Multielemental Elution Behavior of Metal Ions Adsorbed on Iminodiacetic Acid Chelating Resin by Using Hydrogen Peroxide as an Eluent

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In the present work, we investigated the multielemental elution behavior of metal ions adsorbed on iminodiacetic acid (IDA) chelating resin by using hydrogen peroxide (H_2O_2) as an eluent. As a result, V(V), Mo(VI), W(VI), Nb(V) and Ta(V) were efficiently eluted by H_2O_2 . In contrast, other metal ions were rarely recovered. The oxidation states of V(V), Mo(VI), and W(VI) were not changed through the H_2O_2 eluting process, checked by X-ray photoelectron analysis. In addition, the UV-vis adsorption spectra and IR spectra of V(V), Mo(VI) and W(VI) in the H_2O_2 eluent suggested the formation of metal-peroxo complexes through H_2O_2 elution. The desorption of these metal ions from IDA functional groups is explained in term of destabilization along with the coordination of peroxo-ligands to the V(V)-, Mo(VI)- and W(VI)-IDA complexes, and a decrease in the adsorption capacity by electrostatic repulsion between dissociated carboxylic groups of IDA and the oxoanions in the neutral pH shown in 30 wt% H_2O_2 . When this method was applied to the selective separation of V(V), Mo(VI) and W(VI) from other metals in an acid soluble fraction of fly-ash, $83.4 \pm 2.5\%$ of V(V), $88.1 \pm 3.3\%$ of Mo(VI), and $69.3 \pm 5.4\%$ of W(VI) were recovered in a 30 wt% H_2O_2 eluent.

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Introduction

Iminodiacetic acid chelating resin (IDA resin) is a most widely and commercially available chelating resin utilized for the separation and pretreatment of multivalent metal ions. For example, the removal of interferential matrixes prior to instrumental analysis and waste managements, such as precious-metal recycling and hazardous-metal eliminating, was performed.¹⁻⁴ In general, metal ions adsorbed on chelating resin are eluted by using strong acids, such as HNO_3 , HCl , and H_2SO_4 , in order to completely elute adsorbed metal ions from the resin. The elution of metal ions by using strong acids is achieved by exchange between metal ion and proton on the chelating functional groups.⁵ However, strong acids are not desirable solvents for the selective elution of adsorbed metal ions on the chelating resin.⁶

The present work was dealt with the elution of metal ions from IDA resin by using hydrogen peroxide (H_2O_2) as an eluent. H_2O_2 is a common reagent, and is widely used as redox reactive, decomposition, and titration reagents in chemical fields. Recently, the utilization of H_2O_2 is progressing in the “green” synthesis and selective oxidation of hydrocarbons.^{7,8} In fact, H_2O_2 can be recognized as an environmentally-friendly reagent, because it is a simple structural reagent consisting of only

hydrogen and oxygen atoms, and is easily decomposed to H_2O and O_2 by heat, light and catalysis. Therefore, H_2O_2 is considered to be a suitable solvent in the view of its purification of metals in the recycling process.

In this work, the multielemental elution behavior of over 25 kinds of metals adsorbed on IDA resin by using H_2O_2 as an eluent was investigated. This is the first attempt to characterize the elution behavior of metal ions from IDA resin by H_2O_2 . Furthermore, this technique was applied to the separation of metals from an acid-soluble fraction of a fly-ash sample.

Experimental

Instruments and reagents

Shimadzu ICPM 8500 with quadrupole mass filter and a glass concentric nebulizer (flow rate, $500 \mu\text{l min}^{-1}$; Glass Expansion, USA) was mainly used for metallic analysis. The major elements (Na, Ca, Mg, Fe, Al, Zn, Mn, Pb, and Cu) in the fly-ash sample were analyzed by ICP-AES (OPTIMA 3000, Perkin Elmer, Massachusetts, USA). The purified water used throughout the present experiment was prepared by a Milli-Q system (Millipore Gradient, Millipore, Tokyo, Japan). Multielement-containing solutions for recovery tests were prepared by mixing the single-element standard solutions listed in Table 1. According to a material data sheet of the standard solution for V from the manufacturer, it was prepared by dissolving metal V in a mixture of HNO_3 and HCl solutions.

