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Nickel-Catalyzed Suzuki–Miyaura Coupling of Heteroaryl Ethers with Arylboronic Acids

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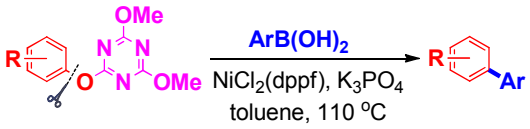


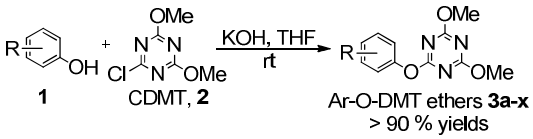
Abstract

Nickel-catalyzed Suzuki–Miyaura coupling of heteroaryl ethers with arylboronic acids was described. Selective activation of the phenol C–O bonds was achieved by converting them into the corresponding aryl 2,4-dimethoxy-1,3,5-triazine-6-yl ethers, in which aryl C–O bond could be selectively cleaved with inexpensive, air-stable $NiCl_2$(dppf) as a catalyst. Coupling of these readily accessible heteroaryl ethers proved tolerant of extensive functional groups.

Transition metal-catalyzed Suzuki–Miyaura reactions have been recognized as a powerful and indispensable method for biaryl synthesis because of the inherent advantages of organoboron reagents, such as air- and moisture-stability, good functional group tolerance, low toxicity and widely availability.[1,2] Relative to aryl halides, recently much attention has been paid to coupling with aryl C–O electrophiles due to their ready availability from natural source and chemical synthesis.[3–6] So far, a wide array of previously unreactive substrates such as aryl methyl ethers,[7] esters,[8,9] carbamates,[10–13] carbonates,[12] sulfamates,[10,12,14,15] phosphoramides,[16] phosphonium salts,[17,18] and phosphates[19] have been identified as competent coupling partners in the cross-coupling reactions. Although significant advances have been made in this field, for the electronically deactivated substrates,[8–15,20,21] cross-coupling reactions usually gave only poor to modest yields. Given low cost and readily accessibility of the phenols, development of new methodology for cross-coupling reactions of aryl C–O electrophiles contributes greatly to the fundamental conception of the reactivity of the relative inert C–O bonds and is, therefore, still considerably important. Herein, we report the new method for effective activation of the phenol C–O bond through converting them into aryl 2,4-dimethoxy-1,3,5-triazine-6-yl (DMT) ethers, allowing for nickel-catalyzed Suzuki–Miyaura coupling of extensive phenol derivatives with arylboronic acids.

In view of high efficiency of 2-chloro-4,6-disubstituted-1,3-5-triazines in formation of the peptide bonds,[22–25] which resulted from the excellent leaving potential of the oxygenated 1,3,5-triazines, we envisioned that activation of the phenol C–O bond for subsequent Suzuki–Miyaura cross-coupling reactions could be achieved through converting the phenols to the corresponding heteroaryl ethers **3** (Scheme 1).

Scheme 1. Preparation of Ar-O-DMT Ethers



The advantage to introduce such a heteroarene is obvious that two C_2-symmetric *ortho* nitrogen atoms may be provided to form the relative nitrogen coordinated transition metal complex,[26] which facilitated the oxidative addition of $[M^0L_n]$ species to the unreactive aryl C–O bond by *ortho* position chelation assistance.[27,28] Furthermore, the high leaving potential of the oxygenated 1,3-5-triazine could also accelerate the transmetallation process in the catalytic cycles of cross-coupling reactions.[29] It is also worth noting that synthesis of these heteroaryl ethers was very simple and effective from the inexpensive 2-chloro-4,6-dimethoxy-1,3,5-triazine (CDMT) **2**.[30] All Ar-O-DMT ethers **3** are the colorless crystals and thus could be separated and purified conveniently by recrystallization from ethanol. They generally exhibit high air- and moisture-stability, allowing for indefinite storage and easy handling in air. A single crystal X-ray diffraction analysis of aryl 2,4-dimethoxy-1,3,5-triazine-6-yl ether **3a** confirmed preliminarily our aforementioned hypothesis (Figure 1).[31] Analysis of the X-ray structure revealed that C_{Ar}–ODMT bond (C(5)–O(2)) distance is 1.411 Å, obviously larger than those of ArO–C_{DMT} bond (O(2)–C(8)) (1.349 Å) and C_{Ar}–OMe bond (C(2)–O(1)) (1.363 Å), which implied that the phenol C–O bond has the potential to be cleaved in subsequent cross-coupling reaction.

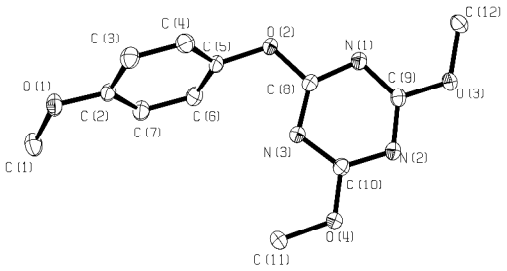
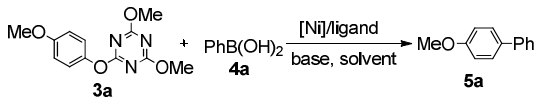


Figure 1. ORTEP drawings of compound 3a. All hydrogen atoms were omitted for clarity.

With this preliminary confirmation, reactivity of these Ar-O-DMT ethers in nickel-catalyzed Suzuki–Miyaura cross-coupling reaction was examined subsequently. Using heteroaryl ether **3a** and phenylboronic acid **4a** as the coupling partners, various reaction parameters including ligand, base, solvent, and temperature were screened (Table 1). Base was found to show significant influence on the coupling reaction and anhydrous K_3PO_4 showed the best efficiency for this transformation. In sharp contrast, the corresponding hydrate base was completely inefficient (entries 5 *vs* 6, Table 1). The effect of solvent on the coupling reaction was rather important; toluene proved to the choice of solvent, whereas other polar solvents such as DME and DMA gave rise to no coupling product, even though reactions were performed at elevated temperature (entry 9, Table 1). Compared with the monodentate ligand catalyst $NiCl_2(PCy_3)_2$, bidentate $NiCl_2$(dppf) was found to be a superior catalyst (entries 6 *vs* 15, Table 1). In addition, $NiCl_2$(dppp) was also effective catalyst for the coupling reaction although a slightly lower yield was attained (entry 13, Table 1). Under the optimal reaction conditions, coupling with phenyl pinacolboronate, instead of phenylboronic acid, only gave trace amount of product (entries 15 *vs* 16, Table 1).

