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Aluminium ion-promoted radical-scavenging reaction of methylated hydroquinone derivatives

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The effect of the aluminium ion (Al^{3+}) on the scavenging reaction of a 2,2-diphenyl-1-picrylhydrazyl radical (DPPH $^\bullet$), as a reactivity model of reactive oxygen species, with hydroquinone (QH_2) and its methylated derivatives (Me_nQH_2 , $n = 1-4$) was investigated using stopped-flow and electrochemical techniques in a hydroalcoholic medium. The second-order rate constants (k) for the DPPH $^\bullet$ -scavenging reaction of the hydroquinones increased with the increasing number of methyl substituents. Upon addition of Al^{3+} , the k values significantly increased depending on the concentration of Al^{3+} . Such an accelerating effect of Al^{3+} on the DPPH $^\bullet$ -scavenging rates of the hydroquinones results from the remarkable positive shift of the one-electron reduction potential (E_{red}) of DPPH $^\bullet$ in the presence of Al^{3+} . These results demonstrate that Al^{3+} , a strong Lewis acid, can act as a radical-scavenging promoter by stabilising the one-electron reduced species of the radical, although Al^{3+} is reported not only to act as a pro-oxidant but also to strongly interact with biomolecules, showing toxicities.

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Introduction

Metal ions are known to play important roles in controlling biological redox reactions.¹ It is also well known that metal ions accelerate electron-transfer reactions by binding to electron acceptors.² Furthermore, they are reported to form transient complexes with the superoxide anion ($\text{O}_2^{\bullet-}$), which is one of the reactive oxygen species (ROS).^{3,4} Among them, a complex of Al^{3+} with $\text{O}_2^{\bullet-}$ contributes to promote the Fenton reaction by reducing Fe^{3+} to Fe^{2+} to produce hydroxyl radicals ($\text{^{\bullet}OH}$), the strongest ROS.⁵ In addition, Al^{3+} as a strong Lewis acid forms a variety of stable complexes with proteins and biomolecules, such as citrate, glutamate and α -ketoglutarate.⁶

Al^{3+} also interacts with molecules containing phosphate groups, such as AMP, ATP, RNA and DNA.⁷ These complexes disrupt the cell metabolic processes, leading to neurological diseases.⁸

Ubiquinol (UQH_2), the reduced form of coenzyme Q_{10} , has a hydroquinone (QH_2) structure as an active centre, showing an efficient scavenging activity against ROS.⁹ In human beings, ROS are generated as side products during the energy production by mitochondrial electron-transport systems or the elimination of virus and bacteria in macrophages and neutrophils. However, excessive ROS cause many diseases, such as cancer, diabetes, cardiovascular disease, Alzheimer's and Parkinson's disease by oxidising proteins, lipids and DNA.^{10,11} Thus, antioxidants are very useful to protect against oxidative stress and may lead to prevention of these diseases. UQH_2 is one of the lipid-soluble antioxidants and efficiently scavenges lipid peroxy radicals.^{12,13} Furthermore, UQH_2 reacts with the α -tocopheroyl radical to regenerate α -tocopherol inside the biomembrane.¹⁴⁻¹⁶ On the other hand, QH_2 is a major benzene metabolite and is widely applied in human and industrial activities. QH_2 is used as an antioxidant in the rubber and food industries due to its antioxidant activity.¹⁷ QH_2 also has a long history of use in pigmentary disorders and is applied in the commercially available cosmetic skin lightning formulations.¹⁸⁻²⁰

The radical-scavenging reactions of phenolic antioxidants, such as flavonoids and α -tocopherol, are affected by redox-inactive metal ions, such as Mg^{2+} , Al^{3+} and Sc^{3+} .²¹⁻²³ However, little is known about the effects of metal ions on the radical-scavenging reaction of QH_2 and its derivatives.