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Table 1 Standard solutions used for the recovery test together with the measured mass number (m/z) for ICP-MS or wavelength for ICP-AES

Element	m/z or wavelength	Species ^a	Solvent ^a	Manufacturer ^a
Al(III)	308.215	Al(NO ₃) ₃	0.2 mol dm ⁻³ HNO ₃	Kanto
Ba(II)	137	Ba(NO ₃) ₂	0.5 mol dm ⁻³ HNO ₃	Kanto
Bi(III)	209	Bi(NO ₃) ₃	0.5 mol dm ⁻³ HNO ₃	Wako
Ca(II)	393.366	CaCO ₃	0.1 mol dm ⁻³ HNO ₃	Kanto
Cd(II)	111	Cd(NO ₃) ₂	0.1 mol dm ⁻³ HNO ₃	Kanto
Ce(III)	140	Ce(NO ₃) ₃	1 mol dm ⁻³ HNO ₃	Kanto
Co(III)	59	Co(NO ₃) ₃	0.1 mol dm ⁻³ HNO ₃	Kanto
Cu(II)	63 or 324.754	Cu(NO ₃) ₂	0.1 mol dm ⁻³ HNO ₃	Kanto
Dy(III)	164	Dy(NO ₃) ₃	1 mol dm ⁻³ HNO ₃	Wako
Er(III)	166	Er ₂ O ₃	1 mol dm ⁻³ HCl	Kanto
Eu(III)	153	Eu(NO ₃) ₃	1 mol dm ⁻³ HNO ₃	Wako
Fe(III)	259.940	Fe(NO ₃) ₃	0.1 mol dm ⁻³ HNO ₃	Wako
Ga(III)	69	Ga(NO ₃) ₃	1 mol dm ⁻³ HNO ₃	Kanto
Hf(IV)	178	HfF ₄	HF 5%	ACROS
In(III)	115	In(NO ₃) ₃	0.2 mol dm ⁻³ HNO ₃	Kanto
La(III)	139	La(NO ₃) ₃	1 mol dm ⁻³ HNO ₃	Wako
Mg(II)	279.079	Mg(NO ₃) ₂	0.1 mol dm ⁻³ HNO ₃	Wako
Mn(II)	55 or 257.610	Mn(NO ₃) ₂	0.1 mol dm ⁻³ HNO ₃	Kanto
Mo(VI)	98	MoO ₃	0.4 mol dm ⁻³ HCl, 0.2 mol dm ⁻³ HNO ₃	Kanto
Na(I)	588.995	NaCl	Water	Kanto
Nb(V)	93	NbF ₅	HF 2%	Kanto
Nd(III)	142	Nd(NO ₃) ₃	1 mol dm ⁻³ HNO ₃	Wako
Ni(III)	60	Ni(NO ₃) ₃	0.1 mol dm ⁻³ HNO ₃	Kanto
Pb(II)	208 or 220.353	Pb(NO ₃) ₂	0.1 mol dm ⁻³ HNO ₃	Kanto
Pr(III)	141	Pr(NO ₃) ₃	1 mol dm ⁻³ HNO ₃	Wako
Re(VII)	185	NH ₄ ReO ₄	Water	ACROS
Sm(III)	147	Sm(NO ₃) ₃	1 mol dm ⁻³ HNO ₃	Wako
Sr(II)	88	SrCO ₃	0.1 mol dm ⁻³ HNO ₃	Kanto
Ta(V)	181	TaF ₅	HF 2%, slight of HNO ₃	Kanto
Tl(I)	205	TlNO ₃	0.5 mol dm ⁻³ HNO ₃	Kanto
V(V)	51	V ^b	0.2 mol dm ⁻³ HCl, 0.5 mol dm ⁻³ HNO ₃	Wako
W(VI)	182	Na ₂ WO ₄	Water	Kanto
Yb(III)	172	Yb(NO ₃) ₃	1 mol dm ⁻³ HNO ₃	Kanto
Zn(II)	66 or 213.586	Zn(NO ₃) ₂	0.1 mol dm ⁻³ HNO ₃	Kanto
Zr(IV)	90	ZrO(NO ₃) ₂	1 mol dm ⁻³ HNO ₃	Kanto

a. All of the standard solutions of these elements were analytical grade for atomic absorption spectrometry. The manufacturers of the standard solutions were Kanto Chemicals Co. Ltd., Wako Pure Chemical Industries, and ACROS Chemicals, respectively. The species were referred from the chemicals and the solvents labeled in the side of the bottle of the standard solution.

b. The standard solution was prepared by dissolving metal V in 0.2 mol dm⁻³ HCl, 0.5 mol dm⁻³ HNO₃. The species of V(V) in the standard solution was estimated as VO₂⁺ by the reference.⁹

