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Palladium-Catalyzed Aminocarbonylation of Alkynes to Succinimides

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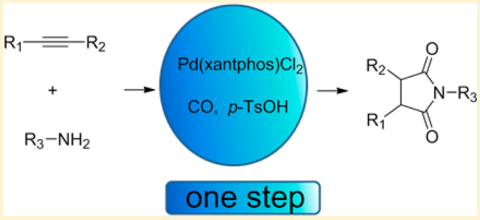
Supporting Information

ABSTRACT: Succinimide derivatives are useful building blocks for the synthesis of natural products and drugs. We describe an efficient route to succinimide derivatives comprising Pd(xantphos)Cl_2-catalyzed aminocarbonylation of alkynes with aromatic or aliphatic amines in the presence of *p*-TsOH. The utility of this route is demonstrated with the synthesis of a large number of succinimide compounds including an important photochromic molecule.



INTRODUCTION

Cyclic imides are important compounds that have numerous applications in chemistry, biology, and material science. Succinimide derivatives, a subclass of cyclic imides, are of particular interest due to the prevalence of the succinimide moiety in nature. Consequently, succinimides are useful building blocks for the synthesis of natural products as well as pharmaceutical and agrochemical compounds, including palasimide,[1] salfredins,[2] phensuximide,[3] and 2-quinolinephthalimide (Figure 1).

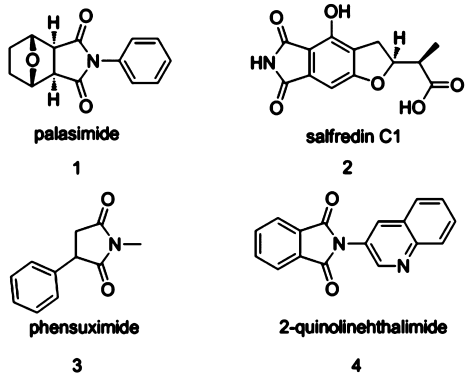


Figure 1. Examples of bioactive compounds containing cyclic imide (succinimide) moieties.

Succinimide derivatives may be prepared using a variety of methods. Classical approaches include condensation reactions between anhydrides and amines at high temperatures or in the presence of Lewis acids[3,4] and the cyclization of amic acids.[3,5] More recent approaches include iridium-catalyzed multicomponent synthesis of glutarimides,[6] ring expansion of 4-formyl-*β*-lactams,[7] iron-catalyzed carbonylative succinimide synthesis using an alkyne, CO and amine,[8] ruthenium- or palladium-catalyzed carbonylation of aromatic compounds affording phthalimides,[9] rhodium-catalyzed 1,4-addition of aryl boronic acids to maleimides, giving chiral 3-substituted succinimide derivatives,[10] and the direct synthesis of cyclic imides from simple diols using a ruthenium-based catalyst.[11] While some succinimide derivatives may be obtained through the aforementioned routes, others are more challenging to synthesize and would benefit from a more efficient and sustainable process.[12]

Carbonylation reactions are widely employed in organic synthesis to generate amides, esters, and carboxylic acids.[13] In earlier studies, an efficient system was developed for the aminocarbonylation of alkenes to yield branched or linear amides.[14] As an extension of this work, we investigated the applicability of the palladium-based catalyst for the aminocarbonylation of alkynes. Aminocarbonylation of alkynes generally yields branched or linear *α*,*β*-unsaturated amides, as documented in the literature.[15] With our system, however, we found that the major products were succinimide derivatives. Herein, we describe this route to succinimides and demonstrate the scope of the reaction that allows access to both *N*-alkyl- and *N*-phenyl-succinimide derivatives. As mentioned above, the iron-catalyzed carbonylative succinimide synthesis using an alkyne, CO, and amine has been reported;[8] however, in contrast to our system, the iron-catalyzed is only active for aliphatic amines.

RESULTS AND DISCUSSION

The reaction of phenylacetylene and aniline in the presence of CO and *p*-TsOH and catalytic amounts of Pd(xantphos)Cl_2, which contains a wide bite-angle bis-phosphine, was initially studied.[16] The effects of CO pressure, reaction time, reaction temperature, and the amount of acid cocatalyst were examined (Figure 2). The yield of the desired *N*-phenyl-succinimide product is greatest under 30 atm of CO; at higher pressures, the yield decreases and the intermolecular product, 2-benzyl-N^1,N^3-diphenylmalonamide, is obtained. The amount of acid cocatalyst also has a large influence on the yield of *N*-phenyl-succinimide. In the absence of the acid cocatalyst, the yield of *N*-phenyl-succinimide is <6%, whereas, at 0.8 mmol of *p*-