Table 1. Optimization of Reaction Conditions[a]



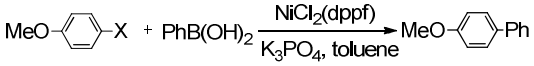
entry	[Ni]/ligand	base	solvent	yield (%)[b]
1	$NiCl_2(PCy_3)_2$	K_2CO_3	toluene	0
2	$NiCl_2(PCy_3)_2$	Cs_2CO_3	toluene	0
3	$NiCl_2(PCy_3)_2$	KF	toluene	< 5
4	$NiCl_2(PCy_3)_2$	KO*t*Bu	toluene	< 5
5	$NiCl_2(PCy_3)_2$	K_3PO_4•$6H_2O$	toluene	0
6	$NiCl_2(PCy_3)_2$	K_3PO_4	toluene	67
7	$NiCl_2(PCy_3)_2$	K_3PO_4	dioxane	< 5
8	$NiCl_2(PCy_3)_2$	K_3PO_4	DME	0[c]
9	$NiCl_2(PCy_3)_2$	K_3PO_4	DMA	0[d]
10	$NiCl_2(PCy_3)_2$	K_3PO_4	*t*BuOH	20
11	$NiCl_2(PPh_3)_2$	K_3PO_4	toluene	47
12	$NiCl_2$(dppe)	K_3PO_4	toluene	38
13	$NiCl_2$(dppp)	K_3PO_4	toluene	81
14	$NiCl_2$(dppb)	K_3PO_4	toluene	< 5
15	**$NiCl_2$(dppf)**	**K_3PO_4**	**toluene**	**90**
16	$NiCl_2$(dppf)	K_3PO_4	toluene	< 5[e]

[a] Reaction Conditions: **3a** (1.0 mmol), **4a** (4.0 mmol), [Ni]/ligand 5 mol %, base (7.0 mmol), solvent (0.15 M), *T* 110 °C, t 24 h. [b] Isolated yield. [c] *T* 80 °C. [d] *T* 130 °C. [e] Phenyl pinacolboronate instead of $PhB(OH)_2$ was used.

In regard to transition metal-catalyzed Suzuki–Miyaura cross-coupling reactions, it is well established that the electrophiles with electron-donating groups are electronically deactivated and generally less susceptible to oxidative addition. For examples, cross-coupling of electronically deactivated aryl pivalates,[8,9] carbamates,[10–13] and sulfamates[10,12,14,15] with arylboronic acids commonly gave poor to modest yields. A comparison of nickel-catalyzed cross-coupling of various 4-anisole-containing C–O electrophiles with phenylboronic acid was outlined in Table 2. The electron-rich aryl methyl ether was completely inactive under the catalytic conditions employed in this study. Coupling with electron-rich aryl mesylate, tosylate, pivalate and carbamate only gave the

desired biaryl in poor to modest yields, although increased yield was obtained when using the corresponding aryl sulfamate as an electrophile. In contrast, coupling of electron-rich Ar-O-DMT ether **3a** with phenylboronic acid gave rise to the biaryl in excellent yield under the present condition.

Table 2. Nickel-Catalyzed Cross-Coupling of Electron-Rich Aryl C–O Electrophiles with Phenylboronic Acid[a]

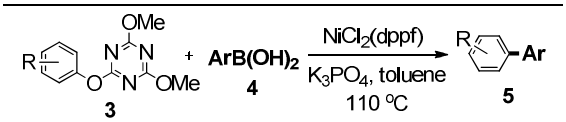


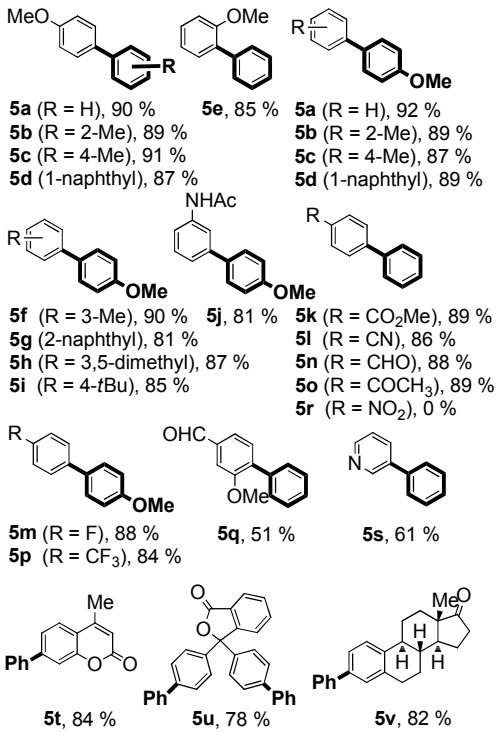
X	OMe	OMs	OTs	OPiv	$OCONMe_2$	OSO_2NMe_2	$OP(O)(OEt)_2$	**ODMT**
yield (%)[b]	0	21	27(51)[c]	24(58)[d]	19(41)[e]	68(80)[e]	46(71)[f]	**90**

[a] Reaction Conditions: Aryl C–O electrophile (1.0 mmol), $PhB(OH)_2$ (4.0 equiv), $NiCl_2$(dppf) (5 mol %), K_3PO_4 (7.0 equiv), toluene (0.15 M), *T* 110 °C, t 24 h. [b] Isolated yield. [c] Literature yield (ref. 32). [d] Literature yield (ref. 9). [e] Literature yield (ref. 12). [f] Literature yield (ref. 19).

Next, the generality of Suzuki coupling with respect to Ar-O-DMT ethers has been investigated. As shown in Table 3, under the present catalytic system, those substrates with electron-donating group(s) exhibited very good compatibility and all gave excellent yields (**5a**–**e**, Table 3). Coupling with Ar-O-DMT ethers was also found to be tolerant of a variety of functional groups (**5j**–**p**, Table 3), such as amide, ester, nitrile, aldehyde, ketone, etc. To our surprise, electronically activated Ar-O-DMT ether **3s** bearing a strong electron-withdrawing nitro group failed to couple with phenylboronic acid (**5r**, Table 3). The reactions proved also tolerant of a lactone or α,β-unsaturated lactone group (**5t**, **5u**, Table 3). In addition, double cross-coupling proceeded in good yield (**5u**, Table 3). It should be emphasized that aryl fluoride was chemically inert under the coupling conditions (**5m**, Table 3).

Table 3. Scope and Limitations of Suzuki Coupling with Ar-O-DMT Ethers[a,b]

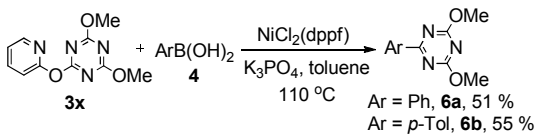




[a] Reaction Conditions: Ar-O-DMT ether (1.0 mmol), $ArB(OH)_2$ (4.0 mmol), $NiCl_2$(dppf) (5 mol %), K_3PO_4 (7.0 mmol), toluene (0.15 M), *T* 110 °C, t 24 h. [b] Isolated yield.

