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2-(1-Benzotriazolyl)pyridine: A Robust Bidentate Ligand for the Palladium-Catalyzed C–C (Suzuki, Heck, Fujiwara–Moritani, Sonogashira), C–N and C–S Coupling Reactions

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Abstract: A new class of bidentate ligand, 1-(pyridine-2-yl)-1*H*-benzo[*d*][1,2,3]triazole has been designed and employed for the palladium-catalyzed C–C (Suzuki, Heck, Fujiwara–Moritani, and Sonogashira), C–N and C–S coupling reactions. The ligand was found to be inexpensive, thermally stable, easy to synthesize from easily accessible starting materials on a multigram scale, show simplicity in use, and robustness in application, making this ligand effective for different coupling reactions. Suitably, the donor ability of the N=N bond of the benzotriazole ring and lone pair of electrons on the N of the pyridine ring enhance the bidentate ability of the ligand.

Keywords: benzotriazoles; Fujiwara–Moritani reaction; Heck reaction; N-arylation; S-arylation; Sonogashira coupling; Suzuki coupling

Introduction

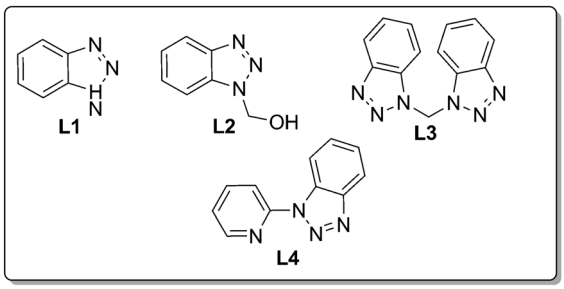
Transition metal-catalyzed carbon-carbon, carbon-nitrogen, and carbon-sulfur bond formating reactions are among the most important processes in chemistry, because they provide key steps in the construction of various organic substrates, complex bioactive molecules, agrochemicals, natural products and pharmaceutically viable molecules.[1] In 2010, the Nobel Prize in Chemistry awarded to Heck, Negishi, and Suzuki for their work on cross-coupling reactions emphasized the importance of palladium in organic synthesis.[2] Among all the metals, palladium has emerged as a powerful tool[3] and allows a wide range of chemically distinct partners to sustain synthetic transformations like C–H functionalization, alkylation, alkynylation, alkenylation, benzylation and a variety of arylation reactions efficiently.[4]

Up to the 1990s, triphenylphosphine was used as a ligand[5] in most of the palladium-catalyzed reactions, and thereafter wide varieties of ligands have been designed to carry out these reactions efficiently under mild reaction conditions.[6] In spite of the tremendous utility of these ligands in palladium-catalyzed organic synthesis, they suffered from several drawbacks, e.g., various phosphine ligands are expensive, air sensitive,[7] and prone to degrade at high temperatures. Many other phosphine-free palladium complexes like N-heterocyclic carbenes,[8–11] carbocyclic carbenes,[12] imines,[13] ureas,[14] thioureas[15] and selenides[16] have emerged as an alternative for these coupling reactions. To the best of our knowledge, the so far known ligands reported in the literatureare limited for a few coupling reactions. Thus, the development of an inexpensive, broadly applicable and robust catalytic system to generate a variety of C(aryl)–C, C(aryl)–N and C(aryl)–S bonds is paramount and challenging.

The mild reaction conditions of these coupling reactions offer significant advantages over traditional methods, which require either activated molecules or harsh reaction conditions. Recently, significant developments in the Suzuki coupling reaction[17] and N-arylation of aryl halides, have been reported by Buchwald[18] and Hartwig.[19] The stereoelectronic effects and the bite angle[20] of the N,N bidentate ligands are significant factors for the coupling reactions. Designed benzotriazole-based ligands are easy to prepare and are thermally and air stable. Suitably, the donor ability of the N=N bond of the benzotriazole ring and

lone pair of electrons on the N of the pyridine ring enhance the bidentate ability of the ligand.

Katritzky's group has extensively explored benzotriazole as a synthetic auxiliary due to its incredible properties.[21] The designed ligand **L4** was suppose to provide a compelling variation to the theme of NN bidentate ligand,[22] since benzotriazole and pyridine can provide electrons for the formation of a complex with metals. Benzotriazole possesses, both electron-donor as well as electron-acceptor properties with respect to the group attached to it.[21] In view of the above facts, and our recent success on the coupling reactions using benzotriazole as a ligand[23,24] we were motivated for the design of a more efficient and practical ligand for the palladium-catalyzed coupling reactions (Scheme 1). Herein for the first time, we are reporting 1-(pyridine-2-yl)-1*H*-benzo[*d*][1,2,3]triazole (**L4**)[25] as a robust, phosphine-free, inexpensive and air stable bidentate ligand for the palladium-catalyzed Suzuki, Heck, Fujiwara–Moritani, Sonogashira, Buchwald–Hartwig (C–N), and C–S coupling reactions (Scheme 2). The designed ligand **L4** could be synthesized on a multigram scale by the reaction of inexpensive and readily available benzotriazole and 2-bromopyridine under copper catalysis in 96% yield.[21,23,24b] It is essential to note that the ligand is air stable and thermally stable up to 274.7 °C.[36,25]

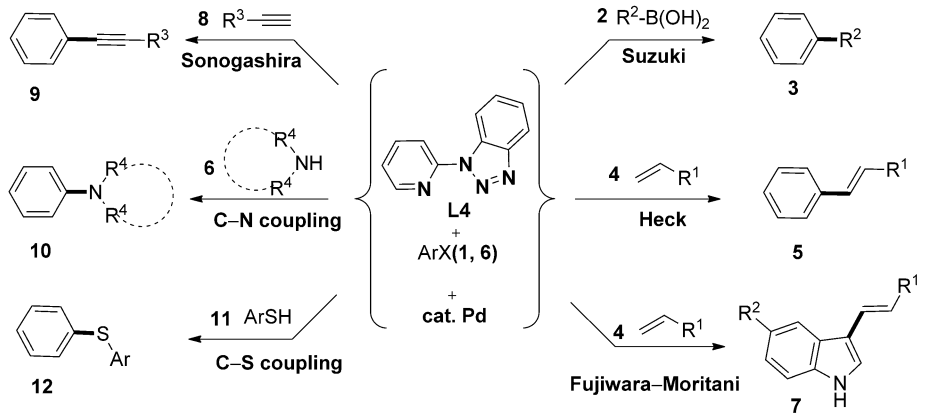


Scheme 1. Ligands **L1**–**L4**, designed for various palladium-catalyzed coupling reactions.

Results and Discussion

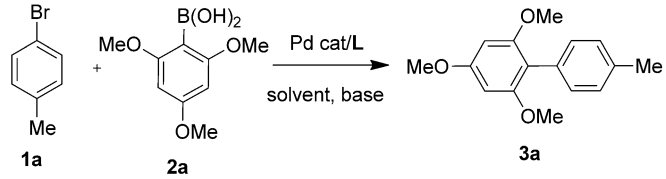
The Suzuki coupling reaction represents one of the most synthetically valuable methods for the synthesis of biaryl derivatives.[17] This reaction has been successfully applied for the synthesis of complex and biologically important natural and synthetic compounds.[26] A search of the literature revealed that the coupling of hindered substrates has been less studied and needs to be explored.[27] Thus, we initiated our study with the sterically hindered 2,4,6-trimethoxyphenylboronic acid (**2a**). To identify the optimal reaction conditions for the reaction, we examined the reaction of 4-bromotoluene (**1a**) with boronic acid **2a**, using 3 mol% of $Pd(OAc)_2$, 6 mol% of ligand **L1** and 2.0 equiv. of K_2CO_3 in 2.0 mL of DMF/H_2O (4:1) at 25 °C. Using above reaction conditions, product **3a** was obtained in only 8% yield (Table 1, entry 1). Increasing the catalyst loading from 3 to 5 mol% and ligand **L1** from 5 to 10 mol% afoorded the desired coupling product **3a** in 42% yield (entry 2). The yield of the product remained the same after 12 h (entry 3). Reaction with ligands **L2** and **L3** provided the coupling product **3a** in 50 and 58% yields, respectively, after 12 h (entries 4 and 5). Fortunately, when ligand **L4** was used, it afforded the desired coupling product **3a** in 93% yield (entry 6). With a selective ligand in hand, other parameters like time, base and solvent were investigated.

The progress of the reaction was monitored at different time intervals at room temperature. After 1 h, coupling product **3a** was obtained in 75% yield (entry 7), and similarly we observed that the reaction was completed after 2 h (entry 8). Decreasing the catalyst loading from 5 to 2 mol% and then to 1 mol%, did not affect the yield of the coupling product **3a** (entries 9 and 10). However, further decreasing the catalyst loading from 1 mol% to 0.8 and then 0.5 mol%, afforded the coupling product in 63 and 52% yields, respectively (entries 11 and 12). Decreas-



Scheme 2. The applications of ligand **L4** in various coupling reactions.

Table 1. Optimization of the reaction conditions for the Suzuki coupling.[a]



Entry	Pd. cat. (mol%)	L [mol%]	Time [h]	Yield [%][b]
1	$Pd(OAc)_2$ (3)	**L1** (6)	02	8
2	$Pd(OAc)_2$ (5)	**L1** (10)	02	42
3	$Pd(OAc)_2$ (5)	**L1** (10)	12	42
4	$Pd(OAc)_2$ (5)	**L2** (5)	12	50
5	$Pd(OAc)_2$ (5)	**L3** (5)	12	58
6	$Pd(OAc)_2$ (5)	**L4** (5)	12	93
7	$Pd(OAc)_2$ (5)	**L4** (5)	01	75
8	$Pd(OAc)_2$ (5)	**L4** (5)	02	93
9	$Pd(OAc)_2$ (2)	**L4** (2)	02	93
10	**$Pd(OAc)_2$ (1)**	**L4 (1)**	02	**93**
11	$Pd(OAc)_2$ (0.8)	**L4** (0.8)	02	63
12	$Pd(OAc)_2$ (0.5)	**L4** (0.5)	02	52
13	$Pd(OAc)_2$ (1)	**L4** (1)	02	70[c]
14	$Pd(OAc)_2$ (1)	**L4** (1)	02	78[d]
15	$Pd(OAc)_2$ (1)	**L4** (1)	02	80[e]
16	$Pd(OAc)_2$ (1)	**L4** (1)	02	79[f (j)]
17	$Pd(OAc)_2$ (1)	**L4** (1)	02	73 [g]
18	$Pd(OAc)_2$ (1)	**L4** (1)	02	78 [h]
19	$Pd_2(dba)_3$ (1)	**L4** (1)	02	85
20	$PdCl_2$ (1)	**L4** (1)	02	60
21	$Pd(OAc)_2$ (1)	**L4** (2)	02	93
22	$Pd(OAc)_2$ (1)	–	06	05

[a] Unless otherwise specified, all reactions were performed with **1a** (1.0 mmol), **2a** (1.2 equiv.), and base K_2CO_3 (2.0 equiv.) in solvent (2.0 mL).
[b] Isolated yields.
[c] Using 1.5 equiv. K_2CO_3.
[d] Using 2.0 equiv. Na_2CO_3.
[e] Using 2.0 equiv. Cs_2CO_3.
[f] Using toluene:H_2O (9:1).
[g] Using DME:H_2O (4:1).
[h] Using DMSO: H_2O (9:1).

ing the amount of base from 2.0 to 1.5 equiv. afforded the product **3a** in lower yield (entry 13). Other bases like Na_2CO_3 and Cs_2CO_3 were found to be inferior for the reaction (entries 14 and 15). Amongst the different solvent systems, DMF/H_2O (4:1) was found to be most efficient (entries 10, 16–18). Other palladium sources like $PdCl_2$, $Pd_2(dba)_3$ were found to be less effective (entries 19 and 20). On changing the catalyst system by increasing the ligand from 1 mol% to 2 mol%, the yield of the product remained the same (entry 21). In the control experiment, a trace amount of coupling product was obtained in the absence of ligand (entry 22).

