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Hypervalent iodine oxidation of phenol derivatives using a catalytic amount of 4-iodophenoxyacetic acid and Oxone® as a co-oxidant

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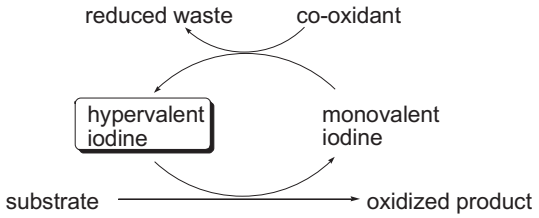
ABSTRACT

Reaction of *p*-substituted phenols **2** with a catalytic amount of 4-iodophenoxyacetic acid (**1**) and Oxone® as a co-oxidant in tetrahydrofuran (THF) or 1,4-dioxane–water gave the corresponding *p*-quinols **3** in excellent yields. Reaction of *p*-dialkoxyarenes 4 in 2,2,2-trifluoroethanol–water gave the corresponding *p*-quinones **5** in excellent yield without purification. These reactions provide efficient and practical methods for the preparation of *p*-quinols and *p*-quinones from *p*-substituted phenols and *p*-dialkoxyarenes, respectively. This quinone synthesis was applied to synthesis of blattellaquinone (**13**), the sex pheromone of the German cockroach *Blattella germanica*.

1. Introduction

Hypervalent iodine compounds, trivalent iodine reagents, such as phenyliodine(III) diacetate (PIDA) and phenyliodine(III) trifluoroacetate (PIFA) and pentavalent iodine reagents, such as Dess–Martin periodinane and *o*-iodoxybenzoic acid (IBX), have been used extensively in recent organic synthesis because of their low toxicity, ready availability and easy handling.[1] For the oxidation reaction, however, stoichiometric amounts of iodine reagents are usually required and produce equimolar amounts of organic iodine waste. Moreover, these reagents are very expensive and some of them are potentially explosive. An excellent solution to these problems can be a catalytic version of hypervalent iodine oxidation in which only a catalytic amount of cheap and safe iodoarene is used (Scheme 1). A hypervalent iodine species is generated in situ by the oxidation of iodoarene with a stoichiometric co-oxidant, and after oxidative transformation, the reduced iodine compound is reoxidized and reused. Therefore, the choice of the co-oxidant is considerably important for the successful reaction. Some requirements of the co-oxidant that should be considered are as follows: (i) it should be easily available, stable, and non-toxic, (ii) it should be able to oxidize monovalent iodine to hypervalent species under mild conditions, (iii) it must not react with the substrate and the oxidized product, (iv) stoichiometric amounts of its reduced compound should be easily separable from the product, and (v) the reduced waste should be environmentally benign.



Scheme 1.

Recently catalytic hypervalent iodine oxidations[2] have been realized using a catalytic amount of iodoarene and co-oxidant such as *m*-chloroperbenzoic acid (*m*-CPBA),[3] Oxone® ($2KHSO_5 \cdot KHSO_4 \cdot K_2SO_4$),[4,5] hydrogen peroxide,[6] and peracetic acid.[7]

We have also reported catalytic hypervalent iodine oxidation of 4-alkoxyphenols to *p*-quinones using a catalytic amount of 4-iodophenoxyacetic acid (**1**) with Oxone® used as a co-oxidant (Scheme 2).[8] *p*-Quinones are structural components of numerous pharmacologically active compounds and useful synthetic intermediates.[9] Because oxidation of *p*-alkoxyphenols using trivalent iodine reagent, such as PIDA and PIFA is a convenient method for synthesis of *p*-quinones,[10] our reported catalytic oxidation provides a practical and useful procedure for *p*-quinone synthesis. This reaction has the following advantages: The reaction proceeds under

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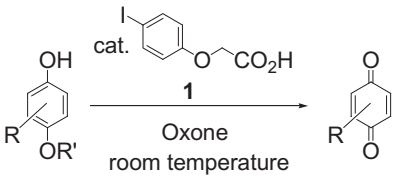
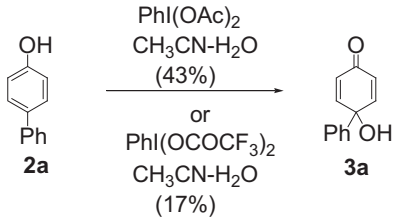


Scheme 2.



Scheme 3.

mild conditions. Oxone® is an inorganic, water-soluble, commercially available, and inexpensive oxidant that has low toxicity.[11] Moreover, the solubility of **1** in alkaline solution makes its separation and recovery steps easier to carry out without the need of a purification step. A possible catalytic cycle for this oxidation is as follows: Iodoarene (**1**) is oxidized by Oxone® to tri- or pentavalent iodine species, which oxidize *p*-alkoxyphenol to yield *p*-quinone and iodine species at a lower oxidation stage. The reduced iodine species would be reoxidized by Oxone®. Although experiments of ^{1}H and ^{13}C NMR of a mixture of **1** and an excess amount of Oxone® in CD_3CN-D_2O showed no presence of hypervalent iodine species, it is well known that Oxone® oxidizes iodoarene to pentavalent iodine.[4,12] Therefore this catalytic oxidation may include an iodine (V) species as an oxidant. However, the formation of pentavalent iodine species usually requires a higher temperature (70 °C) than that in the oxidation using **1** and Oxone®. Therefore, it would be possible that trivalent iodine species is formed and acts as an oxidant.[5] In order to understand the reactivity of this catalytic system, we have investigated further reactions of phenol derivatives with **1** and Oxone®. Here we report full accounts of the oxidations of *p*-carbon substituted phenols[13a] and *p*-dialkoxyarenes[13b] to *p*-quinols and *p*-quinones.

2. Results and discussion

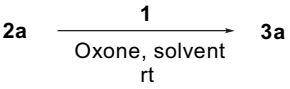
2.1. Oxidation of *p*-substituted phenols

Oxidation of *p*-substituted phenols is a commonly used method for the preparation of *p*-quinols, which are structural components of numerous natural products[14] as well as pharmacologically active compounds[15] and useful synthetic intermediates.[16] Among many reported oxidants for this conversion,[17] hypervalent iodine(III) oxidants are typically used.[18] In contrast to the oxidation of 4-alkylphenols with stoichiometric trivalent iodine compound, oxidation by pentavalent iodines usually takes place at the *ortho* position of the phenols. Ranganathan and co-workers described the reaction of *N*-benzoyltyrosine methyl ester with 4-*tert*-butyliodylbenzene in refluxing toluene to give the corresponding *o*-quinone in 30% yield.[19] Oxidation with IBX also occurred at the *ortho* position, reported by Pettus group[20] and Quideau group.[21] As the reactivity of our novel catalytic system using **1** and Oxone® is similar to that of trivalent iodine, we have investigated the oxidation of *p*-substituted phenols with **1** and Oxone® in the hope of obtaining *p*-quinols in good yields.