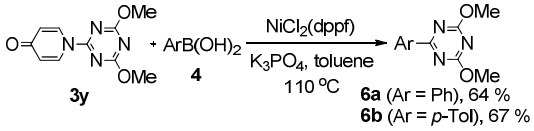
Notably, cross-coupling of 3-hydroxypyridine-derived ether with phenylboronic acid also afforded a Ph-DMT derivative **6a** in an isolated yield of 9 % in addition to the desired 3-phenylpyridine (**5s**, Table 3). However, when its 2-pyridinyl congener **3x** was used as the coupling partner, only product **6a** was obtained in a yield of 51 % (Scheme 2). Coupling of ether **3x** with 4-methylphenylboronic acid proceeded in a similar manner.

Scheme 2. Suzuki Coupling with 2-Hydroxypyridine-Derived Ether 3x



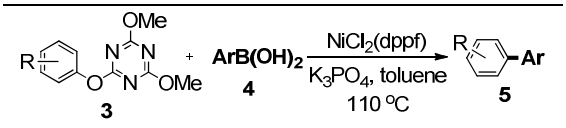
Unlike that of 2- and 3-hydroxy pyridines, reaction of 4-hydroxy pyridine with 1-chloride-3,5-dimethoxy-2,4,6-triazine did not give the corresponding 4-pyridinyl-O-DMT ether and an unexpected isomer was isolated. After careful examination of its ^{1}H and ^{13}C NMR spectra data, its structure was identified as *N*-DMT 4-pyridinone **3y**. A single crystal X-ray diffraction analysis further validated the proposed structure.[31] Unexpectedly, when this *N*-DMT 4-pyridinone **3y** was subjected to subsequent cross-coupling with arylboronic acids, the corresponding Ar-DMT derivatives **6** were also obtained in good yields (Scheme 3). Meanwhile, reaction performed without catalyst $NiCl_2$(dppf) failed to give the corresponding coupling products. Although several classes of *N*-leaving groups, such as diazonium salts,[33] ammonium salts,[34] aryltriazene,[35] azoles,[36] and anilines with an *ortho* position carbonyl group as the ligating group,[37,38] have been reported in the Suzuki–Miyaura coupling, this represented the first example of catalytic Suzuki coupling with an enamine as the leaving group.

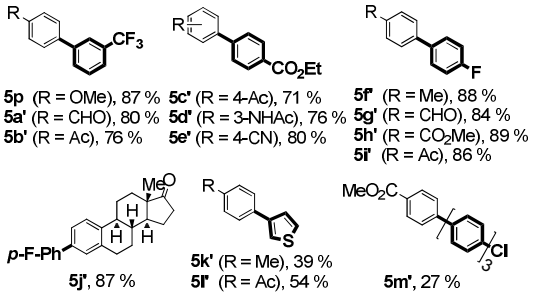
Scheme 3. Suzuki Coupling with *N*-DMT 4-Pyridinone 3y



Furthermore, scope of Suzuki coupling with various arylboronic acids was investigated. As illustrated in Table 4, arylboronic acids incorporating electron-withdrawing groups coupled smoothly with a variety of Ar-O-DMT ethers to afford biaryl products in good to excellent yields. To our disappointment, under the coupling conditions heteroaryl boronic acids are less reactive (**5k′** and **5l′**, Table 4).[39] Additionally, aryl chloride was not able to survive in the coupling reaction. When reaction was performed using 4-chloride phenylboronic acid as the coupling partner, a *p*-tetraphenyl derivative was obtained in a yield of 27 % (**5m′**, Table 4).

Table 4. Scope and Limitations of Suzuki Coupling with Arylboronic Acids[a,b]

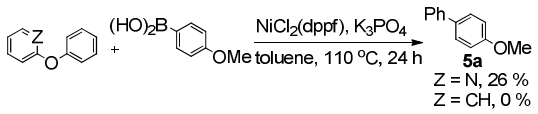




[a] Reaction Conditions: Ar-O-DMT ether **3** (1.0 mmol), $ArB(OH)_2$ (4.0 mmol), $NiCl_2(dppf)$ (5 mol %), K_3PO_4 (7.0 mmol), toluene (0.15 M), *T* 110 °C, t 24 h. [b] Isolated yield.

To investigate the scope of other types of heteroaryl ether, cross-coupling of 2-phenoxypyridine with 4-methoxyphenylboronic acid was therefore carried out. The corresponding biaryl **5a** was obtained in an isolated yield of 26 % by employing the present catalytic condition. Meanwhile, coupling with the simple diphenyl ether gave rise to no desired product (Scheme 4).

Scheme 4. Comparative Suzuki Coupling of 2-Phenoxypyridine and Diphenyl Ether



In summary, we have demonstrated that activation of the phenol C–O bond could conveniently be achieved through converting them into the corresponding aryl triazinyl ethers. These readily accessible heteroaryl ethers showed prominent reactivity in the Suzuki–Miyaura coupling reactions. Coupling reactions with Ar-O-DMT ethers proved tolerant of extensive functional groups, including ester, amide, aldehyde, ketone, nitrile, and so on.

EXPERIMENTAL SECTION

General. All solvents were dried prior to use using the standard methods. The phenols, CDMT **2**, and arylboronic acids were used as received from commercial availability. CDMT **2** was also prepared from cyanuric chloride with methanol on a large scale according to the literature method.[30] HRMS were recorded on Varian 7.0T FTICR-MS. NMR spectroscopy data of the known compounds matches with those reported in the corresponding references. All new compounds were further characterized by elemental analysis or HRMS.

General Procedure for Synthesis of Ar-O-DMT Ethers 3. A mixture of the phenol **1** (20 mmol), CDMT **2** (3.50 g, 20 mmol), and KOH (1.12 g, 20 mmol) in THF (80 mL) was stirred at room temperature overnight. After reaction completion monitoring by TLC, the mixture was filtrated through a short pad of silica gel and washed exhaustively with CH_2Cl_2. The solvent was removed off under vacuum. Recrystallization from ethanol gave the title compounds.

*2,4-Dimethoxy-6-(4'-methoxyphenoxy)-1,3,5-triazine (**3a**) (CAS no. 33950-61-7).* Yield 97%, 5.10 g; m.p. 76–78 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.10 (d, J = 8 Hz, 2H), 6.91 (d, J = 8 Hz, 2H), 4.00 (s, 6H), 3.82 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.7, 173.5, 157.3, 145.2, 122.2, 114.4, 55.5, 55.4. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{12}H_{13}N_3O_4Na$ 286.0798; Found 286.0795.

*2,4-Dimethoxy-6-(2'-methoxyphenoxy)-1,3,5-triazine (**3b**).* Yield 93%, 4.89 g; m.p. 96–98 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.27–7.23 (m, 1H), 7.15 (d, J = 12 Hz, 1H), 6.98 (d, J = 12 Hz, 2H), 3.98

(s, 6H), 3.78(s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.7, 173.2, 151.1, 140.7, 126.9, 122.4, 120.7, 112.5, 55.8, 55.3. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{12}H_{13}N_3O_4Na$ 286.0798; Found 286.0802.

