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Palladium-Catalyzed Direct Alkenylation of 2-Oxazolones: An Entry to 3,4,5-Trisubstituted 2-Oxazolones

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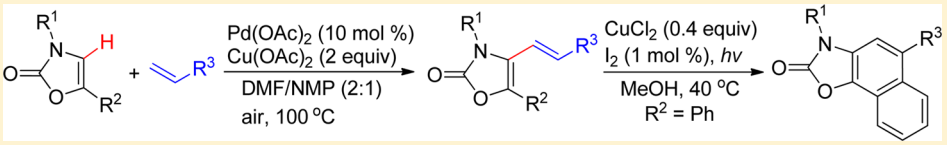
Supporting Information



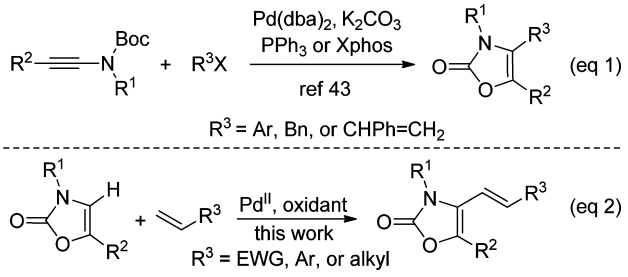
ABSTRACT: Described herein is a novel method for the synthesis of 3,4,5-trisubstituted 2-oxazolones featuring the first Pd-catalyzed dehydrogenative alkenylation of 2-oxazolones, which is realized by employing 10 mol % of $Pd(OAc)_2$ as the catalyst and the use of readily available $Cu(OAc)_2$ as the oxidant. A wide range of functional groups, such as F, Cl, Br, OMe, ester, ketone, amide, alkyl, and aryl substituents, are found to be compatible under the reaction conditions. The utilization of the C−H functionalization strategy provides a straightforward, convenient, and highly atom-economical approach for the construction of 3,4,5-trisubstituted 2-oxazolones. It is worth noting that the 4-alkenyl 2-oxazolones can be smoothly converted into naphtho[1,2-*d*]oxazol-2-ones via a photochemical transformation.

INTRODUCTION

2-Oxazolones are employed in a variety of chemical transformations, such as cycloaddition reactions,[1−4] radical reactions,[5,6] metal-catalyzed cross-coupling reactions,[7] and other reactions.[8] Moreover, some natural or synthetic 2-oxazolones are found to have distinctive biological activities, including anti-inflammatory, antitumor, sedative, and cardiotonic activity.[9] As such, the exploration of novel and efficient procedures for the assembly of 2-oxazolones has remained an attractive task. In contrast to the traditional method involving the condensation of carbonyl groups,[10−15] which suffers from the utilization of strongly acidic or basic conditions or toxic carbonylation reagents, recently the transition-metal-catalyzed approach has emerged as a powerful alternative to prepare 2-oxazolones. For example, Hashmi[16] and Gagosz[17] independently disclosed an elegant method for the synthesis of 3,5-disubstituted 2-oxazolones involving a Au-catalyzed cyclization of *N*-alkynyl *tert*-butyloxycarbamates. Meanwhile, the Jiang group reported a concise approach to 4-methyl-2-oxazolones via the cycloaddition of propargylic alcohols, primary amines, and carbon dioxide.[18] Lautens and co-workers found that 3,5-disubstituted 2-oxazolones could be efficiently assembled by the Pd-catalyzed coupling of *β*,*β*-dibromoenamides with boronic acids.[19] Recently, a dichotomy protocol for the access of 3,5-disubstituted or 3,4,5-trisubstituted 2-oxazolones featuring the Pd-catalyzed cycloisomerization of *N*-alkynyl *tert*-butyloxycarbamates has been realized in our group;[20] however, as for the latter case, only 4-allyl-2-oxazolones could be synthesized, and the development of a general as well as efficient method for the synthesis of 3,4,5-trisubstituted 2-oxazolones both remains challenging and has great value.

On the other hand, cross dehydrogenative coupling reactions are of paramount interest in forming a new C−C bond;[21−25] in particular, Pd-catalyzed oxidative cross-coupling of arenes and alkenes through C−H activation, the so-called oxidative Heck-type reaction or Fujiwara−Moritani reaction,[26] has matured to be among the most reliable methods for furnishing diversely substituted alkenes. Indeed, it has been widely utilized for the introduction of a side chain into various heterocycles and carbocycles, including indoles,[27] furans,[28] pyrroles,[29] thiophenes,[30] caffeines,[31] azoles and related compounds,[32] 5-pyrazolones,[33] chromones,[34] *N*-oxides,[35] indolizines,[36] pyridines,[37] pyridones,[38] benzenes,[39] ferrocenes,[40] and perfluoroarenes.[41,42] In contrast, the Pd-catalyzed direct alkenylation of 2-oxazolones has not been reported so far. Quite recently, we implemented a facile route to 3,4,5-trisubstituted 2-oxazolones by the Pd-catalyzed coupling of *N*-alkynyl *tert*-butyloxycarbamates with aromatic halides and related electrophiles (Scheme 1, eq 1).[43] To our surprise, *β*-haloalkenes, *β*-bromostyrenes, for example, were not amenable to this reaction. As such, the

Scheme 1. Complementary Methods to 3,4,5-Trisubstituted 2-Oxazolones



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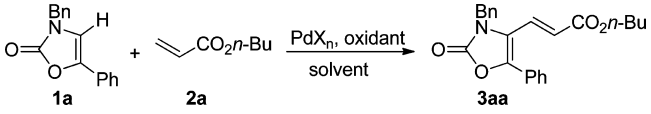
effective synthesis of 4-alkenyl-2-oxazolones constitutes an unmet goal. To address this issue, we hypothesized that the Pd-catalyzed direct alkenylation of 2-oxazolones would provide an operationally simple as well as atom- and step-economical route to 4-alkenyl-2-oxazolones (Scheme 1, eq 2), thus providing a complementary method to our attempts[20,43] to elaborate polysubstituted 2-oxazolones. Herein, we report such a reaction. It should be noted that it represents the first Pd-catalyzed direct C−H olefination of 3,5-disubstituted 2-oxazolones, which may be a class of challenging substrates for direct C4 functionalization due to the unfavorable steric interactions caused by two ortho substituents.