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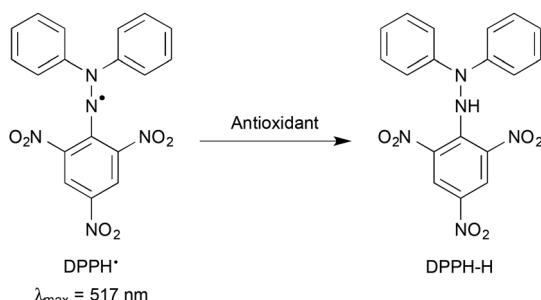
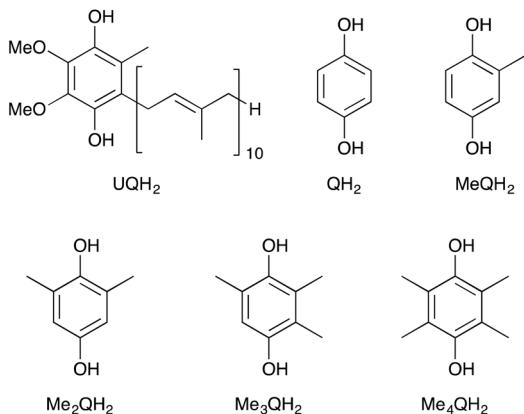
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Fig. 1 DPPH[•] as a model of ROS.Fig. 2 Structures of UQH₂, QH₂ and its methylated derivatives.

Particularly, whether Al³⁺ promotes the radical-scavenging reactions of antioxidants or acts as a pro-oxidant is yet to be clarified.

We report herein the effects of Al³⁺ on the scavenging reaction of a 2,2-diphenyl-1-picrylhydrazyl radical (DPPH[•]) (Fig. 1) with QH₂ and its methylated derivatives, which are methylhydroquinone (MeQH₂), 2,6-dimethylhydroquinone (Me₂QH₂), trimethylhydroquinone (Me₃QH₂) and tetramethylhydroquinone (Me₄QH₂) (Fig. 2).²⁴ DPPH[•] is frequently used as a reactivity model of peroxy radicals, which are relatively less reactive ROS compared to hydroxyl and alkoxyl radicals.^{25–30} In addition, we investigated the effects of the number of methyl substituents of the hydroquinones on the DPPH[•]-scavenging activity. Furthermore, the electron-donating ability of the hydroquinones and the electron-accepting ability of DPPH[•] were also evaluated by cyclic voltammetry (CV) and second-harmonic alternating current voltammetry (SHACV) in the absence and presence of Al³⁺.^{31–35} The strong Lewis acidity of Al³⁺ enhanced the electron-accepting ability of DPPH[•], leading to an acceleration of the DPPH[•]-scavenging reaction by the hydroquinones.

Experimental

Materials

QH₂ and its methylated derivatives were purchased from Tokyo Chemical Industry Co., Ltd, Japan. DPPH[•] was purchased from

Wako Pure Chemical industries, Ltd. Tetra-*n*-butylammonium perchlorate (Bu₄NClO₄), used as a supporting electrolyte for the electrochemical measurements, was purchased from Tokyo Chemical Industry Co., Ltd, Japan. Bu₄NClO₄ was recrystallised from ethanol (EtOH) and dried under vacuum at 313 K. Aluminium perchlorate nonahydrate [Al(ClO₄)₃·9H₂O] was purchased from Wako Pure Chemical Ind. Ltd, Japan. EtOH (spectral grade) used as a solvent was purchased from Nacalai Tesque, Inc., Japan.

Spectral and kinetic measurements

To avoid the effect of molecular oxygen (O₂), the reactions were carried out under strictly deaerated conditions. A continuous flow of argon gas was bubbled through an EtOH-H₂O (9 : 1 v/v) solution (3.0 mL) containing DPPH[•] (5.0–8.9 × 10^{−5} M) or the hydroquinones (1.1–6.6 × 10^{−3} M) in a reservoir of the spectrophotometer for 7 min. The rates of the DPPH[•]-scavenging reactions of the hydroquinones were determined by monitoring the absorbance change at 517 nm due to DPPH[•] using a stopped-flow technique on a UNISOKU RSP-1000-02NM spectrophotometer. The pseudo-first-order rate constants (k_{obs}) were determined by least-squares curve fit using an Apple MacBook Pro personal computer. The first-order plots of $\ln(A - A_{\infty})$ vs. time (A and A_{∞} denoted as the absorbance at the reaction time and the final absorbance, respectively) were linear until three or more half-lives with the correlation coefficient $\rho > 0.999$. The reaction of hydroquinones with DPPH[•] in the presence of various concentrations of Al(ClO₄)₃ was carried out in the same manner.