2,4-Dimethoxy-6-phenoxy-1,3,5-triazine ***(3c)*** *(CAS no. 21002-15-3).* Yield 96%, 4.33 g; m.p. 103–104 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.41 (t, J = 8.8 Hz, 2H), 7.28 (d, J = 8 Hz, 1H), 7.18 (d, J = 8Hz, 2H), 3.99 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.8, 173.2, 151.7, 129.5, 125.9, 121.5, 55.4. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{11}H_{11}N_3O_3Na$ 256.0693; Found 256.0693.

2,4-Dimethoxy-6-(2'-methylphenoxy)-1,3,5-triazine ***(3d)*** *(CAS no. 42030-81-9).* Yield 95%, 4.69 g; m.p. 90–92 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.27–7.17 (m, 3H), 7.07 (d, J = 8 Hz, 1H), 3.98 (s, 6H), 2.19 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.8, 173.1, 150.3, 131.2, 130.16, 127.0, 126.1, 121.6, 55.4, 16.2. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{12}H_{13}N_3O_3Na$ 270.0849; Found 270.0849.

2,4-Dimethoxy-6-(3'-methylphenoxy)-1,3,5-triazine ***(3e)****.* Yield 91%, 4.50 g; m.p. 68–70 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.30–7.26 (m, 1H), 7.07 (d, J = 8 Hz, 1H), 6.99– 6.97 (m, 2H), 4.00 (s, 6H), 2.37 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.7, 173.3, 151.6, 139.7, 129.2, 126.8, 121.9, 118.5, 55.4, 21.3. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{12}H_{13}N_3O_3Na$ 270.0849; Found 270.0849.

2,4-Dimethoxy-6-(4'-methylphenoxy)-1,3,5-triazine ***(3f)*** *(CAS no. 33950-59-3)* Yield 93%, 4.59 g; m.p. 88–90 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.19 (d, J = 8 Hz, 2H), 7.05 (d, J = 8 Hz, 2H), 3.99 (s, 6H), 2.36 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.8, 173.4, 149.5, 135.5, 130.0, 121.1, 55.4, 20.9. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{12}H_{13}N_3O_3Na$ 270.0849; Found 270.0849.

2,4-Dimethoxy-6-(naphthalene-1'-yloxy)-1,3,5-triazine ***(3g)*** *(CAS no. 42030-87-5).* Yield 90%, 5.10 g; m.p. 89–91 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.88 (d, J = 8 Hz, 2H), 7.77 (d, J = 8 Hz, 1H),

7.52–7.45 (m, 3H), 7.30 (d, J = 8 Hz, 1H), 3.95 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.9, 173.8, 147.7, 134.7, 128.0, 126.8, 126.5, 126.2, 125.4, 121.4, 117.9, 55.4. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{15}H_{13}N_3O_3Na$ 306.0849; Found 306.0846.

*2,4-Dimethoxy-6-(naphthalene-2'-yloxy)-1,3,5-triazine (**3h**) (CAS no. 41735-95-9).* Yield 96%, 5.43 g; m.p. 120–122 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.88–7.8 (m, 3H), 7.62 (s, 1H), 7.5–7.47 (m, 2H), 7.33–7.30 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.8, 173.4, 149.3, 133.84, 131.5, 129.5, 127.8, 127.7, 126.6, 125.8, 121.1, 118.4, 55.5. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{15}H_{13}N_3O_3Na$ 306.0849; Found 306.0846.

*2-(3',5'-Dimethylphenoxy)-4,6-dimethoxy-1,3,5-triazine (**3i**).* Yield 94%, 4.90 g; m.p. 75–77 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 6.88 (s, 1H), 6.77(s, 2H), 4.00 (s, 6H), 2.32 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.8, 173.4, 151.6, 139.3, 127.7, 119.0, 55.4, 21.3. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{13}H_{15}N_3O_3Na$ 284.1006; Found 284.1003.

*2-(4'-tert-Butylphenoxy)-4,6-dimethoxy-1,3,5-triazine (**3j**).* Yield 95%, 5.48 g; m.p. 90–93 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.40 (d, J = 8 Hz, 2H), 7.10 (d, J = 8 Hz, 2H), 4.01 (s, 6H), 1.33 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.7, 173.3, 149.3, 148.6, 126.3, 120.7, 55.4, 34.4, 31.4. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{15}H_{19}N_3O_3Na$ 312.1319; Found 312.1313.

*N-(3-((4',6'-Dimethoxy-1',3',5'-triazin-2'-yl)oxy)phenyl)acetamide (**3k**).* Yield 96%, 5.56 g; m.p. 131–133 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.38 (s, 1H), 7.51 (s 1H), 7.30–7.19 (m, 2H), 6.84 (d, J = 8 Hz, 1H), 4.03 (s, 6H), 1.98 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.7, 173.3, 168.7, 151.7, 140.0, 129.6, 117.2, 116.2, 113.0, 55.7, 24.3. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{13}H_{14}N_4O_4Na$ 313.0907; Found 313.0901.

*Methyl 4-((4',6'-dimethoxy-1',3',5'-triazin-2'-yl)oxy)benzoate (**3l**).* Yield 95%, 5.53 g; m.p. 122–124 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.11 (d, *J* = 8 Hz, 2H), 7.26 (d, *J* = 8 Hz, 2H), 4.00 (s, 6H), 3.93 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.8, 172.8, 166.2, 155.2, 131.3, 127.9, 121.6, 55.6, 52.2. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{13}H_{13}N_3O_5Na$ 314.0747; Found 314.0753.

*4-((4',6'-Dimethoxy-1',3',5'-triazin-2'-yl)oxy)benzonitrile (**3m**).* Yield 94%, 4.85 g; m.p. 135–137 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.77 (d, *J* = 8 Hz, 2H), 7.33 (d, *J* = 8 Hz, 2H), 4.02 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.8, 154.8, 133.8, 122.8, 118.1, 110.0, 55.7. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{12}H_{10}N_4O_3Na$ 281.0645; Found 281.0651.

*2-(4'-Fluorophenoxy)-4,6-dimethoxy-1,3,5-triazine (**3n**).* Yield 91%, 4.56 g; m.p. 80–82 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.17–7.14 (m, 2H), 7.12–7.07 (m, 2H), 4.01 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.8, 173.2, 161.5, 159.1, 147.5, 123.0, 122.9, 116.3, 116.0, 55.5. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{11}H_{10}FN_3O_3Na$ 274.0598; Found 274.0602.

*4-((4',6'-Dimethoxy-1',3',5'-triazin-2'-yl)oxy)benzaldehyde (**3o**) (CAS no. 42030-76-2).* Yield 95%, 4.96 g; m.p. 150–152 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 10.02 (s, 1H), 7.96 (d, *J* = 8 Hz, 2H), 3.37 (d, *J* = 8 Hz, 2H), 4.02 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 190.8, 173.8, 172.7, 156.2, 134.1, 131.3, 122.4, 55.6. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{12}H_{11}N_3O_4Na$ 284.0642; Found 284.0641.