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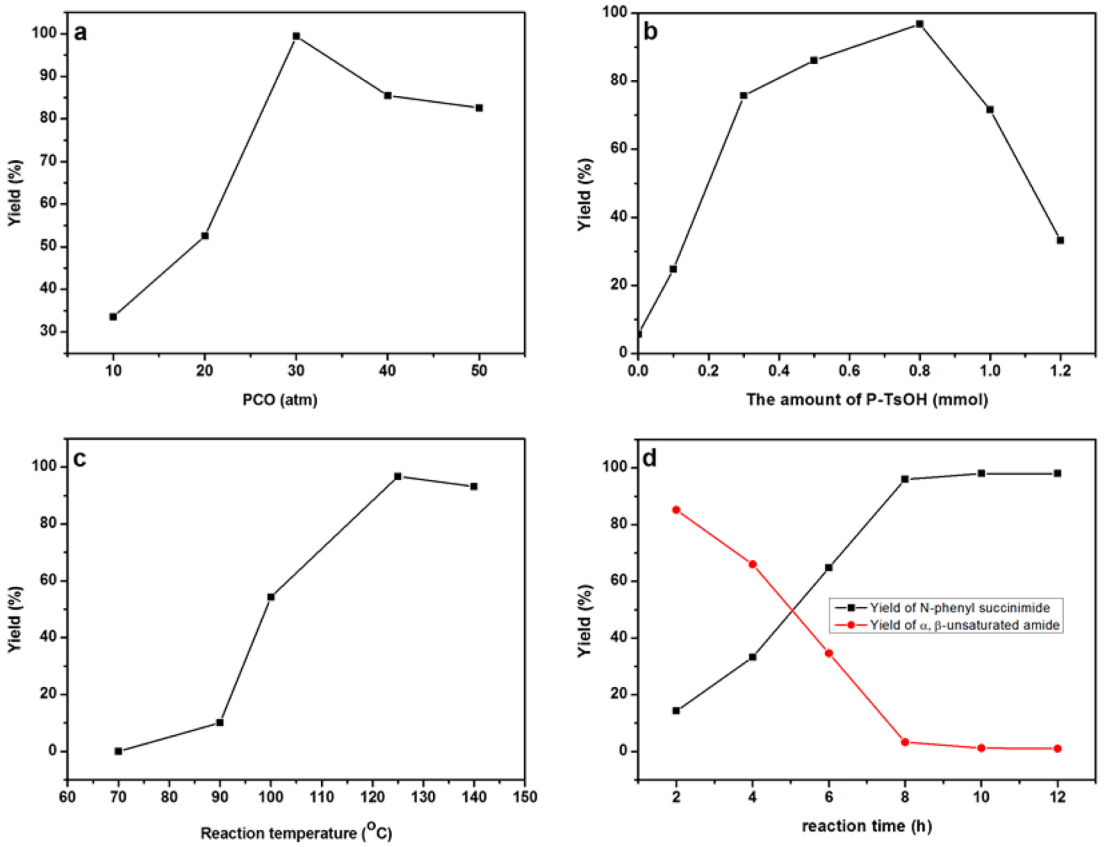

Figure 2. Effect of reaction parameters on the yield of *N*-phenyl-succinimide (1 mmol of aniline, 1.2 mmol of phenyacetylene, 0.05 mmol of $Pd(xantphos)Cl_2$). (a) Influence of CO pressure at 125 °C for 4 h in the presence of 0.8 mmol of *p*-TsOH. (b) The effect of the *p*-TsOH concentration at 125 °C, under 30 atm of CO for 4 h. (c) The effect of reaction temperature under 30 atm of CO for 4 h in the presence of 0.8 mmol of *p*-TsOH. (d) Influence of reaction time at 125 °C, under 30 atm of CO with 0.01 mmol of $Pd(xantphos)Cl_2$ in the presence of 0.8 mmol of *p*-TsOH.

TsOH, the desired product is obtained in 97% yield, and at higher concentrations of acid, the yield decreases. High temperatures and long reaction times are required in order to obtain *N*-phenyl-succinimide in high yield. After just 2 h, the main product is the *α,β*-unsaturated amide, which is consumed as the reaction continues, with the concomitant growth in yield of *N*-phenyl-succinimide, implying a two-step reaction sequence. First, aminocarbonylation of phenylacetylene with aniline yields a branched (or linear) *α,β*-unsaturated amide. Second, an intermolecular reaction with CO generates the *N*-phenyl-succinimide product. However, it is possible that other reaction pathways may also be operating (see below).

Under the optimized conditions, the activity of $Pd(xantphos)Cl_2$ is the same as a mixture $PdCl_2$ and xantphos, which presumably forms the complex in situ (Table 1, entries 1 and 2). Other metal complexes were also evaluated (Table 1, entries 2−5); however, none were as effective as $Pd(xantphos)Cl_2$. Other palladium salts were also evaluated in combination with the xantphos ligand instead of $PdCl_2$, i.e., $Pd(OAc)_2$ or $Pd(acac)_2$, but the yield of *N*-phenyl-succinimide was lower with these salts (Table 1, entries 7 and 8). Interestingly, the Pd(0) precursor, $Pd_2(dba)_3$, in combination with xantphos exhibits good activity, with the yield of the desired product reaching 95% (Table 1, entry 14). In contrast, $Pd(PPh_3)_4$ is inactive with only trace amounts of the product detected (Table 1, entry 15). The nature of the solvent is also important, with THF resulting in the highest yields, and lower yields