RESULTS AND DISCUSSION

Preliminary investigations on the reaction parameters were carried out by employing 3-benzyl-5-phenyloxazol-2(3*H*)-one (**1a**) and butyl acrylate (**2a**) as the model substrates. No reaction occurred when **1a** and **2a** were just treated with 10 mol % of $Pd(OAc)_2$ in *N*,*N*-dimethylmethanamide (DMF) at 100 °C for 8 h, while employing 2 equiv of $Cu(OTf)_2$ as the oxidant led to **3aa** in noticeable yield (11%) (Table 1, entries 1 and 2), indicating that the oxidant was essential for the Pd-catalyzed direct alkenylation reaction. Hence, we extensively screened the oxidants for this reaction, and representative results are included in Table 1 (Table 1, entries 3−9). We were delighted to find that the use of $Cu(OAc)_2{\cdot}H_2O$ instead of $Cu(OTf)_2$ resulted in a significant increase of the yield to 51% (Table 1, entry 3). Furthermore, the reaction promoted by $Cu(OAc)_2$ in air produced **3aa** in 77% yield, while a comparable yield (75%) was observed by replacing air with O_2; therefore, further optimizations were conducted in an air atmosphere. A survey of the amounts of $Cu(OAc)_2$ revealed that the addition of 2 equiv of $Cu(OAc)_2$ was necessary to maintain the high yield (Table 1, entry 5). Other oxidants, including silver salts, led to the product in reduced yields (Table 1, entries 6−9). Various solvents such as HOAc, CH_3CN, dioxane, *N*,*N*-dimethylethanamide (DMAC), and *N*-methylpyrrolidone (NMP) were also investigated, but all resulted in decreased efficiency (Table 1, entries 14−18). Finally, excellent performance was found for the combination use of DMF and NMP (DMF/NMP 2/1), furnishing **3aa** in 81% isolated yield (Table 1, entry 21). Therefore, the best reaction conditions for the Pd-catalyzed C−H olefination of 2-oxazolinones were finally identified as follows: 10 mol % of $Pd(OAc)_2$, 2 equiv of $Cu(OAc)_2$, DMF/NMP (2/1 v/v), 100 °C, and 8 h in air. The structure of the resulting 4-vinyl 2-oxazolone product **3aa** was determined by a single-crystal X-ray analysis (see the Supporting Information).

Table 1. Optimization of the Reaction Parameters[a]



1a **2a** **3aa**

entry	PdX_n	oxidant	solvent	yield (%)[b]
1	$Pd(OAc)_2$		DMF	NR
2	$Pd(OAc)_2$	$Cu(OTf)_2$	DMF	11
3	$Pd(OAc)_2$	$Cu(OAc)_2{\cdot}H_2O$	DMF	51
4	$Pd(OAc)_2$	$Cu(OAc)_2$	DMF	77 (75)[c] (38)[d]
5	$Pd(OAc)_2$	$Cu(OAc)_2$	DMF	52[e]
6	$Pd(OAc)_2$	AgOAc	DMF	trace
7	$Pd(OAc)_2$	Ag_2CO_3	DMF	trace
8	$Pd(OAc)_2$	BQ	DMF	trace
9	$Pd(OAc)_2$	$PhI(OAc)_2$	DMF	32
10	$Pd(PhCN)_2Cl_2$	$Cu(OAc)_2$	DMF	60
11	$Pd(PPh_3)_2Cl_2$	$Cu(OAc)_2$	DMF	52
12	$Pd(OTf)_2$	$Cu(OAc)_2$	DMF	10
13	$PdCl_2$	$Cu(OAc)_2$	DMF	55
14	$Pd(OAc)_2$	$Cu(OAc)_2$	HOAc	48
15	$Pd(OAc)_2$	$Cu(OAc)_2$	CH_3CN	28
16	$Pd(OAc)_2$	$Cu(OAc)_2$	dioxane	12
17	$Pd(OAc)_2$	$Cu(OAc)_2$	DMAC	42
18	$Pd(OAc)_2$	$Cu(OAc)_2$	NMP	51
19	$Pd(OAc)_2$	$Cu(OAc)_2$	DMF/HOAc (4/1)	34
20	$Pd(OAc)_2$	$Cu(OAc)_2$	DMF/PivOH (1/1)	36
21	$Pd(OAc)_2$	$Cu(OAc)_2$	DMF/NMP (2/1)	81

[a]Reaction conditions: **1a** (0.25 mmol), **2a** (0.5 mmol), PdX_n (10 mol %) and oxidant (200 mol %) in 1 mL of solvent at 100 °C in air for 8 h. [b]Isolated yield. [c]Under O_2. [d]Under N_2. [e]1 equiv of $Cu(OAc)_2$ was used.

To explore the scope and limitations of Pd-catalyzed Fujiwara−Moritani reactions of 2-oxazolones, a variety of olefins were examined under the optimal reaction conditions. First, the activated alkenes were treated with **1a**, and in general, the reaction produced 4-alkenyl 2-oxazolones in good yields. For instance, the reaction of ethyl acrylate (**2b**) and benzyl acrylate (**2c**) resulted in 3,4,5-trisubstituted oxazolones **3ab**,**ac** in 75% and 84% yield, respectively; moreover, both of them were obtained as a single *E* isomer (Table 2, **3ab**,**ac**). In addition to monosubstituted alkenes, disubstituted alkenes were also investigated. As an example, methyl methacrylate (**2g**) coupled smoothly with **1a** to afford a mixture of two inseparable regioisomers in an overall 72% yield, and similar to the previous report,[44] it was found that the unconjugated isomer **3ag** was the major product (**3ag**/**3ag**′ 5/1) (Table 2, **3ag**,**ag**′), suggesting that *β*-H elimination was kinetically favorable in this reaction. Additionally, a range of substituted styrenes proved to be effective substrates for the olefination reaction. For example, the reaction of styrene **2h** produced **3ah** in 73% yield (Table 2, **3ah**). It is worth noting that the styrene substrate **2m**, bearing a strong electron-donating group (OMe), gave rise to **3am** in a much lower (47%) yield (Table 2, **3am**). Under the reaction conditions, the transformation of pentafluorostyrene (**2o**) also gave the olefination product **3ao** in a reasonable yield (Table 2, **3ao**). For the unactivated olefin cyclohexene, for instance, the reaction was relatively sluggish and only a moderate yield was observed after 16 h; notably, it enabled the formation of unconjugated **3aq** as the single product (Table 2, **3aq**). Moreover, 1-decene was found to be a viable substrate (Table 2, **3ar** and **3ar**′), while the vinylation of (4*E*)-octene failed under the standard conditions.

