Received: 25 March 2020 | Revised: 18 May 2020 | Accepted: 20 May 2020

DOI: 10.1002/jccs.202000122

JOURNAL OF THE CHINESE CHEMICAL SOCIETY

ARTICLE

Tertiary amines as vinyl source for the formations of aryl or pyrrole ring on amido-substitued 1,4-quinone with the assistance of palladium salt

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Funding information
Ministry of Science and Technology, Grant/Award Number: MOST 107-2113-M-005-006

Abstract

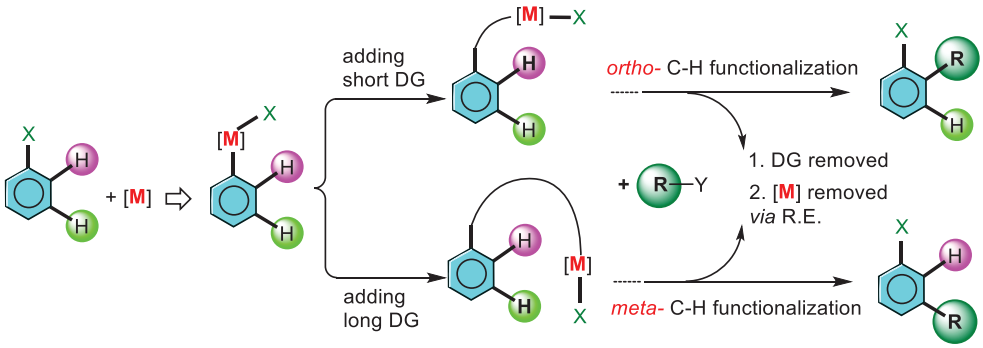
The one-pot synthesis of 3-isopropyl-6-methyl-1H-benzo[f]indole-4,9-dione (**3e**), *N*-(4-[isopentylamino]-3,6-dioxocyclohexa-1,4-dien-1-yl)acetamide (**4d**), 2-(isopentylamino)-6-methylnaphthalene-1,4-dione (**5b**), and 2-(4-acetamido-3,6-dioxocyclohexa-1,4-dien-1-yl)-*N*,*N*-diisopentyl-3-methylbutanamide (**6a**) has been achieved via either pyrrol/aryl ring formations or amination reactions from the Pd(II)-catalyzed reaction of *N*-(3,6-dioxocyclohexa-1,4-dien-1-yl)acetamide (**2a_BQ**) and in the presence of triisopentylamine. More **3**-, **4**-, **5**-, and **6**-like derivatives were obtained while other trialkylamines were used. Crystal structures of **3d_O**, **3e**, **4b**, **4c**, **4d**, **5b,** and **6a** were determined by single-crystal X-ray diffraction methods. The **3**- and **5**-like products reveal the formations of newly generated benzene rings with/without substitutions. The formation of **6a** also implies an unusual reaction pathway of its generation. Based on the structural conformations of various **3**-like products, as well as **6a**, mechanisms were proposed to account for the formations of these compounds. Various fascinating conformations of products observed in this work demonstrate the diversities of this type of reactions.

KEYWORDS

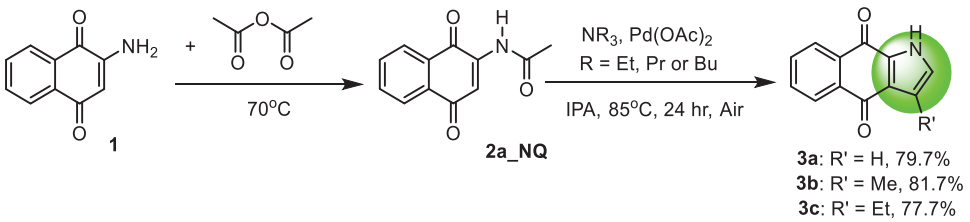
amine, benzene, benzoquinone, C—H activation, palladium, pyrrole

1 | INTRODUCTION

For the last few decades, searching for mild and efficient ways to break the carbon–hydrogen bond, followed by replacing it with various functional groups, called the C—H activation/functionalization process, has stimulated great interest from many chemists of both the synthetic and theoretical realms.[1–15] The C—H bond, either from sp^2 or sp^3 carbon, is well known for its inertness toward most mild chemical reaction methods due to its small polarity, low acidity, and sizable bond strength (≅100 kcal/mol).[16,17] Fortunately, many ingenious methods incorporating directing groups (DGs) have been developed recently (Scheme 1). Among several available categories of DGs, the concept of "removable DGs" is the most appreciated.[18] Through these exquisitely designed pathways, the breaking of C—H bond can be readily achieved by allowing properly selected transition metal moieties as catalytic active species to approach its proximity. Among all the commonly used transition metals, palladium stands out as the most prominent one.[19]



SCHEME 1 The application of short or long removable directing group in *ortho*- or *meta*-C-H activation/functionalization processes



SCHEME 2 The palladium-catalyzed reactions of **2a_NQ** with NR_3 (R: Et, Pr, and Bu) lead to the formation of **3a**, **3b,** and **3c**

1,4-Benzoquinone is the structurally simple member of the quinone family that exhibits redox and bioactive character.[20–24] Several works demonstrated that the C—H functionalization of the benzoquinone framework could be achieved via the replacement of protons with various numbers and forms of amino- and phosphino-groups.[25,26] Besides, a practical way to change the C—H bond to C—C(Ar) bond could be accomplished through the renowned Suzuki-type crossing-coupling reaction.[27,28] In addition, the C—H bond of benzoquinone could be readily altered to C—N or even C—S bond as well.[29] Moreover, the modification of ketone groups on benzoquinone through interaction with benzylic β-C (sp^3)-H bonds of *N*,*N*-dimethylpropanethioamide derivatives has also been decumented.[30]

Our previous works have demonstrated a new and fascinating pathway for creating a pyrrole ring from the reactions of amido-substituted naphthoquinones with tertiary amines, which led to the formations of **3**-type products (Scheme 2).[31,32] Interestingly, the newly added di-carbon fragment in the pyrrole ring of the **3**-type products is in fact originally from the used amine, rather than the former amido-group of **2a_NQ** (or **2b_NQ**). It is clearly shown that the tertiary amine plays dual roles here, both as a base and reactant. Indeed, the reaction routes are rather complicated and involve the participation and interplay of **2a_NQ**, palladium, and amine. Due to these appealing outcomes, we believe that it is worth exploring these types of reactions more thoroughly for benzoquinone-based compounds alongside the aforementioned napthoquinones for comparison.