Electrochemical measurements

The cyclic voltammetry (CV) and second-harmonic alternating current voltammetry (SHACV)³⁶ measurements were performed on an ALS-630A electrochemical analyser in deaerated EtOH-H₂O (9 : 1 v/v) containing 0.1 M Bu₄NClO₄ as a supporting electrolyte. The glassy carbon-working electrode (BAS) was polished with BAS polishing alumina suspension and rinsed with methanol before use. The counter electrode was a platinum wire. The measured potentials were recorded with respect to an Ag/AgNO₃ (0.01 M) reference electrode. One-electron oxidation potentials (E_{ox}) of hydroquinones and one-electron reduction potentials (E_{red}) of DPPH[•] (vs. Ag/AgNO₃) were converted to those vs. SCE by adding 0.29 V.³⁷ All electrochemical measurements were carried out at room temperature under 1 atm Ar.

pH measurements

The pH values of the solutions of hydroquinones in the presence or absence of the metal ion in EtOH-H₂O (9 : 1 v/v) were measured by using a METTLER TOLEDO SevenEasy pH meter.

Results and discussion

Kinetics of the DPPH[•]-scavenging reaction of the hydroquinones in the presence or absence of Al³⁺

The rate of the DPPH[•]-scavenging reaction of the hydroquinones was measured by monitoring the absorbance change



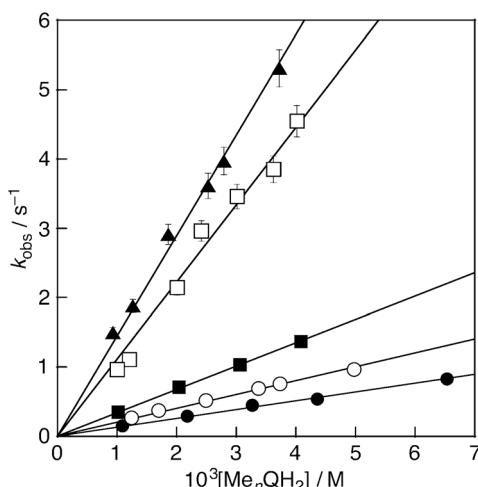


Fig. 3 Plots of k_{obs} vs. $[\text{Me}_n\text{QH}_2]$ ($n = 0-4$) for the reaction of QH_2 (closed circles), MeQH_2 (open circles), Me_2QH_2 (closed squares), Me_3QH_2 (open squares) and Me_4QH_4 (closed triangles) with DPPH^{\cdot} in deaerated $\text{EtOH-H}_2\text{O}$ (9:1 v/v) at 298 K.

Table 1 Second-order rate constants (k) for the DPPH^{\cdot} -scavenging reaction of the hydroquinones in the presence or absence of $\text{Al}(\text{ClO}_4)_3$ in deaerated $\text{EtOH-H}_2\text{O}$ (9:1 v/v) at 298 K

$[\text{Al}(\text{ClO}_4)_3]$ /M	$k/\text{M}^{-1} \text{s}^{-1}$				
	QH_2	MeQH_2	Me_2QH_2	Me_3QH_2	Me_4QH_2
0	1.3×10^2	2.0×10^2	3.4×10^2	1.1×10^3	1.4×10^3
0.05	3.5×10^2	7.0×10^2	1.0×10^3	2.7×10^3	3.0×10^3
0.1	3.9×10^2	9.3×10^2	1.7×10^3	3.4×10^3	3.5×10^3
0.2	3.4×10^2	1.1×10^3	2.8×10^3	5.3×10^3	5.4×10^3
0.3	5.8×10^2	1.3×10^3	3.2×10^3	6.3×10^3	5.8×10^3
0.5	5.2×10^2	1.1×10^3	4.4×10^3	7.5×10^3	8.2×10^3

at 517 nm due to DPPH^{\cdot} using a stopped-flow technique in deaerated $\text{EtOH-H}_2\text{O}$ (9:1 v/v) at 298 K. The decay of the absorbance at 517 nm obeyed pseudo-first-order kinetics, when the concentration of the hydroquinones ($[\text{Me}_n\text{QH}_2]$) ($n = 0-4$) was maintained at a more than 10-fold excess of the DPPH^{\cdot} concentration. The pseudo-first-order rate constants (k_{obs}) increase with increasing $[\text{Me}_n\text{QH}_2]$, exhibiting the first order dependence on $[\text{Me}_n\text{QH}_2]$ (Fig. 3). From the slope of the linear plots of k_{obs} vs. $[\text{Me}_n\text{QH}_2]$, the second-order rate constants (k) were determined for the DPPH^{\cdot} -scavenging reaction (Table 1). The k values of the hydroquinones increased with the increasing number of methyl substituents in the absence of metal ions. Upon addition of $\text{Al}(\text{ClO}_4)_3$ (0.05–0.50 M) to the hydroquinone– DPPH^{\cdot} system, the k values for all the hydroquinones significantly increased with the increasing $\text{Al}(\text{ClO}_4)_3$ concentration (Fig. 4, Table 1).