Under the optimized conditions (Table 1, entry 10), we examined the scope and generality of the reaction by utilizing variety of aryl halides **1a–h** and boronic acids **2a–k** (Table 2). The reaction tolerates various functional groups attached at different positions of the boronic acids **2a–k** that could be useful for later modifications (Table 2, entries 1–14). The reaction of 5-bromoindole **1b** with boronic acids **2b** and **2c** afforded the coupling products **3b** and **3c** in 71 and 73% yields, respectively (entries 2 and 3). Reactions with a less hindered substituent on the boronic acid afforded the coupling products **3d–f** in higher yields (entries 4–6). Coupling of aryl halide **1c** with 4-vinylphenylboronic acid (**2f**), afforded the product **3g** chemoselectively in 92% yield, no Heck coupling product was observed in this reaction (entry 7). Reaction of 1,4-dibromo-2,5-diiodobenzene (**1d**) with *p*-tolylboronic acid (**2g**) provided the coupling products **3h** selectively in 83% yield (entry 8). It was observed that the reaction of hindered 1,2,3,4-tetrabromothiophene (**1e**) with 4.5 equiv. of **2h** furnished the tetrasubstituted coupling product **3i** in 80% yield (entry 9). The reaction conditions were also found to be compatible with sterically hindered heteroarenes with the core nucleus present either in many alkaloids or having a wide range of biological activities.[28] The 4-iodopyrano[4,3-*b*]quinoline (**1f**) and 4-(4-bromophenyl)pyrrolo[1,2-*a*]quinoxaline (**1g**) on reaction with boronic acids **2i**, **2h** and **2j** provided the corresponding coupling products **3j–l** in 79, 83 and 88% yields, respectively (entries 10–12). Fortunately we were pleased to see that one of the most influential phase-II anticancer drugs, 9-bromonoscapine[29] **1h**, on coupling with boronic acids **2k** and **2g** afforded the products **3m** and **3n** in 65 and 72% yields, respectively (entries 13 and 14).

The Heck reaction is another synthetically valuable C–C bond forming reaction used for the synthesis of a wide variety of natural products and biologically active compounds.[30] With the success of designed ligand **L4** in a wide variety of Suzuki coupling reaction, we next optimized suitable conditions for the Heck reaction.[25]

The coupling of 1.0 mmol of 4-bromoanisole (**1i**) with 1.5 equiv. of *n*-butyl acrylate (**4a**), by using 3 mol% $Pd(OAc)_2$, 3 mol% ligand **L4**, and 2.0 equiv. of K_2CO_3 in 2.0 mL of DMF at 120 °C for 10 h, afforded the desired product **5a** in 94% yield (Table 3, entry 1). To establish the scope of the ligand, various olefins and substituted aryl halides were used. Reactions of acrylates **4a**, **4c**, **4d**, acrylonitrile **4f**, styrene **4b** and alkenes **4e**, **4g** with a variety of aryl halides afforded the corresponding coupling products **5a–j** in good to excellent yields (entries 1–10). Aryl halide **1j** provided the coupling product **5b** in 90% yield (entry 2). The *ortho*-substituted aryl halide **1k** provided the desired product **5c** in 82% yield (entry 3). The reaction conditions were also found to be compatible with base sensitive, 4-iodopyrano[4,3-*b*]quinoline **1l**,

Table 2. Suzuki-coupling of aryl/heteroaryl halides with boronic acids using ligand **L4**.[a]

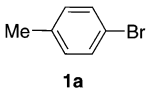
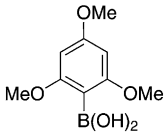
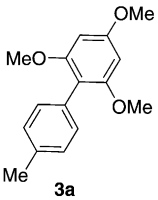
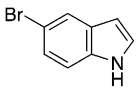
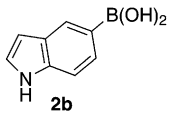
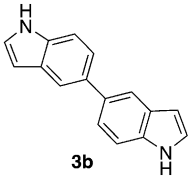
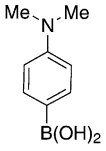
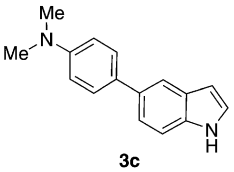
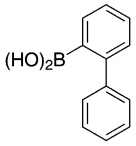
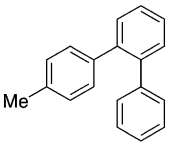
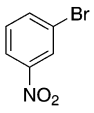
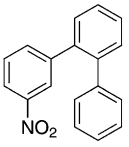
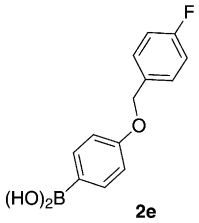
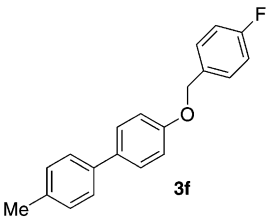
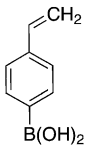
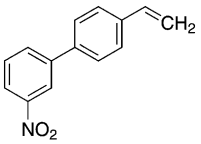
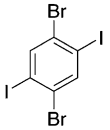
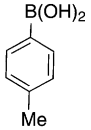
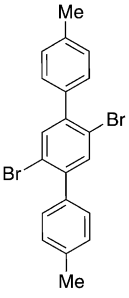
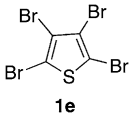
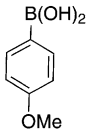
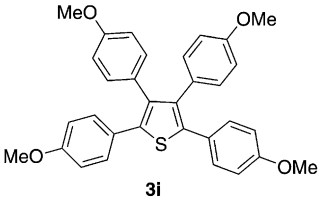
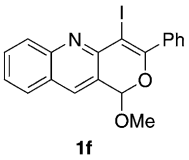
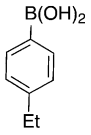
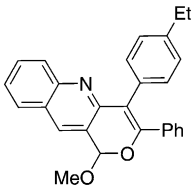
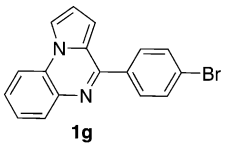
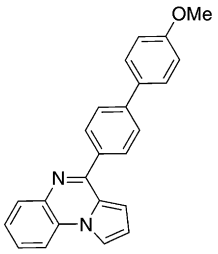
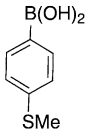
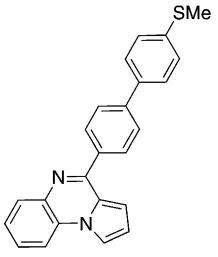
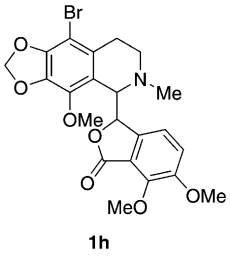
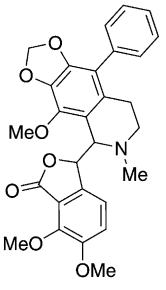
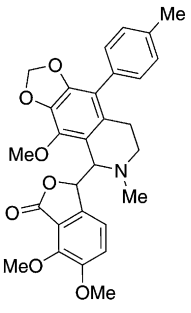
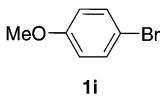
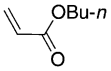
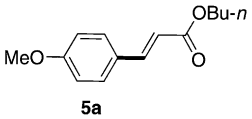
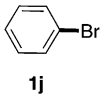
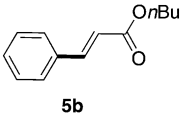
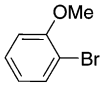
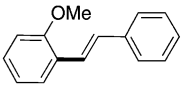
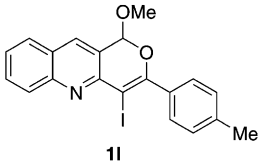
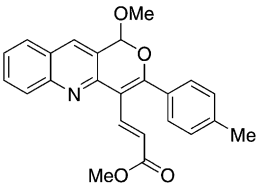
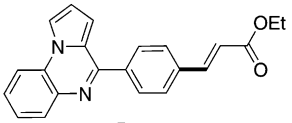
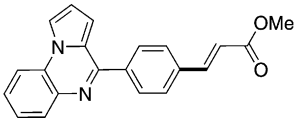
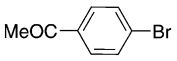
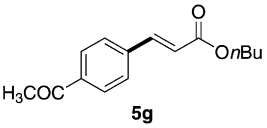
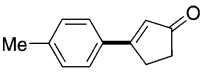
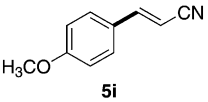
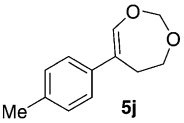
Entry	ArX	Boronic acid	Product	Yield [%][b]
1	 **1a**	 **2a**	 **3a**	93/83[c]
2	 **1b**	 **2b**	 **3b**	71[d]
3	**1b**	 **2c**	 **3c**	73[d]
4	**1a**	 **2d**	 **3d**	89
5	 **1c**	**2d**	 **3e**	91/86[c]
6	**1a**	 **2e**	 **3f**	90
7	**1c**	 **2f**	 **3g**	92
8	 **1d**	 **2g**	 **3h**	83[e]

Table 2. (Continued)

Entry	ArX	Boronic acid	Product	Yield [%][b]
9	 **1e**	 **2h**	 **3i**	80[e]
10	 **1f**	 **2i**	 **3j**	79[d]
11	 **1g**	**2h**	 **3k**	83[d]
12	**1g**	 **2j**	 **3l**	88[d]
13	 **1h**	 **2k**	 **3m**	65[f]
14	**1h**	**2g**	 **3n**	72[f]

[a] Unless otherwise specified, all reactions were performed with aryl halide **1** (1.0 mmol), boronic acids **2** (1.2 equiv.), $Pd(OAc)_2$ (1.0 mol%), **L4** (1 mol%), and K_2CO_3 (2.0 equiv.) in DMF/H_2O at 25 °C for 2–4 h.
[b] Isolated yields.
[c] Using 5 mol% of $Pd(OAc)_2$, 10 mol% of **L1**, and 2 equiv. K_2CO_3 in DMF/water (4:1) at 80 °C for 2 h.
[d] At 25 °C for 6 h.
[e] Using 2.2 equiv. of **2g** and 4.5 equiv. of **2h** for 6 h.
[f] Using 5 mol% of $Pd(OAc)_2$, 5 mol% of **L4**, and 2 equiv. Cs_2CO_3 in DME/water (1:1) at 80 °C for 6 h.