Table 1. Optimization of the Reaction of Phenylacetylene with Aniline and CO To Afford *N*-Phenyl-succinimide[a]

entry	precatalyst	solvent	yield (%)
1	$PdCl_2$/xantphos	THF	97
2	$Pd(xantphos)Cl_2$	THF	97
3	$Pd(dppf)Cl_2$	THF	85
4	$Pd(PPh_3)_2Cl_2$	THF	63
5	$Pd(dppe)Cl_2$	THF	trace
6	$Pd(dppb)Cl_2$	THF	trace
7	$Pd(OAc)_2$/xantphos	THF	49
8	$Pd(acac)_2$/xantphos	THF	61
9	$Pd(xantphos)Cl_2$	CH_3CN	84
10	$Pd(xantphos)Cl_2$	toluene	68
11	$Pd(xantphos)Cl_2$	hexane	54
12	$Pd(xantphos)Cl_2$	H_2O	10
13	$Pd(xantphos)Cl_2$	DMF	trace
14	$Pd_2(dba)_3$/xantphos	THF	95
15	$Pd(PPh_3)_4$	THF	trace

[a]Reaction conditions: phenylacetylene (1.2 mmol), aniline (1 mmol), precatalyst (5 mol % based on aniline), xantphos (0.12 mmol), *p*-TsOH (0.8 mmol), THF (10 mL), CO (30 atm), 125 °C, 4 h. dppe = 1,2-bis(diphenylphosphino)ethane, dppf = 1,10-bis(diphenylphosphino)ferrocene, dppb = 1,2-bis(diphenylphosphino)benzene, xantphos = 4,5-bis(diphenylphosphino)-9,9-dimethylxanthene. Yields were determined by GC analysis relative to aniline using *n*-decane as an internal standard.

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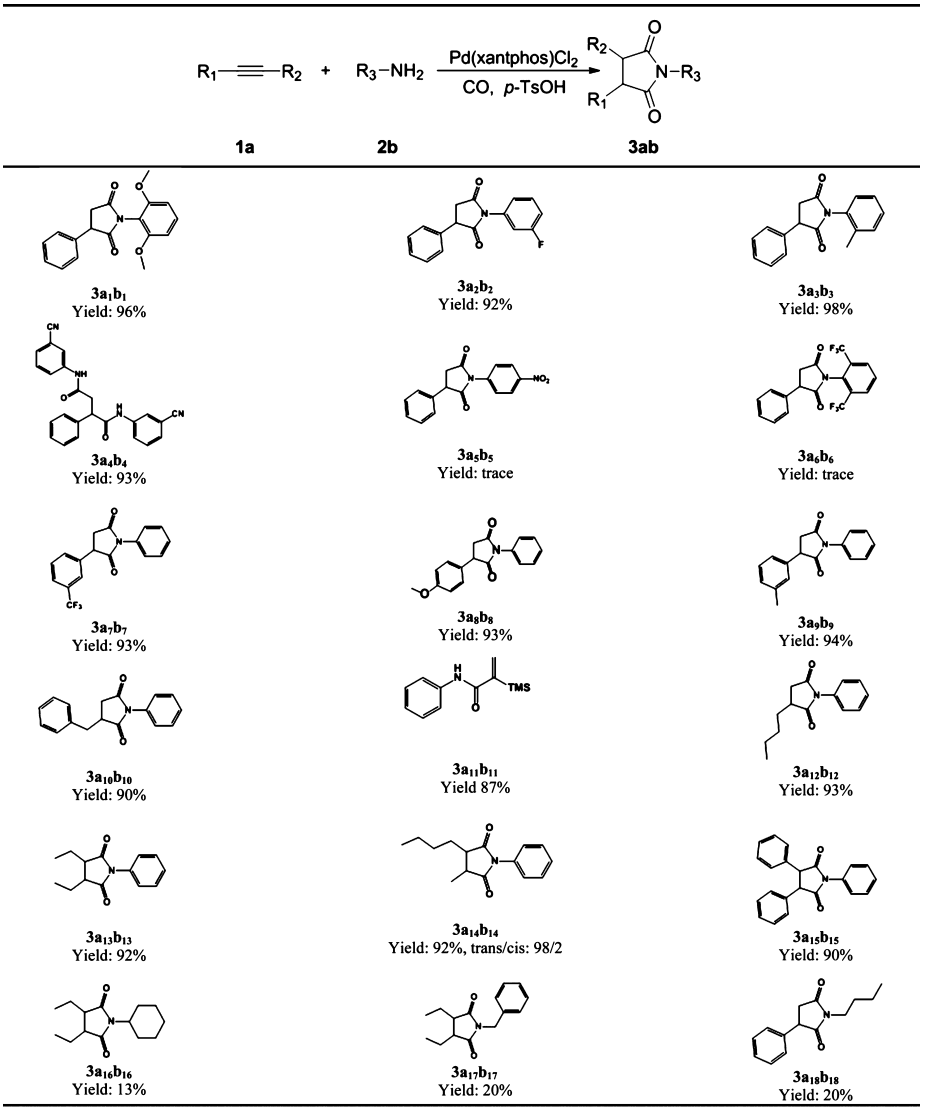
Table 2. Substrate Scope of the Pd(xantphos)Cl_2-Catalyzed Aminocarbonylation of Alkynes (1a) with Amines (2a)[a]