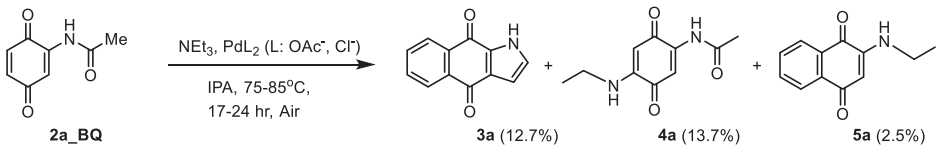
2 | RESULTS AND DISCUSSION

2.1 | Reactions of 2a_BQ with trialkylamines in the presence of palladium salt

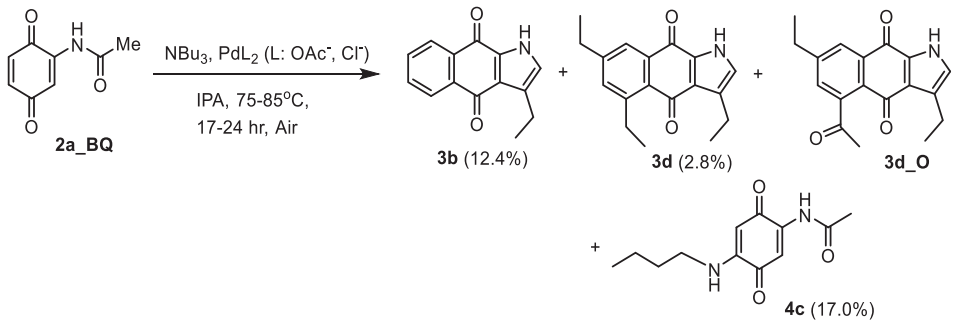
The reaction of *N*-(3,6-dioxocyclohexa-1,4-dien-1-yl)acetamide (**2a_BQ**) with NEt_3 in the presence of palladium salt as a catalyst was carried out (Scheme 3). Unexpectedly, the same compound, **3a**, was obtained as in the aforementioned reaction (Scheme 2), which used **2a_NQ** as the starting material. In addition, a fair amount of **4a** was observed, presumably through a relatively simple amination process. Moreover, another product, a 1,4-naphthoquinone derivative, 2-(ethylamino)naphthalene-1,4-dione (**5a**), was also obtained and identified.

In order to further validate this unique and peculiar observation of forming **3a**, a similar reaction was carried out by using **2a_BQ** as starting material, yet utilizing NBu_3 as the amine source (Scheme 4). Amusingly, compound **3b** was obtained from this reaction, which is the same product as in the preceding reaction (Scheme 3).[33] Moreover, an unexpected production of **3d** was obtained and accompanied by an amination product, **4c**. The identity of **3d** was first characterized by spectroscopic means. Subsequently, single-crystal X-ray diffraction methods were used for this product to further verify its structure. It turned out to be an oxidized product **3d_O**. It is believed that **3d** was the original and major product from the reaction, and **3d_O** was a minor production due to the oxidation of the former during the crystal-growing process. The ORTEP drawing of **3d_O** shown in Figure 1 has unveiled

SCHEME 3 The reactions of **2a_BQ** with NEt_3



SCHEME 4 The reaction of **2a_BQ** with NBu_3



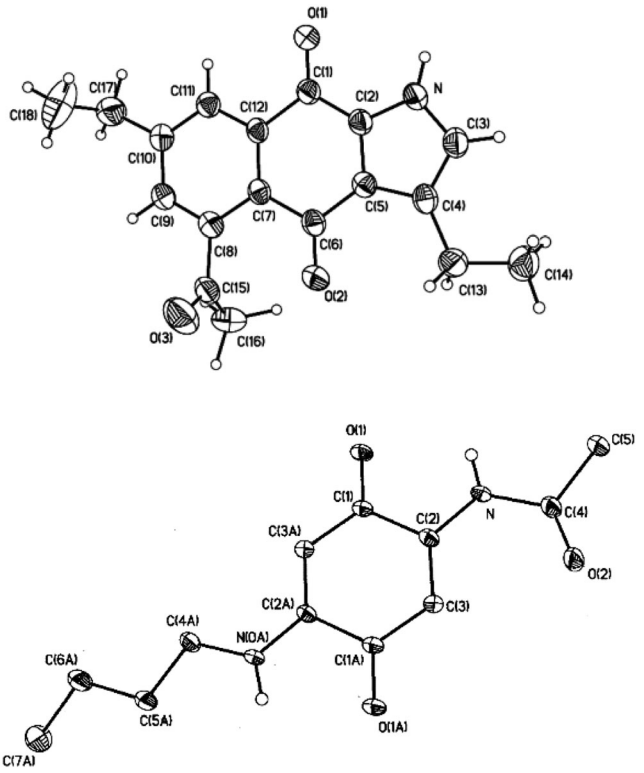
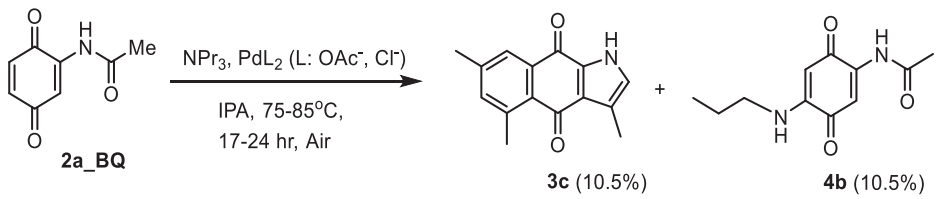


FIGURE 1 The ORTEP drawings of **3d_O** and **4c**

several interesting structural features of this compound.[34] First, a new pyrrole ring on the right-hand side of **2a_BQ** was generated. Second, a benzene ring with two ethyl substituents on the 2,4-positions was formed on the left-hand side of **2a_BQ**. Third, an oxidation process occurred on one of the ethyl groups. It also shows that the three rings are almost coplanar. The backbone of the newly formed benzene ring in **3d_O** could only originate from the source of NBu_3. In principle, it requires two molar equivalents of -Bu groups to build the di-ethyl-substituted benzene ring in **3d** or **3d_O**, while only one molar equivalent of the -Bu group is enough for the formation of a benzene ring in **3b**. This unexpected observation for the generation of a new di-ethyl-substituted benzene ring in **3d** (or **3d_O**) also opens up a new channel for creating a substituted benzene ring on benzoquinone derivatives. Furthermore, the crystal structure of **4c** also shows that an amination reaction took place on the opposite position of the amido-substituent on **2a_BQ** (Figure 1).

