca<sup>2+</sup> > Mg<sup>2+</sup> > Na<sup>+</sup> > K<sup>+</sup> > NO<sub>2</sub><sup>-</sup> (=N.D.) (Fig. 2(e) right).

Fig. 3(b) shows the removal efficiencies at the condition of water scrubbing with adding the bio-solution (NOE-7F\_50X), which indicated the significance of removal efficiencies on particle-bound water-soluble ions were observed for Na<sup>+</sup> (73.9%), Cl<sup>-</sup> (63.8%), NO<sub>3</sub><sup>-</sup> (26.5%) and SO<sub>4</sub><sup>2-</sup> (22.1%) ions at 180 °C and for Cl<sup>-</sup> (37.2%) and K<sup>+</sup> (35.9%) ions at 220 °C, respectively. Fig. 3(c) shows the removal efficiencies at the condition of water scrubbing with adding the bio-solution (NOE-7F\_100X), which indicated the significance of removal efficiencies on particle-bound water-soluble ions were observed for Cl<sup>-</sup> (49.2%), Na<sup>+</sup> (41.8%) and SO<sub>4</sub><sup>2-</sup>



**Table 3.** Particle-bound water-soluble ions concentrations in the cooking fumes with the treatment of water scrubbing with adding the bio-solution (NOE-7F\_50X).

Water-soluble ions (WSIs)	Sample A ( $\mu\text{g}/\text{Nm}^3$ )	Sample B ( $\mu\text{g}/\text{Nm}^3$ )	Sample C ( $\mu\text{g}/\text{Nm}^3$ )	Mean ( $\mu\text{g}/\text{Nm}^3$ )	S.D. ( $\mu\text{g}/\text{Nm}^3$ )
at 180°C					
Cl <sup>-</sup>	1.99	2.56	1.44	2.00	0.56
NO <sub>2</sub> <sup>-</sup>	ND	ND	ND	–	–
NO <sub>3</sub> <sup>-</sup>	2.39	2.90	3.22	2.84	0.42
SO <sub>4</sub> <sup>2-</sup>	4.59	4.97	3.94	4.50	0.52
Na <sup>+</sup>	1.50	0.95	0.72	1.06	0.40
K <sup>+</sup>	2.15	2.16	0.87	1.73	0.74
Mg <sup>2+</sup>	1.18	1.59	1.89	1.55	0.36
Ca <sup>2+</sup>	1.99	2.89	1.02	1.97	0.94
Total WSIs	15.79	18.02	13.10	15.65	
at 220°C					
Cl <sup>-</sup>	1.65	2.32	0.44	1.47	0.95
NO <sub>2</sub> <sup>-</sup>	ND	ND	ND	–	–
NO <sub>3</sub> <sup>-</sup>	3.86	4.54	4.44	4.28	0.37
SO <sub>4</sub> <sup>2-</sup>	7.72	7.79	8.64	8.05	0.51
Na <sup>+</sup>	4.20	3.03	3.03	3.42	0.68
K <sup>+</sup>	0.70	0.89	0.93	0.84	0.12
Mg <sup>2+</sup>	ND	1.11	1.01	0.71	0.07
Ca <sup>2+</sup>	1.01	0.94	0.80	0.91	0.11
Total WSIs	19.14	20.62	19.29	19.68	

**Table 4.** Particle-bound water-soluble ions concentrations in the cooking fumes with the treatment of water scrubbing with adding the bio-solution (NOE-7F\_100X).

Water-soluble ions (WSIs)	Sample A ( $\mu\text{g}/\text{Nm}^3$ )	Sample B ( $\mu\text{g}/\text{Nm}^3$ )	Sample C ( $\mu\text{g}/\text{Nm}^3$ )	Mean ( $\mu\text{g}/\text{Nm}^3$ )	S.D. ( $\mu\text{g}/\text{Nm}^3$ )
at 180°C					
Cl <sup>-</sup>	3.55	2.64	2.02	2.73	0.77
NO <sub>2</sub> <sup>-</sup>	ND	ND	ND	–	–
NO <sub>3</sub> <sup>-</sup>	4.10	4.27	4.43	4.26	0.17
SO <sub>4</sub> <sup>2-</sup>	5.14	4.89	5.47	5.17	0.29
Na <sup>+</sup>	2.72	1.51	2.97	2.40	0.78
K <sup>+</sup>	3.23	1.93	3.19	2.78	0.74
Mg <sup>2+</sup>	1.36	1.26	1.35	1.32	0.06
Ca <sup>2+</sup>	1.66	1.32	1.77	1.59	0.23
Total WSIs	21.76	17.82	22.20	20.25	
at 220°C					
Cl <sup>-</sup>	2.00	1.74	3.63	2.46	1.02
NO <sub>2</sub> <sup>-</sup>	ND	ND	ND	–	–
NO <sub>3</sub> <sup>-</sup>	4.02	4.56	3.93	4.17	0.34
SO <sub>4</sub> <sup>2-</sup>	4.80	4.94	4.25	4.66	0.36
Na <sup>+</sup>	1.85	1.49	3.48	2.27	1.06
K <sup>+</sup>	2.18	1.82	1.88	1.96	0.19
Mg <sup>2+</sup>	1.27	1.25	ND	0.84	0.02
Ca <sup>2+</sup>	1.37	1.13	1.41	1.31	0.15
Total WSIs	17.49	16.93	18.58	17.67	