The species of V(V) in the standard solution was estimated to be mainly VO₂⁺ based on a reference.⁹ Infrared (IR) spectra and UV-visible (UV-vis) spectra were measured on an FTIR spectrometer (FT/IR-6200, JASCO Co. Ltd., Japan) and a UV-vis spectrometer (JASCO V-570 spectrometer, JASCO Co. Ltd., Japan), respectively. IDA resin (Muromac B-1; particle size, 0.3 – 1.3 mm; Na⁺ form) was purchased from Muromachi Tecnos Inc. (Tokyo). The IDA resin was used after purification by loading HCl to the IDA resin. PTFE membrane filters (pore

size, 0.45 μm) were also purchased from Nihon Millipore Kogyo (Tokyo, Japan).

Elution of metal ions from the IDA resin

The typical procedure of adsorption and elution was as follows. First, 1 g of a 100 mg kg⁻¹ metal containing solution was added to 15 g of an acetate buffer solution. The pH of the sample was then adjusted to 5. Next, after 1 g (dry weight) of the IDA resin was added into it, the solution was vigorously shaken for 2 h at 200 rpm. The IDA resin was separated by centrifugation at 3500 rpm for 1 min. The supernatant was removed by decantation, and the resin was washed with a few ml of pure water. The adsorbed metal ions on the IDA resin were eluted by 10 g of a H₂O₂ aqueous solution. Then, 0.1 ml of 1 mg kg⁻¹ Ga, In, and Bi solution was added as internal standard elements for ICP-MS analysis.

In an XPS experiment to identify oxidation states of V, Mo, and W in the H₂O₂ eluent, analytical samples were prepared by following scheme. One-hundred grams of an original solution (pH 5) containing 2.5 g kg⁻¹ for NH₄VO₃, 2.4 g kg⁻¹ for (NH₄)₆Mo₇O₂₄·4H₂O, and 6.7 g kg⁻¹ for Na₂WO₄ were firstly loaded on 10 g of IDA resin in order to adsorb V(V), Mo(VI), and W(VI) on the IDA resin. After washing the resin with pure water, 10 g of a 30 wt% H₂O₂ solution was introduced to the V(V), Mo(VI), and W(VI) adsorbed IDA resin. The H₂O₂ eluent was evaporated so as to remove the solvent. After evaporating, the residues were analyzed by an XPS instrument (ESCA-1000, Shimadzu) to characterize the oxidation states.

Procedure of the recovery test used with an acid soluble fraction of metals in a fly-ash sample

An acid soluble fraction of a fly-ash sample was used for a recovery test in order to evaluate the practical applicability of the present method toward the selective separation of specific metals (V, Mo, and W). The acid soluble fraction was obtained by the following scheme. The fly-ash of some municipal waste, which was collected at an incineration plant in Tokushima city, was homogenized with a mortar. Twenty grams of the ash were treated in 60 g of *aqua regia* at 100°C for 24 h, and then at 180°C for 3 h. The *aqua regia* was filtrated by using a 0.45-μm pore-size membrane filter. The filtrated solution was evaporated by the radiation of an infrared lamp in order to remove hydrochloric acid in the *aqua regia* soluble fraction. The reason why the hydrochloric acid was removed from the acid soluble fraction is that ⁵¹V as analytical isotope is severely interfered from ³⁵Cl¹⁶O in ICP-MS analysis determining original concentration in the acid soluble fraction.¹⁰ The residue was dissolved by 60 g of 2 M HNO₃ with heating at 80°C. The 2 M HNO₃ solution was filtered by a 0.45-μm pore-size membrane filter. The filtrated sample was used as an acid soluble fraction for the recovery test. The original concentrations of V, Mo, and W in the acid soluble fraction were V, 11.6 mg kg⁻¹; Mo, 5.83 mg kg⁻¹; and W, 0.0873 mg kg⁻¹, respectively. The recovery test was performed as follows. At first, 1.5 g of 100 mg kg⁻¹ for V and 0.5 g of 100 mg kg⁻¹ for Mo and W containing solution were spiked to 0.65 g of the acid soluble fraction to estimate their recoveries. Then, 28 g of ammonium acetate buffer solution (pH 4) and 6 g of IDA resin were added to the acid soluble fraction. The solution was vigorously shaken for 2 h at 200 rpm. The IDA resin was separated by centrifugation at 3500 rpm for 1 min. The supernatant was removed by decantation, and the resin was washed with a few ml of pure water. Then, 10 g of a 30 wt% of H₂O₂ solution was added into the IDA resin, and the solution was shaken. The H₂O₂ solution containing IDA resin was centrifuged at 3500 rpm