Because of competitive oligomerization, oxidation of *p*-substituted phenols using a trivalent iodine compound occasionally gives low yields of the desired *p*-quinols, especially in the case of oxidation of 4-arylphenols. For example, Felpin reported in 2007 that the oxidation of 4-phenylphenol (**2a**) with PIDA in acetonitrile and water gave the corresponding *p*-quinol (**3a**) in 43% yield and PIFA caused much more complication than PIDA to reduce the yield to 17% (Scheme 3).[22] Therefore we selected 4-phenylphenol (**2a**) as a model substrate for the catalytic hypervalent iodine oxidation (Table 1). Treatment of **2a** and 0.1 equiv of **1** and 4 equiv of Oxone® in acetonitrile–water (2:1) at room temperature for 24 h gave **3a** in only 38% yield (entry 1). Addition of water shortened the reaction time to 2 h, although yields were not improved (entries 2 and 3). Next the solvent effects of other water-soluble organic solvent on the catalytic reaction were investigated. A similar reaction of **2a** in acetone–water (1:2) gave an almost identical result to that in acetonitrile–water (entry 4). When 2,2,2-trifluoroethanol, the best solvent for the quinone formation of *p*-alkoxyphenols,[8b] was used as a solvent, **3a** was obtained in higher yield (76%) than that of the stoichiometric PIDA oxidation reported by Felpin. However, unfortunately, the reaction required a long reaction time to complete (entry 5). It is interesting that an unfamiliar solvent in hypervalent iodine chemistry, THF gave a better result than CF_3CH_2OH (entry 6). The use of 1,4-dioxane shortened the reaction time with a lower yield (entry 7). When the reaction was performed in a 1:5 mixture of THF–H_2O, the reaction was completed within 5 h and the highest yield was obtained (entry 8). Further addition of water to the THF–H_2O solvent system was ineffective (entry 9). The catalytic oxidation proceeded even in water alone, but a longer reaction time was required (entry 10). We then changed the amounts of **1** and Oxone® (entries 11–15). When the amount of Oxone® was reduced to 1 equiv in a 1:5 mixture of THF–H_2O, the reaction was completed after 13 h to give 86% yield of **3a**. A similar reaction with 0.05 equiv of **1** and 4 equiv of Oxone® required 8 h to finish affording 85% yield of **3a**. When **2a** was treated with 0.025 equiv of **1** and 4 equiv of Oxone®, the reaction time was increased to 13 h (entry 13). The reaction using 0.01 equiv of **1** was not finished after 24 h to afforded 53% yield of **3a**, along with 26% of recovered **2a** (entry 14). No reaction was observed when **2a** was treated with Oxone® in the absence of **1** (entry 15).[23]

Various *p*-substituted phenols (**2b**–**m**) were oxidized with 0.05 equiv of **1** and 4 equiv of Oxone® to the corresponding *p*-quinols (Table 2). We first examined the effect of aryl substituents

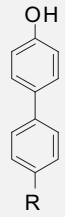
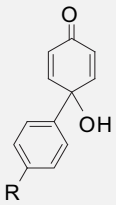
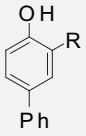
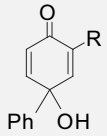
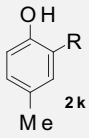
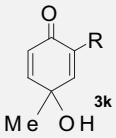
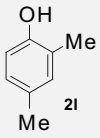
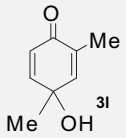
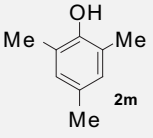
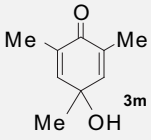
Table 1
Oxidation of **2a** with **1** and Oxone[a]



Entry	1 (equiv)	Oxone (equiv)	Solvent	Time (h)	Yield (%) of **3a**
1	0.1	4	CH_3CN-H_2O (2:1)	24	38
2	0.1	4	CH_3CN-H_2O (1:1)	2.5	35
3	0.1	4	CH_3CN-H_2O (1:2)	1	43
4	0.1	4	Acetone–H_2O (1:2)	2	46
5	0.1	4	$CF_3CH_2OH-H_2O$ (1:2)	12	76
6	0.1	4	THF–H_2O (1:2)	10	80
7	0.1	4	1,4-Dioxane–H_2O (1:2)	3	60
8	0.1	4	THF–H_2O (1:5)	5	89
9	0.1	4	THF–H_2O (1:10)	8	81
10	0.1	4	H_2O	16	54 (30)[b]
11	0.1	1	THF–H_2O (1:5)	13	86
12	0.05	4	THF–H_2O (1:5)	8	85
13	0.025	4	THF–H_2O (1:5)	13	88
14	0.01	4	THF–H_2O (1:5)	24	53 (26)[b]
15	None	4	THF–H_2O (1:5)	No reaction	

[a] Reactions were carried out at room temperature.
[b] Parentheses are recovery of **2a**.

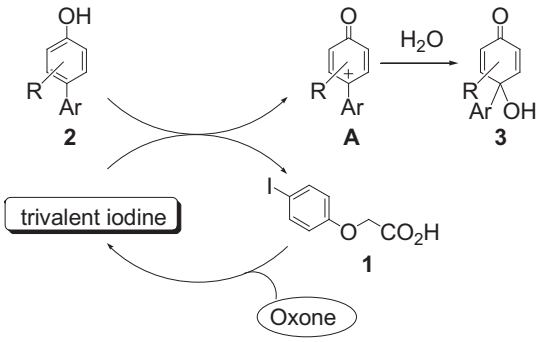
Table 2
Catalytic hypervalent iodine oxidation of *p*-substituted phenols **2**[a]

Entry	Phenol (**2**)	Quinol (**3**)	Solvent[b]	Time (h)	Yield (%)
					
1	**b**:R=Me		A	16	67
2[c]	**c**:R=CH_2OPiV		A	24	58
3	**c**		B	3	87
4[d]	**d**:R=Br		A	7	44
5	**d**		B	4	66
6	**e**:R=CN		A	22	48
7[e]	**e**		B	8	48
					
8	**f**:R=Me		B	5	43
9	**g**:R=*n*-Pr		B	4	77
10[e]	**h**:R=Ph		B	4	85
11[e]	**i**:R=Br		A	7	79
12	**j**:R=$CH_2CH{=}CH_2$		B	Complex mixture	
13[e]			A	4	40
14			B	2	64
15			B	2	75

[a] Reactions were carried out using 0.05 equiv of **1** and 4 equiv of Oxone at room temperature.
[b] A: THF–H_2O=1:5, B: 1,4-dioxane–H_2O=1:2.
[c] Reaction was carried out using 0.2 equiv of **1**.
[d] Reaction was carried out using 0.3 equiv of **1**.
[e] Reaction was carried out using 0.1 equiv of **1**.

at the *para* position. When 4-(4-tolyl)phenol (**2b**) was treated with 0.05 equiv of **1** and Oxone® in THF–H_2O (1:5) at room temperature, the reaction was finished within 16 h to give 67% of *p*-quinol **3b** (entry 1). A similar reaction of 4-(4-pivaloyloxymethylphenyl) phenol (**2c**) in THF–H_2O proceeded slowly to give 58% yield of the corresponding **3c** after 24 h stirring with 0.2 equiv of **1**. In contrast, **2c** reacted more smoothly in 1,4-dioxane–H_2O (1:2) than in THF–H_2O to afford **3c** in 87% yield (entries 2 and 3). Oxidation of 4-bromo derivative **2d** showed similar tendencies to give the corresponding *p*-quinol **3d**. The reaction in THF–H_2O for 7 h gave 44% yield (entry 4), whereas in 1,4-dioxane–H_2O for 4 h it gave 66% yield (entry 5). 4-Arylphenol **2e** bearing the electron-withdrawing cyano group at the *para* position of 4-phenyl group showed lower reactivity, a requirement for larger amounts of **1** and longer reaction time, and gave **3e** in lower yield (entries 6 and 7). Next, the effect of *ortho*-substituents was investigated. Reactions of **2f** and **2g** having alkyl groups at the *ortho* position in 1,4-dioxane–H_2O (1:2) afforded the corresponding **3f** and **3g** in 43 and 77% yields, respectively (entries 8 and 9). Oxidation of 2,4-diphenylphenol (**2h**) with 0.1 equiv of **1** and 4 equiv of Oxone® was occurred only at the *para* position to produced *p*-quinol **3h** (entry 10). In addition, 2-bromo-4-phenylphenol (**2i**) was oxidized at the *para* position to yield **3i** in 79% yield (entry 11). However, **3j** treated with **1** and Oxone® gave a complex mixture because of the labilability of allyl group against the oxidation (entry 12). Reaction of 4-alkylphenols, such as 4-methyl-, 2,4-dimethyl-, and 2,4,6-trimethylphenols **2k**–**m** were also oxidized at the *para*-positions affording **3k**–**m** in moderate to high yields (entries 13–15).