*1-(4-((4',6'-Dimethoxy-1',3',5'-triazin-2'-yl)oxy)phenyl)ethanone (**3p**) (CAS no. 42030-75-1).* Yield 92%, 5.06 g; m.p. 120–121 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.03 (d, *J* = 8 Hz, 2H), 7.29 (d, *J* = 8 Hz, 2H), 4.01 (s, 6H), 2.62 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 196.7, 173.8, 172.7, 155.2, 134.8, 130.1, 121.8, 55.6, 26.6. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{13}H_{13}N_3O_4Na$ 298.0798; Found 298.0797.

*2,4-Dimethoxy-6-(3'-(trifluoromethyl)phenoxy)-1,3,5-triazine (**3q**).* Yield 90%, 5.42 g; m.p. 51–53 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.58–7.56 (m, 2H), 7.51 (s, 1H), 7.43–7.41 (m, 1H), 4.03 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.8, 172.8, 151.7, 132.2, 131.8, 130.1, 125.2, 124.8, 122.8, 122.1, 119.0, 55.5. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{12}H_{10}F_3N_3O_3Na$ 324.0567; Found 324.0573.

*4-((4',6'-Dimethoxy-1',3',5'-triazin-2'-yl)oxy)-3-methoxybenzaldehyde (**3r**).* Yield 93%, 5.40 g; m.p. 149–151 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 9.97 (s, 1H), 7.52 (d, *J* = 8 Hz, 2H), 7.33 (d, *J* = 8 Hz, 1H), 3.99 (s, 6H), 3.86 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 191.0, 173.8, 172.7, 152.0, 135.3, 124.9, 123.1, 111.0, 56.1, 55.5. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{13}H_{13}N_3O_5Na$ 314.0747; Found 314.0753.

*2,4-Dimethoxy-6-(4'-nitrophenoxy)-1,3,5-triazine (**3s**) (CAS no. 28690-95-1).* Yield 92%, 5.10 g; m.p. 135–137 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.32 (d, *J* = 8 Hz, 2H), 7.38 (d, *J* = 8 Hz, 2H), 4.03 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.8, 172.4, 156.2, 145.4, 125.4, 122.5, 55.7. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{11}H_{10}N_4O_5Na$ 301.0543; Found 301.0541.

*2,4-Dimethoxy-6-(pyridine-3'-yloxy)-1,3,5-triazine (**3t**).* Yield 91%, 4.25 g; m.p. 98–100 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.55–8.53 (m, 2H), 7.56 (d, *J* = 8 Hz, 1H), 7.40–7.36 (m, 1H), 4.01 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.8, 172.9, 148.4, 147.16, 143.6, 129.1, 123.9, 55.6. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{10}H_{10}N_4O_3Na$ 257.0645; Found 257.0648.

*7-((4',6'-Dimethoxy-1',3',5'-triazin-2'-yl)oxy)-4-methyl-2H-chromen-2-one (**3u**).* Yield 91%, 5.72 g; m.p. 204–206 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.67 (d, *J* = 8 Hz, 1H), 7.27 (m, 1H), 7.18 (dd, *J* = 4.4 Hz, 1H), 6.32 (s, 1H), 4.05 (s, 6H), 2.48 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.8, 172.7, 160.4, 154.2, 153.9, 151.9, 125.6, 118.1, 114.6, 110.6, 55.7, 18.7. HRMS (ESI-TOF) m/z: $[M+Na]^+$

Calcd. for $C_{15}H_{13}N_3O_5Na$ 338.0747; Found 338.0747.

3,3-Bis(4'-((4'',6''-dimethoxy-1'',3'',5''-triazin-2''-yl)oxy)phenyl)isobenzofuran-1(3H)-one ***(3v)***. Yield 88%, 10.50 g; m.p. 207–209 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.97 (d, *J* = 8 Hz, 1H), 7.76–7.72 (m, 1H), 7.61–7.58 (m, 2H), 7.41 (d, *J* = 8 Hz, 4H), 7.18 (d, *J* = 8 Hz, 4H), 4.00 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.7, 172.9, 169.4, 151.8, 151.5, 138.1, 134.4, 129.6, 128.5, 126.2, 124.1, 121.6, 115.1, 90.7, 55.6. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{30}H_{24}N_6O_8Na$ 619.1548; Found 619.1539.

(8R,9S,13S,14S)-3-((4',6'-dimethoxy-1',3',5'-triazin-2'-yl)oxy)-13-methyl-7,8,9,11,12,13,15,16-octahydro-6H-cyclopenta[a]phenanthren-17(14H)-one ***(3w)***. Yield 94%, 7.69 g; m.p. 155–157 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.30 (d, *J* = 8 Hz, 1H), 6.95 (dd, *J* = 4.8 Hz, 1H), 6.89 (d, *J* = 4 Hz, 1H), 4.01 (s, 6H), 2.92–2.90 (m, 2H), 2.55–2.48 (m, 1H), 2.43–2.39 (m, 1H), 2.2–2.13 (m, 1H), 2.09–1.99 (m, 3H), 1.69–1.62 (m, 2H), 1.59–1.48 (m, 4H), 1.46–1.40 (m, 1H), 0.92 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 220.8, 173.7, 173.3, 149.6, 138.0, 137.4, 126.4, 121.2, 118.6, 55.4, 50.4, 47.9, 44.1, 37.9, 35.8, 31.5, 29.4, 26.3, 25.7, 21.5, 13.8. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{23}H_{27}N_3O_4Na$ 432.1894; Found 432.1903.

2,4-Dimethoxy-6-(pyridine-2'-yloxy)-1,3,5-triazine ***(3x)***. Yield 90%, 4.21 g; m.p. 68–70 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.43 (d, *J* = 4 Hz, 1H), 7.86–7.81 (m, 1H), 7.28–7.24 (m, 1H), 7.13 (d, *J* = 8 Hz, 1H), 4.00 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 173.8, 172.8, 158.7, 148.5, 139.8, 122.1, 115.9, 55.5. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{10}H_{10}N_4O_3Na$ 257.0645; Found 257.0648.

1-(4',6'-Dimethoxy-1',3',5'-triazin-2'-yl)pyridine-4(1H)-one ***(3y)***. Yield 92%, 4.30 g; m.p. 179–181 °C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.78 (d, *J* = 8 Hz, 2H), 6.44 (d, *J* = 8 Hz, 2H), 4.14 (s, 6H). ^{13}C NMR

(100 MHz, $CDCl_3$) δ: 181.0, 173.1, 164.3, 134.0, 118.7, 56.0. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{10}H_{10}N_4O_3Na$ 257.0645; Found 257.0648.