Effect of Al^{3+} on the redox behaviour of the hydroquinones and DPPH^{\cdot}

The one-electron oxidation potentials (E_{ox}) of the hydroquinones were determined by cyclic voltammetry (CV) and

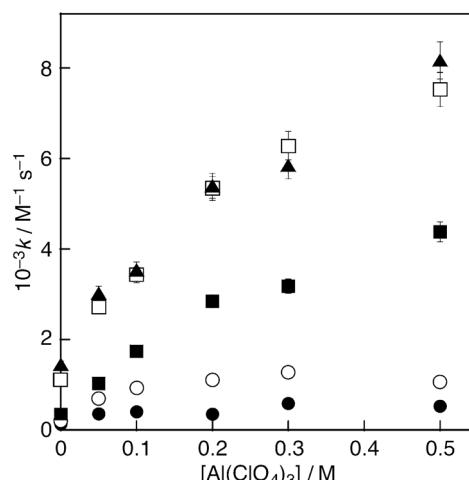


Fig. 4 Plots of k vs. $[\text{Al}(\text{ClO}_4)_3]$ for the reaction of QH_2 (closed circles), MeQH_2 (open circles), Me_2QH_2 (closed squares), Me_3QH_2 (open squares) and Me_4QH_4 (closed triangles) with DPPH^{\cdot} in deaerated $\text{EtOH-H}_2\text{O}$ (9:1 v/v) at 298 K.

second-harmonic alternating current voltammetry (SHACV)³⁶ measurements in the presence or absence of Al^{3+} in $\text{EtOH-H}_2\text{O}$ (9:1 v/v) to investigate the detailed effects of Al^{3+} on the DPPH^{\cdot} -scavenging reaction of the hydroquinones. The E_{ox} values of the hydroquinones were determined from the intersection of SHACV waves (Fig. 5). In the absence of the metal ion, the E_{ox} values of the hydroquinones were shifted to the negative direction with the increasing number of methyl substituents (Table 2). The electron-donating methyl substituents contribute to an increase in the electron density, leading to an enhancement of the electron-donating ability of the hydroquinones.

Upon addition of $\text{Al}(\text{ClO}_4)_3$ (0.05–0.5 M), the E_{ox} values of hydroquinones were significantly shifted to the positive direction

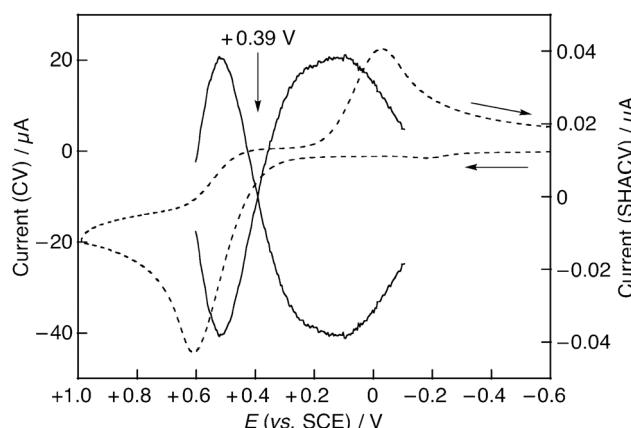


Fig. 5 Cyclic voltammogram (CV) (dashed line) and second-harmonic alternating current voltammogram (SHACV) (solid line) of QH_2 (2.4×10^{-3} M) recorded at the scan rate of 0.1 V s^{-1} and 4 mV s^{-1} , respectively, on a glassy carbon working electrode in $\text{EtOH-H}_2\text{O}$ (9:1 v/v) ($0.1 \text{ M Bu}_4\text{NClO}_4$).

Table 2 The E_{ox} values of hydroquinones and the E_{red} values of DPPH[•] in EtOH–H₂O (9 : 1 v/v) in the presence or absence of Al(ClO₄)₃

[Al(ClO ₄) ₃]/M	E_{ox} (vs. SCE) ^a /V					E_{red} (vs. SCE)/V
	QH ₂	MeQH ₂	Me ₂ QH ₂	Me ₃ QH ₂	Me ₄ QH ₂	
0	+0.39	+0.36	+0.29	+0.23	+0.19	+0.23
0.05	+0.48	+0.42	+0.36	+0.29	+0.24	+0.67 ^a
0.1	+0.54	+0.47	+0.39	+0.33	+0.28	+0.69 ^a
0.2	+0.55	+0.48	+0.40	+0.34	+0.28	+0.70 ^a
0.3	+0.56	+0.50	+0.42	+0.36	+0.30	+0.70 ^a
0.5	+0.56	+0.50	+0.42	+0.36	+0.32	+0.69 ^a