The oxidations of *p*-substituted phenols **2** with a catalytic amount of **1** and Oxone® have occurred at the *para*-positions not at the *ortho*-positions. This strongly suggests that the reaction would include a trivalent iodine species generated in situ as an oxidant of phenols to *p*-quinols. A possible reaction mechanism of this oxidation is shown in Scheme 4. Iodoarene **1** would be oxidized by Oxone® to an iodine(III) species. The resultant trivalent iodine species reacts with 4-arylphenol to give cationic intermediate (**A**) stabilized by the 4-aryl group and the iodine(I) derivative, before its further oxidation to an iodine(V) species. The intermediate **A** is then hydrolyzed to *p*-quinol. In the case of the reaction of **2e** having an electron-withdrawing cyano group, the weaker stability of **A** is expected to decrease its reactivity to give low yield.



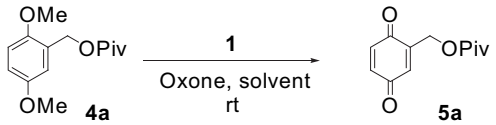
Scheme 4.

2.2. Oxidation of *p*-dialkoxyarenes

Oxidative dearomatization of phenol ethers using metal oxidants such as cerium(IV) ammonium nitrate (CAN)[24] and silver(II) oxide–nitric acid[25] is one of the most efficient procedures for synthesis of quinones, because the phenol ethers are stable under various conditions and are easily prepared. Hypervalent iodine oxidation using PIFA, has been reported as a convenient metal-free procedure.[26] In this reaction, an excess of PIFA was required because of the stability of the phenol ethers under oxidation conditions. Therefore, successful catalytic oxidation of phenol ethers to quinone provides a useful environmentally benign transformation. We envisioned an application of our catalytic hypervalent iodine oxidation to this conversion.

We examined reactions of 1,4-dimethoxy-2-(pivaloyloxymethyl)benzene (**4a**) with **1** in the presence of Oxone® under various conditions. The results are presented in Table 3. We first investigated oxidation using an excess amount of **1** and Oxone® because of the low reactivity of *p*-dialkoxyarenes. The reaction was completed within 1 h to give the corresponding *p*-benzoquinone **5a** in quantitative yield when **4a** was treated with 4 equiv of **1** and Oxone® in acetonitrile–water (2:1) at room temperature (entry 1). This result encouraged us to explore the catalytic use of **1** in the oxidation of **4a** to **5a**. Although the use of 0.2 equiv of **1** with 4 equiv

Table 3
Oxidative dearomatization of **4a** with **1** and Oxone[a]



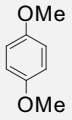
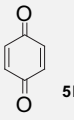
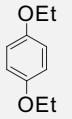
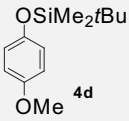
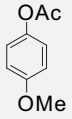
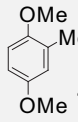
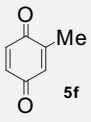
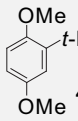
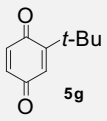
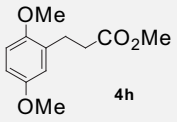
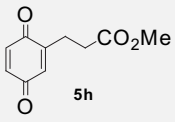
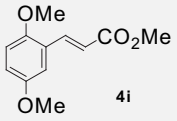
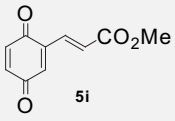
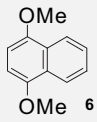
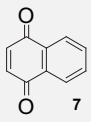
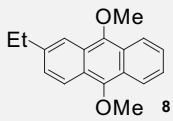
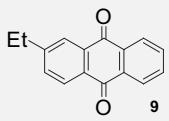
Entry	**1** (equiv)	Oxone (equiv)	Solvent	Time (h)	Yield (%) of **5a**
1	4	4	CH_3CN–H_2O (2:1)	1	quant
2	0.2	4	CH_3CN–H_2O (2:1)	10	quant
3	0.2	4	CH_3CN–H_2O (1:1)	5	quant
4	0.2	4	CH_3CN–H_2O (1:2)	2	quant
5	0.2	4	CH_3CN–H_2O (1:5)	3	33[b]
6	0.2	1	CH_3CN–H_2O (1:2)	24	quant
7	0.1	4	CH_3CN–H_2O (1:2)	4	quant
8	None	4	CH_3CN–H_2O (1:2)	No reaction	
9	0.1	4	THF–H_2O (1:2)	4	5[c]
10	0.1	4	Acetone–H_2O (1:2)	5	[d]
11	0.1	4	CF_3CH_2OH–H_2O (1:2)	1	quant
12	0.05	4	CF_3CH_2OH–H_2O (1:2)	1	quant
13	0.025	4	CF_3CH_2OH–H_2O (1:2)	4	quant
14	0.01	4	CF_3CH_2OH–H_2O (1:2)	48	94

[a] Reactions were carried out at room temperature.
[b] Unreacted **4a** was recovered (67%).
[c] Unreacted **4a** was recovered (95%).
[d] Reaction was not completed and gave unknown by-products.

of Oxone® slowed the reaction, a quantitative yield of **5a** was obtained after 10 h (entry 2). Because Kita and co-workers reported that water was considerably effective as a solvent to PIFA oxidation of *p*-dimethoxybenzenes,[26] we examined the addition of water to the reaction mixture (entries 3–5). In a 1:2 mixture of acetonitrile–water, the reaction was completed within 2 h to give **5a** in quantitative yield (entry 4). However, further addition of water necessitated a longer reaction time to give a 1:2 mixture of **5a** and unreacted **4a**, which was observed using the ^{1}H NMR spectrum of the crude mixture after 3 h (entry 5). A much slower reaction (24 h) was observed using 1 equiv of Oxone® (entry 6). However, a similar reaction with 0.1 equiv of **1** increased the reaction time slightly (4 h) (entry 7). No reaction was observed without **1** (entry 8). Next, we investigated a change in the organic solvent. A similar reaction in a 1:2 mixture of THF and water proceeded slowly to give **5a** and unreacted **4a** (1:20) after 4 h (entry 9). Acetone was not a suitable solvent (entry 10). In contrast, CF_3CH_2OH[8b] was proven effective in this oxidation reaction (entries 11–14). Both reactions of **4a** with 0.1 equiv and 0.05 equiv of **1** were finished within 1 h to give **5a** (entries 11 and 12). The reaction was completed within 4 h to give **5a** in quantitative yield when **4a** was treated with 0.025 equiv of **1** and 4 equiv of Oxone® in CF_3CH_2OH–H_2O (1:2) at room temperature (entry 13). The reaction using 0.01 equiv of **1** was finished after 48 h to afford **5a** in 94% yield (entry 14).