General Procedure for Suzuki Coupling of Ar-O-DMT Ethers with Arylboronic Acids. To a Schlenk tube were added in turn ether **3** (1.0 mmol), arylboronic acid **4** (4.0 mmol), $NiCl_2$(dppf) (0.05 mmol), and K_3PO_4 (7.0 mmol) in Ar_2. Toluene (7 mL) was injected by syringe. The mixture was stirred at a pre-heated oil bath (110 ^oC) for 24 h. The reaction mixture was cooled to room temperature and CH_2Cl_2 (25 mL) added. After filtration via a short pad of celite, the filtrate was condensed under vacuum and the residue was purified by flash column chromatography to provide the biaryl products.

*4-Methoxy-1,1'-biphenyl (**5a**) (CAS no. 613-37-6).* ^1H NMR (400 MHz, $CDCl_3$) δ: 7.56–7.52 (m, 4H), 7.42 (t, *J* = 8 Hz, 2H), 7.30 (t, *J* = 8 Hz, 1H), 6.98 (d, *J* = 8 Hz, 2H), 3.85 (s, 3H).

*4'-Methoxy-2-methyl-1,1'-biphenyl (**5b**) (CAS no. 92495-54-0).* ^1H NMR (400 MHz, $CDCl_3$) δ: 7.24–7.20 (m, 6H), 6.92 (d, *J* = 8 Hz, 2H), 3.80 (s, 3H), 2.26 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 158.6, 141.6, 135.5, 134.4, 130.4, 130.3, 130.0, 127.1, 125.8, 113.6, 55.3, 20.6.

*4-Methoxy-4'-methyl-1,1'-biphenyl (**5c**) (CAS no. 53040-92-9).* ^1H NMR (400 MHz, $CDCl_3$) δ: 7.42 (d, *J* = 8 Hz, 2H), 7.34 (d, *J* = 8 Hz, 2H), 7.14 (d, *J* = 8Hz, 2H), 6.88 (d, *J* = 8 Hz, 2H), 3.75 (s, 3H), 2.30 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 157.8, 136.9, 135.3, 132.6, 128.4, 126.9, 125.5, 113.1, 54.2, 20.0.

*1-(4'-Methoxyphenyl)naphthalene (**5d**) (CAS no. 27331-33-5).* ^1H NMR (400 MHz, $CDCl_3$) δ: 7.85–7.80 (m, 2H), 7.74 (d, *J* = 8 Hz, 1H), 7.44–7.39 (m, 2H), 7.36–7.31 (m, 4H), 6.94 (d, *J* = 8 Hz,

2H), 3.80 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 157.8, 138.8, 132.8, 132.0, 130.7, 130.0, 127.2, 126.2, 125.8, 125.0, 124.8, 124.6, 124.3, 112.6, 54.3.

*2-Methoxy-1,1'-biphenyl (**5e**) (CAS no. 86-26-0).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.53 (d, *J* = 8 Hz, 2H), 7.42–7.38 (m, 2H), 7.33–7.29 (m, 3H),7.04–6.97 (m, 2H)，3.80 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 156.4, 138.5, 130.9, 130.7, 129.5, 128.6, 128.0, 126.9, 120.8, 111.2, 55.5.

*4'-Methoxy-3-methyl-1,1'-biphenyl (**5f**) (CAS no. 17171-17-4).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.55 (d, *J* = 8 Hz, 2H), 7.4–7.34 (m, 3H), 7.15(d, *J* = 4 Hz, 1H), 7.00 (d, *J* = 8 Hz, 2H), 3.88 (s, 3H), 2.44 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 158.0, 139.7, 137.2, 132.8, 127.6, 127.1, 126.5, 126.3, 122.8, 113.1, 54.3, 20.5.

*2-(4'-Methoxyphenyl)naphthalene (**5g**) (CAS no. 59115-45-6).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.99 (s, 1H), 7.91–7.84 (m, 3H), 7.73–7.65 (m, 3H), 7.50–7.46 (m, 2H), 7.03 (d, *J* = 12 Hz, 2H), 3.88 (s, 3H).

*4'-Methoxy-3,5-dimethyl-1,1'-biphenyl (**5h**) (CAS no. 473774-78-6).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.51 (d, *J* = 12 Hz, 2H), 7.16 (s, 2H), 6.96–6.94 (m, 3H), 3.83 (s, 3H), 2.36 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 159.0, 140.8, 138.2, 134.0, 128.3, 128.2, 124.7, 114.1, 55.3, 21.4.

*4-(tert-Butyl)-4'-methoxy-1,1'-biphenyl (**5i**) (CAS no. 19812-91-0).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.52–7.42 (m, 6H), 6.95 (d, *J* = 12 Hz, 2H), 3.81 (s, 3H), 1.35 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 159.0, 149.6, 138.0, 133.7, 128.0, 126.4, 125.7, 114.2, 55.3, 34.54, 31.4.

*N-([1,1'-Biphenyl]-3-yl)acetamide (**5j**) (CAS no. 2113-54-4).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.72 (s, 1H), 7.57 (d, *J* = 8 Hz, 2H), 7.50 (d, *J* = 8Hz, 1H), 7.4–7.32 (m, 6H), 2.19 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 168.4, 144.7, 142.1, 138.3, 129.4, 128.7, 127.5, 127.2, 123.1, 118.8, 118.6, 24.7.

*Methyl [1,1'-biphenyl]-4-carboxylate (**5k**) (CAS no. 720-75-2).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.11(d,

J = 8 Hz, 2H), 7.68–7.62 (m, 4H), 7.47 (dd, *J* = 8.4 Hz, 2H), 7.41 (d, *J* = 4 Hz, 1H), 3.94 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 167.0, 145.6, 140.0, 130.1, 128.9, 128.9, 128.1, 127.3, 127.0, 52.1.

*[1,1'-Biphenyl]-4-carbonitrile (**5l**) (CAS no. 2920-38-9).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.69 (dd, *J* = 12 Hz, 4H), 7.58(d, *J* = 12 Hz, 2H), 7.5–7.42 (m, 3H). ^{13}C NMR (100MHz, $CDCl_3$) δ: 145.6, 139.1, 132.6, 129.1, 128.6, 127.7, 127.2, 118.9, 110.9.

*4-Fluoro-4'-methoxy-1,1'-biphenyl (**5m**) (CAS no. 450-39-5).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.5–7.45 (m, 4H), 7.09 (t, *J* = 8 Hz, 2H), 6.97 (d, *J* = 12 Hz, 2H), 3.84 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 163.3, 160.9, 159.1, 137.0, 132.8, 128.2, 128.1, 128.0, 127.7, 115.6, 115.4, 114.2, 55.3.

*[1,1'-Biphenyl]-4-carbaldehyde (**5n**) (CAS no. 3218-36-8).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 10.04 (s, 1H), 7.94 (d, *J* = 8 Hz, 2H), 7.74 (d, *J* = 8 Hz, 2H), 7.62 (d, *J* = 4 Hz, 2H)，7.47 (t, *J* = 8 Hz, 2H), 7.41 (t, *J* = 8 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 190.8, 146.1, 138.6, 134.1, 129.2, 127.9, 127.4, 126.6, 126.3.