Although the use of trialkylamine as the precursor of an alkyl (or alkenyl) fragment in the presence of catalytically metallic species has been reported elsewhere, it is still quite a rare observation with regard to forming an additional benzene ring for the 1,4-quinone backbone.[35–37] To further consolidate the previous conclusion that the newly formed benzene ring originates from the source of tertiary amine, another reaction of **2a_BQ** with NPr_3 under a similar reaction condition was carried out (Scheme 5). Interestingly, **3c** accompanied by **4c** were obtained. The identity of **3c** was further confirmed by spectroscopic means. Obviously, it requires two molar equivalents of -Pr groups to build the di-methyl-substituted benzene ring in **3c**. Accordingly, **3**-like product with substituent free benzene ring is not available from this reaction pathway. Moreover, the determination of the crystal structure of **4b** clearly indicates that a ready amination reaction indeed occurred (Figure 2).

Furthermore, a **3**-like product, **3e**, was observed form the reaction of **2a_BQ** with triisopentylamine under similar reaction conditions. On first glance, the newly formed benzene ring with a methyl substituent seems peculiar from its resolved crystal structure (Scheme 6, Figure 3). Nevertheless, it could be that the newly formed methyl-substituted benzene ring is in fact from the isopentyl group of the used triisopentylamine. In addition, **4d** was



SCHEME 5 The reactions of **2a_BQ** with NPr_3

yielded in fair quantity, and its crystal structure clearly shows that it is a product of the amination process (Figure 3). The isolation of **5b** and its later resolved crystal structural data imply that it could be a transit form before the process of further generation of **3e**. Another interesting observation in this reaction is the formation of **6a**. The crystal structure of **6a** reveals that oxidation took place on the alkyl group of the originally used amine source (Figure 3).

Various conditions were screened for the reaction as shown in Scheme 4 in order to evaluate the influences of different ratios of ingredients to the distribution of the products. The results are as displayed in Table 1. In general, the yields of **4d** and **6a** are higher than that of **3e** and **5b**. It is thought to be because the formations of the latter two compounds require more and devious pathways to achieve the objective. As shown in entry 3, a higher reaction temperature (95°C) is not beneficial to the products with a newly formed ring, such as **3e** or **5b**. It is also clearly indicated in entry 6 that the presence of palladium salt is essential to the formation of **3e**, **5b,** and **6a**. Moreover, the yields of the corresponding products increase till the amount of used amine reaches around four molar equivalents (entry 9–11); then, the yields decrease again while it is in large excess (entry 8).

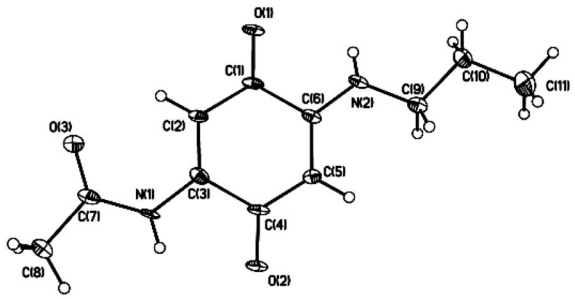
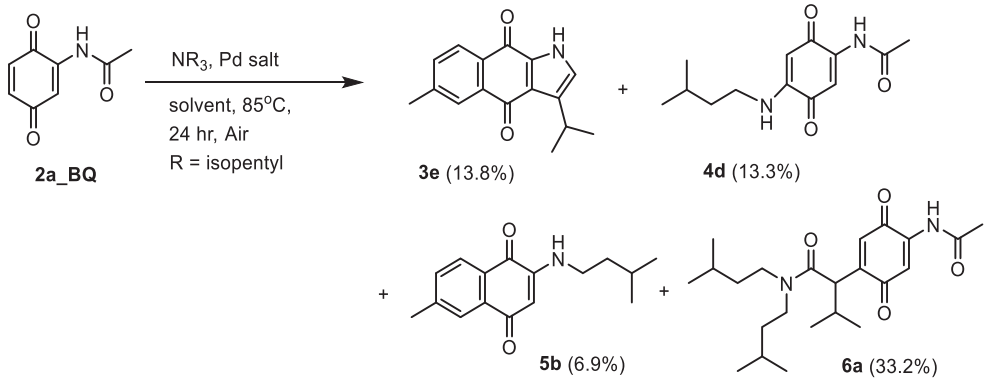


FIGURE 2 The ORTEP drawing of **4b**

2.2 | Proposed mechanism for the formations of 3b and 3d

To the best of our knowledge, the observation of the newly formed benzene ring in **3**-like compounds is the first example of converting 1,4-benzoquinone to 1,4-naphthoquinone derivatives using trialkyamine as the constructing moiety, as illustrated in this work. As known, the most frequently used method for the conversion of 1,4-benzoquinone to 1,4-naphthoquinone derivatives utilizes the conventional Diels-Alder reaction pathway by involving 1,3-butadiene derivative as the dienophile.[38–43] Yet, there were no 1,3-butadiene derivatives to start with in the aforementioned reactions executed. Therefore, the reaction pathways for the formation of **3**-like compounds must be unprecedented routes.

Based on the experimental observations, the reaction mechanism for the formations of **3**-like products is proposed below using NBu_3 as an example (Scheme 7). First, the deprotonation of **2a_BQ** by NBu_3 is carried out to form a cationic intermediate **I**. Second, the addition of *N*-butyl-*N*-butylidenebutan-1-aminium, presumably generated from the reaction of NBu_3 with $Pd(OAc)_2$, to **III**, which is converted from **I**, leads to the formation of **IV**. The formation of an iminium ion from the tertiary amine is critical