[a]Reaction conditions: Pd(xantphos)Cl_2 (5 mol % based on aniline), **1a** (1 mmol), **2b** (1.2 mmol), CO (30 atm), 125 °C, 8 h, *p*-TsOH (0.8 mmol). Yields are isolated yields. For $\mathbf{3a_{16}b_{16}}$, $\mathbf{3a_{17}b_{17}}$, and $\mathbf{3a_{18}b_{18}}$, yields were determined by GC analysis relative to aniline with *n*-decane as an internal standard.

obtained in DMF, CH_3CN, hexane, toluene, and water (Table 1, entries 1 and 9−13).

The scope of the reaction was explored under optimized conditions using Pd(xantphos)Cl_2 (5 mol %) as the catalyst (Table 2). The system is most efficient for anilines with electron-donating substituents. In contrast, anilines with electron-withdrawing substituents afford only trace amounts of succinimide product, i.e., $\mathbf{3a_5b_5}$ and $\mathbf{3a_6b_6}$ in Table 2, although, in the latter case, steric reasons are also likely to be responsible for the low yield. Interestingly, reaction with 3-aminobenzonitrile does not give a succinimide; instead, the product $\mathbf{3a_4b_4}$ is obtained in 93% yield. Substituents on phenylacetylene do not appear to have a large effect on the reaction, and both electron-donating and electron-withdrawing substituents give succinimide products in good yield, e.g., $\mathbf{3a_7b_7}$, $\mathbf{3a_8b_8}$, and $\mathbf{3a_9b_9}$ in Table 2. The system catalyzes both terminal and internal alkynes in high yield, e.g., $\mathbf{3a_{13}b_{13}}$, $\mathbf{3a_{14}b_{14}}$, and $\mathbf{3a_{15}b_{15}}$, and aromatic and aliphatic alkynes in yields around 90%. Both aromatic and aliphatic amines may be employed, although the aromatic amines give much higher yields (85−90% vs <20%) of the succinimide products. In this respect, it should be noted that the majority of routes to succinimide derivatives have focused on *N*-alkyl-succinimides, and the synthesis of *N*-phenyl-succinimides is more challenging. Moreover, *N*-phenyl-succinimides, and the structurally related *N*-phenylmaleimides (which may be obtained from *N*-phenyl-succinimides via dehydrogenation[17]), have a number of important applications.[18,19] *N*-phenyl-succinimides may be converted to their nonaromatic analogues via a simple exchange reaction at room temperature.[20] The reverse reaction, however, is not facile.

To demonstrate the utility of the Pd(xantphos)Cl_2-catalyzed method, an important photochromic molecule[21] was prepared using this procedure (Scheme 1). Notably, the corresponding alkyne can be prepared in a facile manner using the palladium-catalyzed Sonogashira reaction. The alkyne then reacts with CO to form the *N*-phenyl-succinimide product. From the alkyne to the final product, only three steps are required, and compared