Under the optimized reaction conditions, a number of 3,5-disubstituted 2-oxazolones were then varied by utilizing **2a** as the coupling partner, and as expected, the reaction proceeded successfully to generate the desired 3,4,5-trisubsituted 2-oxazolones in moderate to good yields (Table 3). The relatively electron poor 3,5-disubstituted 2-oxazolone **1b** afforded the corresponding product **3ba** in 48% yield, while the alkenylation of electron-rich substrate **1h** gave 76% of **3ha**, which implied that the electronic effect of 2-oxazolones had some influence on this Pd-catalyzed oxidative Heck-type reaction (Table 3, **3ba**,**ha**). The halide functional groups, including F, Cl, and

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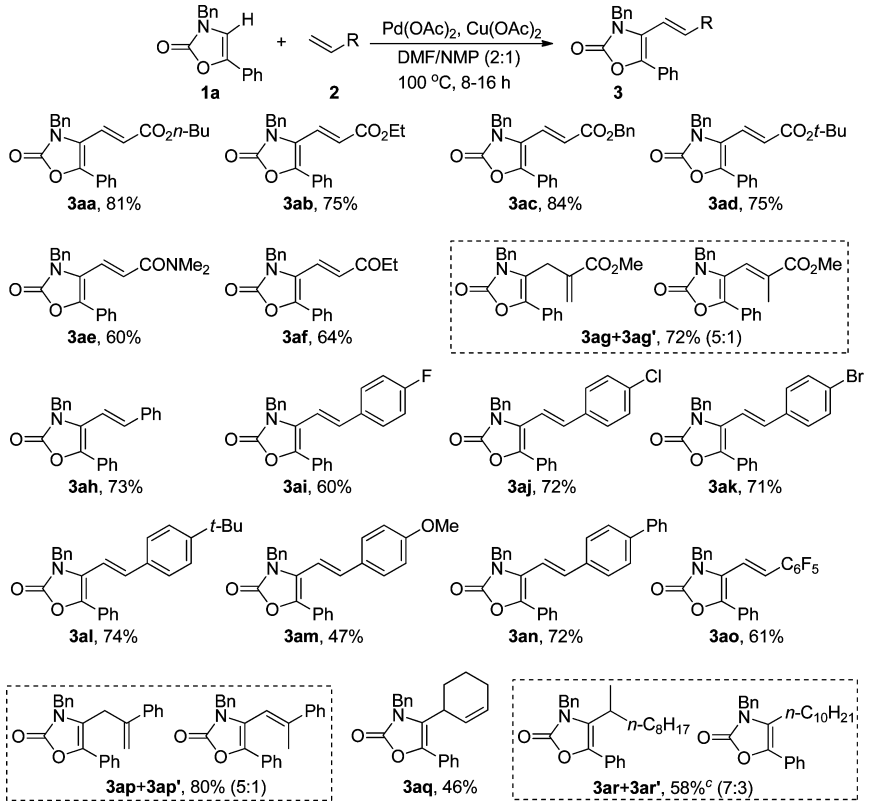
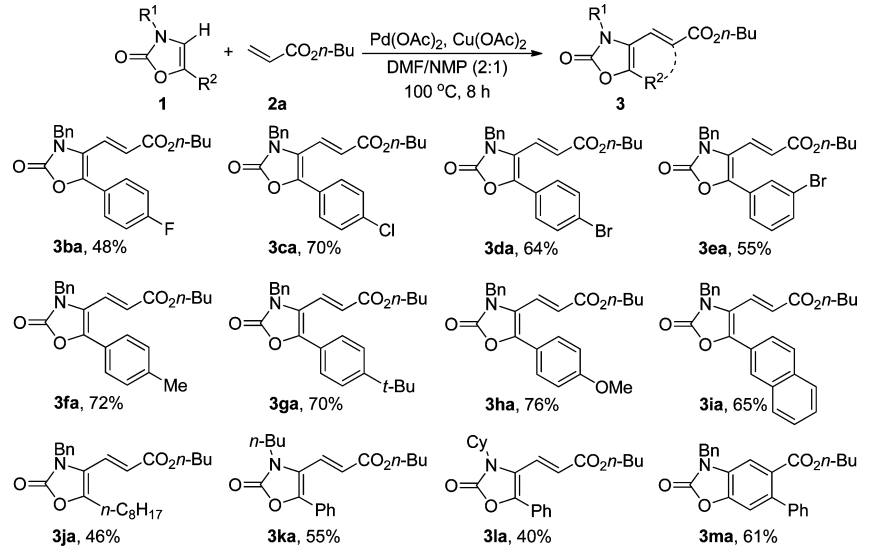
Table 2. Scope of Olefins 2[a,b]



[a]Reaction conditions: **1a** (0.25 mmol), **2** (0.5 mmol), $Pd(OAc)_2$ (10 mol %) and $Cu(OAc)_2$ (200 mol %) in 1 mL of DMF/NMP (2:1) at 100 °C for 8−16 h. [b]Isolated yield. [c]Overall yield after hydrogenation catalyzed by 10 mol % of Pd/C.

Table 3. Pd-Catalyzed Direct Alkenylation of 2-Oxazolones with 2a[a,b]



[a]Reaction conditions: **1** (0.25 mmol), **2a** (0.5 mmol), $Pd(OAc)_2$ (10 mol %) and $Cu(OAc)_2$ (200 mol %) in 1 mL of DMF/NMP (2/1) at 100 °C for 8 h. [b]Isolated yield.

Br, were well tolerated, and no byproducts resulting from the Heck reaction[45] of C−X bonds were observed (**3ba**−**ea**), thus making this reaction a useful method for the assembly of highly functionalized 3,4,5-trisubsituted 2-oxazolones. In addition, the reaction of 5-alkyl-2-oxazolone **1j** took place as well, albeit in a moderate yield (Table 3, **3ja**). Then, we briefly investigated the influence of substituents on the nitrogen atom of 2-oxazolones. In comparison with the *N*-*n*-Bu substrate **1k**, the sterically demanding *N*-Cy equivalent **1l** resulted in the expected product **3la** in a lower yield (Table 3, **3ka**,**la**). Interestingly, conducting the coupling with 5-vinyl-2-oxazolone **1m** gave the benzo[*d*]-oxazol-2(3*H*)-one derivative **3ma** in 61% yield (Table 3, **3ma**). We speculated that the Pd-catalyzed vinylation followed by a 6π electrocyclization[46] might account for the formation of **3ma**.

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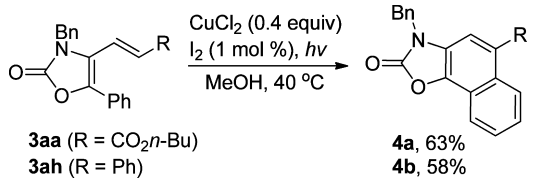
Having established a facile access to prepare 3,4,5-trisubstituted 2-oxazolones, the synthetic utility of this method was investigated. In view of the literature[47] and our previous work,[43] a photochemical transformation of **3aa**, catalyzed by $CuCl_2$ and I_2, produced naphtho[1,2-*d*]oxazol-2-one **4a** in 63% yield (Scheme 2). Likewise, naphtho[1,2-*d*]oxazol-2-one **4b** was also assembled from **3ah** in 58% yield. The structure of naphtho[1,2-*d*]oxazol-2-ones was identified by an X-ray diffraction analysis of **4a** (see the Supporting Information).