We next investigated the oxidation of various *p*-dialkoxyarenes **4b**–**i**, **6**, and **8** with 0.05 equiv of **1** and 4 equiv of Oxone® in CF_3CH_2OH–H_2O (1:2) at room temperature under the standard conditions (Table 4). The results are presented in Table 4. Reaction of 1,4-dimethoxybenzene (**4b**) gave *p*-benzoquinone (**5b**) in good yield (entry 1). 1,4-Diethoxybenzene (**4c**) was also oxidized to **5b** (entry 2). Although 4-(*tert*-butyldimethylsilyloxy)anisole (**4d**) reacted smoothly to give **5b** (entry 3), the electron-withdrawing acetyl group decreased the reactivity to give only 4% of **5b** and 96% of unreacted **4e** after 24 h (entry 4). 1,4-Dimethoxybenzenes having an alkyl group, such as methyl and bulky *tert*-butyl groups at the 2-position, were oxidized to the corresponding *p*-quinones **5f** and **5g** with excellent yields (entries 5 and 6). Very recently, oxidation of **4f** and **4g** with an excess amount of CAN in CH_3CN–H_2O was reported to give dimeric quinones in moderate to high yields,[27] but no diquinone was detected in the reactions of **4f** and **4g** with **1** and

Table 4
Catalytic hypervalent iodine oxidation of *p*-dialkoxyarenes with **1** and Oxone[a]

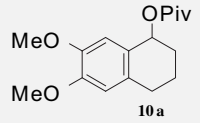
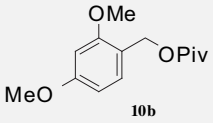
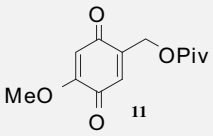
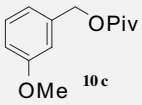
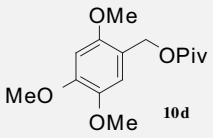
Entry	Dialkoxyarene	Quinone	Time (h)	Yield (%)
1	 **4b**	 **5b**	1	86
2	 **4c**	**5b**	1	94
3	 **4d**	**5b**	1.5	94
4	 **4e**	**5b**	24	4[b]
5	 **4f**	 **5f**	0.5	89
6	 **4g**	 **5g**	1	quant
7	 **4h**	 **5h**	1	quant
8	 **4i**	 **5i**	1.5	95
9[c]	 **6**	 **7**	1	34
10[c]	 **8**	 **9**	2	79

[a] Reactions were carried out using 0.05 equiv of **1** and 4 equiv of Oxone in CF_3CH_2OH-H_2O (1:2) at room temperature.
[b] Unreacted **4e** was recovered (96%).
[c] Reaction was carried out in in CF_3CH_2OH-H_2O (2:1).

Oxone. Propanoate ester **4h** was converted to the corresponding quinone **5h** in quantitative yield (entry 7). 2-Vinyl-substituted 1,4-benzoquinone **5i**[28] was directly obtained in excellent yield by the reaction of **4i** (entry 8). Low solubility of the starting materials in CF_3CH_2OH–H_2O (1:2) required a change in the ratio of CF_3CH_2OH to H_2O (entries 9 and 10). Anthraquinone (**9**) was obtained in high yield (entry 10), but the yield of 1,4-naphthoquinone (**7**) was low because of its low stability under the reaction conditions used for this study (entry 9).

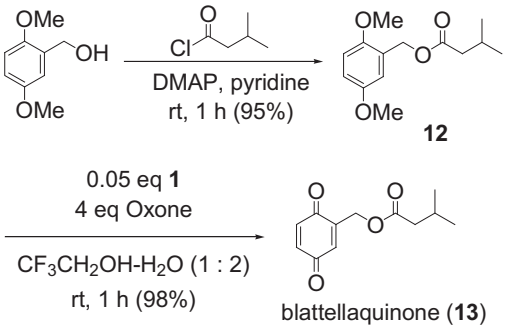
Because oxidation of *p*-dimethoxybenzenes proceeded smoothly, we attempted oxidation of methoxylated benzenes **10a**–**d** with other substitution patterns (Table 5). Unfortunately, reactions under the standard conditions were not satisfactory. Thus, *o*-dimethoxy derivative **10a** was treated with 0.05 equiv of **1** and 4 equiv of Oxone® in CF_3CH_2OH–H_2O (1:2) at room temperature to give a complex mixture (entry 1). Oxidation of *m*-dimethoxybenzene **10b** afforded methoxyquinone **11** in only 12% yield with a complex mixture (entry 2). This result indicated that monomethoxy benzene could be oxidized to quinone. The reaction of the anisole derivative **10c** with 0.3 equiv of **1** proceeded very slowly to give *p*-quinone **5a** in 9% yield with 72% of unreacted **10c** after 48 h (entry 3). Oxidation of trimethoxybenzene **10d** gave **11** in low yield (29%) (entry 4).

Table 5
Oxidation of several methoxylarenes

Entry	Methoxyarene	Product	Time (h)	Yield (%)
1[a]	 **10a**	Complex mixture		
2[b]	 **10b**	 **11**	23	12
3[b]	 **10c**	**3a**	48	9[c]
4[a]	 **10d**	11	1	29

[a] Reactions were carried out using 0.05 equiv of **1** and 4 equiv of Oxone in CF_3CH_2OH–H_2O (1:2) at room temperature.
[b] Reactions were carried out using 0.3 equiv of **1**.
[c] Unreacted **10c** was recovered (72%).

Finally, we applied this reaction to the synthesis of blattellaquinone (**13**),[24b] the sex pheromone of the German cockroach, *Blattella germanica*, isolated in 2005 (Scheme 5). Reaction of commercially available 2,4-dimethoxybenzyl alcohol with isovaleryl chloride in the presence of 4-(*N*,*N*-dimethylamino)pyridine (DMAP) and pyridine gave acylated product **12** in 95% yield. Oxidation of **12** with 0.05 equiv of **1** and 4 equiv of Oxone® in CF_3CH_2OH–H_2O (1:2) at room temperature for 1 h afforded pure **13** in 98% yield without purification. The CAN oxidation of **12** under standard conditions gave **13** in 69% yield after silica gel column chromatography.[29]



Scheme 5.

3. Conclusion

Oxidation of phenol derivatives with a catalytic amount of **1** in the presence of Oxone® as a co-oxidant is very similar to that with trivalent iodine. Reaction of *p*-substituted phenols (**2**) with **1** and Oxone® in THF or 1,4-dioxane–water gave the corresponding *p*-quinols **3** in excellent yields. Reaction of *p*-dialkoxyarenes **4** in CF_3CH_2OH–H_2O (1:2) gave the corresponding *p*-quinones **5** in excellent yield without purification. These reactions provide efficient and practical methods for the preparation of *p*-quinols and *p*-quinones from *p*-substituted phenols and *p*-dimethoxybenzenes, respectively. This quinone synthesis was applied to the synthesis of blattellaquinone (**13**), the sex pheromone of the German cockroach *B. germanica*.