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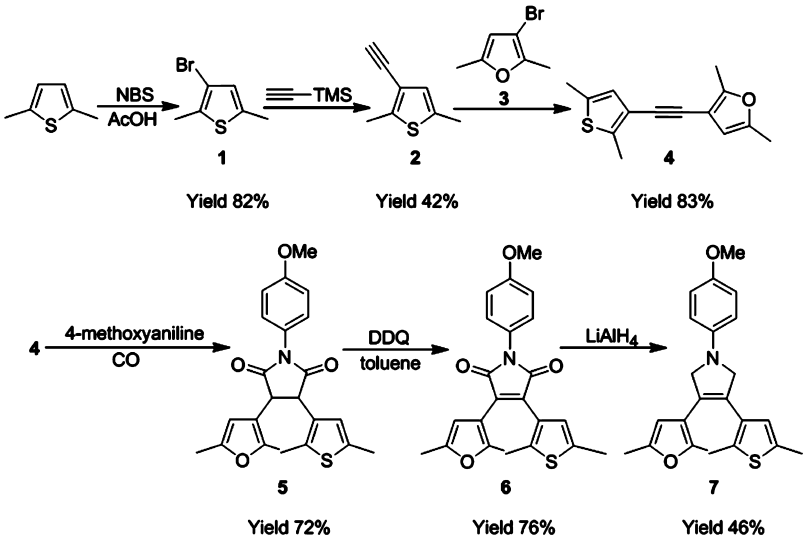
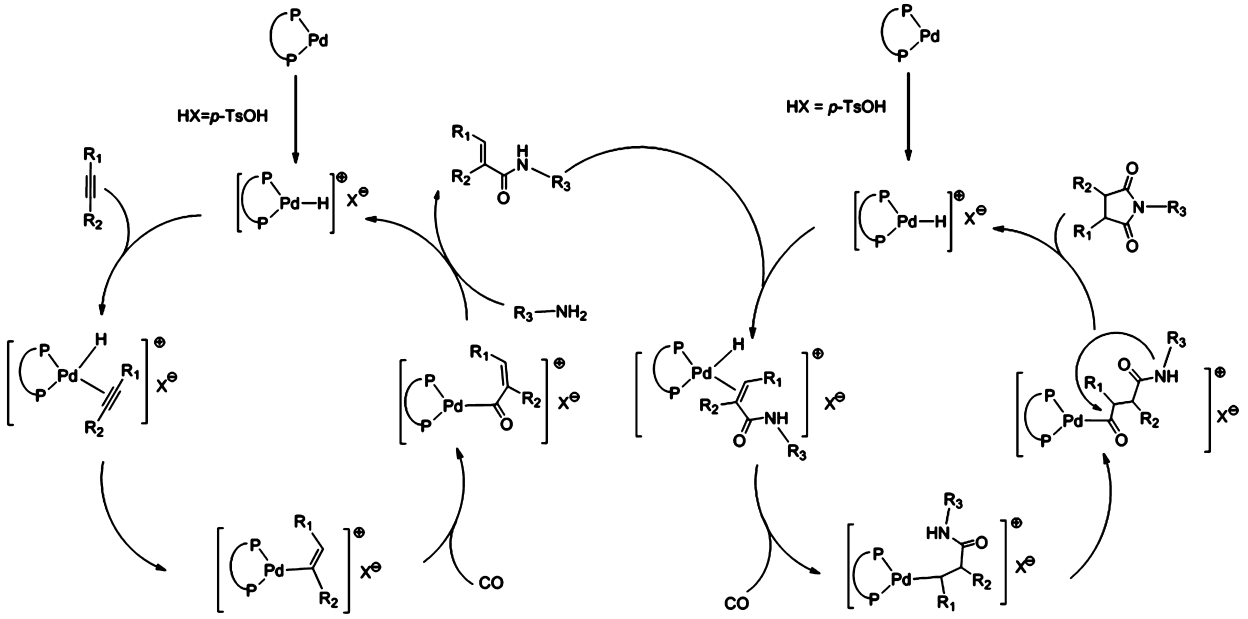
Scheme 1. Synthesis of the Photochromic Molecule 7



Scheme 2. Proposed Mechanism



with the literature method, the starting materials used in our route are easily prepared and are much cheaper.

The full mechanistic details of this reaction have not been determined, but presumably involve aminocarbonylation of the alkyne as the first step with the resulting alkene transferred into the second step where the succinimide is formed. A possible reaction mechanism is shown in Scheme 2, the first cycle involves the formation of an α,β-unsaturated amide by intermolecular reaction; the reaction mechanism should be similar to the hydroformylation of alkynes to α,β-unsaturated aldehydes reported previously.[22] The carbon−carbon double bond of α,β-unsaturated amide can be further activated by the catalyst,[14] reacting with CO to form the final product (the second cycle in Scheme 2).

In conclusion, we have shown that Pd(xantphos)Cl_2 efficiently catalyzes the carbonylation of alkynes with CO and amines to yield succinimide derivatives in the presence of *p*-TsOH. The reaction may be applied to both aliphatic and aromatic amines and represents an ideal method to transform simple starting materials into valuable succinimide derivatives.

■ EXPERIMENTAL SECTION

Catalytic Procedure. A mixture of the desired amount of precatalyst, ligand, alkyne, amine, *p*-TsOH, and THF (10 mL) was added to a Teflon tube that was placed in an autoclave (autoclave volume = 30 mL). The autoclave was sealed and purged with carbon monoxide to remove the air and then charged with the required pressure of CO. The reaction mixture was stirred at a required temperature for required time. After cooling, the CO was released and the reaction mixture was purified by flash column chromatography on silica gel to afford the desired product. The yield of the product was determined by weighing the isolated product or by GC analysis.

Procedure for the Preparation of 3,4-Diaryl-2,5-dihydropyrroles. *2,5-Dimethyl-3-bromofuran (**1**) or 2,5-Dimethyl-3-bromothiophene (**2**).* *N*-bromosuccinimide (NBS) (10 mmol) was slowly added to 50 mL of a glacial acetic acid solution containing 2,5-dimethylthiophene (for **1**, 10 mmol) or 2,5-dimethylfuran (for **2**, 10 mmol) at room temperature. After stirring for 3 h, the solution was

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poured onto excess ice-cold water and the product was extracted with dichloromethane. The dichloromethane solution was washed with an aqueous sodium carbonate solution (20 mL) and water (30 mL). The organic layer was washed with water (2 × 15 mL), dried over $MgSO_4$, and filtered. The solvent was removed under reduced pressure, and the residue was purified by column chromatography on silica gel using hexane as the eluent. Yield of **1** is 82% and **2** is 67%.