Scheme 2. Transformations of 3,4,5-Trisubstituted 2-Oxazolones



3aa (R = CO_2n-Bu)
3ah (R = Ph)

4a, 63%
4b, 58%

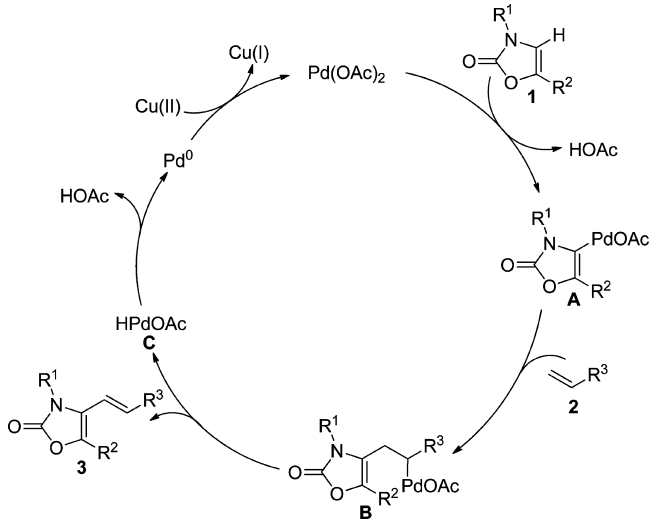
To gain insights into this Pd-catalyzed C−H alkenylation reaction, an intermolecular kinetic isotope effect (KIE) experiment was performed, and consequently, a relatively small KIE value was observed (k_H/k_D = 1.3), implying that the palladium-catalyzed C−H cleavage may not be the rate-determining step in the overall catalytic cycle[48] (Scheme 3).

On the basis of the above results, we propose a possible mechanism for this reaction, which is similar to that reported by Fujiwara and co-workers.[26] As shown in Scheme 4, the reaction may consist of the following steps: (1) generation of the intermediate **A** via an electrophilic palladation of 2-oxazolones, (2) carbopalladation of **A** with olefins **2** to afford the alkyl palladium species **B**, (3) β-H elimination generating 3,4,5-trisubstituted 2-oxazolones **3** in conjunction with the release of intermediate **C** (HPdOAc), (4) reductive elimination of the palladium hydride species **C** followed by oxidation of Pd(0) by Cu(II) to regenerate the Pd(II) catalyst.

CONCLUSION

In summary, we have developed a novel and general method for the synthesis of 4-alkenyl-2-oxazolones featuring the first Pd-catalyzed Fujiwara−Moritani reaction of 2-oxazolones. Various functional groups, such as F, Cl, Br, OMe, ester, ketone, amide, alkyl, and aryl substituents, are found to be well tolerated under the reaction conditions. The utilization of a C−H functionalization strategy provides a direct, convenient, and highly atom-economical approach for the construction of 3,4,5-trisubstituted 2-oxazolones. Moreover, the 4-vinyl-2-oxazolone products thus obtained can be successfully converted into naphtho[1,2-*d*]oxazol-2-ones via a photochemical transformation, and we believe that the method presented here will be useful for organic synthesis and medicinal chemistry.

Scheme 4. Possible Mechanism



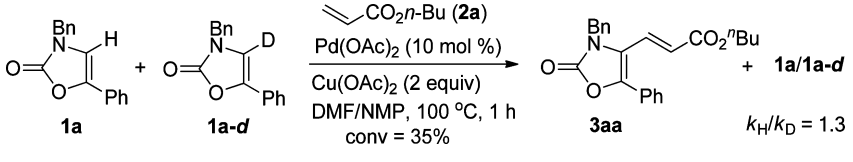
EXPERIMENTAL SECTION

General Considerations. Unless stated otherwise, all reactions were performed in an air atmosphere. The chemicals and solvents were purchased from commercial suppliers and used without further purification. ^{1}H NMR, ^{13}C NMR, and ^{19}F NMR spectra were measured on a 400 and 600 MHz NMR spectrometers using $CDCl_3$ as the solvent with tetramethylsilane (TMS) as the internal standard. Chemical shifts are given in δ relative to TMS, and the coupling constants are given in Hz. Column chromatography was performed using silica gel (300−400 mesh). High-resolution mass spectra (HRMS) analyses were carried out using a TOF-MS instrument with an ESI source. The 3,5-disubstituted oxazolone substrates were synthesized according to our previous reports.[20]

General Procedure for the Pd-Catalyzed Direct Alkenylation of 2-Oxazolones. To a mixture of **1a** (63 mg, 0.25 mmol), $Pd(OAc)_2$ (5.6 mg, 0.025 mmol), and $Cu(OAc)_2$ (91 mg, 0.50 mmol) in 1 mL of DMF/NMP (2/1) was added **2a** (71 μL, 0.5 mmol) in an air atmosphere. After it was stirred at 100 °C for 8 h, the reaction mixture was quenched by water, extracted with ethyl acetate, washed with brine, dried over Na_2SO_4, and concentrated. Column chromatography on silica gel (petroleum ethers/EtOAc 10/1) gave 76 mg (yield: 81%) of **3aa** as a yellow solid: mp 68−70 °C; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.93 (t, J = 7.2 Hz, 3H), 1.32−1.43 (m, 2H), 1.59−1.67 (m, 2H), 4.14 (t, J = 6.8 Hz, 2H), 5.04 (s, 2H), 6.14 (d, J = 16.4 Hz, 1H), 7.27−7.50 (m, 9H), 7.56−7.60 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 13.7, 19.1, 30.5, 46.6, 64.7, 119.7, 120.4, 126.6, 126.8, 127.0, 128.1, 128.1, 128.9, 129.0, 129.7, 135.4, 141.4, 155.0, 166.0; HRMS (ESI) calcd for $C_{23}H_{24}NO_4$ $(M + H)^+$ 378.1705, found 378.1703.

Crystal data for **3aa**: $C_{23}H_{23}NO_4$ (377.42), orthorhombic, space group, $P2_12_12_1$, a = 5.9205(6) Å, b = 11.3365(13) Å, c = 29.609(3)Å, U = 1987.3(4) Å^3, Z = 4, T = 296(2) K, absorption coefficient 0.086 mm^{-1}, 17002 reflections collected, 4488 independent reflections (R(int) = 0.0513), refinement by full-matrix least squares on F^2, 4488/0/253 data/restraints/parameters, goodness of fit on F^2 0.926, final R indices ($I > 2\sigma(I)$) R1 = 0.0464 and wR2 = 0.1006, R indices (all data) R1 = 0.1069 and wR2 = 0.1241, largest difference peak and hole 0.135 and −0.140 e Å^{-3}. Crystallographic data of **3aa** have been deposited

Scheme 3. Preliminary Mechanism Study



1a **1a-*d*** **3aa** k_H/k_D = 1.3

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with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-956154.