SCHEME 6 The reaction of **2a_BQ** with triisopentylamine

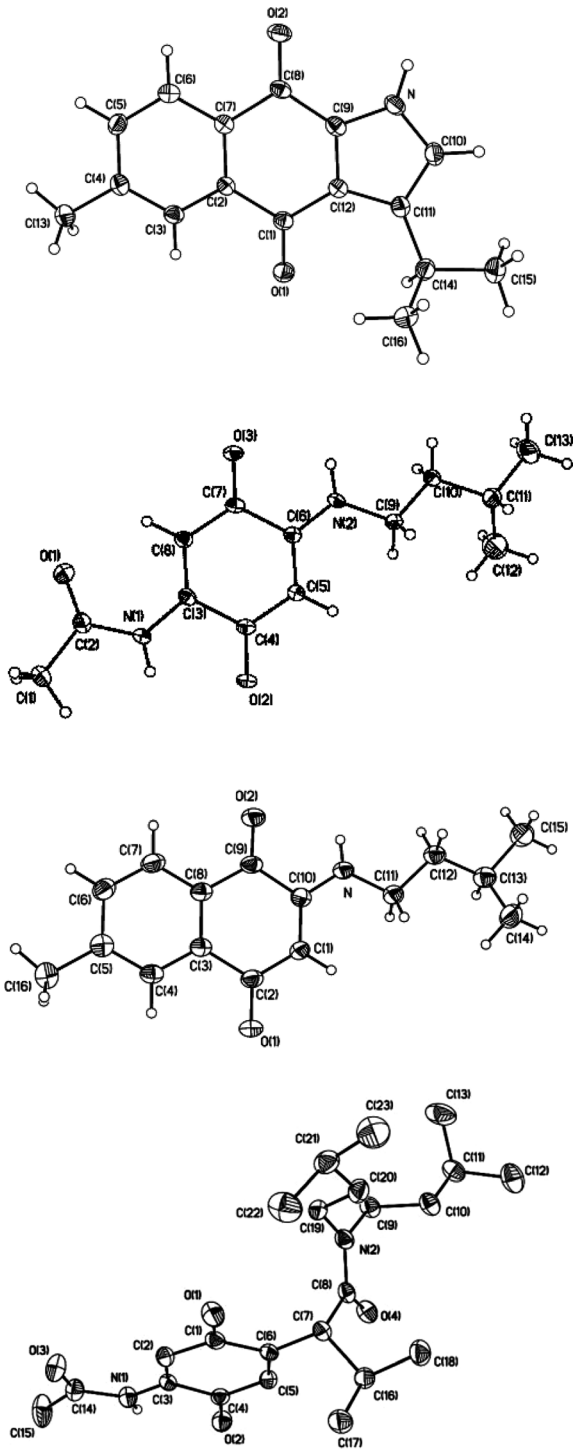


FIGURE 3 ORTEP drawings of **3e**, **4d**, **5b,** and **6a**

to the realization of this reaction. Third, protonation followed by deprotonation processes on **IV** yields **V and** then **VI** by releasing one $HNBu_2$ molecule. Subsequently, there are two plausible routes, **Routes 1** and **2**, which might lead to the formation of **3b** and **3d**, respectively. The first route is an intramolecular cyclization process that leads to the formation of a nonsubstituted benzene ring in **XI** and eventually to the formation of **3b** through procedures stated elsewhere.[31] The second route is a more complicated cyclization process involving a Diels-Alder-type reaction between **VI** and (E)-*N*,*N*-dibutylbut-1-en-1-amine. This process eventually bought about the formation of a diethyl-substituted benzene ring in **XII**. A further cyclization process of forming a pyrrole ring, as demonstrated before, will lead the reaction to the formation of **3d**. It might further be converted to **3d_O** during the crystal-growing process in an oxygen-dissolved solvent. This mechanism asserts that the sequence of the formation of a benzene ring before the pyrrole ring is upheld by the observation of **5**-like products. As shown in this proposed mechanism, the palladium catalyst is indispensable.

2.3 | Proposed mechanism for the formation of 6a

The mechanism for the formation of **6a** by using triisopentyl amine as a reactant is proposed (Scheme 8). First, the reaction of $PdCl_2$ with the utilized triisopentyl amine yields an iminium ion **XIII**. This is followed by the attack of H_2O to form **XIV**. Subsequently, **XV** results from the removal of a proton of the base from **XIV**. Then, the $PdCl_2$ attacks the hydroxyl group of **XV** to form **XVI,** followed by the removal of HCl to yield **XVII**. Next, an amido-form compound, **XVII**, is generated via a β-hydrogen elimination process. Then, a deprotonated **XVIII** attacks **2a_BQ** to yield **XIX**. Finally, the removal of a proton leads to the formation of **6a**.

2.4 | Abstract

The reaction of *N*-(3,6-dioxocyclohexa-1,4-dien-1-yl)acetamide **2a_BQ** with various trialkylamines led to the **3**- and **5**-like products having new substituted/nonsubstituted benzene rings fused to their former quinone framework. In addition, the amination process led to the formation of **4**-like products in relatively large quantities. The production of **6a** was quite unexpected yet informative. Although the yields are not satisfactory for the objected products in this type of reactions, it unfolds an interesting new channel for creating additional pyrrole and/or substituted benzene rings on benzoquinone derivatives.

3 | EXPERIMENTAL

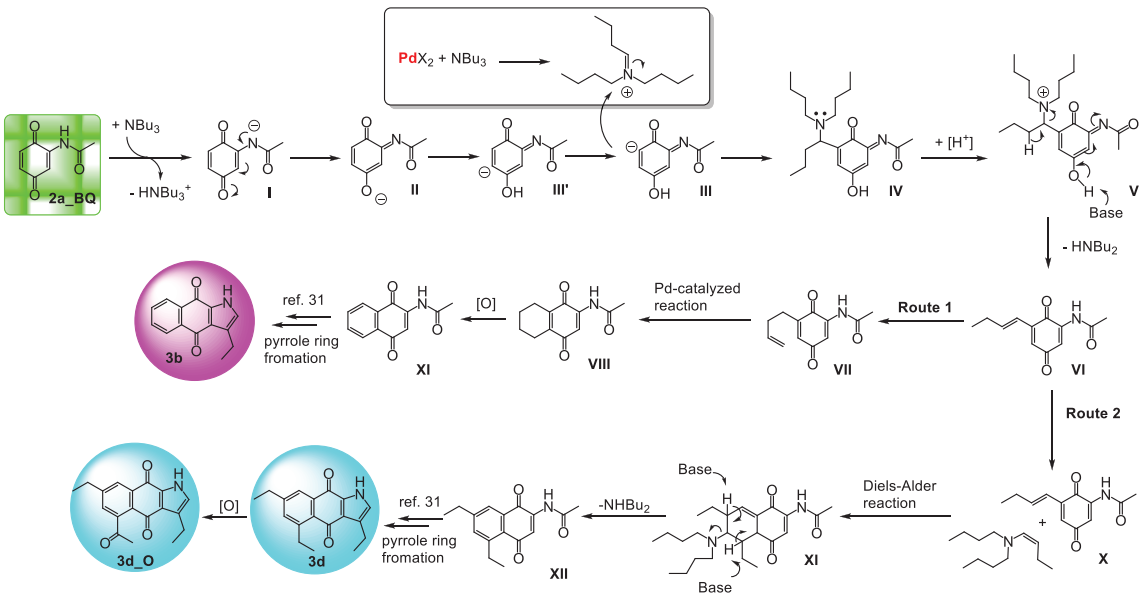
3.1 | General procedure

All reactions were carried out under a nitrogen atmosphere using standard Schlenk techniques or in a