*3-Ethynyl-2,5-dimethylthiophene (**3**).* A 25 mL Schlenk tube was charged with $Pd(PPh_3)_4$ (0.5 mol %), PPh_3 (1 mol %), and copper iodide (1 mol %). TMEDA (1 M), **2** (3 mmol), and ethynyltrimethylsilane (1.2 equiv) were added successively under a nitrogen atmosphere. The solution was stirred for 20 h at 80 °C and then cooled to room temperature. K_2CO_3 (3 mmol) was added, and the mixture was stirred for a further 3 h. The residue was purified by column chromatography on silica gel using hexane as the eluent to afford the product in 42% yield.

*3-((2,5-Dimethylthiophen-3-yl)ethynyl)-2,5-dimethylfuran (**4**).* A 25 mL Schlenk tube was charged with $Pd(PPh_3)_4$ (0.5 mol %), PPh_3 (1 mol %), and copper iodide (1 mol %). TMEDA (1 M), **1** (3 mmol), and **3** (1.2 equiv) were added successively under a nitrogen atmosphere. The reaction mixture was heated at 80 °C for 20 h. After cooling to room temperature, the mixture was quenched with water (15 mL) and the aqueous phase was extracted with diethyl ether (3 × 20 mL). The organic phases were combined, dried over anhydrous Na_2SO_4, and concentrated under vacuum, and the residue was purified by silica gel column chromatography using hexane as the eluent. The product yield of **4** is 72%.

*3-(2,5-Dimethylfuran-3-yl)-4-(2,5-dimethylthiophen-3-yl)-1-(4-methoxyphenyl)pyrrolidine-2,5-dione (**5**) and 3-(2,5-Dimethylfuran-3-yl)-4-(2,5-dimethylthiophen-3-yl)-1-(4-methoxyphenyl)-1H-pyrrole-2,5-dione (**6**).* A mixture of $PdCl_2$ (0.05 mmol), xantphos (0.06 mmol), 3-((2,5-dimethylthiophen-3-yl)ethynyl)-2,5-dimethylfuran (1 mmol), 4-methoxyaniline (1 mmol), *p*-TsOH (0.8 mmol), and THF (10 mL) was added to a Teflon tube that was placed in an autoclave (volume = 30 mL). The autoclave was sealed and purged with carbon monoxide to remove the air and then charged with CO (30 atm). The reaction mixture was stirred at 125 °C for 12 h. After cooling, the CO was released and 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ 1.2 equiv) was added and the resulting mixture was stirred for 3 h at room temperature. The product was purified by flash column chromatography on silica gel using ethyl acetate and hexane as the eluent to afford the product in 76% yield.

*3-(2,5-Dimethylfuran-3-yl)-4-(2,5-dimethylthiophen-3-yl)-1-(4-methoxyphenyl)-2,5-dihydro-1H-pyrrole (**7**).* Compound **6** (1 mmol) was dissolved in dry THF (10 mL) and added dropwise to a suspension of $LiAlH_4$ in THF. The reaction mixture was stirred for 5 h at 0 °C, and then water (1 mL) and 15% NaOH solution (1 mL) were added and the mixture was stirred for 1 h at 0 °C. Water (3 mL) was added to the reaction mixture, and the product was extracted into CH_2Cl_2. The solvent was removed under vacuum, and the product was purified by flash column chromatography on silica gel using ethyl acetate and hexane as the eluent to afford the product in 46% yield.

Spectroscopic Data. *1,3-Diphenylpyrrolidine-2,5-dione (**3ab**).* White solid (243 mg, 97% yield): mp 136−138 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.51 (td, J = 6.9, 1.6 Hz, 2H), 7.48−7.40 (m, 3H), 7.41−7.29 (m, 5H), 4.23 (dd, J = 9.8, 4.8 Hz, 1H), 3.42 (dd, J = 18.6, 9.7 Hz, 1H), 3.04 (dd, J = 18.5, 4.8 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.6, 175.1, 137.2, 132.0, 129.3, 129.2, 128.7, 128.1, 127.4, 126.5, 46.0, 37.3. HRMS (ESI): calculated for $C_{16}H_{13}NO_2$ $[M + Na]^+$ 274.0844, found 274.0843.

*1-(2,6-Dimethoxyphenyl)-3-phenylpyrrolidine-2,5-dione (**3a$_1$b$_1$**).* White solid (298 mg, 96% yield): mp 200−203 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54−7.38 (m, 2H), 7.36 (dt, J = 8.6, 6.4 Hz, 3H), 6.53 (t, J = 2.2 Hz, 1H), 6.48 (d, J = 2.2 Hz, 2H), 4.21 (dd, J = 9.7, 4.8 Hz, 1H), 3.40 (dd, J = 18.5, 9.7 Hz, 1H), 3.03 (dd, J = 18.5, 4.9 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.5, 175.0, 161.1, 137.1, 133.4, 129.3, 128.1, 127.4, 105.0, 101.2, 55.6, 45.6, 37.2. HRMS (ESI): calculated for $C_{18}H_{17}NO_4$ $[M + Na]^+$ 334.1055, found 334.1050.