(13.3%) ions at 180°C and for SO<sub>4</sub><sup>2-</sup> (10.9%) ion only at 220°C, respectively. Moreover, Fig. 3(d) shows the removal efficiencies at the condition of water scrubbing with adding the bio-solution (NOE-7F\_200X), which indicated the significance of removal efficiencies on particle-bound water-soluble ions were observed for Na<sup>+</sup> (86.6%), Cl<sup>-</sup> (85.9%), K<sup>+</sup> (59.2%), and SO<sub>4</sub><sup>2-</sup> (35.8%) ions

at 180°C and for Na<sup>+</sup> (88.4%), K<sup>+</sup> (57.9%), and Cl<sup>-</sup> (25.1%) ions at 220°C, respectively. For Cl<sup>-</sup> ion at 180°C, the mean removal efficiencies by WSB with adding NOE-7F\_200X (Fig. 3(d)) were 1.6 times in magnitude higher than that by water scrubbing only (Fig. 3(a)) and 1.4 times higher than that by WSB with adding NOE-7F\_50X (Fig. 3(b)). For Na<sup>+</sup> ion at 180°C, the mean removal efficiencies by WSB

**Table 5.** Particle-bound water-soluble ions concentrations in the cooking fumes with the treatment of water scrubbing with adding the bio-solution (NOE-7F\_200X)

Water-soluble ions (WSIs)	Sample A ( $\mu\text{g}/\text{Nm}^3$ )	Sample B ( $\mu\text{g}/\text{Nm}^3$ )	Sample C ( $\mu\text{g}/\text{Nm}^3$ )	Mean ( $\mu\text{g}/\text{Nm}^3$ )	S.D. ( $\mu\text{g}/\text{Nm}^3$ )
at 180°C					
Cl <sup>-</sup>	0.79	0.78	0.77	0.78	0.01
NO <sub>2</sub> <sup>-</sup>	ND	ND	ND	–	–
NO <sub>3</sub> <sup>-</sup>	4.45	3.16	3.13	3.58	0.76
SO <sub>4</sub> <sup>2-</sup>	4.57	3.52	3.48	3.86	0.62
Na <sup>+</sup>	0.77	0.53	0.33	0.55	0.22
K <sup>+</sup>	0.88	0.56	0.47	0.64	0.22
Mg <sup>2+</sup>	ND	ND	ND	–	–
Ca <sup>2+</sup>	ND	ND	ND	–	–
Total WSIs	11.46	8.55	8.18	9.41	
at 220°C					
Cl <sup>-</sup>	1.90	1.90	0.87	1.55	0.60
NO <sub>2</sub> <sup>-</sup>	ND	ND	ND	–	–
NO <sub>3</sub> <sup>-</sup>	2.86	4.60	3.62	3.69	0.87
SO <sub>4</sub> <sup>2-</sup>	6.62	7.63	6.19	6.81	0.74
Na <sup>+</sup>	0.06	0.51	0.14	0.24	0.24
K <sup>+</sup>	0.43	0.83	0.51	0.59	0.21
Mg <sup>2+</sup>	ND	1.19	1.05	0.75	0.10
Ca <sup>2+</sup>	0.74	1.19	0.75	0.89	0.25
Total WSIs	12.61	17.85	13.13	14.52	

with adding NOE-7F\_200X (Fig. 3(d)) were ~2.3 times in magnitude higher than that by water scrubbing only (Fig. 3(a)) and 1.2 times higher than that by WSB with adding NOE-7F\_50X (Fig. 3(b)). For K<sup>+</sup> ion at 180°C and 220°C, the mean removal efficiencies by WSB with adding NOE-7F\_200X (Fig. 3(d)) were much higher than that by water scrubbing only (Fig. 3(a)) or by WSB with adding NOE-7F\_50X.

Compared the results in Figs.3(a)–(d), it is indicated that adding NOE-7F bio-solution by diluted 200 folds into wet scrubber water and forming blended circulation water has the good removal efficiencies and reaches removal efficiencies higher than 80% for both Na<sup>+</sup> (86.6%) and Cl<sup>-</sup> (85.9%). In current stages, it is speculated that the addition of NOE-7F in the influent water had the enhanced effect on the particle-bound water-soluble ions removal and mainly promoted highly the hydrophilicity of particle-bound water-soluble ions in the water scrubber. In the future, more insightful experimental runs on such topics could be suggested.

## CONCLUSION

It revealed that adding NOE-7F bio-solution diluted ranged from 50–200 folds into wet scrubber water and forming blended circulation water is a practical way to enhance the removal efficiencies of particle-bound water-soluble ions from cooking fume. Totally, the removal efficiencies at the condition of water scrubbing with adding the bio-solution (NOE-7F\_200X) possesses the significance of removal efficiencies on particle-bound water-soluble ions were observed for Cl<sup>-</sup>, Na<sup>+</sup> and SO<sub>4</sub><sup>2-</sup> ions at 180°C and for Na<sup>+</sup>, K<sup>+</sup> and Cl<sup>-</sup> ions at 220°C,

respectively. Particularly, it is indicated that adding NOE-7F bio-solution by diluted 200 folds into wet scrubber water and forming blended circulation water has the good removal efficiencies and reaches removal efficiencies higher than 80% for both Na<sup>+</sup> (86.6%) and Cl<sup>-</sup> (85.9%). This study hints that the wet scrubber with adding bio-solution process has the potential to remove particle-bound water-soluble ions from cooking fume, helping kitchen environments to improve the indoor air quality for the concerns of public health.

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