Table 3. Heck reaction aryl/heteroaryl halides with alkenes/acrylates using ligand **L4**.[a]

Entry	ArX	Alkene	Product	Yield [%][b]
1	 **1i**	 **4a**	 **5a**	94
2	 **1j**	**4a**	 **5b**	90
3	 **1k**	 **4b**	 **5c**	82
4	 **1l**	 **4c**	 **5d**	77
5	**1g**	 **4d**	 **5e**	85[c]
6	**1g**	**4c**	 **5f**	84[c]
7	 **1m**	**4a**	 **5g**	91
8	**1a**	 **4e**	 **5h**	68[d]
9	**1i**	 **4f**	 **5i**	89
10	**1a**	 **4g**	 **5j**	76

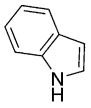
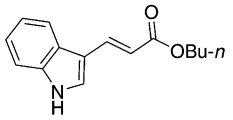
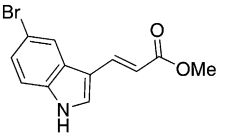
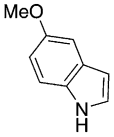
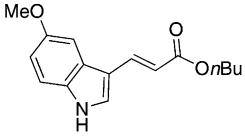
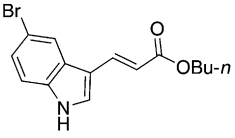
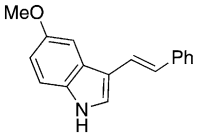
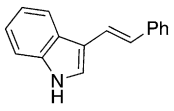
[a] Unless otherwise specified, all reactions were performed with aryl halide **1** (1.0 mmol), olefin **4** (1.5 equiv.), $Pd(OAc)_2$ (3.0 mol%), **L4** (3.0 mol%), K_2CO_3 (2.0 equiv.) in 3.0 mL of DMF at 120 °C for 8–10 h.
[b] Isolated yields.
[c] Using 5 mol% $Pd(OAc)_2$, 5 mol% ligand **L4**, and 2 equiv. of K_3PO_4.
[d] Using 3 equiv. of KF.

and furnished the coupling product **5d** in 77% yield (entry 4). Quinoxaline derivative **1g** on reaction with acrylates **4d** and **4c** using K_3PO_4 afforded the corresponding coupling product **5e** and **5f** in 85% and 84% yields, respectively (entries 5 and 6). Reaction of aryl halide **1m** bearing an electron-withdrawing keto group with acrylate **4a**, afforded the alkenylated product **5g** in 91% yield (entry 7). Coupling of **1a** with 2-cyclopenten-1-one (**4e**) was also found to be compatible, and afforded the desired product **5h** in 68% yield (entry 8). The reaction of **1i** with acrylonitrile (**4f)** afforded the desired product **5i** in 89% yield (entry 9). Interestingly, coupling of aryl halide **1a** with 4,5-dihydro-1,3-dioxepine (**4g**) provided the desired coupling product **5j** in 76% yield (entry 10).

The efficacy of ligand **L4** was further extended for the oxidative-Heck (Fujiwara–Moritani)[25,31] coupling reaction between indoles and alkenes. Reaction of substituted indoles (**6a**, **6b** and **1b**) with 1.5 equiv. of alkene **4a**, **4b**, **4c**, using 2 mol% $Pd(OAc)_2$, 2 mol% of ligand **L4**, and 2.0 equiv. $Cu(OAc)_2$ as oxidant in 2.0 mL of DMF:DMSO (4:1) at 120 °C for 12 h afforded the alkenylated products **7a–f** regioselectively at the 3-position of the indole in 70–80% yields (Table 4, entries 1–6). It is interesting to note that the reaction of 5-bromoindole (**1b**) with alkene **4c** afforded the Fujiwara–Moritani coupling product **7b** regioselectively at the 3-position of the indole in 70% yield, no Heck coupling product was observed at the 5-position of indole (entry 2).

During the last decade, the Sonogashira reaction has become one of the most widely used methods for the incorporation of an alkyne functionality into organic compounds.[32] A wide variety of natural products, pharmaceuticals, agriculture chemicals, organic materials was synthesized by using the Sonogashira coupling reaction. After attaining successful results in Suzuki, Heck and Fujiwara–Moritani coupling reactions, we next checked the efficacy and versatility of the ligand **L4** in the Sonogashira coupling reaction.[4b] The coupling of aryl bromide **1i** with alkyne **8a** was used as a test reaction. After exploring a wide range of conditions,[25] we found that coupling product **9a** was obtained in 90% yield using 2 mol% $Pd(OAc)_2$, 2 mol% **L4**, and 2 equiv. K_2CO_3 in 2 mL of DMF at 100 °C for 1 h without any homocoupling of the alkyne (Table 5, entry 1). Reactions proceeded well with *ortho*-substituted halide **1k** (entry 2). Alkyne **8c** bearing an electron-rich thiophene ring, proved favourable for the reaction (entries 3 and 4). 1,4-Dibromo-2,5-diiodobenzene **1d**, and 2,3,4,5-tetrabromothiophene **1e** afforded the coupling products **9e** and **9f** selectively in 73% and 80% yields (entries 5 and 6). Thiophene halide **1e**, on coupling with **8c**, afforded the tetra-alkynylated coupling product **9g** in 60% yields (entry 7). Compounds **9e**, **9f** and **9g** are useful synthetic intermediate and can be further used for metal-catalyzed tandem reactions[23a,b] and Bergman cyclizations.[33]

Table 4. Fujiwara–Moritani reaction of indoles with alkene/acrylates using ligand **L4**.[a]

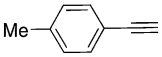
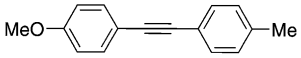
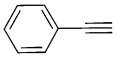
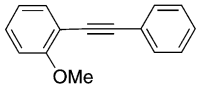
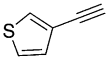
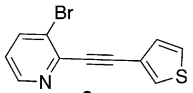
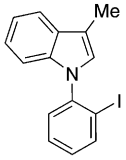
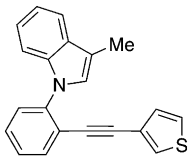
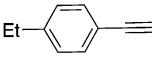
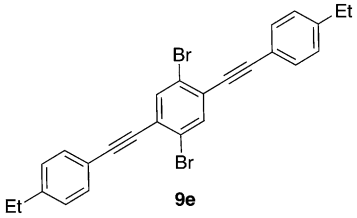
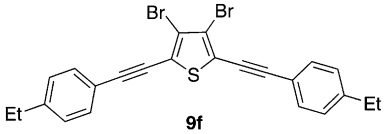
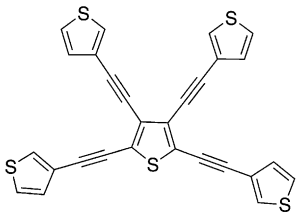
Entry	Indole	Alkene	Product	Yield [%][b]
1	 **6a**	**4a**	 **7a**	80
2	**1b**	**4c**	 **7b**	70
3	 **6b**	**4a**	 **7c**	76
4	**1b**	**4a**	 **7d**	72
5	**6b**	**4b**	 **7e**	77
6	**6a**	**4b**	 **7f**	75

[a] All the reactions were performed using an N-heterocycle **6** (1.0 mmol) and olefin **4** (1.5 equiv.), $Pd(OAc)_2$ (2 mol%), $Cu(OAc)_2$ (2 equiv.) and **L4** (2 mol%) in 2.0 mL of DMF:DMSO (4:1) at 120 °C for 12 h.

[b] Isolated yield.

The obtained successful results in various palladium-catalyzed C–C coupling reactions (Suzuki, Heck, Fujiwara–Moritani and Sonogashira), encouraged us to expand the applicability of the ligand **L4** for other important class of C–N[23c,d,34] and C–S[23e,34] coupling reactions. Coupling of N-heterocycle **6a** with aryl halides **1k** and **1n** under optimized reaction conditions[25] provided the desired cross-coupling products **10a** and **10b** in 78 and 67% yields, respectively (Table 6, entries 1 and 2). Electron-rich 3-methylindole (**6c**), 2-methylindole (**6d**) and pyrrole (**6e**) on reaction with halides **1a**, **1p** and **1i** afforded the *N*-arylated products **10c–f** in 73–77% yields (entries 3–6). Reaction of 4-

Table 5. Sonogashira coupling using ligand **L4**.[a]

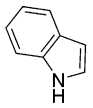
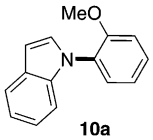
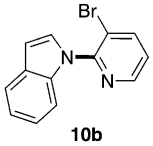
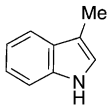
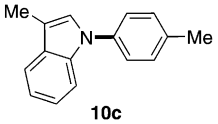
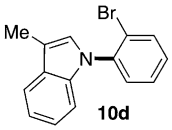
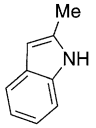
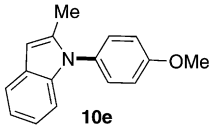
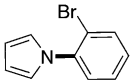
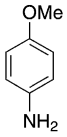
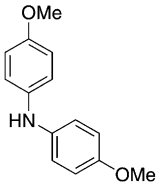
Entry	ArX	Alkyne	Product	Yield [%][b]
1	**1i**	 **8a**	 **9a**	90
2	**1k**	 **8b**	 **9b**	77
3	 **1n**	 **8c**	 **9c**	81
4	 **1o**	**8c**	 **9d**	75
5	**1d**	 **8d**	 **9e**	73[c]
6	**1e**	**8d**	 **9f**	80[c]
7	**1e**	**8c**	 **9g**	60[d]

[a] Unless otherwise specified, all reactions were carried out using aryl halide **1** (1.0 mmol), alkyne **8** (1.2 equiv.), $Pd(OAc)_2$ (2.0 mol%), **L4** (2.0 mol%), K_2CO_3 (2.0 equiv.) in DMF (2.0 mL) at 100 °C for 1–2 h.
[b] Isolated yield.
[c] Using alkyne (2 equiv.), K_2CO_3 (4 equiv.), $Pd(OAc)_2$ (2 mol%), and **L4** (2 mol%).
[d] Using **8c** (4 equiv.), K_2CO_3 (8 equiv.), $Pd(OAc)_2$ (5 mol%), and **L4** (5 mol%).

methoxyaniline (**6f**) afforded the coupling product in 53% yield using 10 mol% **L4** and 10 mol% $Pd(OAc)_2$ (entry 7).