*1-([1,1'-Biphenyl]-4-yl)ethanone (**5o**) (CAS no. 92-91-1).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.04 (d, *J* = 12 Hz, 2H), 7.68 (d, *J* = 12 Hz, 2H), 7.63 (d, *J* = 4 Hz, 2H), 7.47 (t, *J* = 8 Hz, 2H), 7.40 (t, J = 8 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 197.6, 145.8, 139.9, 135.8, 128.9, 128.9, 128.2, 127.2, 127.2, 26.67.

*4'-Methoxy-3-(trifluoromethyl)-1,1'-biphenyl (**5p**) (CAS no. 194873-98-8).* ^{1}H NMR (400 MHz, CDCl3) δ: 7.79 (s, 1H), 7.72 (d, *J* = 8 Hz, 1H), 7.55–7.52 (m, 4H), 6.99 (d, *J* = 12 Hz, 2H), 3.86 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 159.7, 141.6, 132.2, 131.2, 130.9, 129.9, 129.1, 128.2, 123.5, 123.4, 123.4, 123.3, 123.2, 123.2, 114.4, 55.3.

*2-Methoxy-[1,1'-biphenyl]-4-carbaldehyde (**5q**) (CAS no. 248263-04-9).* ^{1}H NMR (400 MHz, $CDCl_3$)

δ: 10.05 (s, 1H), 7.60–7.29 (m, 8H), 3.93 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 191.8, 156.9, 137.2, 136.8, 136.8, 131.3, 129.4, 128.1, 127.9, 124.4, 109.6, 55.7.

*3-Phenylpyridine (**5s**) (CAS no. 1008-88-4).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.85 (s, 1H), 8.59 (d, *J* = 4 Hz, 1H), 7.87 (d, *J* = 8 Hz, 1H), 7.59 (d, *J* = 12 Hz, 2H), 7.51–7.46 (m, 2H), 7.43–7.34 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 149.2, 149.0, 138.5, 137.3, 135.0, 129.8, 128.8, 127.8, 124.2.

*4-Methyl-7-phenyl-2H-chromen-2-one (**5t**).* M.p. 99–101 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.7–7.65 (m, 3H), 7.58–7.56 (m, 2H), 7.52 (t, *J* = 8.8 Hz, 2H), 7.45 (t, *J* = 8.8 Hz, 1H), 6.32 (s, 1H), 2.5 (s, 3H). ^{13}C NMR (100MHz, $CDCl_3$) δ: 160.9, 153.9, 152.2, 144.9, 139.1, 129.1, 128.5, 127.2, 124.9, 123.0, 118.9, 115.1, 114.8, 18.6. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{16}H_{12}O_2Na$ 259.0730; Found 259.0735.

*3,3-Di([1,1'-biphenyl]-4-yl)isobenzofuran-1(3H)-one (**5u**).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.91 (d, *J* = 8 Hz, 1H), 7.67 (t, *J* = 4.8 Hz, 1H), 7.59 (d, *J* = 8 Hz, 1H), 7.54–7.49 (m, 9H), 7.37–7.28 (m, 10). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 168.7, 150.9, 140.5, 139.2, 138.7, 133.2, 128.4, 127.8, 126.6, 126.5, 126.2, 126.1, 125.1, 124.6, 123.1, 90.4. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{32}H_{22}O_2Na$ 461.1512; Found 461.1518.

*(8R,9S,13S,14S)-13-Methyl-3-phenyl-7,8,9,11,12,13,15,16-octahydro-6H-cyclopenta[a]phenanthren-17(14H)-one (**5v**).* M.p. 178–180 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.58 (d, J = 8 Hz, 2H), 7.44–7.32 (m, 6H), 2.99 (dd, *J* = 4.8 Hz, 2H), 2.55–2.44 (m, 2H), 2.38–2.32 (m, 1H), 2.19–1.97 (m, 4H), 1.69–1.45 (m, 6H), 0.92 (s,3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 220.9, 141.0, 138.9, 138.8, 136.9, 128.7, 127.7, 127.1, 127.0, 125.8, 124.6, 50.5, 48.0, 44.4, 38.2, 35.9, 31.6, 29.5, 26.5, 25.7, 21.6, 13.9. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{24}H_{26}ONa$ 353.1876; Found 353.1874.

*3'-(Trifluoromethyl)-[1,1'-biphenyl]-4-carbaldehyde (**5a'**).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 10.09 (s, 1H), 8.00 (d, *J* = 8 Hz, 2H), 7.88 (s, 1H), 7.82 (d, *J* = 8 Hz, 1H), 7.77 (d, *J* = 8 Hz, 2H), 6.68 (d, *J* = 8 Hz, 1H), 7.63 (m, 1H).^{13}C NMR (100 MHz, $CDCl_3$) δ: 191.7, 145.5, 140.5, 135.7, 130.8, 130.6, 130.4, 129.5, 127.8, 125.3, 125.1, 125.1, 125.0, 125.0, 124.2, 124.2, 124.1, 124.1. MS m/z: 250(M^+). Anal. Calcd for $C_{14}H_9F_3O$: C, 67.20; H, 3.63. Found: C 67.28, H, 3.61.

*1-(3'-(Trifluoromethyl)-[1,1'-biphenyl]-4-yl)ethanone (**5b'**) (CAS no. 709667-96-9).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.07 (d, *J* = 8 Hz, 2H), 7.87 (s, 1H), 7.80 (d, *J* = 8 Hz, 2H), 7.70–7.65 (m, 3H), 7.61–7.57 (s, 1H), 2.66 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 197.5, 144.1, 140.6, 136.4, 131.5, 130.5, 129.4, 129.0, 127.3, 124.8, 124.8, 124.0, 123.9, 122.7, 26.6.

*Ethyl 4'-acetyl-[1,1'-biphenyl]-4-carboxylate (**5c'**) (CAS no. 119838-61-8).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.14 (d, *J* = 8 Hz, 2H), 8.06 (d, *J* = 8 Hz, 2H), 7.73–7.68 (m, 4H), 4.41 (q, *J* = 8 Hz, 2H), 2.66 (s, 3H), 1.43 (t, *J* = 8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 197.6, 166.3, 144.5, 144.1, 136.4, 130.2, 130.1, 129.0, 127.4, 127.2, 61.1, 26.7, 14.3.

*Ethyl 3'-acetamido-[1,1'-biphenyl]-4-carboxylate (**5d'**).* M.p. 117–119 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.09 (d, J = 8 Hz, 2H), 7.80 (s, 1H), 7.63 (d, *J* = 8 Hz, 2H), 7.53 (d, *J* = 8 Hz, 1H), 7.48–7.35 (m, 3H), 4.40 (q, *J* = 8 Hz, 2H), 2.21 (s, 3H), 1.41 (t, *J* = 8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 168.4, 166.5, 145.0, 140.9, 138.5, 130.0, 129.5, 129.4, 127.0, 123.2, 119.5, 118.7, 61.0, 24.7, 14.3. HRMS (ESI-TOF) m/z: $[M–H]^-$ Calcd. for $C_{17}H_{16}NO_3$ 282.1134; Found 282.1137.