*1-(3-Fluorophenyl)-3-phenylpyrrolidine-2,5-dione (**3a$_2$b$_2$**).* White solid (247 mg, 92% yield): mp 146−148 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.55−7.30 (m, 6H), 7.21−7.10 (m, 3H), 4.23 (dd, J = 9.7, 4.8 Hz, 1H), 3.42 (dd, J = 18.6, 9.7 Hz, 1H), 3.05 (dd, J = 18.6, 4.9 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.2, 174.7, 163.8, 161.4, 136.8, 133.2, 133.1, 130.4, 130.3, 129.4, 128.2, 127.4, 122.1, 122.1, 115.9, 115.7, 114.2, 113.9, 45.9, 37.2. HRMS (ESI): calculated for $C_{16}H_{12}FNO_2$ $[M + Na]^+$ 292.0750, found 292.0748.

*3-Phenyl-1-(o-tolyl)pyrrolidine-2,5-dione (**3a$_3$b$_3$**).* White solid (259 mg, 98% yield): mp 162−163 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45 (t, J = 7.0 Hz, 2H), 7.42−7.25 (m, 6H), 7.14 (dd, J = 13.8, 7.8 Hz, 1H), 4.27 (td, J = 9.9, 4.7 Hz, 1H), 3.45 (ddd, J = 18.6, 9.7, 3.9 Hz, 1H), 3.07 (ddd, J = 18.5, 10.6, 4.7 Hz, 1H), 2.21 (d, J = 17.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.7, 175.3, 139.1, 137.1, 131.9, 129.2, 128.9, 128.7, 128.1, 126.5, 124.3, 46.0, 37.4, 21.5. HRMS (ESI): calculated for $C_{17}H_{15}NO_2$ $[M + Na]^+$ 288.1000, found 288.0997.

*N^1,N^4-Bis(3-cyanophenyl)-2-phenylsuccinamide (**3a$_4$b$_4$**).* White solid (367 mg, 93% yield); ^{1}H NMR (400 MHz, DMSO-*d*6) δ 10.60 (s, 1H), 10.42 (s, 1H), 8.15−8.01 (m, 2H), 7.76 (ddt, J = 13.3, 7.5, 2.4 Hz, 2H), 7.57−7.20 (m, 9H), 4.27 (dd, J = 9.8, 5.2 Hz, 1H), 3.26 (dd, J = 16.1, 9.7 Hz, 1H), 2.82 (dd, J = 16.1, 5.3 Hz, 1H). ^{13}C NMR (101 MHz, DMSO-*d*6) δ 172.1, 170.4, 155.7, 140.4, 140.2, 139.6, 130.7, 129.1, 128.0, 127.7, 127.2, 127.1, 124.0, 123.9, 122.0, 121.9, 119.1, 119.1, 112.0, 68.2, 48.3. HRMS (ESI): calculated for $C_{24}H_{18}N_4O_2$ $[M + Na]^+$ 417.1328, found 417.1320.

*1-Phenyl-3-(3-(trifluoromethyl)phenyl)pyrrolidine-2,5-dione (**3a$_7$b$_7$**).* White solid (249 mg, 93% yield): mp 170−173 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.68−7.49 (m, 6H), 7.48−7.42 (m, 1H), 7.40−7.32 (m, 2H), 4.31 (dd, J = 9.8, 5.2 Hz, 1H), 3.46 (dd, J = 18.5, 9.8 Hz, 1H), 3.05 (dd, J = 18.5, 5.2 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.9, 174.4, 137.8, 131.7, 130.8, 129.9, 129.3, 128.9, 126.4, 125.1, 124.5, 105.0, 45.5, 36.9. HRMS (ESI): calculated for $C_{17}H_{12}F_3NO_2$ $[M + Na]^+$ 342.0718, found 342.0702.

*3-(4-Methoxyphenyl)-1-phenylpyrrolidine-2,5-dione (**3a$_8$b$_8$**).* White solid (297 mg, 93% yield): mp 170−173 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.55−7.47 (m, 2H), 7.46−7.40 (m, 1H), 7.38−7.33 (m, 2H), 7.29−7.24 (m, 2H), 6.99−6.93 (m, 2H), 4.18 (dd, J = 9.7, 4.8 Hz, 1H), 3.85 (s, 3H), 3.40 (dd, J = 18.5, 9.7 Hz, 1H), 3.01 (dd, J = 18.6, 4.8 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.7, 175.2, 159.3, 132.0, 129.2, 129.0, 128.7, 128.4, 126.5, 114.7, 55.4, 45.3, 31.1. HRMS (ESI): calculated for $C_{17}H_{15}NO_3$ $[M + Na]^+$ 304.0950, found 304.0951.

*1-Phenyl-3-(m-tolyl)pyrrolidine-2,5-dione (**3a$_9$b$_9$**).* White solid (249 mg, 94% yield): mp 180−181 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.57−7.40 (m, 3H), 7.30 (m, 3H), 7.19 (m, 3H), 4.19 (dd, J = 9.7, 4.7 Hz, 1H), 3.40 (dd, J = 18.6, 9.7 Hz, 1H), 3.03 (dd, J = 18.6, 4.7 Hz, 1H), 2.41 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 176.73, 175.3, 139.1, 137.1, 132.0, 129.2, 128.9, 128.7, 128.1, 126.5, 124.3, 46.0, 37.4, 21.5. HRMS (ESI): calculated for $C_{17}H_{15}NO_2$ $[M + Na]^+$ 288.1000, found 288.1003.