We next investigated the application of ligand **L4** in the coupling of aryl thiols with aryl bromides. The coupling of aryl bromide **1i** with thiophenol **11a** was used as a test reaction. After screening a wide range of conditions,[25] we found that coupling product **12a** was obtained in 94% yield using 1 mol% $Pd(OAc)_2$, 1 mol% **L4**, 1.4 equiv. KO-*t*-Bu in 2.0 mL of DMSO at 100 °C for 12 h (Table 7, entry 1). Aryl halides **1q** and **1r** with an *ortho*-substituted electron-donating group afforded *S*-arylated product **12b** and **12c** in 93 and 92% yields, respectively (entries 2 and 3). Perbromothiophene **1e** provided the tetra-*S*-arylated and highly crowded product 2,3,4,5-[tetrakis(4-methoxyphenyl)thio]thiophene **12d** in 83% yield (entry 4). Aryl halide **1k** on reaction with 2-methylbenzenethiol (**11d**) afforded the product **12e** in 87% yield (entry 5). Coupling of octanethiol (**11e**) with electron-rich aryl halide **1i** provided the desired couple product **12f** in 67% yield (entry 6).

Table 6. N-Arylation of indoles, pyrrole and aniline with aryl halides using ligand **L4**.[a]

Entry	N-Heterocycle	ArX	Product	Yield [%][b]
1	 **6a**	**1k**	 **10a**	78
2	**6a**	**1n**	 **10b**	67
3	 **6c**	**1a**	 **10c**	77
4	**6c**	 **1p**	 **10d**	74
5	 **6d**	**1i**	 **10e**	73
6	 **6e**	**1p**	 **10f**	74
7	 **6f**	**1i**	 **10g**	53[c]

[a] All the reactions were performed with an N-heterocycle **6** (1.0 mmol), aryl or heteroaryl halide **1** (1.2 equiv.), $Pd(OAc)_2$ (5.0 mol%), **L4** (5.0 mol%), and KO-*t*-Bu (2.0 equiv.), in DMSO (2.0 mL) at 120 °C for 24 h.
[b] Isolated yields.
[c] Using $Pd(OAc)_2$ (10.0 mol%), **L4** (10.0 mol%).

Conclusions

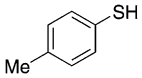
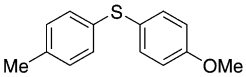
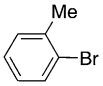
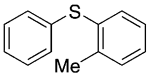
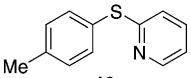
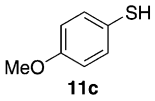
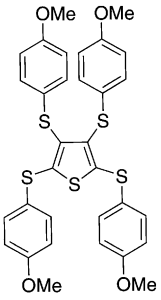
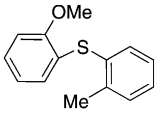
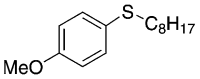
In conclusion, we have designed an affordable and robust N,N-type bidentate ligand 1-(pyridine-2-yl)-1*H*-benzo[*d*][1,2,3]triazole (**L4**) for the palladium-catalyzed coupling reactions. Developed ligand **L4** efficiently catalyzed the C–C (Suzuki, Heck, Fujiwara–Moritani, and Sonogashira), C–N and C–S coupling reaction. Noteworthy is the efficacy of ligand **L4** to tolerate a variety of functional groups attached to reactants as well as simplicity, low cost and ready accessibility of ligand on a multigram scale. This ligand is expected to find applications in organic synthesis in general and in the synthesis of a variety of heterocycles as well as in material science. Furthermore, studies on the practical applications of such cross-coupling reactions are in progress within the group.

Experimental Section

General Methods

All the reactions were performed in oven-dried Schlenks flask under an argon atmosphere. Column chromatography was performed using silica gel (100–200 mesh). Thin layer chromatography (TLC) was performed on silica gel GF254 plates. ^1H and ^{13}C NMR spectra were recorded at 300 and 75 MHz or 400 and 100 MHz, respectively. Thin-layer chro-

Table 7. S-Arylation of thiols with aryl halides using ligand **L4**.[a]

Entry	ArX	Thiol	Product	Yield [%][b]
1	**1i**	 **11a**	 **12a**	94
2	 **1q**	 **11b**	 **12b**	93
3	 **1r**	**11a**	 **12c**	92[c]
4	**1e**	 **11c**	 **12d**	83[d]
5	**1k**	 **11d**	 **12e**	87
6	**1i**	 **11e**	 **12f**	67

[a] Unless otherwise specified, all reactions were performed using arenethiol **11** (1.2 equiv.), aryl halide **1** (1.0 mmol), KO-*t*-Bu (1.4 equiv.), $Pd(OAc)_2$ (1.0 mol%) and **L4** (1.0 mol%) in DMSO (1.0 mL) at 100 °C for 8–12 h.
[b] Isolated yields.[c] At 80 °C.
[d] Using thiol **11c** (4.0 equiv.), KO-*t*-Bu (5.0 equiv.), $Pd(OAc)_2$ (2.0 mol%) and **L4** (2.0 mol%) in DMSO (4.0 mL) at 100 °C

matography was performed using commercially prepared 60 F_{254} silica gel plates and visualization was effected with short wavelength UV light (254 nm) and staining over an I_2 chamber. All melting points are uncorrected. High resolution mass spectra were recorded on a double focusing magnetic sector mass spectrometer.

Procedure for the Synthesis of Pyrroloquinoxalines (1g)

To a well-stirred solution of 4-bromobenzaldehyde 5 (1.2 equiv.), benzotriazole (1.0 equiv.) and 10 mol% $AlCl_3$ in THF, 1-(2-aminophenyl)pyrrole (1.0 mmol) was added. The reaction mixture was stirred at room temperature for 8–10 h. After the completion of the reaction, the mixture was extracted with ethyl acetate and water. The organic phases were washed with NaOH brine and dried with Na_2SO_4. The solvent was evaporated under vacuum and the obtained crude reaction mixture was purified by column chromatography (hexane/ethyl acetate) to afford the desired product in excellent yields.

4-(4-Bromophenyl)pyrrolo[1,2-*a*]quinoxaline (1g):[37] The product was obtained as white needles (DCM/ether); yield: 308.9 mg (96%); mp 104–106 °C; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 8.00$–7.90 (m, 2H), 7.90–7.80 (m, 3H), 7.70–7.60 (m, 2H), 7.50 (td, $J = 8.7$ and 1.5 Hz, 1H), 7.50 (td, $J = 8.0$ and 1.4 Hz, 1H), 6.94 (t, $J = 3.0$ Hz, 1H), 6.93 (t, $J = 2.9$ Hz, 1H); ^{13}C (100 MHz, $CDCl_3$): $\delta = 153.0$, 137.2, 136.0, 131.7, 130.2, 127.7, 127.0, 125.3, 124.9, 124.1, 114.8, 114.1, 113.6, 108.5; IR (KBr): $\nu = 3139$, 3110, 3079, 3043, 2919, 1612, 1587, 1531, 1473, 1420, 1391, 1369, 1097, 823, 749, 710 cm^{-1}; HR-MS (ESI): $m/z = 322.0106$, calcd. for $C_{17}H_{11}BrN_2$ ($M + H^+$): 322.0106.

Procedure for the Synthesis of Ligand ($BtCH_2Bt$) L3

A flask was charged with CuI (10 mol%), $BtCH_2Cl$ (1.0 mmol) and benzotriazole (1.0 equiv.) in DMF (5 mL). The reaction mixture was then heated at 100 °C in the pres-

ence of base K_2CO_3 (2.0 equiv.) for 5–6 h. After the completion of reaction, reaction mixture was allowed to come to room temperature. To the reaction mixture was added ethyl acetate, and the resulting suspension was filtered. The filtrate was concentrated, and the residue was purified by column chromatography on silica gel to provide the desired product.

Di(1*H*-benzo[*d*][1,2,3]triazol-1-yl)methane (L3):[38] The product was obtained as white needles (DCM/ether); yield: 0.225 g (90%); mp 78–80 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.06 (d, J = 8.4 Hz, 1H), 7.95 (d, J = 8.4 Hz, 1H), 7.87–7.83 (m, 2H), 7.56 (dt, J = 6.3 and 0.9 Hz, 1H), 7.42–7.36 (m, 5H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 146.3, 145.0, 132.6, 128.6, 127.5, 124.6, 120.2, 118.5, 109.9, 64.8; HR-MS (ESI): m/z = 250.0965, calcd. for $C_{13}H_{10}N_6$ ($M+H^+$): 250.0967.

Procedure for the Synthesis of Ligand (BtPy) L4[24b]

To a solution of DMSO (3.0 mL), CuI (5.0 mol%), KO-*t*-Bu (1.4 equiv.), benzotriazole (1.0 mmol) and 1.1 equiv. of 2-bromopyridine was added. The reaction mixture was allowed to stirred at 120 °C for 12 h. After the completion, of reaction, the resulting solution was filtered, and the reaction mixture was extracted with ethyl acetate and water. The organic layer was evaporated under reduced pressure. The crude reaction mixture was purified by column chromatography using ethyl acetate/hexane as the eluent.

1-(Pyridine-2-yl)-1*H*-benzo[*d*][1,2,3]triazole (L4):[24b] The product was obtained as white needles (DCM/ether); yield: 0.182 g (96%); mp 109–111 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.67–8.61 (m, 2H), 8.30 (d, J = 8.4 Hz, 1H), 8.13(d, J=8.1 Hz, 1H), 7.94 (td, J = 7.5 and 8.1 Hz, 1H), 7.61 (td, J = 7.5 and 7.8 Hz, 1H), 7.46 (td, J = 7.8 and 7.5 Hz, 1H), 7.47–7.27 (m, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 151.6, 148.3, 146.7, 138.8, 131.5, 128.7, 124.9, 122.2, 119.7, 114.8, 114.4; IR (KBr): ν = 3112, 3065, 1595, 1475, 1287, 1073, 1061, 784, 752, 735 cm^{-1}; HR-MS (ESI): m/z = 196.0750, calcd. for $C_{11}H_8N_4$ ($M+H^+$): 196.0749.