4. Experimental section

4.1. General

Melting points are uncorrected. IR spectra were recorded using JASCO FT/IR-460 Plus spectrophotometer. ^{1}H NMR spectra were determined with JEOL JNM-ECX400P (400 MHz) and Varian Gemini 300 (300 MHz) spectrometers, tetramethylsilane as an internal standard. ^{13}C NMR spectra were determined with JEOL JNM-ECX400P (100 MHz) and Varian Gemini 300 (75 MHz) spectrometers. All ^{13}C NMR spectra were determined with complete proton decoupling. High resolution MS were determined with JEOL JMS-GCmate II and JEOL JMS-AX505HD instruments. Column chromatography was performed on Silica Gel 60 PF_{254} (Nacalai Tesque) under pressure. Commercially available phenols **2a**, **2d**, **2e**, **2k**, **2l**, and **2m** and dialkoxyarenes **4b**, **4c** **4f**, **6**, and **8** were purchased from suppliers, such as Aldrich, Wako Pure Chemical Industries, Ltd., and Tokyo Chemical Industry (TCI) Co., Ltd. Substrates for the oxidations have already been reported in the literature and were prepared as described or according to literature procedures: **2f**,[30] **2h**,[30] **2i**,[31] **2j**,[32] **4d**,[33] **4g**,[34] **4h**,[35] **4i**.[28,36] All known *p*-quinols and *p*-quinones are identified by comparison with the authentic samples.

*4.1.1. 4′-Methyl-4-hydroxybiphenyl (**2b**).* Hydrogenation of **2e** with HCO_2NH_4–Pd–C gave **2b**: colorless crystals; mp 152–154 °C (Et_2O–hexane) (lit.[37] 153–154 °C); ν_{max} (KBr) 3600–3100, 1612, 1599, 1531, 1502 cm^{-1}; δ_H (400 MHz $CDC1_3$) 2.38 (3H, s), 4.83 (1H, br s), 6.89 (2H, d, *J* 8.7 Hz), 7.22 (2H, d, *J* 8.2 Hz), 7.43 (2H, d, *J* 8.7 Hz), 7.46 (2H, d, *J* 8.7 Hz); δ_C (100 MHz, $CDCl_3$) 21.0, 115.6 (2), 126.6 (2), 128.2 (2), 129.4 (2), 134.0, 136.4, 137.9, 154.8.

*4.1.2. 4-(4-Hydroxyphenyl)benzyl 2,2-dimethylpropanoate (**2c**).* Phenol **2c** was synthesized from **2e** by usual protection of phenolic hydroxy group by *tert*-butyldimethylsilyl group, stepwise reductions of nitrile group to hydroxymethyl group by diisobutylaluminum hydride and sodium borohydride, followed by pivaloylation of primary alcohol and desilylation. Compound **2c**: pale yellow crystals; mp 118–119 °C (EtOH); ν_{max} (KBr) 3600–3100, 1700, 1609, 1522, 1502, 1442, 1404, 1371 cm^{-1}; δ_H (400 MHz $CDC1_3$) 1.25 (9H, s), 5.14 (2H, s), 5.23–5.34 (1H, br), 6.88 (2H, d, *J* 8.7 Hz), 7.37 (2H, d, *J* 8.7 Hz), 7.45 (2H, d, *J* 8.7 Hz), 7.52 (2H, d, *J* 8.2 Hz); δ_C (100 MHz, $CDCl_3$) 27.2, 38.8, 66.0, 115.7 (2), 126.8 (2), 128.2 (2), 128.3 (2), 133.3, 134.7, 140.5, 155.3, 178.7; *m*/*z* (EI) 284 (M^+); HRMS, found 284.14418. $C_{18}H_{20}O_3$ requires 228.14125.

*4.1.3. 2-Propyl-4-phenylphenol (**2g**).* Hydrogenation of **2j** with H_2–Pd–C gave **2g**.: colorless crystals; mp 48–49 °C (Et_2O–hexane); ν_{max} (KBr) 3600–3100, 1610, 1515, 1488, 1454, 1417, 1374 cm^{-1}; δ_H

(400 MHz $CDC1_3$) 1.01 (3H, t, *J* 7.6 Hz), 1.70 (3H, sixtet, *J* 7.6 Hz), 2.64 (2H, t, *J* 7.6 Hz), 4.72 (1H, br s), 6.82 (1H, d, *J* 8.2 Hz), 7.27–7.43 (5H, m), 7.52–7.56 (2H, m); δ_C (100 MHz, $CDCl_3$) 14.0, 23.0, 32.2, 115.5, 125.7, 126.6, 126.7 (3), 128.6, 128.7, 129.1, 133.9, 141.0, 153.0; *m*/*z* (EI) 212 (M^+); HRMS, found 212.12085. $C_{15}H_{16}O$ requires 212.12012.

4.2. General procedure for oxidation of 4-substituted phenols 2

Compound **2** (0.5 mmol) was added to a solution of **1** (0.025 mmol) in THF–water (1:5, 5 ml) or 1,4-dioxane–water (1:2, 5 mL), followed by Oxone® (4 mmol) at room temperature. After **2** was completely consumed as indicated by TLC, the mixture was diluted with ethyl acetate and washed with water. The organic layer was then washed with aqueous saturated sodium bicarbonate solution and dried, concentrated. The residue was purified by column chromatography on silica gel to give pure **3**.

*4.2.1. 4-Hydroxy-4-phenylcyclohexa-2,5-dienone (**3a**).* Following the general procedure, **2a** (68 mg, 0.4 mmol) was treated with **1** (11.1 mg, 0.04 mmol) and Oxone® (984 mg, 1.6 mmol) in THF–H_2O (1:5, 4 mL) to give **3a** (66 mg, 89%) as pale yellow crystals; mp 105–106 °C (Et_2O–hexane) (lit.[22] 107–109 °C); ν_{max} (KBr) 3600–3100, 1660, 1621, 1600, 1491, 1450, 1396, 1384, 1360 cm^{-1}; δ_H (400 MHz $CDC1_3$) 2.76 (1H, br s), 6.22 (2H, d, *J* 10.1 Hz), 6.90 (2H, d, *J* 10.1 Hz), 7.30–7.41 (3H, m), 7.46–7.50 (2H, m); δ_C (100 MHz, $CDCl_3$) 71.0, 125.2 (2), 126.9 (2), 128.4, 128.9 (2), 138.7, 150.8 (2), 185.8.

*4.2.2. 4-Hydroxy-4-(4-methylphenyl)-2,5-cyclohexadienone (**3b**).* Following the general procedure, **2b** (55 mg, 0.3 mmol) was treated with **1** (4.2 mg, 0.015 mmol) and Oxone® (738 mg, 1.2 mmol) in THF–H_2O (1:5, 3 mL) to give **3b** (40 mg, 67%) as colorless crystals; mp 134–136 °C (Et_2O–hexane) (lit.[38] 134–137 °C); ν_{max} (KBr) 3600–3100, 1665, 1614, 1509, 1444, 1391 cm^{-1}; δ_H (400 MHz $CDC1_3$) 2.35 (3H, s), 2.52–2.60 (1H, br), 6.21 (2H, d, *J* 10.1 Hz), 6.89 (2H, d, *J* 10.1 Hz), 7.19 (2H, d, *J* 7.8 Hz), 7.36 (2H, d, *J* 8.2 Hz); δ_C (100 MHz, $CDCl_3$) 21.1, 70.9, 125.2 (2), 126.8 (2), 129.6 (2), 135.7, 138.4, 150.9 (2), 185.7.