Compound ***3ab:*** 75% yield (66 mg); yellow solid, mp 63−65 °C; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.27 (t, J = 7.2 Hz, 3H), 4.19 (q, J = 7.2 Hz, 2H), 5.04 (s, 2H), 6.14 (d, J = 16.4 Hz, 1H), 7.27−7.52 (m, 9H), 7.55−7.64 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz): δ 14.1, 46.6, 60.8, 119.7, 120.4, 126.5, 126.8, 127.0, 128.0, 128.1, 129.0, 129.0, 129.7, 135.4, 141.4, 154.9, 165.9; HRMS (ESI) calcd for $C_{21}H_{20}NO_4$ $(M + H)^+$ 350.1392, found 350.1390.

Compound ***3ac:*** 84% yield (86 mg); yellow solid, mp 85−87 °C; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 5.07 (s, 2H), 5.22 (s, 2H), 6.23 (d, J = 16.2 Hz, 1H), 7.27−7.52 (m, 13H), 7.55 (d, J = 16.8 Hz, 1H), 7.61 (d, J = 6.6 Hz, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 46.6, 66.5, 119.7, 119.8, 126.5, 126.7, 127.0, 128.0, 128.1, 128.3, 128.5, 128.6, 129.0, 129.0, 129.8, 135.3, 135.6, 141.7, 154.9, 165.7; HRMS (ESI) calcd for $C_{26}H_{22}NO_4$ $(M + H)^+$ 412.1549, found 412.1545.

Compound ***3ad:*** 75% yield (71 mg); yellow solid, mp 90−92 °C; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.47 (s, 9H), 5.04 (s, 2H), 6.09 (d, J = 16.4 Hz, 1H), 7.27−7.51 (m, 9H), 7.58 (d, J = 7.6 Hz, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 28.0, 46.6, 81.1, 119.8, 122.4, 126.6, 126.8, 126.8, 127.1, 128.0, 128.9, 129.0, 129.5, 135.4, 140.9, 154.9, 165.1; HRMS (ESI) calcd for $C_{23}H_{24}NO_4$ $(M + H)^+$ 378.1705, found 378.1702.

Compound ***3ae:*** 60% yield (52 mg); yellow oil; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 2.61 (s, 3H), 2.94 (s, 3H), 5.04 (s, 2H), 6.45 (d, J = 15.6 Hz, 1H), 7.24−7.31 (m, 3H), 7.32−7.46 (m, 5H), 7.50 (d, J = 15.6 Hz, 1H), 7.58 (d, J = 7.2 Hz, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 35.8, 36.6, 46.6, 120.2, 120.7, 125.9, 125.9, 126.6, 126.9, 127.9, 128.8, 129.1, 129.3, 135.8, 140.0, 155.1, 165.2; HRMS (ESI) calcd for $C_{21}H_{21}N_2O_3$ $(M + H)^+$ 349.1552, found 349.1549.

Compound ***3af:*** 64% yield (53 mg); yellow oil; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 1.03 (t, J = 7.4 Hz, 3H), 1.03 (q, J = 7.4 Hz, 2H), 5.05 (s, 2H), 6.43 (d, J = 16.4 Hz, 1H), 7.27−7.49 (m, 9H), 7.53−7.60 (m, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 7.8, 35.3, 46.8, 120.2, 125.4, 126.4, 126.6, 126.8, 127.1, 128.1, 129.0, 129.1, 129.8, 135.6, 142.0, 155.0, 199.1; HRMS (ESI) calcd for $C_{21}H_{20}NO_3$ $(M + H)^+$ 334.1443, found 334.1439.

Compound ***3ag:*** 72% overall yield (63 mg) for **3ag** and **3ag′** (**3ag**/**3ag′** 5/1); white solid, mp 86−88 °C; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 3.55 (s, 2H), 3.80 (s, 3H), 4.76 (s, 2H), 5.48 (s, 1H), 6.24 (s, 1H), 7.185−7.45 (m, 10H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 25.7, 45.5, 52.3, 118.9, 124.7, 126.5, 127.2, 128.1, 128.1, 128.7, 128.8, 128.9, 134.6, 135.9, 136.4, 155.2, 166.4; HRMS (ESI) calcd for $C_{21}H_{20}NO_4$ $(M + H)^+$ 350.1392, found 350.1389.

Compound ***3ah:*** 73% yield (65 mg); yellow oil; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 4.97 (s, 2H), 6.67 (d, J = 16.8 Hz, 1H), 6.82 (d, J = 16.8 Hz, 1H), 7.27−7.47 (m, 13H), 7.60 (d, J = 7.8 Hz, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 46.3, 112.6, 121.7, 125.6, 126.5, 126.9, 127.9, 128.0, 128.2, 128.7, 128.8, 128.8, 128.9, 135.2, 135.7, 136.0, 136.3, 155.3; HRMS (ESI) calcd for $C_{24}H_{20}NO_2$ $(M + H)^+$ 354.1494, found 354.1488.

Compound ***3ai:*** 60% yield (56 mg); yellow oil; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 4.98 (s, 2H), 6.59 (d, J = 16.8 Hz, 1H), 6.77 (d, J = 16.8 Hz, 1H), 7.06 (t, J = 8.6 Hz, 2H), 7.25−7.44 (m, 10H), 7.62−7.65 (m, 2H); ^{19}F NMR ($CDCl_3$, 565 MHz) δ −111.9; ^{13}C NMR ($CDCl_3$, 150 MHz) δ 46.4, 112.4, 115.9 (d, J = 21.8 Hz), 121.6, 125.7, 126.9, 128.0, 128.1 (d, J = 8.1 Hz), 128.3, 128.8, 129.0, 131.9 (d, J = 3.4 Hz), 134.0, 136.1, 136.3, 155.3, 162.9 (d, J = 248.1 Hz); HRMS (ESI) calcd for $C_{24}H_{19}FNO_2$ $(M + H)^+$ 372.1400, found 372.1398.

Compound ***3aj:*** 72% yield (70 mg); yellow solid, mp 100−102 °C; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 4.98 (s, 2H), 6.64 (d, J = 16.8 Hz, 1H), 6.75 (d, J = 16.8 Hz, 1H), 7.18 (d, J = 8.4 Hz, 2H), 7.28−7.41 (m, 10H), 7.57−7.60 (m, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 46.4, 113.3, 121.5, 125.7, 126.8, 127.6, 127.9, 128.0, 128.4, 128.8, 129.0, 129.0, 133.6, 134.3, 134.5, 136.2, 136.4, 155.2; HRMS (ESI) calcd for $C_{24}H_{19}ClNO_2$ $(M + H)^+$ 388.1104, found 388.1099.