^a Determined by SHACV at the rate of 4 mV s⁻¹ on a glassy carbon working electrode (0.1 M Bu₄NClO₄).

depending on the concentration of Al³⁺ (Table 2). Thus, the one-electron donating ability of the hydroquinones was decreased in the presence of Al³⁺. The pK_a values of the hydroquinones in H₂O and DMSO are listed in Table 3.^{38,39} The pH values of the hydroquinone solutions in the presence or absence of Al(ClO₄)₃ in EtOH–H₂O (9 : 1 v/v) are shown in Table 4. The pK_a values of the hydroquinones used in this study in aqueous solution are in the range of 9.9–11.3 (Table 3). Thus, all the hydroquinones do not undergo deprotonation and exist in their neutral forms. The one-electron reduction potential (E_{red}) of DPPH[•] was also determined using CV in the presence or absence of Al³⁺. In the absence of Al³⁺, two well-defined reversible redox waves were observed as shown in Fig. 6 (dashed line), from which the one-electron reduction potential of DPPH[•] was determined to be +0.23 V vs. SCE. In the presence of 0.1 M Al(ClO₄)₃, however, the cyclic voltammogram of DPPH[•] was remarkably changed and the E_{red} value of DPPH[•] was significantly shifted to the positive direction (Fig. 6, Table 2). These results indicated that the DPPH anion (DPPH[–]), the one-electron reduced species of DPPH[•], strongly interacted with Al³⁺ to enhance the electron-accepting ability of DPPH[•]. The effects of metal ions on the E_{red} of DPPH[•] differed by the Lewis acidity.⁴⁰

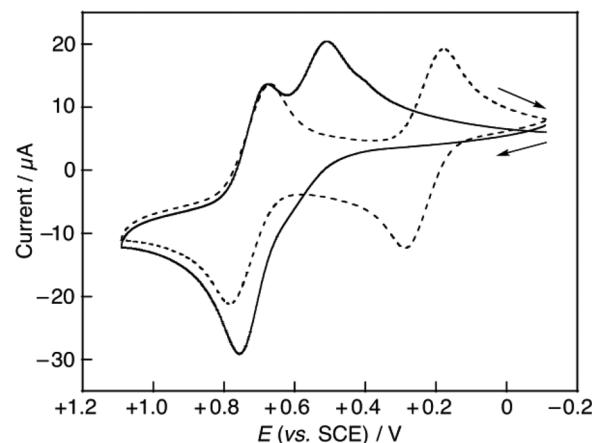
Table 3 The pK_a values of hydroquinones

	QH ₂	MeQH ₂	Me ₂ QH ₂	Me ₃ QH ₂	Me ₄ QH ₂
pK _a	9.9 ^a	10.1 ^a	—	—	11.3 ^a
	19.1 ^b	18.3 ^b	19.0 ^b	17.8 ^b	20.0 ^b

^a The pK_a values in aqueous solution.³⁸ ^b The pK_a values in DMSO.³⁹

Table 4 The pH values of hydroquinone solutions in EtOH–H₂O (9 : 1 v/v) containing 0.1 M Bu₄NClO₄ in the presence or absence of Al(ClO₄)₃

[Al(ClO ₄) ₃]/M	QH ₂	MeQH ₂	Me ₂ QH ₂	Me ₃ QH ₂	Me ₄ QH ₂
0	5.5	4.7	4.7	4.5	4.6
0.05	2.1	2.2	2.1	2.1	2.1
0.1	1.7	1.8	1.6	1.7	1.7
0.2	1.5	1.5	2.0	1.6	1.5
0.3	1.3	1.1	1.2	1.1	1.1
0.5	0.9	0.7	0.8	0.8	0.8

**Fig. 6** Cyclic voltammograms of DPPH[•] (2.0 × 10⁻³ M) in the absence (dashed line) and presence (solid line) of 0.1 M Al(ClO₄)₃ recorded at the scan rate 0.1 V s⁻¹ on a glassy carbon working electrode in EtOH–H₂O (9 : 1 v/v) (0.1 M Bu₄NClO₄).