*4.2.3. 4-Hydroxy-4-(4-tert-butylcarbonyloxymethylphenyl)-2,5-cyclohexadienone (**3c**).* Following the general procedure, **2c** (57 mg, 0.2 mmol) was treated with **1** (2.8 mg, 0.01 mmol) and Oxone® (492 mg, 0.8 mmol) in 1,4-dioxane–H_2O (1:2, 2 mL) to give **3c** (52 mg, 87%) as colorless crystals; mp 115–116 °C (Et_2O–hexane); ν_{max} (KBr) 3600–3100, 1737, 1690, 1657, 1620, 1599, 1513, 1479, 1459, 1417, 1395, 1365 cm^{-1}; δ_H (400 MHz $CDC1_3$) 1.22 (9H, s), 2.72–2.83 (1H, br), 5.10 (2H, s), 6.23 (2H, d, *J* 10.01 Hz), 6.89 (2H, d, *J* 10.1 Hz), 7.35 (2H, d, *J* 7.8 Hz), 7.48 (2H, d, *J* 8.7 Hz); δ_C (100 MHz, $CDCl_3$) 27.1 (3), 38.8, 65.5, 70.9, 125.5 (2), 126.9 (2), 128.1 (2), 136.8, 138.4, 150.6 (2), 178.3, 185.6; [found: C, 71.57; H, 6.67. $C_{18}H_{20}O_4$ requires C, 71.98; H, 6.71%]; *m*/*z* (EI) 300 (M^+); HRMS, found 300.13377. $C_{18}H_{20}O_4$ requires 300.13616.

*4.2.4. 4-Hydroxy-4-(4-bromophenyl)-2,5-cyclohexadienone (**3d**).* Following the general procedure, **2d** (47 mg, 0.3 mmol) was treated with **1** (4.2 mg, 0.015 mmol) and Oxone® (738 mg, 1.2 mmol) in 1,4-dioxane–H_2O (1:2, 3 mL) to give **3d** (52 mg, 66%) as pale yellow crystals; mp 175–177 °C (Et_2O–hexane)(lit.[39] 175–177 °C); ν_{max} (KBr) 3600–3100, 1665, 1615, 1477, 1397, 1367 cm^{-1}; δ_H (400 MHz $CDC1_3$), 2.60–2.66 (1H, br), 6.24 (2H, d, *J* 9.6 Hz), 6.85 (2H, d, *J* 10.1 Hz), 7.35 (2H, d, *J* 8.7 Hz), 7.51 (2H, d, *J* 8.2 Hz); δ_C (100 MHz, $CDCl_3$) 70.7, 122.6, 127.1 (2), 127.2 (2), 132.0 (2), 137.7, 150.2 (2), 185.4.

*4.2.5. 4-Hydroxy-4-(4-cyanophenyl)-2,5-cyclohexadienone (**3e**).* Following the general procedure, **2e** (78 mg, 0.4 mmol) was treated with **1** (11.1 mg, 0.04 mmol) and Oxone® (984 mg, 1.6 mmol) in 1,4-dioxane–H_2O (1:2, 4 mL) to give **3e** (40 mg, 48%) as pale yellow crystals; mp 174–175 °C (Et_2O–hexane) (lit.[38] 173–174 °C); ν_{max} (KBr) 3600–3100, 2230, 1666, 1624, 1605, 1501, 1405 cm^{-1}; δ_H (400 MHz $CDC1_3$) 2.74–2.93 (1H, br), 6.28 (2H, d, *J* 9.6 Hz), 6.85 (2H, d, *J* 10.1 Hz), 7.61 (2H, d, *J* 8.7 Hz), 7.68 (2H, d, *J* 8.7 Hz); δ_C (100 MHz, $CDCl_3$) 70.8, 112.3, 118.3, 126.3 (2), 127.7 (2), 132.7 (2), 143.9, 149.5 (2), 185.1.

*4.2.6. 4-Hydroxy-2-methyl-4-phenyl-2,5-cyclohexadienone (**3f**).* Following the general procedure, **2f** (50 mg, 0.27 mmol) was treated with **1** (3.9 mg, 0.014 mmol) and Oxone® (664 mg, 1.08 mmol) in 1,4-dioxane–H_2O (1:2, 3 mL) to give **3f** (23 mg, 43%) as colorless crystals; mp 73–75 °C (Et_2O–hexane); ν_{max} (KBr) 3600–3100, 1662, 1632, 1609, 1490, 1450, 1369 cm^{-1}; δ_H (400 MHz $CDC1_3$) 1.91 (3H, d, *J* 1.4 Hz), 2.44–2.51 (1H, br), 6.22 (1H, d, *J* 9.6 Hz), 6.67–6.69 (1H, m), 6.87 (1H, dd, *J* 9.6, 2.7 Hz), 7.29–7.40 (3H, m), 7.45–7.49 (2H, m); δ_C (100 MHz, $CDCl_3$) 15.6, 71.4, 125.2 (2), 126.9, 128.2, 128.8 (2), 133.6, 139.4, 146.3, 150.5, 186.4; *m*/*z* (EI) 200 (M^+); HRMS, found 200.08480. $C_{13}H_{12}O_2$ requires 200.08373.

*4.2.7. 4-Hydroxy-4-phenyl-2-propyl-2,5-cyclohexadienone (**3g**).* Following the general procedure, **2g** (51 mg, 0.24 mmol) was treated with **1** (3.3 mg, 0.012 mmol) and Oxone® (590 mg, 0.96 mmol) in 1,4-dioxane–H_2O (1:2, 2.4 mL) to give **3g** (42 mg, 77%) as a pale yellow oil; ν_{max} (neat) 3600–3100, 1667, 1634, 1489, 1449, 1393 cm^{-1}; δ_H (400 MHz $CDC1_3$) 0.92 (3H, t, *J* 7.6 Hz), 1.49 (2H, sixtet, *J* 7.5 Hz), 2.29 (2H, td, *J* 7.6, 3.2 Hz), 2.38–2.42 (1H, br), 6.21 (1H, d, *J* 9.6 Hz), 6.62–6.63 (1H, m), 6.85 (1H, dd, *J* 9.6, 2.5 Hz), 7.29–7.40 (3H, m), 7.45–7.49 (2H, m); δ_C (100 MHz, $CDCl_3$) 13.8, 21.3, 30.9, 71.4, 125.2 (2), 127.1, 128.2, 128.8 (2), 137.4, 139.5, 145.6, 150.1, 185.9; *m*/*z* (EI) 228 (M^+); HRMS, found 228.11624. $C_{15}H_{16}O_2$ requires 228.11503.

*4.2.8. 4-Hydroxy-2,4-diphenyl-2,5-cyclohexadienone (**3h**).* Following the general procedure, **2h** (49 mg, 0.2 mmol) was treated with **1** (5.6 mg, 0.012 mmol) and Oxone® (492 mg, 0.8 mmol) in 1,4-dioxane–H_2O (1:2, 2 mL) to give **3h** (44 mg, 85%) as a pale yellow oil; ν_{max} (neat) 3600–3100, 1667, 1631, 1491, 1447, 1382 cm^{-1}; δ_H (400 MHz $CDC1_3$) 2.51–2.60 (1H, br), 6.35 (1H, d, *J* 10.0 Hz), 6.91–6.97 (2H, m), 7.32–7.44 (8H, m), 7.52–7.56 (2H, m); δ_C (100 MHz, $CDCl_3$) 71.5, 125.3 (2), 127.6, 128.2 (2), 128.4 (2), 128.8 (2), 129.0 (2), 134.7, 136.9, 139.2, 147.6, 149.6, 184.6; *m*/*z* (EI) 262 (M^+); HRMS, found 262.09956. $C_{18}H_{14}O_2$ requires 262.09938.