Compound ***3ak:*** 71% yield (77 mg); yellow solid, mp 120−122 °C; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 5.02 (s, 2H), 6.70 (d, J = 16.6 Hz, 1H), 6.77 (d, J = 16.6 Hz, 1H), 7.16 (d, J = 8.4 Hz, 2H), 7.34−7.37 (m, 4H), 7.40−7.44 (m, 4H), 7.49 (d, J = 8.4 Hz, 2H), 7.62 (d, J = 8.0 Hz, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 46.4, 113.3, 121.5, 122.7, 125.7, 126.8, 127.8, 127.9, 128.0, 128.4, 128.8, 129.0, 132.0, 133.6, 134.7, 136.2, 136.4, 155.2; HRMS (ESI) calcd for $C_{24}H_{19}BrNO_2$ $(M + H)^+$ 432.0599, found 432.0590.

Compound ***3al:*** 74% yield (76 mg); yellow oil; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 1.32 (s, 9H), 4.95 (s, 2H), 6.64 (d, J = 16.8 Hz, 1H), 6.81 (d, J = 16.8 Hz, 1H), 7.29−7.46 (m, 12H), 7.60 (d, J = 8.0 Hz, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 31.1, 34.7, 46.3, 111.8, 121.9, 125.5, 125.8, 126.3, 127.0, 127.9, 128.1, 128.1, 128.7, 128.9, 133.0, 135.4, 135.7, 136.3, 152.2, 155.3; HRMS (ESI) calcd for $C_{28}H_{28}NO_2$ $(M + H)^+$ 410.2120, found 410.2117.

Compound ***3am:*** 47% yield (45 mg); yellow oil; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 3.81 (s, 3H), 4.96 (s, 2H), 6.52 (d, J = 16.8 Hz, 1H), 6.77 (d, J = 16.8 Hz, 1H), 6.87 (d, J = 8.6 Hz, 2H), 7.21−7.40 (m, 10H), 7.59−7.63 (m, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 46.3, 55.3, 110.3, 114.3, 122.1, 125.5, 127.0, 127.9, 128.0, 128.2, 128.4, 128.5, 128.7, 129.0, 135.3, 135.5, 136.4, 155.3, 160.2; HRMS (ESI) calcd for $C_{25}H_{22}NO_3$ $(M + H)^+$ 384.1600, found 384.1595.

Compound ***3an:*** 72% yield (77 mg); yellow solid, mp 122−124 °C; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 5.00 (s, 2H), 6.72 (d, J = 16.8 Hz, 1H), 6.85 (d, J = 16.8 Hz, 1H), 7.29−7.41 (m, 11H), 7.44 (t, J = 7.4 Hz, 2H), 7.56−7.64 (m, 6H); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 46.4, 112.6, 121.9, 125.7, 126.9, 127.0, 127.0, 127.5, 127.6, 128.0, 128.0, 128.3, 128.8, 128.9, 129.0, 134.6, 134.7, 136.1, 136.3, 140.2, 141.6, 155.3; HRMS (ESI) calcd for $C_{30}H_{24}NO_2$ $(M + H)^+$ 430.1807, found 430.1799.

Compound ***3ao:*** 61% yield (68 mg); yellow solid, mp 133−135 °C; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 5.05 (s, 2H), 6.70 (d, J = 17.2 Hz, 1H), 7.13 (d, J = 17.2 Hz, 1H), 7.32−7.48 (m, 8H), 7.61−7.64 (m, 2H); ^{19}F NMR ($CDCl_3$, 565 MHz) δ −161.9 (dd, J = 20.8, 13.8 Hz), −154.2 (t, J = 20.8 Hz), −142.4 (dd, J = 21.5, 7.8 Hz); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 46.8, 111.1−111.3 (m), 117.2−117.3 (m), 121.0, 121.2−121.4 (m), 126.3, 126.7, 127.3, 128.9, 129.1, 128.1, 135.6, 136.8−137.2 (m), 138.4, 143.7−144.0 (m), 145.4−145.6 (m), 155.2; HRMS (ESI) calcd for $C_{24}H_{15}F_5NO_2$ $(M + H)^+$ 444.1023, found 444.1020.

Compound ***3ap:*** 80% overall yield (73 mg) for **3ap** and **3ap′** (**3ap**/**3ap′** 5/1); yellow oil; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 3.57 (s, 2H), 4.76 (s, 2H), 5.03 (s, 1H), 5.50 (s, 1H), 7.15−7.38 (m, 13H), 7.41 (d, J = 7.6 Hz, 2H); ^{13}C NMR ($CDCl_3$, 151 MHz) δ 29.0, 45.5, 113.9, 120.0, 124.8, 125.6, 127.0, 127.7, 127.9, 128.0, 128.3, 128.6, 128.8, 128.8, 136.1, 136.3, 139.4, 141.9, 155.4; HRMS (EI) calcd for $C_{25}H_{22}NO_2$ $(M + H)^+$ 368.1651, found 368.1648.

Compound ***3aq:*** 46% yield (38 mg); yellow oil; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.49−1.58 (m, 2H), 1.71−1.82 (m, 2H), 1.96−2.12 (m, 2H), 3.65 (br, 1H), 4.89−5.05 (m, 2H), 5.49 (d, J = 10.0 Hz, 1H), 5.81−5.92 (m, 1H), 7.24−7.48 (m, 8H), 7.49 (d, J = 7.2 Hz, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 22.2, 24.3, 27.7, 32.7, 46.0, 126.0, 126.5, 126.7, 126.8, 127.6, 128.0, 128.1, 128.4, 128.7, 130.0, 135.1, 136.5, 155.8; HRMS (ESI) calcd for $C_{22}H_{22}NO_2$ $(M + H)^+$ 332.1651, found 332.1649.

Compound ***3ar:*** 58% overall yield (57 mg) for **3ar** and **3ar′** (**3ar**/**3ar′** 7/3) after hydrogenation catalyzed by 10 mol % of Pd/C; colorless oil; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 0.88−1.27 (m, 20H), 2.80−2.93 (m, 1H), 4.96 (s, 2H), 7.51−7.25 (m, 10H); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 14.1, 19.7, 22.6, 27.8, 29.1, 29.2, 29.3, 29.9, 31.8, 34.7, 46.3, 124.7, 126.5, 126.9, 127.5, 127.8, 128.3, 128.5, 128.8, 129.0, 134.8, 156.1; HRMS (ESI) calcd for $C_{26}H_{34}NO_2$ $(M + H)^+$ 392.2590, found 392.2583.