General Procedure for the Suzuki Reaction (3a–n)

To a mixture of DMF/water (4:1; 2 mL), $Pd(OAc)_2$ (1.0 mol%), ligand **L4** (1.0 mol%) were added aryl halide (0.5 mmol), arylboronic acid (1.2 equiv.) and K_2CO_3 (2.0 equiv.). The reaction mixture was then flushed with nitrogen and stirred at room temperature until the aryl halide was consumed, as determined by TLC. The reaction mixture was extracted with ethyl acetate and water. Organic layer was evaporated under reduced pressure. The crude reaction mixture was purified using silica gel column chromatography using ethyl acetate/hexane as the eluent.

2,4,6-Trimethoxy-4′-methylbiphenyl (3a):[39] The product was obtained as a white needles (DCM/ether); yield: 240.0 mg (93%), mp 48–50 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.45 (d, J = 7.8 Hz, 2H), 7.23 (d, J = 7.8 Hz, 2H), 6.76 (s, 2H), 3.91 (s, 6H), 3.88 (s, 3H), 2.39 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 153.5, 138.5, 137.4, 137.2, 137.1, 129.5, 126.9, 104.2, 60.9, 56.2, 21.1; IR (KBr): ν = 2933, 2834, 1588, 1500, 1458, 1420, 1237, 1131, 809, 767 cm^{-1}; HR-MS (ESI): m/z = 258.1259, calcd. for $C_{16}H_{18}O_3$ ($M+H^+$): 258.1256.

1*H*,1′*H*-5,5′-Biindole (3b):[40] The product was obtained as white needles (DCM/ether); yield: 116.9 mg (71%); mp 80–85 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.13 (brs, 2H), 7.89 (s, 2H), 7.54–7.44 (m, 4H), 7.25–7.22 (m, 2H), 6.61 (s, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 134.9, 134.8, 128.4, 124.6, 122.5, 119.3, 111.0, 102.9; HR-MS (ESI): m/z = 232.1001, calcd. for $C_{16}H_{12}N_2$ ($M+H^+$): 232.1000.

4-(1*H*-Indol-5-yl)-*N*,*N*-dimethylaniline (3c):[41] The product was obtained as white needles (DCM/ether); yield: 172.2 mg (73%); mp 134–136 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.07 (brs, 1H), 7.80 (s, 1H), 7.54 (d, J = 8.7 Hz, 2H), 7.41 (dd, J = 8.7 and 2.7 Hz, 2H), 7.23–7.17 (m, 1H), 6.82 (d, J = 8.7 Hz, 2H), 6.57 (s, 1H), 2.98 (s, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 149.5, 134.8, 133.6, 131.1, 128.4, 127.9, 124.6, 121.6, 118.3, 113.1, 111.1, 102.9, 40.8; IR (KBr): ν = 3003, 2955, 2899, 2834, 1606, 1511, 1495, 1242, 1175, 1029, 832 cm^{-1}; HR-MS: m/z = 236.1316, calcd. for $C_{16}H_{16}N_2$ ($M+H^+$): 236.1313.

2-(4-Methylphenyl)-biphenyl (3d):[39] The product was obtained as a colourless oil; yield: 217.3 mg (89%): ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.33–7.25 (m, 4H), 7.23–7.18 (m, 1H), 7.13–7.07 (m, 4H), 6.95–6.89 (m, 3H), 6.54 (d, J = 7.2 Hz, 1H), 2.29 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 141.7, 140.5, 138.5, 137.1, 131.7, 130.6, 129.8, 129.7, 128.6, 127.8, 127.4, 127.2, 127.0, 126.4, 21.1; HR-MS (ESI): m/z = 244.1252, calcd. for $C_{19}H_{16}$ ($M+H^+$): 244.1252.

2-(3-Nitrophenyl)-biphenyl (3e):[39] The product was obtained as white needles (DCM/ether); yield: 249.1 mg (91%); mp: 60–62 °C: ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.00–7.96 (m, 2H), 7.39 (s, 4H), 7.32–7.22 (m, 2H), 7.14 (s, 3H), 7.04–7.03 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$) δ = 148.1, 143.3, 141.0, 140.5, 138.0, 136.1, 130.8, 130.3, 129.9, 128.7, 128.6, 128.2, 127.9, 127.0, 124.6, 121.5; IR (KBr): ν = 2960, 2923, 2851, 1532, 1466, 1453, 1437, 1347, 1085, 875, 766, 748, 701 cm^{-1}; HR-MS (ESI): m/z = 275.0945, calcd. for $C_{18}H_{13}NO_2$ ($M+H^+$): 275.0946.

4′-(4-Flurobenzyloxy)-4-methylbiphenyl (3f):[39] The product was obtained as white needles (DCM/ether); yield: 262.9 mg (90%); mp 100–105 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.44–7.31 (m, 6H), 7.15 (d, J = 7.8, 2H), 7.02–6.91 (m, 4H), 4.96 (s, 2H), 2.29 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 164.1, 160.9, 157.9, 137.8, 136.4, 134.1, 132.7, 129.4, 129.3, 129.2, 127.9, 126.6, 115.6, 115.3, 115.0, 69.4, 21.0; IR (KBr): ν = 2916, 2863, 1497, 1236, 806 cm^{-1}; HR-MS (ESI): m/z = 292.1263, calcd. for $C_{20}H_{17}FO$ ($M+H^+$): 292.1263.

3-Nitro-4′-vinylbiphenyl (3g):[39] The product was obtained as white needles (DCM/ether); yield: 206.1 mg (92%); mp 68–70 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.36 (s, 1H), 8.11 (d, J = 7.2 Hz, 1H), 7.84 (d, J = 7.1 Hz, 1H), 7.54–7.37 (m, 5H), 6.73 (q, J = 10.8 Hz, 1H), 5.78 (d, J = 17.7 Hz, 1H), 5.26 (d, J = 10.8 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 148.7, 142.3, 137.8, 136.3, 135.9, 132.7, 129.7, 127.2, 126.9, 126.6, 121.9, 121.6, 114.8; IR (KBr): ν = 3082, 2960, 2925, 2851, 1668, 1625, 1527, 1511, 1344, 902, 843.1, 805.9, 730.4 cm^{-1}; HR-MS (ESI): m/z = 225.0790, calcd. for $C_{14}H_{11}NO_2$ ($M+H^+$): 225.0790.

2′,5′-Dibromo-4,4″-dimethyl-1,1′:4′,1″-terphenyl (3h): The product was obtained as white needles (DCM/ether); yield: 343.1 mg (83%); mp 162–164 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.60 (s, 2H), 7.32 (d, J = 8.0 Hz, 4H), 7.24 (d, J = 6.4 Hz, 4H), 2.4 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 142.6, 137.9, 136.6, 135.2, 129.1, 128.8, 121.4, 21.3; HR-MS (ESI): m/z = 413.9621, calcd. for $C_{20}H_{16}Br_2$ ($M+H^+$): 413.9619.

2,3,4,5-Tetrakis(4-methoxyphenyl)thiophene (3i):[42] The product was obtained as yellow needles (DCM/ether); yield: 406.4 mg (80%); mp 178–180 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.13(d, J=8.8 Hz, 4H), 6.84 (d, J = 8.8 Hz, 4H), 6.74 (d, J = 8.8 Hz, 4H), 6.65 (d, J = 8.8 Hz, 4H), 3.75 (s, 6H), 3.72 (s, 6H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 158.6, 158.0, 138.3, 137.2, 131.9, 130.3, 129.1, 127.0, 113.7, 113.3, 55.2, 55.0; HR-MS (ESI): m/z = 508.1705, calcd. for $C_{32}H_{28}O_4S$ ($M+H^+$): 508.1708.

4-(4-Ethylphenyl)-1-methoxy-3-phenyl-1*H*-pyrano[4,3-*b*]quinoline (3j):[43] The product was obtained as orange needles (DCM/ether); yield: 310.0 mg (79%); mp 92–94 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.05 (s, 1H), 7.97 (d, J = 8.4 Hz, 1H), 7.77 (d, J = 8.1 Hz, 1H), 7.60 (td, J = 6.9 and 1.2 Hz, 1H), 7.42 (t, J = 8.1 Hz, 1H), 7.35–7.31 (m, 4H), 7.23–7.13 (m, 5H), 6.29 (s, 1H), 3.74 (s, 3H), 2.67 (q, J = 7.5 Hz, 2H), 1.26 (t, J = 7.8 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 153.2, 150.0, 148.8, 143.7, 135.5, 132.7, 132.3, 132.2, 129.9, 129.5, 128.7, 128.4, 128.0, 127.6, 127.3, 126.8, 126.4, 125.7, 122.6, 117.5, 100.0, 56.1, 28.6, 15.4; HR-MS (ESI): m/z = 393.1729, calcd. for $C_{27}H_{23}NO_2$ ($M+H^+$): 393.1729.

4-(4′-Methoxybiphenyl-4-yl)pyrrolo[1,2-*a*]quinoxaline (3k):[37] The product was obtained as white needles (DCM/ether); yield: 290.6 mg (83%); mp 187–190 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.06 (d, J = 7.5 Hz, 4H), 7.90 (d, J = 8.1 Hz, 1H), 7.73 (d, J = 7.8 Hz, 2H), 7.60 (d, J = 8.4 Hz, 2H), 7.50–7.40 (m, 2H), 7.07–7.01 (m, 3H), 6.90 (s, 1H), 3.90 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.3, 154.0, 142.2, 136.7, 136.2, 133.0, 130.1, 129.0, 128.2, 127.0, 126.8, 125.3, 125.2, 114.6, 114.3, 114.0, 113.6, 108.6, 55.3; HR-MS (ESI): m/z = 350.1418, calcd. for $C_{24}H_{18}N_2O$ ($M+H^+$): 350.1419.