*4.2.9. 2-Bromo-4-hydroxy-4-phenyl-2,5-cyclohexadienone (**3i**).* Following the general procedure, **2i** (75 mg, 0.3 mmol) was treated with **1** (8.3 mg, 0.03 mmol) and Oxone® (738 mg, 1.2 mmol) in THF–H_2O (1:5, 3 mL) to give **3i** (63 mg, 79%) as colorless crystals; mp 115–116 °C (Et_2O–hexane)(lit.[22] 115–116 °C); ν_{max} (KBr) 3600–3100, 1651, 1624, 1589, 1490, 1448, 1391, 1348, 1328 cm^{-1}; δ_H (400 MHz $CDC1_3$) 2.75–2.80 (1H, br), 6.34 (1H, d, *J* 10.1 Hz), 6.94 (1H, dd, *J* 10.1, 3.2 Hz), 7.34 (1H, d, *J* 3.2 Hz), 7.35–7.43 (3H, m), 7.45–7.50 (2H, m); δ_C (100 MHz, $CDCl_3$) 73.6, 123.2, 125.2 (2), 125.5, 128.8, 129.1 (2), 137.5, 150.9, 151.1, 178.5.

*4.2.10. 4-Hydroxy-4-methy-2,5-cyclohexadienone (**3k**).* Following the general procedure, **2k** (78 mg, 0.6 mmol) was treated with **1** (16.7 mg, 0.06 mmol) and Oxone® (1.475 g, 2.4 mmol) in THF–H_2O (1:5, 6 mL) to give **3k**[33] (30 mg, 40%) as a pale yellow oil; ν_{max} (neat) 3600–3100, 1666, 1620, 1395 cm^{-1}; δ_H (400 MHz $CDC1_3$) 1.49 (3H, s), 1.92–1.97 (1H, br), 6.14 (2H, d, *J* 10.1 Hz), 6.89 (2H, d, *J* 10.1 Hz); δ_C (100 MHz, $CDCl_3$) 26.7, 67.2, 127.3 (2), 151.8 (2), 185.2.

*4.2.11. 4-Hydroxy-2,4-dimethy-2,5-cyclohexadienone (**3l**).* Following the general procedure, **2l** (61 mg, 0.5 mmol) was treated with **1** (6.9 mg, 0.025 mmol) and Oxone® (1.229 g, 2.0 mmol) in 1,4-dioxane–H_2O (1:2, 5 mL) to give **3l** (44 mg, 64%) as colorless

crystals; mp 67–69 °C (Et_2O–hexane)(lit.[23] 62–65 °C); ν_{max} (neat) 3600–3100, 1666, 1632, 1606, 1447, 1399, 1376, 1348 cm^{-1}; δ_H (400 MHz $CDC1_3$) 1.46 (3H, s), 1.87 (3H, s), 2.10–2.17 (1H, br), 6.11 (1H, d, *J* 10.1 Hz), 6.64–6.67 (1H, m), 6.85 (1H, dd, *J* 10.1, 3.2 Hz); δ_C (100 MHz, $CDCl_3$) 15.6, 26.8, 67.5, 127.0, 133.7, 147.4, 151.8, 186.0.

*4.2.12. 4-Hydroxy-2,4,6-trimethy-2,5-cyclohexadienone (**3m**).* Following the general procedure, **2m** (54 mg, 0.4 mmol) was treated with **1** (5.7 mg, 0.02 mmol) and Oxone® (984 mg, 1.6 mmol) in 1,4-dioxane–H_2O (1:5, 4 mL) to give **3m**[33] (45 mg, 75%) as a pale yellow oil; ν_{max} (neat) 3600–3100, 1673, 1636, 1448, 1396, 1372 cm^{-1}; δ_H (400 MHz $CDC1_3$) 1.43 (3H, s), 1.80–1.82 (1H, br), 1.87 (6H, s), 6.62 (2H, s); δ_C (100 MHz, $CDCl_3$) 15.8 (2), 27.0, 67.2, 133.5 (2), 147.1 (2), 186.6.

*4.2.13. 2,5-Dimethoxybenzyl 2,2-dimethylpropanoate (**4a**).* Treatment of 2,5-dimethoxybenzyl alcohol with pivaloyl chloride and pyridine gave **4a** as a colorless oil; ν_{max} (neat) 1730, 1593, 1502, 1480, 1463 cm^{-1}; δ_H (300 MHz $CDC1_3$) 1.24 (9H, s), 3.76 (3H, s), 3.78 (3H, s), 5.13 (2H, s), 6.78 (1H, d, *J* 8.4 Hz), 6.81 (1H, d, *J* 7.8 Hz), 6.87–6.91 (1H, br); δ_C (75 MHz, $CDCl_3$) 27.3 (3), 33.9, 55.6, 56.0, 61.4, 111.3, 113.0, 114.5, 125.9, 151.1, 153.3, 178.0; *m*/*z* (EI) 252 (M^+); HRMS, found 252.1359. $C_{14}H_{20}O_4$ requires 252.1362.

4.3. General procedure for oxidation of *p*-dialkoxyarenes 4, 6, and 8

Compound **4**, **6**, and **8** (0.5 mmol) was added to a solution of **1** (0.025 mmol) in CF_3CH_2OH–H_2O (2:1, 5 ml), followed by Oxone® (4 mmol) at room temperature. After **2** was completely consumed, as indicated by TLC, the mixture was diluted with ethyl acetate and washed with water. The organic layer was then washed with aqueous saturated sodium bicarbonate solution and dried, concentrated to give pure **5**, **7**, and **9**. If necessary, the product was purified using column chromatography on silica gel to give pure quinone.

*4.3.1. 3,6-Dioxocyclohexa-1,4-dienylmethyl 2,2-dimethylpropanoate (**5a**).* Following the general procedure, **4a** (51 mg, 0.2 mmol) was treated with **1** (3 mg, 0.01 mmol) and Oxone® (492 mg, 0.8 mmol) in CF_3CH_2OH–H_2O (1:2, 4 mL) to give **5a**[8] (46 mg, quant) as yellow crystals; mp 71–72 °C (ethyl acetate–hexane); ν_{max} (KBr) 1735, 1658, 1484, 1459, 1440 cm^{-1}; δ_H (270 MHz, $CDCl_3$) 1.27 (9H, s), 4.99 (2H, d, *J* 1.9 Hz), 6.64–6.68 (1H, m), 6.74–6.88 (2H, m); δ_C (75 MHz, $CDCl_3$) 27.2 (3), 38.9, 59.4, 131.1, 136.5, 136.6, 143.6, 177.5, 186.1, 186.9.

*4.3.2. 1,4-Benzoquinone (**5b**).* Following the general procedure, **4b** (138 mg, 1 mmol) was treated with **1** (14 mg, 0.05 mmol) and Oxone® (2.459 g, 4 mmol) in CF_3CH_2OH–H_2O (1:2, 10 mL) to give **5b** (93 mg, 86%) as yellow crystals, which was directly identical to the commercial sample supplied by Nacalai Chemicals, Ltd.

Following the general procedure, **4c** (166 mg, 1 mmol) was treated with **1** (14 mg, 0.05 mmol) and Oxone® (2.459 g, 4 mmol) in CF_3CH_2OH–H_2O (1:2, 10 ml) to give **5b** (103 mg, 94%) as yellow crystals.

Following the general procedure, **4d** (238 mg, 1 mmol) was treated with **1** (14 mg, 0.05 mmol) and Oxone® (2.459 g, 4 mmol) in CF_3CH_2OH–H_2O (1:2, 10 ml) to give **5b** (101 mg, 94%) as yellow crystals.