TABLE 1 Various reaction conditions for the productions of **3e**, **4d**, **5b,** and **6a**

					Yield (%)			
Entry	**Temp. (°C)**	**Time (hr)**	**Pd salt**	**Amine (eq.)**	**3e**	**4d**	**5b**	**6a**
1	75	24	$Pd(OAc)_2$	4	4.0	24.8	7.6	27.7
2	85	24	$Pd(OAc)_2$	4	8.9	10.7	5.8	34.6
3	95	24	$Pd(OAc)_2$	4	ND	14.2	ND	15.2
4	85	18	$Pd(OAc)_2$	4	5.4	10.2	7.0	32.6
5	85	12	$Pd(OAc)_2$	4	7.2	22.1	3.7	27.4
6	85	24	—	4	ND	25.6	ND	3.8
7	85	24	$Pd(TFA)_2$	4	6.8	9.1	3.1	32.2
8	85	24	$PdCl_2$	8	9.3	5.2	9.1	18.0
9	85	24	$PdCl_2$	4	13.8	13.3	6.9	33.2
10	85	24	$PdCl_2$	2	10.3	20.2	3.5	19.0
11	85	24	$PdCl_2$	1	9.1	12.4	2.7	20.1
12[a]	85	24	$PdCl_2$	4	14.4	9.0	6.6	22.5

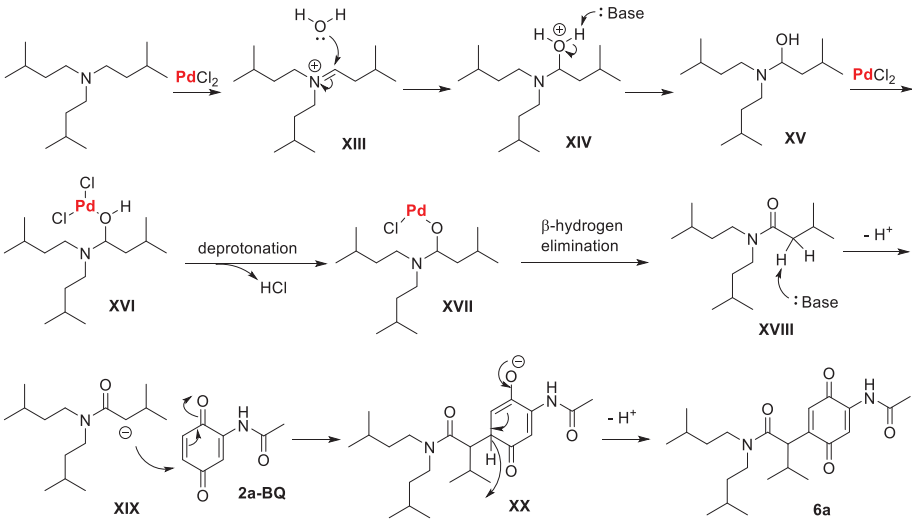
Note: Reaction conditions: The reactions were carried out with 0.2 mmol **2a_BQ**, 10 mol% Pd salt, and 2 ml solvent in air.
Abbreviation: ND, not detected.
[a]Solvent is Tert-butyl alcohol.



SCHEME 7 Proposed mechanism for the formations of **3b** and **3d** (or **3d_O**) using NBu_3 as amine source

nitrogen-flushed glove box. Freshly distilled solvents were used. All processes of separations of the products were performed by centrifugal thin layer chromatography (CTLC; Chromatotron, Harrison model 8924) or column chromatography packed with silica gel. GC–MS analysis was performed on an Agilent 5890 gas chromatograph (Restek Rtx-5MS fused silica capillary column: 30 m, 0.25 mm, 0.5 μm) with an Agilent® 5972 mass selective detector. Routine ^{1}H NMR and ^{13}C NMR spectra were recorded on a Varian-400 spectrometer at 400.441 MHz and 100.7 MHz, respectively. The chemical shift for the former and the latter are reported in ppm relative to internal standards TMS ($\delta = 0.0$) and $CHCl_3$ ($\delta = 77$), respectively. Mass spectra were recorded on a JOEL JMS-SX/SX 102A GC/MS/MS spectrometer. Electrospray ionization-high resolution mass spectra (ESI-HRMS) were recorded on a Finnigan/Thermo Quest Mat 95 XL mass spectrometer.

SCHEME 8 Proposed mechanism for the formation of **6a** by using triisopentyl amine as reactant



3.2 | The syntheses of *N*-(3,6-dioxocyclohexa-1,4-dien-1-yl)acetamide (2a_BQ) and *N*-(3,6-dimethoxycyclohexa-1,4-dien-1-yl)propionamide (2b_BQ)[44]

A 100-ml round flask was charged with a stir bar and 5.1 mmol *N*-(2,5-dimethoxyphenyl)acetamide (1.0 g). The solid was dissolved in 25 ml H_2O and 0.64 ml methanol. Subsequently, 7.7 mmol phenyliodine diacetate (2.5 g) was added to the solution. The solution was stirred at 25°C and was monitored with TLC. Later, 25 ml of H_2O was added before it was extracted several times with CH_2Cl_2. Then, the organic phase of this solution was removed in a separatory funnel, and the collected organic product was extracted with a mixture of 50 ml of H_2O and 50 ml of saturated $NaHCO_3$ several times. The collected organic layer was dried over anhydrous $MgSO_4$. Next, the solution was filtered and concentrated first and later purified by column chromatography packed with silica gel using a mixed solvent (Hexanes/ethyl acetate = 2/1) as eluent. A gold-color solid powder **2a_BQ** was obtained in 73.0% yield (0.62 g, 3.70 mmol). Similar procedures were carried out for the preparation of **2b_BQ**, except 1.76 mmol *N*-(2,5-dimethoxyphenyl)propionamide (0.37 g) and 2.66 mmol phenyliodine diacetate (8.6 g) were used. A gold-color solid powder **2b_BQ** was obtained in 40.0% yield (0.12 g, 0.68 mmol).