4-[4′-(Methylthio)biphenyl-4-yl]pyrrolo[1,2-*a*]quinoxaline (3l):[37] The product was obtained as white needles (DCM/ether); yield: 322.2 mg (88%); mp 173–175 °C; ^{1}H NMR (400 MHz, $CDCl_3$): δ = 8.10–8.00 (m, 3H), 7.99–7.98 (m, 1H), 7.88–7.86 (m, 1H), 7.73 (d, J = 8.0 Hz, 2H), 7.60 (d, J = 8.0 Hz, 2H), 7.51–7.45 (m, 2H), 7.34 (d, J = 8.8 Hz, 2H), 7.04 (m, 1H), 6.90 (t, J = 3.3 Hz, 1H), 2.53 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 153.8, 141.8, 138.1, 137.2, 136.2, 130.2, 129.1, 127.4, 127.1, 127.0, 126.9, 126.8, 125.2, 114.6, 113.9, 113.6, 108.5, 15.7; IR (KBr): ν = 2919, 1458, 1475, 1423, 1369, 1318, 1098, 816, 761, 742, 721 cm^{-1}; HR-MS (ESI): m/z = 366.1190, calcd. for $C_{24}H_{18}N_2S$ ($M+H^+$): 366.1191.

6,7-Dimethoxy-3-(4-methoxy-6-methyl-9-phenyl-5,6,7,8-tetrahydro[1,3]dioxolo[4,5-*g*]isoquinolin-5-yl)isobenzofuran-1(3*H*)-one (3m): The product was obtained as white needles (DCM/ether); yield: 317.2 mg (65%); mp 189–191 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.37–7.24 (m, 3H), 7.18 (d, J = 6.9 Hz, 3H), 6.98 (d, J = 8.1 Hz, 1H), 5.90 (s, 1H), 5.84 (s, 1H), 5.57 (s, 1H), 4.49 (s, 1H), 4.07–3.96 (m, 6H), 3.83 (s, 3H), 2.51 (s, 3H), 2.21–2.16 (m, 2H), 1.32–1.06 (m, 2H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 167.9, 152.4, 147.7, 146.2, 140.8, 139.6, 133.7, 129.9, 128.3, 127.5, 118.0, 117.9, 116.6, 100.9, 62.3, 61.3, 59.5, 56.9, 29.7; IR (KBr): ν = 2942, 2856, 2795, 1752, 1492, 1439, 1376, 1262, 1276, 1059, 1077, 1014, 1034, 706 cm^{-1}; HR-MS (ESI): m/z = 489.1785, calcd. for $C_{28}H_{27}NO_7$ ($M+H^+$): 489.1788.

6,7-Dimethoxy-3-(4-methoxy-6-methyl-9-*p*-tolyl-5,6,7,8-tetrahydro[1,3]dioxolo[4,5-*g*]isoquinolin-5-yl)isobenzofuran-1(3*H*)-one (3n):[44] The product was obtained as white needles (DCM/ether); yield: 361.5 mg (72%); mp 210–212 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.26–7.22 (m, 2H), 7.13 (d, J = 7.8 Hz, 2H), 7.09 (d, J = 8.1 Hz, 1H), 6.12 (d, J = 8.1 Hz, 1H), 5.97 (s, 1H), 5.91 (s, 1H), 5.56 (d, J = 4.2 Hz, 1H), 4.50 (d, J = 4.2 Hz, 1H), 4.11 (d, J = 5.4 Hz, 6H), 3.90 (s, 3H), 2.56 (s, 3H), 2.38 (s, 3H), 2.27–2.18 (m, 1H), 2.14–2.13 (m, 2H), 1.69–1.62 (m 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 168.1, 152.3, 147.6, 146.0, 140.9, 139.5, 137.3, 133.7, 131.1, 130.9, 130.0, 129.8, 129.0, 120.6, 117.9, 117.8, 117.7, 116.5, 115.1, 100.8, 82.1, 62.4, 61.1, 59.6, 50.9, 46.8, 27.1, 21.3; IR (KBr): ν = 2936, 2903, 2853, 2806, 1758, 1497, 1467, 1458, 1438, 1422, 1377, 1270, 1084, 1056, 1032, 1010, 819, 715 cm^{-1}; HR-MS (ESI): m/z = 503.1942, calcd. for $C_{29}H_{29}NO_7$ ($M+H^+$): 503.1944.

General Procedure for the Heck Reaction (5a–j)

A mixture of aryl halide (1.0 mmol), $Pd(OAc)_2$ (3.0 mol%), **L4** (3.0 mol%) and K_2CO_3 (2.0 equiv.) in 3.0 mL of DMF was flushed with nitrogen with the addition of alkene (1.5 equiv.) and the reaction mixture was stirred at 120 °C with the progress of reaction being monitored by TLC. After completion of the reaction, the mixture was diluted with ethyl acetate and water. The organic layer was washed with brine, dried over Na_2SO_4, and concentrated under reduced pressure. The residue was purified by silica gel chromatography using ethyl acetate/hexane as eluent.

(*E*)-Butyl 3-(4-methoxyphenyl)acrylate (5a):[45] The product was obtained as a viscous colourless oil; yield: 219.9 mg (94%); ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.64 (d, J = 15.9 Hz, 1H), 7.46 (d, J = 8.7 Hz, 2H), 6.90 (d, J = 8.7 Hz, 2H), 6.32 (d, J = 15.9, Hz, 1H), 4.19 (t, J = 6.9 Hz, 2H), 3.82 (s, 3H), 1.73–1.64 (m, 2H), 1.44 (q, J = 7.5 Hz, 2H), 0.96 (t, J = 7.5 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 167.4, 161.3, 144.2, 130.8, 127.2, 115.7, 113.3, 64.2, 55.3, 30.7, 19.2, 10.9; HR-MS (ESI): m/z = 234.1256, calcd. for $C_{14}H_{18}O_3$ ($M+H^+$): 234.1256.

(*E*)-Butyl 3-phenylacrylate (5b):[46] The product was obtained as a colourless oil; yield: 182.5 mg (90%); ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.61 (d, J = 16.2 Hz, 1H), 7.45 (dd, J = 3.6 and 1.5 Hz, 2H), 7.39–7.30 (m, 3H), 6.34 (d, J = 15.9 Hz, 1H), 4.16 (t, J = 6.9 Hz, 2H), 1.64–1.59 (m, 2H), 1.40–1.32 (m, 2H), 0.96 (t, J = 7.2 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 167.1, 144.5, 134.5, 130.4, 129.3, 128.8, 127.5, 118.2, 64.4, 31.6, 19.2, 13.7; HR-MS (ESI): m/z = 204.1150, calcd. for $C_{13}H_{16}O_2$ ($M+H^+$): 204.1150.

(*E*)-1-Methoxy-2-styrylbenzene (5c):[47] The product was obtained as a viscous colourless oil; yield: 171.3 mg (82%): ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.52 (d, J = 8.0 Hz, 1H), 7.45 (t, J = 8.1 Hz, 3H), 7.26 (t, J = 7.3 Hz, 2H), 7.18–7.14 (m, 2H), 7.03 (d, J = 16.1 Hz, 1H), 6.89 (t, J = 7.4 Hz, 1H), 6.82 (d, J = 8.0 Hz, 1H), 3.80 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 156.9, 137.9, 129.1, 128.6, 128.5, 127.3, 126.5, 123.4, 120.7, 110.9, 55.5; IR (KBr): ν = 2925, 1592, 1486, 1480, 1242, 1105, 1029, 964, 752, 689 cm^{-1}; HR-MS (ESI): m/z = 210.1046, calcd. for $C_{15}H_{14}O$ ($M+H^+$): 210.1045.

(*E*)-Methyl3-(1-methoxy-3-(*p*-tolyl)-1*H*-pyrano[4,3-*b*]quinolin-4-yl)acrylate (5d):[43] The product was obtained as a pale yellow needles (DCM/ether); yield: 298.0 mg (77%); mp 149–150 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.24 (d, J = 8.8 Hz, 1H), 8.19 (s, 1H), 7.82–7.79 (m, 3H), 7.73 (t, J =

5.8 Hz, 1H), 7.54–7.51 (m, 3H), 7.28 (d, $J=8.08$ Hz, 2H), 6.21 (s, 1H), 3.77 (s, 3H), 3.74 (s, 3H), 2.41 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=169.0$, 162.6, 148.9, 148.2, 141.1, 139.5, 132.9, 13o.8, 130.5, 130.2, 129.4, 129.2, 127.6, 126.5, 126.3, 122.7, 119.2, 110.9, 100.7, 56.7, 51.3, 21.5; HR-MS (ESI): $m/z=387.1471$, calcd. for $C_{24}H_{21}NO_4$ ($M+H^+$): 387.1471.

(*E*)-Ethyl 3-{4-(pyrrolo[1,2-*a*]quinoxalin-4 yl)phenyl}acrylate (5e):[37]: The product was obtained as white needles (DCM/ether); yield: 290.8 mg (85%); mp 89–91 °C; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=8.05$–8.01 (m, 4H), 7.90 (d, $J=8.0$ Hz, 1H), 7.80 (d, $J=16.1$ Hz, 1H), 7.70 (d, $J=8.0$ Hz, 2H), 7.50 (t, $J=8.0$ Hz, 1H), 7.49 (t, $J=9.5$ Hz, 1H), 7.01–6.99 (m, 1H), 6.90 (t, $J=3.0$ Hz, 1H), 6.53 (d, $J=16.1$ Hz, 1H), 4.29 (q, $J=8.0$ Hz, 2H), 1.35 (t, $J=7.3$ Hz, 3H); ^{13}C (100 MHz, $CDCl_3$): $\delta=166.8$, 153.3, 143.8, 140.0, 136.1, 135.7, 130.2, 129.1, 128.2, 127.7, 127.1, 125.3, 125.1, 119.1, 114.7, 114.1, 113.6, 108.4, 60.6, 14.3; IR (KBr): $\nu=2926$, 1718, 1627, 1437, 1370, 1320, 1172, 986, 831, 750, 742, 712 cm^{-1}; HR-MS (ESI): $m/z=342.1365$, calcd. for $C_{22}H_{18}N_2O_2$ ($M+H^+$): 342.1368.

(*E*)-Methyl 3-{4-(pyrrolo[1,2-*a*]quinoxalin-4-yl)phenyl}-acrylate (5f):[37] The product was obtained as pale yellow needles (DCM/ether); yield: 275.6 mg (84%); 102–104 °C; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=8.04$ (d, $J=7.8$ Hz, 4H), 7.90 (d, $J=7.8$ Hz, 1H), 7.80–7.70 (m, 3H), 7.50–7.40 (m, 2H), 7.03 (d, $J=18.3$ Hz, 2H), 6.50 (d, $J=15.9$ Hz, 1H), 3.80 (s, 3H); ^{13}C (75 MHz, $CDCl_3$): $\delta=167.3$, 153.3, 144.2, 140.2, 136.1, 135.7, 130.3, 129.2, 128.3, 127.8, 127.2, 125.4, 125.1, 119.7, 114.8, 114.1, 113.7, 108.5, 51.8; HR-MS (ESI): $m/z=328.1212$, calcd. for $C_{21}H_{16}N_2O_2$ ($M+H^+$): 328.1212.