*4.3.3. 2-Methyl-1,4-benzoquinone (**5f**).* Following the general procedure, **4f** (152 mg, 1 mmol) was treated with **1** (14 mg, 0.05 mmol) and Oxone® (2.459 g, 4 mmol) in CF_3CH_2OH–H_2O (1:2, 10 ml) to give **5f** (109 mg, 89%) as yellow crystals, which was directly identical to the commercial sample supplied by Wako Pure Chemical Industries, Ltd.

*4.3.4. 2-tert-Butyl-1,4-benzoquinone (**5g**).* Following the general procedure, **4g** (50 mg, 0.26 mmol) was treated with **1** (3.6 mg, 0.013 mmol) and Oxone® (633 mg, 1.03 mmol) in CF_3CH_2OH–H_2O (1:2, 3 mL) to give **5g** (42 mg, quant) as orange crystals, which was directly identical to the commercial sample supplied by TCI Co., Ltd.

*4.3.5. Methyl 3-(3,6-dioxocyclohexa-1,4-dienyl)propanoate (**5h**).* Following the general procedure, **4h** (60 mg, 0.27 mmol) was treated with **1** (3.7 mg, 0.013 mmol) and Oxone® (664 mg, 1.08 mmol) in CF_3CH_2OH–H_2O (1:2, 3 mL) to give **5h** (52 mg, quant.) as a colorless oil; ν_{max} (neat) 1735, 1655, 1602, 1438 cm^{-1}; δ_H (300 MHz $CDC1_3$) 2.59 (2H, t, *J* 6.9 Hz), 2.77 (2H, t, *J* 7.1 Hz), 3.69 (3H, s), 6.58–6.62 (1H, m), 6.73 (1H, dd, *J* 9.9, 2.5 Hz), 6.78 (1H, d, *J* 9.9 Hz); δ_C (75 MHz, $CDCl_3$) 24.7, 31.9, 51.9, 132.9, 136.3, 136.6, 147.3, 172.2, 186.8, 187.2; *m*/*z* (EI) 194 (M^+); HRMS, found 194.0580. $C_{10}H_{10}O_4$ requires 194.0579.

*4.3.6. (E)-Methyl 3-(3,6-dioxocyclohexa-1,4-dienyl)-2-propenoate (**5i**).* Following the general procedure, **4i** (50 mg, 0.22 mmol) was treated with **1** (3 mg, 0.011 mmol) and Oxone® (553 mg, 0.9 mmol) in CF_3CH_2OH–H_2O (1:2, 2.4 mL) to give **5i**[28] (40 mg, 95%) as yellow crystals; ν_{max} (KBr) 1727, 1710, 1660, 1611, 1590, 1435 cm^{-1}; δ_H (300 MHz $CDC1_3$) 3.82 (3H, s), 6.81 (1H, d, *J* 6.0 Hz), 6.828 (1H, s), 6.83 (1H, d, *J* 16.2 Hz), 6.90 (1H, d, *J* 6.0 Hz), 7.52 (1H, d, *J* 16.2 Hz); δ_C (75 MHz, $CDCl_3$) 52.2, 127.2, 133.1, 135.4, 136.5, 136.9, 139.2, 165.9, 185.5, 186.9; *m*/*z* (EI) 192 (M^+); HRMS, found 192.0441. $C_{10}H_8O_4$ requires 192.0423.

*4.3.7. 1,4-Naphthoquinone (**7**).* Following the general procedure, **6** (94 mg, 0.5 mmol) was treated with **1** (7 mg, 0.025 mmol) and Oxone® (1.23 g, 2 mmol) in CF_3CH_2OH–H_2O (2:1, 5 mL) to give **7** (27 mg, 34%) as yellow crystals, which was directly identical to the commercial sample supplied by TCI Co., Ltd.

*4.3.8. 3-Ethylanthra-8,10-quinone (**9**).* Following the general procedure, **8** (80 mg, 0.3 mmol) was treated with **1** (8 mg, 0.03 mmol) and Oxone® (738 mg, 1.2 mmol) in CF_3CH_2OH–H_2O (2:1, 3 mL) to give **9** (56 mg, 79%) as yellow crystals, which was directly identical to the commercial sample supplied by TCI Co., Ltd.

*4.3.9. Blattellaquinone (**13**).* To a solution of 2,5-dimethoxybenzyl alcohol (168 mg, 1 mmol) in puridine (1 mL), isovaleryl chloride (179 mg, 1.5 mmol), and DMAP (5 mg) were added at 0 °C. The mixture was stirred at room temperature for 1 h. The resulting mixture was diluted with Et_2O and washed with water. The organic layer was then washed with 10% HCl, water, brine, and dried, then concentrated. The residue was purified by column chromatography on silica gel to give pure 2,5-dimethoxybenzyl 3-methylbutanoate (**12**) (240 mg, 95%) as a colorless oil; ν_{max} (neat) 1735, 1593, 1503, 1465 cm^{-1}; δ_H (300 MHz $CDC1_3$) 0.96 (6H, d, *J* 6.6 Hz), 2.04–2.23 (1H, m), 2.22 (1H, dd, *J* 22.0, 6.6 Hz), 2.29 (1H, dd, *J* 22.0, 9.4 Hz), 3.76 (3H, s), 3.78 (3H, s), 5.14 (2H, s), 6.79 (1H, d, *J* 7.9 Hz), 6.82 (1H, d, *J* 8.5 Hz), 6.89–6.93 (1H, br); δ_C (75 MHz, $CDCl_3$) 22.4 (2), 25.8, 43.4, 55.7, 56.0, 61.3, 111.4, 113.5, 115.4, 125.4, 151.4, 153.2, 172.7; *m*/*z* (EI) 252 (M^+); HRMS, found 252.1357. $C_{14}H_{20}O_4$ requires 252.1362.

Compound **12** (75 mg, 0.3 mmol) was added to a solution of **1** (4.2 mg, 0.015 mmol) in CF_3CH_2OH–H_2O (1:2, 3 mL) followed by Oxone® (738 mg, 1.2 mmol) at room temperature for 1 h. The mixture was diluted with ethyl acetate and washed with water. The organic layer was then washed with aqueous saturated sodium bicarbonate solution and dried, then concentrated to give pure **13**[24b] (65 mg, 98%) as yellow crystals, mp 46–47 °C (hexane); ν_{max} (KBr) 1744, 1648 cm^{-1}; δ_H (300 MHz, $CDCl_3$) 0.99 (6H, d, *J* 6.6 Hz),

2.07–2.22 (1H, m), 2.30 (2H, d, *J* 6.9 Hz), 5.00 (2H, d, *J* 1.9 Hz), 6.69 (1H, br q, *J* 2.0 Hz), 6.77 (1H, d, *J* 10.0 Hz), 6.80 (1H, dd, *J* 10.0, 1.0 Hz); δ_C (75 MHz, $CDCl_3$) 22.5 (2), 25.7, 43.1, 59.2, 131.3, 136.3, 136.4, 143.1, 171.9, 185.9, 186.7; *m*/*z* (EI) 222 (M^+); HRMS, found 222.08822. $C_{12}H_{14}O_4$ requires 222.08921.

Using CAN oxidation: A mixture of **12** (51 mg, 0.2 mg) and CAN (329 mg, 0.6 mmol) in CH_3CN–H_2O (2:1, 3 mL) was stirred at room temperature for 15 min. The reaction mixture was diluted with ethyl acetate and washed with water. The organic layer was then washed with aqueous saturated sodium bicarbonate solution and dried, concentrated. The residue was purified by column chromatography on silica gel (10% ethyl acetate in hexane) to give pure **13** (29 mg, 69%).

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