3.2.1 | Spectroscopic data for 2a_BQ

^{1}H NMR(400 MHz, $CDCl_3$, δ/ppm): 8.04 (s, 1H), 7.57 (d, J = 2.4 Hz, 1H), 6.78–6.71 (m, 2H), 2.24 (s, 3H).

3.2.2 | Spectroscopic data for 2b_BQ

^{1}H NMR(400 MHz, $CDCl_3$, δ/ppm): 8.00 (s, 1H), 7.59 (s, 1H), 6.79–6.71 (m, 2H), 2.47 (q, J = 7.6 Hz, 2H), 1.22 (t, J = 5.7 Hz, 3H).

3.3 | The syntheses of 1H-benzo[f]indole-4,9-dione (3a), *N*-(4-(ethylamino)-3,6-dioxocyclohexa-1,4-dien-1-yl)acetamide (4a), and 2-(ethylamino)naphthalene-1,4-dione (5a)

A 20-ml Schlenk tube was charged with 0.2 mmol **2a_BQ** (0.033 g) and 0.02 mmol $PdCl_2$ (0.004 g) and a stir bar. Subsequently, 2 ml IPA and 0.8 mmol NEt_3 (111 μl) were added to the tube. The reaction was carried out at 75°C for 18 hr with the cap opened. It was then cooled down to 25°C and diluted with ethyl acetate. The solution was filtered through the Celite column. Next, the solution was concentrated first and later purified by column chromatography packed with silica gel using a mixed solvent (hexanes/dichloromethane/ethyl acetate = 6/4/1) as the eluent. The first eluted orange-yellow color solid powder **5a** was obtained in 2.5% yield (0.001 g, 0.005 mmol). The second eluted compound was yellow-color solid powder **3a**. It was obtained in 12.7% yield (0.005 g, 0.025 mmol). The third obtained compound was a purple-color solid powder **4a**. It was eluted using a mixed solvent (hexanes/ethyl acetate = 3/1) as the eluent. It was obtained in 13.7% yield (0.0057 g, 0.027 mmol).

3.3.1 | Spectroscopic data for 3a

^{1}H NMR(400 MHz, $CDCl_3$, δ/ppm): 9.73 (s, 1H), 8.22 (d, J = 2.8 Hz, 1H), 8.17 (d, J = 2.8 Hz, 1H), 7.70 (t, J = 3.6 Hz, 2H), 7.15 (t, J = 2.8 Hz, 1H), 6.84 (t, J = 2.4 Hz, 1H); ^{13}C NMR (100 MHz, DMSO-d^6, δ/ppm): 180.75, 175.15, 134.08, 133.97, 133.87, 133.55, 132.74, 128.44, 127.51, 126.72, 126.42, 108.555; HRMS (EI, M^+, m/z): Calcd. for $C_{12}H_7NO_2$[M^+]: 197.05 m/z; found: 197.0481; Elemental Anal. Calcd. for $C_{12}H_7NO_2$: N, 7.10%; C, 73.09%; H, 3.58%. Found: N, 6.64%; C, 71.96%; H, 3.84%.

3.3.2 | Spectroscopic data for 4a

^{1}H NMR (400 MHz, $CDCl_3$, δ/ppm): 8.61 (s, 1H), 7.35 (s, 1H), 6.10 (s, 1H), 5.41 (s, 1H), 3.23–3.16 (m, 2H), 2.25 (s, 3H), 1.31 (t, J = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, CDCl3, δ/ppm): 183.40, 178.75, 169.51, 147.98, 141.34, 109.53, 93.83, 37.30, 29.68, 13.35; HRMS (EI, M^+, m/z): Calcd. For $C_{10}H_{12}N_2O_3$: 208.08 m/z; found: 208.0856 m/z.

3.3.3 | Spectroscopic data for 5a

^{1}H NMR (400 MHz, $CDCl_3$, δ/ppm): 8.10 (d, J = 7.6 Hz, 1H), 8.04 (d, J = 7.6 Hz, 1H), 7.72 (t, J = 7.2 Hz, 1H), 7.61 (t, J = 7.6 Hz, 1H), 5.82 (s, 1H), 5.73 (s, 1H), 3.25–3.20(m, 2H), 1.34 (t, J = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, δ/ppm): 133.65, 126.75, 125.85, 123.38, 119.55, 116.61, 109.46, 44.99, 4.24, 32.39; HRMS (EI, M^+, m/z): Calcd. for $C_{12}H_{11}NO_2$: 201.08 m/z; found: 201.0781 m/z.

3.4 | The syntheses of 3-ethyl-1H-benzo[f]indole-4,9-dione (3b), 3,5,7-triethyl-1H-benzo[f]indole-4,9-dione (3d), *N*-(4-[butylamino]-3,6-dioxocyclohexa-1,4-dien-1-yl)acetamide (4c)

A 20-ml Schlenk tube was charged with 0.2 mmol **2a_BQ** (0.033 g) and 0.02 mmol $PdCl_2$ (0.004 g) and a stir bar. Subsequently, 2 ml IPA and 0.8 mmol NBu_3 (196 μl) were added to the tube. The reaction was carried out at 75°C for 24 hr with the cap opened. It was then cooled down to 25°C and diluted with ethyl acetate. The solution was filtered through Celite column. Next, the solution was concentrated first and later purified by column chromatography packed with silica gel using a mixed solvent (hexanes/ethyl acetate = 7/1) as the eluent. The first collected band is a yellow-color solid and was later characterized as **3d**. It was obtained in S4% yield (0.002 g, 0.007 mmol). A yellow-color solution was collected as the second band. Later, this yellow-color solid powder was identified as **3b**. It was obtained in 6.7% yield (0.003 g, 0.013 mmol). The third collected band is a purple-color solid and was later characterized as **4c**. It was obtained in 10.6% yield (0.005 g, 0.021 mmol).

3.4.1 | Spectroscopic data for 3b

^{1}H NMR(400 MHz, $CDCl_3$, δ/ppm): 9.51 (s, 1H), 8.18 (d, J = 4.4 Hz, 1H), 814 (d, J = 4.4 Hz, 1H), 7.68 (t, J = 5.2 Hz, 2H), 6.94 (d, J = 2.4 Hz, 1H), 2.91 (q, J = 7.2 Hz, 2H), 1.29 (t, J = 4.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, δ/ppm): 181.69, 175.93, 134.74, 133.42, 133.29, 132.75, 130.28, 126.84, 1,216.12, 124.55, 123.94, 19.25, 14.10; HRMS (EI, M^+, m/z): Calcd. For $C_{14}H_{11}NO_2$: 225.08 m/z; found: 225.0786 m/z; Elemental Anal. Calcd. for $C_{14}H_{11}NO_2$: N, 6.22%; C, 74.65%; H, 4.92%. Found: N, 5.79%; C, 73.65%; H, 4.91%.