(*E*)-Butyl 3-(4-acetylphenyl)acrylate (5g):[48] The product was obtained as a colourless oil; yield: 222.8 mg (91%); ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=7.97$ (d, $J=8.3$ Hz, 2H), 7.69 (d, $J=16.1$ Hz, 1H), 7.61 (d, $J=8.3$ Hz, 2H), 6.53 (d, $J=16.0$ Hz, 1H), 4.23 (t, $J=6.6$ Hz, 2H), 1.73–1.65 (m, 2H), 2.61 (s, 3H), 1.48–1.41 (m, 2H), 0.97 (t, $J=7.3$ Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=197.1$, 166.5, 142.9, 138.8, 138.0, 128.8, 128.1, 120.8, 64.6, 30.7, 26.6, 19.2, 13.7; HR-MS (ESI): $m/z=246.1253$, calcd. for $C_{15}H_{18}O_3$ ($M+H^+$): 246.1256.

3-*p*-Tolylcyclopent-2-enone (5h): The product was obtained as white needles (DCM/ether); yield: 117.0 mg (68%); mp 136–138 °C; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=$ 7.56 (d, $J=8.1$ Hz, 2H), 7.26 (d, $J=7.8$ Hz, 2H), 6.54 (s, 1H), 3.02–3.05 (m, 2H), 2.56–2.59 (m, 2H), 2.41(s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=209.4$, 174.1, 141.9, 131.3, 129.6, 126.8, 126.6, 35.3, 29.7, 21.6; HR-MS (ESI): $m/z=$ 172.0888, calcd. for $C_{12}H_{12}O$ ($M+H^+$): 172.0888.

(*E*)-3-(4-Methoxyphenyl)acrylonitrile (5i):[49] The product was obtained as a colourless liquid; yield: 140.8 mg (89%); ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=7.69$ (d, $J=8.8$ Hz, 1H), 7.29 (d, $J=8.1$ Hz, 1H), 7.20 (d, $J=16.1$ Hz, 1H), 6.85–6.80 (m, 2H), 5.60 (d, $J=16.1$ Hz, 1H), 3.74 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=161.9$, 149.9, 130.8, 128.9, 126.1, 118.6, 114.3, 114.1, 93.1, 55.3; IR (KBr): $\nu=2962$, 2933, 2840, 2212, 1628, 1603, 1573, 1252, 1174, 802, 768 cm^{-1}; HR-MS (ESI): $m/z=159.0680$, calcd. for $C_{10}H_9NO$ ($M+H^+$): 159.0684.

6-(*p*-Tolyl)-4,5-dihydro-1,3-dioxepine (5j): The product was obtained as a colourless liquid; yield: 144.4 mg (76%); ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=7.08$–7.04 (m, 4H), 6.37 (dd, $J=2.2$ and 7.3 Hz, 1H), 5.10 (d, $J=7.3$ Hz, 1H), 4.84 (dd, $J=3.6$ and 7.3 Hz, 1H), 4.75 (d, $J=7.32$ Hz, 1H), 3.90–3.86 (m, 1H), 3.71–3.68 (m, 1H), 3.37- 3.32 (m, 1H), 2.25 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=145.9$, 137.8, 136.6, 129.3, 127.8, 112.3, 98.1, 47.9, 21.0; HR-MS (ESI): $m/z=$ 190.0995 calcd. for $C_{12}H_{14}O_2$ ($M+H^+$): 190.0994.

General Procedure for the Fujiwara–Moritani Reaction (7a–f)

$Pd(OAc)_2$ (2.0 mol%) and **L4** (2.0 mol%) were added to a mixture of the alkene (1.5 equiv.), copper(II) acetate (2.0 equiv.) and the N-heterocycle (1.0 mmol) in DMF:DMSO (4:1, 2.0 mL). The reaction mixture was then flushed with nitrogen and heated at 120 °C for 12 h. After completion of the reaction, the mixture was cooled to room temperature, then filtered and washed with saturated aqueous NaCl solution. The resultant solution was extracted with ethyl acetate. The combined organic fractions were dried over anhydrous Na_2SO_4 and concentrated under vacuum to yield the crude product. The crude product was purified by column chromatography (ethyl acetate/hexane).

(*E*)-Butyl 3-(1*H*-indol-3-yl)acrylate (7a):[50] The product was obtained as yellow needles (DCM/ether); yield: 194.4 mg (80%); mp 81–85 °C; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=8.60$ (s, 1H), 7.87–7.82 (m, 2H), 7.40 (d, $J=1.8$, Hz, 1H), 7.33 (d, $J=7.2$ Hz, 1H), 7.22–7.15 (m, 2H), 6.40 (d, $J=$ 15.9 Hz, 1H), 4.15 (t, $J=6.6$ Hz, 2H), 1.68–1.58 (m, 2H), 1.39 (q, $J=7.5$ Hz, 2H), 0.90 (t, $J=7.5$ Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=167.4$, 161.3, 144.2, 130.8, 127.2, 115.7, 113.3, 64.2, 30.7, 19.2, 10.9; IR (KBr): $\nu=3271$, 2959, 2929, 2868, 1682, 1572, 1616, 1433, 1272, 1227, 1181, 1115, 1085, 970, 819, 724 cm^{-1}; HR-MS (ESI): $m/z=243.1259$, calcd. for $C_{15}H_{17}NO_2$ ($M+H^+$): 243.1259.

(*E*)-Methyl 3-(5-bromo-1*H*-indol-3-yl)acrylate (7b): The product was obtained as white needles (DCM/ether); yield: 195.3 mg (70%); mp 128–130 °C; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=8.67$ (brs, 1H), 7.95–7.94 (m, 1H), 7.78 (d, $J=$ 16.1 Hz, 1H), 7.40–7.39 (m, 1H), 7.30–7.27 (m, 1H), 7.19 (d, $J=5.9$ Hz, 1H), 6.32 (d, $J=16.1$ Hz, 1H), 3.75 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=168.5$, 137.7, 135.6, 129.5, 126.9, 126.2, 123.0, 114.8, 113.5, 113.1, 113.1, 51.5; HR-MS (ESI): $m/z=278.9895$, calcd. for $C_{12}H_{10}BrNO_2$ ($M+H^+$): 278.9895.

(*E*)-Butyl 3-(5-methoxy-1*H*-indol-3-yl)acrylate (7c): The product was obtained as white needles (DCM/ether); yield: 207.4 mg (76%); mp 160–162 °C; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=8.44$ (brs, 1H), 7.83 (d, $J=16.1$ Hz, 1H), 7.38 (d, $J=2.9$ Hz, 1H), 7.25–7.24 (m, 1H), 7.21–7.18 (m, 1H), 6.85 (dd, $J=2.2$ and 8.8 Hz, 1H), 6.30 (d, $J=15.4$ Hz, 1H), 4.15 (t, $J=6.2$ Hz, 2H), 3.82 (s, 3H), 1.65–1.60 (m, 2H), 1.41–1.35 (m, 2H), 0.90 (t, $J=7.3$ Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=168.6$, 155.4, 138.3, 132.0, 129.2, 125.9, 113.3, 113.2, 112.6, 112.4, 102.5, 64.1, 55.9, 30.9, 19.2, 13.8; HR-MS (ESI): $m/z=273.1365$, Calcd for $C_{16}H_{19}NO_3$ ($M+H^+$): 273.1365.

(*E*)-Butyl 3-(5-bromo-1*H*-indol-3-yl)acrylate (7d):[51] The product was obtained as white needles (DCM/ether); yield: 231.2 mg (72%); mp 143–145 °C; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=8.68$ (brs, 1H), 8.01 (s, 1H), 7.82 (d, $J=16.1$ Hz, 1H), 7.45–7.44 (m, 1H), 7.35–7.32 (m, 1H), 7.27–7.24 (m, 1H), 6.38 (d, $J=16.1$ Hz, 1H), 4.20 (t, $J=6.6$ Hz, 2H), 1.72–

1.65 (m, 2H), 1.46–1.39 (m, 2H), 0.95 (t, $J=7.3$ Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=168.4$, 137.5, 135.7, 129.6, 126.9, 126.2, 123.0, 114.8, 113.8, 113.0, 64.3, 30.8, 19.2, 13.7; IR (KBr): $\nu=3199$, 3171, 2955, 2899, 1660, 1622, 1452, 1389, 1288, 1259, 1234, 1063, 970, 841, 795 cm^{-1}; HR-MS (ESI): $m/z=321.0364$, calcd. for $C_{15}H_{16}BrNO_2$ ($M+H^+$): 321.0364.

(*E*)-5-Methoxy-3-styryl-1*H*-indole (7e): The product was obtained as yellow needles (DCM/ether); yield: 191.7 mg (77%); mp 110–112 °C; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=$ 8.09 (brs, 1H), 7.52 (d, $J=7.2$ Hz, 2H), 7.41–7.19 (m, 7H), 7.05 (d, $J=16.5$ Hz, 1H), 6.92 (dd, $J=6.6$ and 2.1 Hz, 1H), 3.92 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=154.7$, 138.5, 131.9, 128.6, 126.6, 126.1, 125.8, 125.2, 124.3, 121.6, 115.4, 112.6, 112.1, 102.4, 56.1; HR-MS (ESI): $m/z=249.1155$, calcd. for $C_{17}H_{15}NO$ ($M+H^+$): 249.1154.

(*E*)-3-Styryl-1*H*-indole (7f):[51] The product was obtained as pale yellow needles (DCM/ether); yield: 164.2 mg (75%); mp 100–102 °C; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=8.22$ (brs, 1H), 8.11 (s, 1H), 7.53 (d, $J=7.2$ Hz, 2H), 7.39–7.32 (m, 5H), 7.28–7.13 (m, 3H), 7.06 (d, $J=16.5$ Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=138.2$, 135.4, 128.7, 126.3, 125.8, 125.6, 124.5, 122.8, 120.8, 115.3, 113.8, 112.8; IR (KBr): $\nu=3056$, 3021, 2960, 2923, 2853, 1624, 1598, 1455, 1337, 1315, 950, 738 cm^{-1}; HR-MS (ESI): $m/z=219.1049$, calcd. for $C_{16}H_{13}N$ ($M+H^+$): 219.1048.