Compound ***3ba:*** 48% yield (47 mg); white solid, mp 74−76 °C; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.94 (t, J = 7.4 Hz, 3H), 1.31−1.42 (m, 2H), 1.58−1.66 (m, 2H), 4.14 (t, J = 6.8 Hz, 2H), 5.03 (s, 2H), 6.14 (d, J = 16.4 Hz, 1H), 7.12−7.18 (m, 2H), 7.25−7.43 (m, 6H), 7.53−7.58 (m, 2H); ^{19}F NMR ($CDCl_3$, 565 MHz) δ −109.3; ^{13}C NMR ($CDCl_3$, 100 MHz) δ 13.7, 19.1, 30.5, 46.7, 64.8, 116.3 (d, J = 22.0 Hz), 119.6, 120.6, 123.0 (d, J = 3.5 Hz), 126.6, 127.8, 128.1, 129.0 (d, J = 8.4 Hz), 129.1, 135.3, 140.4, 154.8, 163.3 (d, J = 250.2 Hz), 165.9; HRMS (ESI) calcd for $C_{23}H_{23}FNO_4$ $(M + H)^+$ 396.1611, found 396.1608.

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Compound ***3ca:*** 70% yield (72 mg); yellow oil; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 0.94 (t, J = 7.2 Hz, 3H), 1.33−1.42 (m, 2H), 1.58−1.66 (m, 2H), 4.15 (t, J = 6.6 Hz, 2H), 5.02 (s, 2H), 6.15 (d, J = 16.2 Hz, 1H), 7.25−7.34 (m, 3H), 7.35−7.44 (m, 5H), 7.49−7.52 (m, 2H); ^{13}C NMR ($CDCl_3$, 151 MHz) δ 13.6, 19.1, 30.5, 46.7, 64.9, 120.1, 121.2, 125.3, 126.6, 127.7, 128.0, 128.1, 129.1, 129.3, 135.3, 135.7, 139.9, 154.7, 165.8; HRMS (ESI) calcd for $C_{23}H_{23}ClNO_4$ $(M + H)^+$ 412.1316, found 412.1315.

Compound ***3da:*** 64% yield (73 mg); white solid, mp 82−84 °C; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.94 (t, J = 7.4 Hz, 3H), 1.32−1.42 (m, 2H), 1.59−1.67 (m, 2H), 4.15 (t, J = 6.6 Hz, 2H), 5.02 (s, 2H), 6.16 (d, J = 16.4 Hz, 1H), 7.27−7.46 (m, 8H), 7.56−7.60 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 13.7, 19.1, 30.5, 46.7, 64.9, 120.1, 121.3, 124.0, 125.7, 126.6, 127.7, 128.2, 128.2, 129.1, 132.3, 135.2, 140.0, 154.7, 165.8; HRMS (ESI) calcd for $C_{23}H_{23}BrNO_4$ $(M + H)^+$ 456.0810, found 456.0807.

Compound ***3ea:*** 55% yield (63 mg); white solid, mp 80−82 °C; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.94 (t, J = 7.4 Hz, 3H), 1.35−1.45 (m, 2H), 1.61−1.70 (m, 2H), 4.15 (t, J = 6.6 Hz, 2H), 5.02 (s, 2H), 6.17 (d, J = 16.4 Hz, 1H), 7.27−7.45 (m, 7H), 7.48−7.58 (m, 2H), 7.74−7.76 (m, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 13.7, 19.1, 30.5, 46.7, 64.9, 120.6, 121.8, 123.1, 125.3, 126.6, 127.5, 128.2, 128.7, 129.1, 129.6, 130.5, 132.5, 135.2, 139.2, 154.6, 165.7; HRMS (ESI) calcd for $C_{23}H_{23}BrNO_4$ $(M + H)^+$ 456.0810, found 456.0806.

Compound ***3fa:*** 72% yield (70 mg); yellow oil; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.94 (t, J = 7.4 Hz, 3H), 1.32−1.42 (m, 2H), 1.58−1.66 (m, 2H), 2.40 (s, 3H), 4.14 (t, J = 6.6 Hz, 2H), 5.04 (s, 2H), 6.13 (d, J = 16.4 Hz, 1H), 7.24−7.31 (m, 5H), 7.32−7.45 (m, 2H), 7.47−7.53 (m, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 13.6, 19.0, 21.4, 30.5, 46.6, 64.7, 119.2, 119.7, 123.9, 126.5, 126.9, 128.0, 128.2, 129.0, 129.7, 135.5, 140.1, 141.8, 154.9, 166.1; HRMS (ESI) calcd for $C_{24}H_{26}NO_4$ $(M + H)^+$ 392.1862, found 392.1859.

Compound ***3ga:*** 70% yield (76 mg); yellow solid, mp 110−112 °C; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 0.94 (t, J = 7.4 Hz, 3H), 1.34 (s, 9H), 1.36−1.44 (m, 2H), 1.62−1.68 (m, 2H), 4.14 (t, J = 6.6 Hz, 2H), 5.05 (s, 2H), 6.12 (d, J = 16.4 Hz, 1H), 7.29−7.35 (m, 3H), 7.38−7.41 (m, 2H), 7.49−7.56 (m, 5H); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 13.7, 19.1, 30.5, 31.1, 34.8, 46.7, 64.7, 119.4, 119.7, 123.9, 125.9, 126.5, 126.8, 128.0, 128.3, 129.0, 135.5, 141.9, 153.2, 155.0, 166.1; HRMS (ESI) calcd for $C_{27}H_{32}NO_4$ $(M + H)^+$ 434.2331, found 434.2327.

Compound ***3ha:*** 76% yield (77 mg); yellow oil; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.93 (t, J = 7.4 Hz, 3H), 1.31−1.43 (m, 2H), 1.57−1.67 (m, 2H), 3.85 (s, 3H), 4.13 (t, J = 6.6 Hz, 2H), 5.03 (s, 2H), 6.10 (d, J = 16.4 Hz, 1H), 6.97 (d, J = 8.8 Hz, 2H), 7.27−7.40 (m, 5H), 7.44 (d, J = 16.4 Hz, 1H), 7.49−7.53 (m, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 13.6, 19.1, 30.5, 46.6, 55.3, 64.6, 114.5, 118.6, 119.2, 119.2, 126.6, 128.0, 128.3, 128.7, 129.0, 135.5, 141.9, 155.0, 160.8, 166.2; HRMS (ESI) calcd for $C_{24}H_{26}NO_5$ $(M + H)^+$ 408.1811, found 408.1809.

Compound ***3ia:*** 65% yield (69 mg); yellow solid, mp 94−96 °C; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.95 (t, J = 7.4 Hz, 3H), 1.34−1.44 (m, 2H), 1.59−1.68 (m, 2H), 4.16 (t, J = 6.6 Hz, 2H), 5.07 (s, 2H), 6.20 (d, J = 16.4 Hz, 1H), 7.30−7.43 (m, 5H), 7.52−7.59 (m, 3H), 7.65−7.68 (m, 1H), 7.84−7.91 (m, 3H), 8.07 (s, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 13.7, 19.1, 30.5, 46.7, 64.8, 120.1, 120.7, 123.5, 124.1, 126.6, 127.0, 127.0, 127.4, 127.7, 128.1, 128.1, 128.5, 128.8, 129.1, 132.9, 133.4, 135.4, 141.3, 154.9, 166.0; HRMS (ESI) calcd for $C_{27}H_{26}NO_4$ $(M + H)^+$ 428.1862, found 428.1858.