We previously reported that the radical-scavenging mechanism of a vitamin E model is significantly affected by solvents.^{22b} In a protic solvent, such as methanol, an electron transfer from the vitamin E model to radicals followed by proton transfer is favorable compared to one-step hydrogen-atom transfer. Based on these results, the DPPH[•]-scavenging reaction by hydroquinones in the hydroalcoholic medium would proceed *via* the electron transfer. The free energy change (ΔG_{et}) of the electron transfer from hydroquinones to DPPH[•] is calculated by using eqn (1),

$$\Delta G_{\text{et}} = F(E_{\text{ox}} - E_{\text{red}}) \quad (1)$$

where F is the Faraday constant, which is negative ($\Delta G_{\text{et}} < 0$) in the presence of Al³⁺. Al³⁺ enhanced the electron transfer by strongly stabilizing DPPH[–] and increased the k values of the hydroquinones depending on its concentration, in spite of decreasing the one-electron donor ability of hydroquinones.

Fig. 7 shows the free-energy-change dependence of log k for the radical-scavenging reaction of DPPH[•] with a series of hydroquinones in the absence and presence of Al³⁺ (0.5 M).



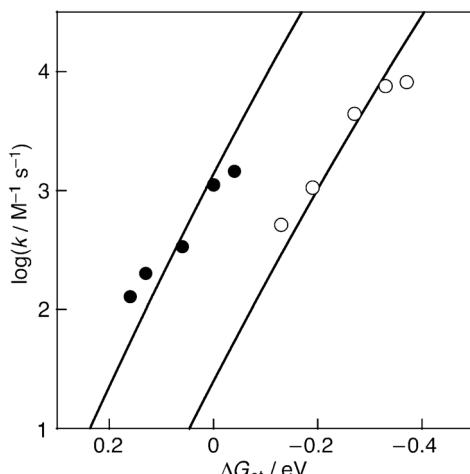


Fig. 7 Plots of $\log k$ vs. ΔG_{et} for the DPPH^{\cdot} -scavenging reaction by the hydroquinone derivatives in the absence of metal ions (closed circles) and the presence of Al^{3+} (0.5 M) (open circles). The lines represent the curve fits to eqn (2) with $\lambda = 1.78$ and 2.19 eV for the reaction without and with Al^{3+} (0.5 M), respectively.

The dependence of outer-sphere electron transfer has been well established by Marcus as given by eqn (2),⁴¹

$$1/k = 1/k_{\text{diff}} + 1/\{Z \exp[-(\lambda/4)(1 + \Delta G_{\text{et}}/\lambda)^2/k_B T]\} \quad (2)$$

in which k_{diff} is the diffusion rate constant ($10^{10} \text{ M}^{-1} \text{ s}^{-1}$),^{42,43} λ is the reorganization energy of electron transfer, k_B is the Boltzmann constant and Z is the collision frequency ($1 \times 10^{11} \text{ M}^{-1} \text{ s}^{-1}$). The λ value is determined to be 1.78 eV for the radical-scavenging reaction in the absence of metal ions. In the presence of Al^{3+} , the rate constants increase with a decrease in the ΔG_{et} value as shown in Fig. 7. The λ value in the presence of Al^{3+} is 2.19 eV, which is larger than that in the absence of metal ions, suggesting that trivalent Al^{3+} strongly binds to DPPH^{\cdot} as an electron transfer product in electron transfer from the hydroquinones to DPPH^{\cdot} .^{2,44}

Conclusions

The DPPH^{\cdot} -scavenging activity of the hydroquinones increased with the increasing number of methyl substituents in the de-*arated* hydroalcoholic medium. Upon addition of $\text{Al}(\text{ClO}_4)_3$ to the hydroquinone- DPPH^{\cdot} system, the k values of the hydroquinones were significantly increased depending on the concentration of Al^{3+} , in spite of decreasing the electron-donating ability of the hydroquinones. Al^{3+} , one of the strong Lewis acids, strongly stabilized the DPPH^{\cdot} generated by the electron transfer from the hydroquinones to DPPH^{\cdot} . In addition, the electron transfer occurred voluntarily ($\Delta G_{\text{et}} < 0$) in the presence of Al^{3+} according to the electrochemical data. The strong Lewis acids, such as Al^{3+} , significantly accelerated the electron-transfer reaction and enhanced the radical-scavenging reaction of phenolic antioxidants. The results obtained in this study demonstrate that Al^{3+} , a strong Lewis acid, can act as a radical

scavenging promoter by stabilising the one-electron reduced species of the radical, although Al^{3+} is reported not only to act as a pro-oxidant but also to strongly interact with biomolecules, showing toxicities.

Acknowledgements

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