*3-Benzyl-1-phenylpyrrolidine-2,5-dione (**3a$_{10}$b$_{10}$**).* White solid (238 mg, 90% yield): mp 148−150 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.53−7.30 (m, 6H), 7.28−7.17 (m, 4H), 3.43−3.22 (m, 2H), 3.12 (dd, J = 13.8, 8.0 Hz, 1H), 2.92 (dd, J = 18.5, 9.1 Hz, 1H), 2.68 (dd, J = 18.5, 4.7 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 178.2, 175.2, 136.7, 131.8, 129.2, 129.2, 128.9, 128.6, 127.3, 126.5, 41.3, 36.6, 33.4. HRMS (ESI): calculated for $C_{17}H_{15}NO_2$ $[M + Na]^+$ 288.1000, found 288.1003.

*N-Phenyl-2-(trimethylsilyl)acrylamide (**3a$_{11}$b$_{11}$**).* White solid (191 mg, 87% yield); ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.62 (d, J = 7.7 Hz, 2H), 7.43−7.32 (m, 3H), 7.26 (d, J = 18.5 Hz, 1H), 7.15 (d, J = 14.8 Hz, 1H), 6.37 (d, J = 18.5 Hz, 1H), 0.19 (s, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 163.1, 145.8, 137.9, 136.9, 129.0, 124.4, 119.9, −1.73; HRMS (ESI): calculated for $C_{12}H_{17}NOSi$ $[M + Na]^+$ 242.0977, found 242.0977.

*3-Butyl-1-phenylpyrrolidine-2,5-dione (**3a$_{12}$b$_{12}$**).* White solid (215 mg, 93% yield): mp 70−71 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54−7.45 (m, 2H), 7.46−7.37 (m, 1H), 7.37−7.26 (m, 2H), 3.30−2.79 (m, 2H), 2.64−2.55 (m, 1H), 2.12−1.95 (m, 1H), 1.52−1.32 (m, 5H), 1.01−0.93 (m, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 179.0, 175.7, 132.0, 129.1, 128.5, 126.5, 40.0, 34.6, 31.2, 28.8, 22.4, 13.9. HRMS

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(ESI): calculated for $C_{14}H_{17}NO_2$ $[M + Na]^+$ 254.1157, found 254.1157.

*3,4-Diethyl-1-phenylpyrrolidine-2,5-dione (**3a$_{13}$b$_{13}$**).* White solid (213 mg, 92% yield): mp 65−66 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.69−7.55 (m, 2H), 7.46 (s, 1H), 7.42−7.32 (m, 2H), 7.19−7.08 (m, 1H), 6.26 (t, J = 7.3 Hz, 1H), 2.44 (q, J = 7.5 Hz, 2H), 2.25 (p, J = 7.5 Hz, 2H), 1.11 (td, J = 7.6, 2.1 Hz, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.7, 138.8, 138.2, 136.5, 129.0, 124.1, 119.9, 21.4, 20.5, 13.8. HRMS (ESI): calculated for $C_{14}H_{17}NO_2$ $[M + Na]^+$ 254.1157, found 254.1157.

*3-Butyl-4-methyl-1-phenylpyrrolidine-2,5-dione (**3a$_{14}$b$_{14}$**).* White solid (225 mg, 92% yield): mp 75−76 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.52−7.46 (m, 2H), 7.40 (ddd, J = 6.6, 4.8, 1.9 Hz, 1H), 7.31 (dd, J = 8.4, 1.2 Hz, 2H), 2.70 (qd, J = 7.3, 5.3 Hz, 1H), 2.57 (dt, J = 8.7, 5.0 Hz, 1H), 2.10−1.94 (m, 1H), 1.80−1.63 (m, 1H), 1.48 (d, J = 7.3 Hz, 4H), 1.42 (ddd, J = 11.0, 7.0, 3.9 Hz, 3H), 0.97 (t, J = 7.1 Hz, 3H); ^{13}C NMR (101 MHz, $CDCl_3$) δ 178.9, 178.1, 132.1, 129.1, 128.4, 126.4, 48.1, 41.1, 30.6, 28.9, 22.6, 16.6, 13.9. HRMS (ESI): calculated for $C_{15}H_{19}NO_2$ $[M + Na]^+$ 268.1308, found 268.1313.

*1,3,4-Triphenylpyrrolidine-2,5-dione (**3a$_{15}$b$_{15}$**).* White solid (294 mg, 90% yield): mp 243−244 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.53 (m, 2H), 7.49−7.34 (m, 10H), 7.34−7.29 (m, 3H), 4.26 (s, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.6, 136.6, 132.0, 129.4, 129.2, 128.8, 128.2, 127.7, 126.5, 55.5. HRMS (ESI): calculated for $C_{22}H_{17}NO_2$ $[M + Na]^+$ 350.1157, found 350.1154.

■ ASSOCIATED CONTENT

Supporting Information

NMR spectra of all new compounds. 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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