Compound ***3ja:*** 46% yield (48 mg); yellow oil; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 0.88 (t, J = 7.0 Hz, 3H), 0.94 (t, J = 7.4 Hz, 3H), 1.17−1.41 (m, 12H), 1.59−1.68 (m, 4H), 2.59 (t, J = 7.4 Hz, 2H), 4.13 (t, J = 6.6 Hz, 2H), 4.92 (s, 2H), 5.96 (d, J = 16.2 Hz, 1H), 7.17 (d, J = 16.2 Hz, 1H), 7.22−7.26 (m, 2H), 7.28−7.32 (m, 1H), 7.33−7.38 (m, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 13.7, 14.0, 19.1, 22.6, 25.5, 27.2, 28.9, 29.0, 29.1, 30.5, 31.7, 46.2, 64.7, 118.3, 119.6, 126.7, 127.6, 128.0, 129.0, 135.5, 144.4, 155.2, 166.2; HRMS (ESI) calcd for $C_{25}H_{36}NO_4$ $(M + H)^+$ 414.2644, found 414.2642.

Compound ***3ka:*** 55% yield (47 mg); yellow oil; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.82−1.12 (m, 6H), 1.34−1.44 (m, 4H), 1.59−1.68 (m, 4H), 3.84 (t, J = 7.6 Hz, 2H), 4.22 (t, J = 6.6 Hz, 2H), 6.26 (d, J = 16.4 Hz, 1H), 7.25−7.49 (m, 3H), 7.52−7.61 (m, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 13.6, 13.7, 19.1, 19.7, 30.6, 31.1, 43.0, 64.9, 119.1, 119.5, 126.9, 127.1, 128.6, 129.0, 129.6, 141.7, 154.5, 166.3; HRMS (ESI) calcd for $C_{20}H_{26}NO_4$ $(M + H)^+$ 344.1862, found 344.1860.

Compound ***3la:*** 40% yield (37 mg); yellow solid, mp 80−82 °C; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 0.97 (t, J = 7.4 Hz, 3H), 1.24−1.46 (m, 5H), 1.66−1.73 (m, 3H), 1.83−1.94 (m, 4H), 2.21−2.23 (m, 2H), 3.77−3.84 (m, 1H), 4.22 (t, J = 6.6 Hz, 2H), 6.18 (d, J = 16.4 Hz, 1H), 7.36−7.45 (m, 3H), 7.51 (d, J = 16.4 Hz, 1H), 7.53−7.56 (m, 2H); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 13.7, 19.1, 24.8, 25.8, 29.7, 30.6, 55.1, 65.0, 119.6, 121.9, 126.7, 127.1, 128.9, 129.0, 129.3, 139.8, 153.4, 166.0; HRMS (ESI) calcd for $C_{22}H_{28}NO_4$ $(M + H)^+$ 370.2018, found 370.2015.

Compound ***3ma:*** 61% yield (61 mg); yellow oil; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 0.80 (t, J = 7.4 Hz, 3H), 1.01−1.07 (m, 2H), 1.24−1.32 (m, 2H), 3.99 (q, J = 7.4 Hz, 2H), 5.08 (s, 2H), 7.22 (s, 1H), 7.24−7.30 (m, 2H), 7.34−7.45 (m, 9H); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 13.6, 18.9, 30.1, 46.4, 65.2, 110.3, 112.1, 127.2, 127.4, 127.8, 128.2, 128.4, 128.5, 129.1, 129.9, 134.3, 138.6, 141.0, 144.3, 154.6, 168.1; HRMS (ESI) calcd for $C_{25}H_{23}NNaO_4$ $(M + Na)^+$ 424.1525, found 424.1520.

Compound ***4a.*** This compound was prepared from **3aa** according to the method described in the literature[47] in 63% yield: white solid, mp 100−102 °C; ^{1}H NMR ($CDCl_3$, 600 MHz) δ 1.01 (t, J = 7.4 Hz, 3H), 1.44−1.53 (m, 2H), 1.75−1.81 (m, 2H), 4.37 (t, J = 6.6 Hz, 2H), 5.13 (s, 2H), 7.31−7.42 (m, 5H), 7.54−7.57 (m, 1H), 7.59−7.62 (m, 1H), 7.81 (s, 1H), 8.10 (d, J = 8.2 Hz, 1H), 8.96 (d, J = 8.8 Hz, 1H); ^{13}C NMR ($CDCl_3$, 150 MHz) δ 13.8, 19.4, 30.7, 46.5, 65.2, 113.4, 119.5, 119.7, 123.7, 125.3, 126.7, 126.8, 127.4, 127.7, 128.5, 128.8, 129.1, 134.5, 140.3, 154.8, 166.6; HRMS (ESI) calcd for $C_{23}H_{22}NO_4$ $(M + H)^+$ 376.1549, found 376.1545.

Crystal data for **4a**: $C_{23}H_{21}NO_4$ (375.41), triclinic, space group, $P\bar{1}$, a = 9.4027(6) Å, b = 10.4191(6) Å, c = 10.7784(6) Å, U = 951.30(10) Å^3, Z = 2, T = 296(2) K, absorption coefficient 0.086 mm^{-1}, 15375 reflections collected, 4325 independent reflections (R(int) = 0.0326), refinement by full-matrix least squares on F^2, 4325/0/253 data/restraints/parameters, goodness of fit on F^2 = 1.029, final R indices ($I > 2\sigma(I)$) R1 = 0.0444 and wR2 = 0.1077, R indices (all data) R1 = 0.0781 and wR2 = 0.1264, largest difference peak and hole 0.154 and −0.227 e Å^{-3}. Crystallographic data of **4a** have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication no. CCDC-956155.

Compound ***4b:*** 58% yield; white solid, mp 122−124 °C; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 5.11 (s, 2H), 7.06 (s, 1H), 7.27−7.50 (m, 11H), 7.57 (t, J = 7.6 Hz, 1H), 7.82 (d, J = 8.6 Hz, 1H), 8.11 (d, J = 8.4 Hz, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 46.2, 110.0, 119.4, 119.6, 124.9, 126.1, 127.0, 127.2, 127.5, 127.6, 128.2, 128.3, 128.4, 129.0, 130.2, 134.9, 136.5, 137.4, 140.0, 155.3; HRMS (ESI) calcd for $C_{24}H_{18}NO_2$ $(M + H)^+$ 352.1338, found 352.1333.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Text, figures, tables, and CIF files giving spectroscopic data of products **3** and **4**, details of the KIE experiment, and crystallographic data for **3aa** and **4a**. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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