3.4.2 | Spectroscopic data for 3d

^{1}H NMR(400 MHz, $CDCl_3$, δ/ppm): 9.31 (s, 1H), 7.93 (s, 1H), 7.29(s, 1H), 6.91 (d, J = 2.0 Hz, 1H), 3.26 (q, J = 7.6 Hz, 2H), 2.90 (q, J = 7.6 Hz, 2H), 2.73 (q, J = 7.6 Hz, 2H), 1.33–1.20 (m, 9H); ^{13}C NMR (100 MHz, $CDCl_3$, δ/ppm): 184.40, 176.13, 148.81, 148.82, 136.26, 135.17, 131.75, 130.04, 129.24, 125.70, 124.74, 123.73, 29.68, 28.74, 19.33, 15.44, 14.90, 14.11; HRMS (EI, M^+, m/z): Calcd. For $C_{18}H_{19}NO_2$: 281.14 m/z; found: 281.1411 m/z.

3.4.3 | Spectroscopic data for 4c

^{1}H NMR (400 MHz, $CDCl_3$, δ/ppm): 8.62 (s, 1H), 7.35 (s, 1H), 6.16 (s, 1H), 5.41 (s, 1H), 3.14 (q, J = 6.4 Hz, 2H), 2.23 (s, 3H), 1.68–1.61 (m, 2H), 1.44–1.38 (m, Hz, 2H), 0.95 (t, J = 7.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, δ/ppm): 183.41, 178.69, 169.49, 148.15, 141.39, 109.50, 93.76, 42.26, 30.12, 25.03, 20.12, 13.61; HRMS (EI, M^+, m/z): Calcd. For $C_{12}H_{16}N_2O_3$: 236.12 m/z; found: 236.1164 m/z; Elemental Anal. Calcd. for $C_{12}H_{16}N_2O_3$: N, 11.86%; C, 61.00%; H, 6.83%. Found: N, 10.48%; C, 61.74%; H, 6.79%.

3.5 | The syntheses of 3,5,7-trimethyl-1H-benzo[f]indole-4,9-dione (3c) *N*-(3,6-dioxo-4-[propylamino]cyclohexa-1,4-dien-1-yl) acetamide(4b)

A 20-ml Schlenk tube was charged with 0.2 mmol **2a_BQ** (0.033 g) and 0.02 mmol $PdCl_2$ (0.004 g) and a stir bar.

Subsequently, 2 ml IPA and 0.8 mmol NPr_3 (155 μl) were added to the tube. The reaction was carried out at 75°C for 24 hr with the cap opened. It was then cooled down to 25°C and diluted with ethyl acetate. The solution was filtered through Celite column. Next, the solution was concentrated first and later purified by column chromatography packed with silica gel using a mixed solvent (hexanes/ethyl acetate = 7/1) as the eluent. The first collected band is a golden yellow-color solid and was later characterized as **3c**. It was obtained in 10.46% yield (0.0050 g, 0.021 mmol). A purple-color solution was collected as the second band. Later, this purple-color solid powder was identified as **4b**. In this condition, the yield of **4b** is rather low. In order to increase the yield of **4b**, a similar reaction was carried out for the preparation of **4b** except using $Pd(OAc)_2$ as the catalyst and a temperature under 85°C. In this way, **4b** was obtained in 10.36% yield (0.0046 g, 0.021 mmol).

3.5.1 | Spectroscopic data for 3c

^{1}H NMR(400 MHz, $CDCl_3$, δ/ppm): 9.205 (s, 1H), 7.90(s, 1H), 7.26 (s, 1H), 6.89 (s, 1H), 2.79 (s, 3H), 2.42 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$, δ/ppm): 184.84, 175.80, 142.54, 141.88, 138.55, 134.87, 131.75, 129.42, 125.85, 124.58, 122.90, 110.00, 29.69, 23.29, 21.36; HRMS (EI, M^+, *m/z*): Calcd. for $C_{15}H_{13}NO_2$: 239.09 *m/z*; found: 239.0944 *m/z*.

3.5.2 | Spectroscopic data for 4b

^{1}H NMR (400 MHz, $CDCl_3$, δ/ppm): 8.62 (s, 1H), 7.35 (s, 1H), 6.19 (s, 1H), 5.41 (s, 1H), 3.11 (q, J = 6.8 Hz, 2H), 2.23 (s, 3H), 1.73–1.64 (m, 2H), 0.99 (t, J = 7.6 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, δ/ppm): 183.40, 178.70, 169.51, 148.16, 141.37, 109.49, 93.79, 44.22, 25.02, 21.47, 11.43; HRMS (EI, M^+, *m/z*): Calcd. for $C_{11}H_{14}N_2O_3$: 222.10 *m/z*; found: 222.1000 *m/z*; Elemental Anal. Calcd. for $C_{11}H_{14}N_2O_3$: N, 12.61%; C, 59.45%; H, 6.35%. Found: N, 11.84%; C, 59.68%; H, 5.92%.

3.6 | The syntheses of 3-isopropyl-6-methyl-1H-benzo[f]indole-4,9-dione(3e), *N*-(4-(isopentylamino)-3,6-dioxocyclohexa-1,4-dien-1-yl)acetamide (4d), 2-(isopentylamino)-6-methylnaphthalene-1,4-dione(5b), and 2-(4-acetamido-3,6-dioxocyclohexa-1,4-dien-1-yl)-*N*,*N*-diisopentyl-3-methylbutanamide(6a)

A 20-ml Schlenk tube was charged with 0.2 mmol **2a_BQ** (0.033 g) and 0.02 mmol $PdCl_2$ (0.004 g) and a stir bar. Subsequently, 2 ml IPA and 0.4 mmol triisopentylamine (233 μl) were added to the tube. The reaction was carried out at 85°C for 24 hr with the cap opened. It was then cooled down to 25°C and diluted with ethyl acetate. The solution was filtered through Celite column. The reaction mixture was acidified with 1 M HCl, extracted with ethyl acetate, and dried over $MgSO_4$. Next, the solution was concentrated first and later purified by column chromatography packed with silica gel using a mixed solvent (hexanes/ethyl acetate = 24/1) as the eluent. The first collected band is an orange-color solid and was later characterized as **5b**. It was obtained in 6.9% yield (0.004 g, 0.016 mmol). A golden yellow-color solution was collected as the second band. Later, this golden yellow-color solid powder was identified as **3e**. It was obtained in 13.8% yield (0.007 g, 0.028 mmol). The third collected band is a purple-color solid and was later characterized as **4d**. It was obtained in 13.3% yield (0.007 g, 0.028 mmol). A yellow-color solution was collected as the fourth band. Later, this yellow-color solid powder was identified as **6a**. It was obtained in 33.2% yield (0.0269 g, 0.067 mmol).