Table 2 Recoveries of metal ions adsorbed on IDA resin by using 30 wt% H₂O₂ and 2 M HNO₃ as an eluent

Element	Recovery, %	
	30 wt% H ₂ O ₂ ^a	2 M HNO ₃
Mo(VI)	94.4 ± 2.3	92.1
V(V)	93.8 ± 2.2	91.0
Nb(V)	80.1 ± 4.4	82.2
Ta(V)	76.8 ± 3.8	79.3
W(VI)	66.5 ± 2.3	62.4
Zr(IV)	2.60 ± 0.04	36.3
Tl(I)	2.13 ± 0.06	32.1
Ba(II)	0.88 ± 0.08	94.8
Cd(II)	0.57 ± 0.55	95.2
Sr(II)	0.56 ± 0.05	94.4
Yb(III)	0.53 ± 0.52	91.4
Er(III)	0.48 ± 0.49	92.5
Dy(III)	0.44 ± 0.46	93.0
Ce(III)	0.01 ± 0.00 ₂	94.8
Pr(III)	0.00 ₄ ± 0.00 ₁	94.8
Eu(III)	0.01 ± 0.00 ₂	96.2
Nd(III)	0.01 ± 0.00 ₀₀₃	95.9
Sm(III)	0.01 ± 0.00 ₃	95.6
Pb(II)	0.28 ± 0.24	82.0
Hf(IV)	0.20 ± 0.03	75.5
Co(III)	0.15 ± 0.08	94.8
Ni(III)	0.06 ± 0.03	97.7
Al(III)	ADL ^b	42.2
Fe(III)	ADL ^b	84.1
La(III)	ADL ^b	95.8
Mn(II)	ADL ^b	98.0
Zn(II)	ADL ^b	99.2

a. Mean ± standard deviation, $n = 3$.

b. The ADL indicates that the concentration in the H₂O₂ eluent was less than the instrumental detection limit measured by ICP-AES or ICP-MS.

for 1 min, and filtered by a 0.45- μ m pore-size disposable membrane filter. The H₂O₂ eluent was diluted by 50-fold with the addition of 0.1 M HNO₃. Then, 0.2 g of a 1 mg kg⁻¹ Re solution was added to the analytical solution for an internal standard correction in the ICP-MS analysis. The recovery and removal rate were estimated using the following Eqs. (1) and (2), respectively:

$$\text{Recovery \%} = (C_1/C_0) \times 100, \quad (1)$$

$$\text{Removal rate \%} = (C_1 - C_0)/C_0 \times 100. \quad (2)$$

C_0 and C_1 are the amounts (μ g) of the metal ion contained in the original solution loaded to the IDA resin, and that in the eluted H₂O₂ solution, respectively. The recovery and removal rate were used as an index of recovering the target metals (V, Mo and W), and of removing the other metals, respectively.

Results and Discussion

Elution behavior of metal ions adsorbed on the IDA resin by H₂O₂

The recoveries of metal ions by using 30 wt% H₂O₂ as the eluent are listed in Table 2, together with those by 2 M HNO₃. As can be seen in Table 2, V(V), Mo(VI), W(VI), Nb(V), and Ta(V) showed higher recoveries than other metal ions in the

Fig. 1 Dependence of the H₂O₂ concentration in the elution process on the recoveries of V, Mo and W.

H₂O₂ eluting process. Furthermore, the recoveries of V(V), Mo(VI), W(VI), Nb(V), and Ta(V) by the H₂O₂ elution were similar to those by 2 M HNO₃ elution, which provided complete elution of the adsorbed metal ions on the IDA resin.¹¹ This result means that V(V), Mo(VI), W(VI), Nb(V), and Ta(V) adsorbed on the IDA resin could be almost removed by H₂O₂ elution. Thus, the dependence of the recoveries of V(V), Mo(VI), and W(VI) on the H₂O₂ concentration was examined. The results are shown in Fig. 1. It can be seen in Fig. 1 that the V(V), Mo(VI), and W(VI) recoveries increased with an increase in the H₂O₂ concentration. Since 30 wt% H₂O₂ is the highest concentration in commercially available H₂O₂, we used it for experiments of H₂O₂ elution after this.