*Ethyl 4'-cyano-[1,1'-biphenyl]-4-carboxylate (**5e'**) (CAS no. 89409-89-2).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.15 (d, *J* = 8 Hz, 2H), 7.76 (d, *J* = 8 Hz, 2H), 7.72 (d, *J* = 8 Hz, 2H), 7.66 (d, *J* = 8 Hz, 2H), 4.42 (q, *J* = 8 Hz, 2H), 1.42 (t, *J* = 8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 166.1, 144.4, 143.2, 132.7,

130.5, 130.3, 127.9, 127.1, 118.6, 111.7, 61.2, 14.3.

*4-Fluoro-4'-methyl-1,1'-biphenyl (**5f'**) (CAS no. 72093-43-7).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.53–7.50 (m, 2H), 7.43 (d, *J* = 8 Hz, 2H), 7.23 (d, *J* = 8 Hz, 2H), 7.10 (t, *J* = 8 Hz, 2H), 2.38 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 163.5, 161.1, 137.4, 137.3, 137.2, 137.0, 129.5, 128.5, 128.4, 126.8, 115.6, 115.4, 21.0.

*4'-Fluoro-[1,1'-biphenyl]-4-carbaldehyde (**5g'**) (CAS no. 60992-98-5).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 10.06 (s, 1H), 7.95 (d, *J* = 12 Hz, 2H), 7.72 (d, *J* = 12 Hz, 2H), 7.63–7.59 (m, 2H), 7.20–7.15 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 191.8, 164.3, 157.8, 146.1, 135.8, 135.1, 130.3, 129.1, 129.0, 127.5, 116.1, 115.9.

*Methyl 4'-fluoro-[1,1'-biphenyl]-4-carboxylate (**5h'**) (CAS no. 80254-87-1).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.10 (d, *J* = 12 Hz, 2H), 7.63–7.57 (m, 4H), 7.18–7.13 (m, 2H), 3.94 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 166.9, 164.1, 161.7, 144.6, 136.1, 136.1, 130.1, 128.9, 128.9, 126.9, 116.0, 115.7, 52.1.

*1-(4'-Fluoro-[1,1'-biphenyl]-4-yl)ethanone (**5i'**) (CAS no. 720-74-1).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.03 (d, *J* = 12 Hz, 2H), 7.65–7.57 (m, 4H), 7.16 (t, *J* = 12 Hz, 2H), 2.64 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 197.7, 164.2, 161.7, 144.7, 136.0, 135.9, 135.8, 128.9, 128.9, 127.0, 116.0, 115.8, 26.69.

*(8R,9S,13S,14S)-3-(4-Fluorophenyl)-13-methyl-7,8,9,11,12,13,15,16-octahydro-6H-cyclopenta[a]phenanthren-17(14H)-one (**5j'**).* M.p. 181–183 ^{o}C, ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.54–7.50 (m, 2H), 7.37–7.32 (m, 2H), 7.28 (s, 1H), 7.13–7.07 (m, 2H), 2.99 (dd, *J* = 4.4 Hz, 2H), 2.55–2.44 (m, 2H), 2.38–2.31 (m, 1H), 2.20–1.96 (m, 4H), 1.69–1.45 (m, 6H), 0.92 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 220.8, 163.5, 161.1, 138.9, 137.8, 137.1, 137.0, 128.5, 128.4, 127.6, 125.9, 124.4, 115.6, 115.4,

50.5, 48.0, 44.3, 38.2, 35.8, 31.6, 29.5, 26.5, 25.7, 21.6, 13.8. HRMS (ESI-TOF) m/z: $[M+Na]^+$ Calcd. for $C_{24}H_{25}FONa$ 371.1782; Found 371.1784.

*3-(p-Tolyl)thiophene (**5k'**) (CAS no. 16939-05-2).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 7.50 (d, *J* = 12 Hz, 2H), 7.40–7.34 (m, 3H), 7.21 (d, *J* = 12 Hz, 2H), 2.37 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 142.3, 136.8, 133.0, 129.4, 126.3, 126.3, 126.0, 119.6, 21.1.

*1-(4-(Thiophen-3-yl)phenyl)ethanone (**5l'**) (CAS no. 172035-84-6).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.00 (d, *J* = 12 Hz, 2H), 7.69 (d, *J* = 12 Hz, 2H), 7.59–7.58 (m, 1H), 7.44–7.43 (m, 3H), 2.62 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 197.5, 141.1, 140.2, 135.6, 129.0, 126.7, 126.3, 126.1, 122.0, 26.6.

*Methyl 4'''-chloro-[1,1':4',1'':4'',1'''-quaterphenyl]-4-carboxylate (**5m'**).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.12 (d, *J* = 8 Hz, 2H), 7.71–7.63 (m, 8H), 7.56 (m, 3H), 7.43 (m, 3H), 3.95 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 165.9, 143.9, 138.7, 138.1, 137.8, 132.6, 129.1, 128.0, 127.8, 127.3, 127.2, 126.7, 126.6, 126.4, 126.3, 126.0, 125.8, 51.1. ESI-MS $[M–Cl]^+$: 362.5. Anal. Calcd for $C_{26}H_{19}ClO_2$: C, 78.29; H, 4.80. Found: C 78.20, H, 4.79.

*2,4-Dimethoxy-6-phenyl-1,3,5-triazine (**6a**) (CAS no. 18213-73-5).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.52 (d, *J* = 8 Hz, 2H), 7.59 (t, *J* = 8 Hz, 1H), 7.50 (t, *J* = 8.8 Hz, 2H), 4.15 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 174.9, 172.9, 135.0, 132.8, 129.0, 128.4, 55.2.

*2,4-Dimethoxy-6-(p-tolyl)-1,3,5-triazine (**6b**) (CAS no. 42010-75-3).* ^{1}H NMR (400 MHz, $CDCl_3$) δ: 8.39 (d, *J* = 8 Hz, 2H), 7.27 (d, *J* = 8 Hz, 2H), 4.12 (s, 6H), 2.43 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$) δ: 174.9, 172.8, 143.5, 132.3, 129.2, 129.0, 55.1, 21.6.

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Supporting Information

^{1}H and ^{13}C NMR spectra copies of compounds **3a–y**, **5a–q, 5s–v, 5a′–m′**, **6a** and **6b**; crystallographic data of compounds **3a** and **3y**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(31) See Supporting Information for crystallographic data of compounds **3a** and **3y**.

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(39) Other heteroaryl boronic acids, such as 2-furylboronic acid, 3- and 4-pyridinylboronic acids, 5-pyrimidinylboronic acid, etc., were also examined under the present catalytic system. All of them afforded the responding biaryl in poor yields.