3.6.1 | Spectroscopic data for 3e

^{1}H NMR (400 MHz, $CDCl_3$, δ/ppm): 9.89 (s, 1H), 8.02 (d, J = 8.0 Hz, 1H), 7.98 (s, 1H), 7.45 (d, J = 7.6 Hz, 1H), 6.96 (s, 1H), 3.47–3.57 (m, 1H), 2.48 (s, 3 H), 1.29–1.31 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$, δ/ppm): 181.74, 176.08, 144.51, 135.64, 134.77, 133.29, 133.02, 130.72, 127.55, 126.30, 123.88, 122.07, 29.68, 25.59, 22.87, 21.85; HRMS (EI, M^+, *m/z*): Calcd. for $C_{16}H_{15}NO_2$: 253.11 *m/z*; found: 253.1107 *m/z*; Elemental Anal. Calcd. for $C_{16}H_{15}NO_2$: N, 5.53%; C, 75.87%; H, 5.97%. Found: N, 5.62%; C, 75.64%; H, 5.85%.

3.6.2 | Spectroscopic data for 4d

^{1}H NMR (400 MHz, $CDCl_3$, δ/ppm): 8.63 (s, 1H), 7.33 (s, 1H), 6.14 (s, 1H), 5.40 (s, 1H), 3.11–3.17 (m, 2H), 2.21 (s, 3H), 1.63–1.68 (m, 1H), 1.51–1.57 (m, 2H), 0.89–0.94 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$, δ/ppm): 183.38, 178.63, 169.54, 148.07, 141.38, 109.46, 93.69, 40.76, 36.77, 25.84, 25.02, 22.44, 22.28; HRMS (EI, M^+, *m/z*): Calcd. for $C_{13}H_{18}N_2O_3$: 250.13 *m/z*; found: 250.1321 *m/z*; Elemental Anal. Calcd. for $C_{13}H_{18}N_2O_3$: N, 11.19%; C, 62.38%; H, 7.25%. Found: N, 8.95%; C, 63.53%; H, 7.74%.

3.6.3 | Spectroscopic data for 5b

^{1}H NMR (400 MHz, $CDCl_3$, δ/ppm): 7.93 (d, J = 7.6 Hz, 1H), 7.89 (s, 1H), 7.39 (d, J = 8.0 Hz, 1H), 5.87 (s, 1H),

5.69 (s, 1H), 3.15–3.20 (m, 2H), 2.46 (s, 3H), 1.64–1.72 (m, 1H), 1.51–1.60 (m, 2H), 0.94–0.96 (m, 6H); ^{13}C NMR (100 MHz, $CDCl_3$, δ/ppm): 183.24, 181.62, 148.06, 146.13, 133.62, 132.52, 128.45, 128.17, 126.70, 126.53, 100.38, 40.77, 36.94, 25.93, 22.36, 22.04; HRMS (EI, M^+, *m*/*z*): Calcd. for $C_{16}H_{19}NO_2$: 257.14 *m*/*z*; found: 257.1424 *m*/*z*.

3.6.4 | Spectroscopic data for 6a

^{1}H NMR (400 MHz, $CDCl_3$, δ/ppm): 8.12 (s, 1H), 7.53 (s, 1H), 7.05 (s, 1H), 3.84 (d, J = 10.4 Hz, 1H), 3.27–3.35 (m, 1H), 3.24 (t, J = 7.8 Hz, 2H), 3.03–3.11 (m, 1H), 1.22–2.24 (m, 1H), 2.21 (s, 3H), 1.53–1.61 (m, 1H), 1.43–1.53 (m, 1H), 1.29–1.40 (m, 4H), 0.91–0.96 (m, 9H), 0.85–0.87 (m, 6H), 0.74–0.75 (d, J = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, δ/ppm): 186.97, 182.74, 170.68, 169.34, 148.91, 137.94, 130.19, 114.16, 46.54, 45.31, 45.09, 38.58, 36.33, 34.63, 26.25, 26.17, 24.82, 22.57, 22.46, 22.37, 21.74, 20.06; HRMS (EI, M^+, *m*/*z*); Elemental Anal. Calcd. for $C_{23}H_{36}N_2O_4$: N, 6.92%; C, 68.29%; H, 8.97%. Found: N, 6.90%; C, 68.00%; H, 8.93%.

3.7 | X-ray crystallographic studies

Crystals of **3d_O**, **3e**, **4b**, **4c**, **4d**, **5b**, and **6a** were obtained by placing samples in crystal-growing glassware, which contains toluene, THF, or a mixed solvent (hexanes/CH_2Cl_2), in an environment of 25°C for a few days. Suitable crystals of these compounds were sealed in thin-walled glass capillaries under nitrogen atmosphere and mounted on a Bruker AXS SMART 1000 diffractometer. Intensity data were collected in 1350 frames with increasing ω (width of 0.3° per frame). The absorption correction was based on the symmetry-equivalent reflections using the SADABS program. The space group determination was based on a check of the Laue symmetry and systematic absences and was confirmed using the structure solution. The structure was solved by direct methods using a SHELXTL package. All non-H atoms were located from successive Fourier maps, and hydrogen atoms were refined using a riding model. Anisotropic thermal parameters were used for all non-H atoms, and fixed isotropic parameters were used for H atoms.

ACKNOWLEDGMENTS

We thank the Ministry of Science and Technology of the ROC (Grant MOST 107-2113-M-005-006) for financial support.

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How to cite this article: Jhou J-N, Cheng C-W, Hong F-E. Tertiary amines as vinyl source for the formations of aryl or pyrrole ring on amido-substitued 1,4-quinone with the assistance of palladium salt. *J Chin Chem Soc*. 2020;1–11. https://doi.org/10.1002/jccs.202000122