Subsequent elution by using 2 M HNO₃ after 30 wt% H₂O₂ elution was tested. The recoveries of the metal ions by H₂O₂ elution and a 2 M HNO₃ subsequent elution are shown in Fig. 2, together with those by 2 M HNO₃ single elution. As a result, the trend of the recoveries by 2 M HNO₃ subsequent elution was complementary observed against those by H₂O₂ elution. In fact, the summation of the recoveries by H₂O₂ elution and subsequent HNO₃ elution was quite similar to those of 2 M single HNO₃ elution. This result indicates that H₂O₂ elution did not affect the adsorption status of these metal ions, except for V(V), Mo(VI), W(VI), Nb(V), and Ta(V).

Investigation of the elution mechanisms of V(V), Mo(VI), and W(VI) ion by the H₂O₂ treatment

It is widely known that H₂O₂ is a redox-active reagent, and has both redox functions, as a reductant and an oxidizer. The oxidation state of metal ions strongly affects the formations and stabilities of complexes. Thus, the oxidation numbers of V, Mo, and W in the H₂O₂ eluent were checked by XPS analysis. Accordingly, the X-ray energies of the V, Mo, and W in the H₂O₂ eluent were 517.4, 232.5, and 35.4 eV, which could be identified as 2p_{3/2} vanadate, 3d_{5/2} molybdate, and 4f_{7/2} tungstate by the NIST XPS database, respectively.¹² That is, the oxidation states of V, Mo, and W in the H₂O₂ eluent were confirmed to be V(V), Mo(VI), and W(VI), respectively. The oxidation states did not change throughout the treatment process. In other words, no redox reactions occurred in the H₂O₂ elution.

Early transition-element ions in their highest oxidation state (d^0 electron configuration) can be functioned as Lewis acids toward hydrogen peroxide.¹³ Thus, the UV-vis absorption spectra and IR spectra of V(V), Mo(VI) and W(VI) ions before and after H₂O₂ elution were investigated in order to track the

Fig. 2 Recoveries of metal ions obtained by 30 wt% H_2O_2 elution (upper), 2 M HNO_3 subsequent elution after the 30 wt% H_2O_2 elution (middle) and 2 M HNO_3 single elution (lower). The error bar was estimated as the standard deviation of the recovery in 3-times replicate experiments.

coordination process of peroxo ligands. The UV-vis absorption spectra are shown in Fig. 3. The adsorption peaks of V(V), Mo(VI) and W(VI) ions in the H_2O_2 eluent were shifted to higher wavelength number. The adsorption peaks of V, Mo and W in the H_2O_2 eluent were 326, 309, and 242 nm, respectively, and similar to those of peroxo-complexes.^{14,15} Furthermore, the IR spectra of V(V), Mo(VI) and W(VI) in the H_2O_2 eluent are shown in Fig. 4. The IR spectra of the H_2O_2 eluent show a peak at around 920 cm^{-1} for V(V), a narrow peak at 900 cm^{-1} and a broad peak between 800 and 880 cm^{-1} for Mo(VI), and two peaks at 830 – 850 and 920 – 925 cm^{-1} for W(VI). Reynolds and Butler have reported that the wavenumbers of the O–O stretching of the peroxo-complexes were observed in 900 – 920 and 875 – 900 cm^{-1} for V(V), 900 and 865 – 875 cm^{-1} for Mo(VI), and 835 cm^{-1} for W(VI), respectively.¹⁴ The present UV and IR studies suggest the formation of peroxo-complexes through the H_2O_2 elution process. Peroxo-complexes of V(V), Mo(VI) and W(VI) are highly stable, due to the coordination of two peroxide groups in the equatorial plane.¹⁶ In addition, Funahashi *et al.* have reported that the substitution of the peroxo-ligand to VO_4^{2-} and MoO_4^{2-} ions is very labile.¹⁷ In such a neutral pH range shown in the 30 wt% H_2O_2 solution (30 wt% H_2O_2 solution shows *ca.* pH 7), mono- and diperoxo-species become predominated species.^{18,19} Mo(VI) and W(VI) ions

Fig. 3 UV-vis absorption spectra observed in the original solution and the H_2O_2 eluent. The gray and black lines indicate the UV-vis absorption spectrum of each metal in the original solution and the H_2O_2 eluting solution, respectively. The condition of the H_2O_2 elution is mentioned in the Experimental section. The H_2O_2 concentration was set at 0.1 wt%. The original V, Mo, and W solutions were prepared by dissolving NH_4VO_3 , $(\text{NH}_4)_6\text{Mo}_7\text{O}_{24} \cdot 4\text{H}_2\text{O}$, and Na_2WO_4 into pure water, respectively.

form a 1:1 octahedral complex $([\text{MO}_3(\text{IDA})]^{2-})$, (M: Mo(VI) or W(VI)), where a nitrogen and two proton-dissociated carboxylic acids of IDA coordinate the metal core, with the IDA functional group in a weak acidic and neutral pH range.²⁰ It is expected that substitution of the peroxide ligand causes a depression of the stability of the metal-IDA complex as a side reaction. Furthermore, the adsorption capacities of the V(V), Mo(VI) and W(VI) ions to the IDA ligands in both the neutral and basic pH range are remarkably weaker than those in the acidic pH range.^{20,21} Depression of the adsorption capacity may be caused by electrostatic repulsion between the oxo (peroxo)-anions and the dissociated carboxylic acid groups in IDA. In fact,

Fig. 4 Infrared spectra observed in the H_2O_2 eluent. The H_2O_2 eluents were freeze-dried, and then the residues were mixed with KBr. The KBr pellets were used for IR analysis.

the predominant species of the oxoanion are shifted from H_2VO_4^- to HVO_4^{2-} for V(V), from HMoO_4^- to MoO_4^{2-} for Mo(VI), and from HWO_4^- to WO_4^{2-} for W(VI), also, the anionic properties increase toward the high pH region.²² In conclusion, the desorption of these metal ions from IDA functional groups was generated by destabilization along with coordination of the peroxo-ligands to the V(V), Mo(VI) and W(VI)-IDA complex, and a decrease in the adsorption capacity by the electrostatic repulsion between IDA and oxoanions generated in the neutral pH range.

Separation of V, Mo, and W in an acid soluble fraction of incineration fly-ash of waste

The method was applied to the separation of V, Mo, and W in an acid soluble fraction of fly-ash. The recoveries of V, Mo, W and the removal rates of major metals are summarized in Table 3. The recoveries of V, Mo, and W were 83.4, 88.1, and 69.3%, respectively. The relative standard deviations of the recoveries of V, Mo and W were less than 10%. The concentrations of almost all major elements in the acid soluble fraction were less than the instrumental detection limits, measured by ICP-AES or ICP-MS. The removal rates of all of these elements were higher than 92%.

Conclusions

Consequently, the H_2O_2 elution and the subsequent elution of HNO_3 to the IDA resin allows metal ions to be separated into three groups. Alkaline and alkaline earth elements ions are firstly separated from other multivalent metal ions in the adsorption to IDA resin because of their very low chelating ability. Secondly, V(V), Mo(VI), W(VI), Nb(V), and Ta(V) can be separated by H_2O_2 elution from other multivalent metal ions adsorbed on the IDA resin. Finally, the remaining metal ions adsorbed on the IDA resin can be subsequently eluted by a HNO_3 solution.

A highly selective separation of oxoanion-forming elements, such as V, Mo, W, Nb, and Ta, from over 20 elements adsorbed IDA resin by using H_2O_2 was established. Especially, V, Mo, and W are designated as stockpiled mineral species by the

Table 3 Recoveries and removal rates of metal ions from the acid soluble fraction of fly-ash with the IDA resin adsorption/ H_2O_2 elution method

Element	Spike/ μg	Found/ μg	Recovery, % ^a	RSD ^b
V(V)	160	133	83.4 $\pm$ 2.5	3.0
Mo(VI)	53.3	48.5	88.1 $\pm$ 3.3	3.7
W(VI)	52.6	36.5	69.3 $\pm$ 5.4	7.8
	Before/ μg	After treatment/ μg	Removal rate, % ^a	
Ca	23100	4.48	>99.9	
Na	4912	106	97.8	
Mg	1663	ADL ^c	99.7	
Al	5041	ADL ^c	99.8	
Fe	2301	ADL ^c	>99.9	
Zn	142	ADL ^c	99.9	
Mn	52.2	ADL ^c	99.6	
Pb	47.0	ADL ^c	92.4	
Cu	27.6	ADL ^c	98.1	
Ni	13.6	ADL ^c	99.8	
Ga	2.17	ADL ^c	>99.9	
Co	1.16	ADL ^c	99.3	
In	0.03	ADL ^c	97.3	

a. Mean $\pm$ standard deviation, $n = 3$.

b. Relative standard deviation, %.

c. ADL indicates that the concentration in the H_2O_2 eluent after the treatment was less than the instrumental detection limit measured by ICP-AES or ICP-MS.

Japanese Government.²³ Since this method provides a selective separation of these elements from many elements in a one-step process, this will be a useful method for recycling them from industrial wastes.

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