General Procedure for the Sonogashira Reaction (9a–g)

A flask was charged with $Pd(OAc)_2$ (2.0 mol%), **L4** (2.0 mol%), K_2CO_3 (2.0 equiv.) and 1.0 mmol of aryl halide in 2.0 mL of DMF under a nitrogen atmosphere. After stirring at room temperature for 15 min, the terminal alkyne (1.2 equiv.), was added to the flask, and the reaction mixture stirred at the 100 °C for 1–2 h. After the completion of reaction, the mixture was cooled to room temperature, diluted with ethyl acetate and the resulting suspension was filtered. The filtrate was concentrated, and the residue was purified by column chromatography on silica gel to provide the desired product (ethyl acetate/hexane).

1-Methoxy-4-(*p*-tolylethynyl)benzene (9a):[52] The product was obtained as white needles (DCM/ether); yield: 199.9 mg (90%); mp: 120–122 °C; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=$ 7.44 (d, $J=8.8$ Hz, 2H), 7.39 (d, $J=8.0$ Hz, 2H), 7.13 (d, $J=$ 8.0 Hz, 2H), 6.85 (d, $J=8.8$ Hz, 2H), 3.80 (s, 3H), 2.34 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=159.4$, 138.0, 132.9, 131.3, 129.0, 128.9, 120.4, 115.5, 113.9, 88.6, 88.1, 55.2, 21.5; HR-MS (ESI): $m/z=222.1046$, calcd. for $C_{16}H_{14}O$ ($M+H^+$): 222.1045.

1-Methoxy-2-(phenylethynyl)benzene (9b):[53] The product was obtained as a pale yellow oil; yield: 160.8 mg (77%); ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=7.57$–7.49 (m, 4H), 7.33–7.28 (m, 3H), 6.96 (m, 2H), 3.91 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=159.9$, 133.5, 131.6, 129.7, 128.3, 128.2, 126.5, 123.5, 120.5, 112.4, 110.7, 93.4, 85.7, 55.8; IR (KBr): $\nu=3057$, 3020, 2959, 2938, 2215, 1593, 1497, 1275, 1245, 751, 690 cm^{-1}; HR-MS (ESI): $m/z=208.0889$, calcd. for $C_{15}H_{12}O$ ($M+H^+$): 208.0888.

3-Bromo-2-(thiophen-3-ylethynyl)pyridine (9c): The product was obtained as a yellow oil; yield: 213.1 mg (81%); ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=8.42$ (dd, $J=1.4$ and 4.6 Hz, 1H), 7.79 (dd, $J=1.4$ and 8.2 Hz, 1H), 7.60–7.59 (m, 1H), 7.23–7.21 (m, 1H), 7.19–7.17 (m, 1H), 7.01–6.98 (m, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=147.6$, 143.0, 139.2, 130.2, 129.3, 125.1, 122.9, 122.8, 120.4, 88.7, 86.5; IR (KBr): $\nu=$ 3045, 3105, 2925, 2849, 2212, 1565, 1461, 1438, 1399, 1020, 783, 749, 624 cm^{-1}; HR-MS: $m/z=262.9404$, calcd. for $C_{11}H_6BrNS$ ($M+H^+$): 262.9404.

3-Methyl-1-(2-(thiophen-3-ylethynyl)phenyl)-1*H*-indole (9d):[24] The product was obtained as a yellow oil; yield: 234.8 mg (75%); ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=7.70$–7.66 (m, 2H), 7.49–7.44 (m, 2H), 7.39–7.35 (m, 2H), 7.27 (d, $J=$ 5.0 Hz, 2H), 7.23–7.21 (m, 1H), 7.19 (dd, $J=2.0$ and 3.2 Hz, 1H), 7.11 (d, $J=3.2$ Hz, 1H), 6.79 (d, $J=5.2$ Hz, 1H), 2.44 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=141.1$, 136.8, 133.3, 129.7, 129.5, 129.2, 129.0, 126.9, 126.8, 126.7, 125.3, 122.1, 120.6, 119.7, 119.1, 111.3, 111.1, 90.0, 86.3, 9.9; IR (KBr): $\nu=$ 3103, 2931, 2851, 1594, 1489, 1459, 1360, 867, 777 cm^{-1}; HR-MS: $m/z=313.0928$, calcd. for $C_{21}H_{15}NS$ ($M+H^+$): 313.0925.

4,4′-(2,5-Dibromo-1,4-phenylene)bis(ethyne-2,1-diyl)bis-(ethylbenzene) (9e): The product was obtained as white needles (DCM/ether); yield: 357.2 mg (73%); mp: 176–178 °C; ^{1}H NMR (300 MHz, $CDCl_3$): $\delta=7.75$ (s, 2H), 7.49 (d, $J=$ 8.1 Hz, 4H), 7.20 (d, $J=8.1$ Hz, 4H), 2.67 (q, $J=7.5$ Hz, 4H), 1.24 (t, $J=7.5$ Hz, 6H); ^{13}C NMR (75 MHz, $CDCl_3$): $\delta=145.7$, 136.5, 135.9, 135.2, 132.3, 131.7, 129.7, 128.0, 127.3, 125.5, 125.3, 123.8, 122.5, 120.0, 119.6, 119.3, 119.0, 114.2, 111.7, 95.7, 86.5, 28.9, 28.7, 15.4, 15.3; IR (KBr): $\nu=3042$, 3029, 2959, 2924, 2864, 2214, 1509, 1448, 1420, 1371, 1052, 880, 827, 750, 710 cm^{-1}; HR-MS: $m/z=489.9934$, calcd. for $C_{26}H_{20}Br_2$ ($M+H^+$): 489.9932.

3,4-Dibromo-2,5-bis[(4-ethylphenyl)ethynyl]thiophene (9f): The product was obtained as yellow needles (DCM/ether); yield: 396.1 mg (80%); mp 115–117 °C; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=7.41$ (d, $J=8.2$ Hz, 4H), 7.13 (d, $J=$ 8.2 Hz, 4H), 2.60 (q, $J=7.7$ Hz, 4H), 1.17 (t, $J=7.7$ Hz, 6H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=145.9$, 131.7, 128.0, 121.3, 119.0, 118.6, 98.9, 80.4, 28.9, 15.3; HR-MS: $m/z=$ 495.9499, calcd. for $C_{24}H_{18}Br_2S$ ($M+H^+$): 495.9496.

3,3′,3″,3‴-[Thiophene-2,3,4,5-tetrayltetrakis(ethyne-2,1-diyl)]tetrathiophene (9g): The product was obtained as light yellow needles (DCM/ether); yield: 304.2 mg (60%); mp 115–117 °C; ^{1}H NMR (400 MHz, $CDCl_3$): $\delta=7.62$–7.59 (m, 4H), 7.33–7.30 (m, 4H), 7.25–7.20 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta=130.1$, 130.0, 129.9, 129.7, 127.8, 125.8, 125.5, 121.6, 121.2, 121.1 (2C), 121.0, 120.5, 118.1, 94.4, 93.2, 91.4, 82.1, 80.9, 80.4, 80.3; IR (KBr): $\nu=3103$, 2955, 2925, 2851, 2207, 1660, 1622, 1407, 1354, 872, 775, 683 cm^{-1}; HR-MS: $m/z=507.9543$, calcd. for $C_{28}H_{12}S_5$ ($M+H^+$): 507.9543.

General Procedure for the N-arylation Reaction (10a–g)

To a solution of DMSO (2.0 mL), $Pd(OAc)_2$ (5.0 mol%), **L4** (5.0 mol%), KO-*t*-Bu (2.0 equiv.), 1.0 mmol of the N-heterocycle and 1.2 equiv. of heteroaryl halide were added. The mixture was then heated at 120 °C under a nitrogen atmosphere until the aryl halide was consumed, as determined by TLC. The reaction mixture was washed with ethyl acetate and water. The organic layer was then washed with brine and dried over Na_2SO_4. The solvent was removed under vacuum, and the crude residue was purified by column chro-

matography on silica gel using hexanes or a mixture of hexane and ethyl acetate as eluent.

1-(2-Methoxyphenyl)-1*H*-indole (10a):[54] The product was obtained as white needles (DCM/ether); yield: 173.9 mg (78%); mp 68–70 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.77–7.73 (m, 1H), 7.51–7.34 (m, 4H), 7.33–7.12 (m, 3H), 6.72 (d, J = 3.0 Hz, 1H), 6.59 (d, J = 3.3 Hz, 1H), 3.85 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 158.2, 136.3, 132.8, 128.9, 128.3, 125.9, 122.1, 121.0, 120.0, 114.7, 110.3, 102.8, 55.6; IR (KBr): ν = 2927, 2854, 1596, 1474, 1455, 1275, 1246, 1093, 1021, 744 cm^{-1}; HR-MS: m/z = 223.0998, calcd. for $C_{15}H_{13}NO$ (M+H$^+$): 223.0997.

1-(3-Bromo-pyridin-2-yl)-1*H*-indole (10b):[23c] The product was obtained as a colorless oil; yield: 182.1 mg (67%); ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.48 (d, J = 3.6 Hz, 1H), 8.03 (dd, J = 1.6 and 6.3 Hz, 1H), 7.59 (dd, J = 1.3 and 5.4 Hz, 1H), 7.43 (d, J = 3.3 Hz, 1H), 7.35 (d, J = 8.1 Hz, 1H), 7.28–7.08 (m, 3H), 6.63 (d, J = 3.0 Hz, 1H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 150.2, 147.8, 143.3, 135.9, 129.0, 127.7, 123.4, 122.6, 121.7, 120.9, 115.7, 111.9, 104.4; IR (KBr): ν = 3055, 2924, 2853, 1567, 1474, 1458, 1330, 1210, 1022, 742, 614 cm^{-1}; HR-MS: m/z = 271.9949, calcd. for $C_{13}H_9BrN_2$ (M+H$^+$): 271.9949.

3-Methyl-1-*p*-tolyl-1*H*-indole (10c):[55] The product was obtained as a colourless oil; yield: 170.2 mg (77%); ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.65–7.52 (m, 2H), 7.37 (d, J = 8.1 Hz, 1H), 7.32–7.12 (m, 6H), 2.43 (s, 3H), 2.40 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 136.1, 131.0, 129.6, 129.1, 128.1, 125.3, 123.1, 121.3, 119.6, 113.8, 111.4, 30.1, 20.6; IR (KBr): ν = 2925, 2962, 2857, 1616, 1512, 793, 756 cm^{-1}; HR-MS: m/z = 221.1204, calcd. for $C_{16}H_{15}N$ (M+H$^+$): 221.1204.

1-(2-Bromophenyl)-3-methyl-1*H*-indole (10d):[23c] The product was obtained as a colourless oil; yield: 210.8 mg (74%); ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.79 (d, J = 8.0 Hz, 1H), 7.68–7.66 (m, 1H), 7.45 (q, J = 8.0 Hz, 2H), 7.34–7.32 (m, 1H), 7.23–7.21 (m, 2H), 7.13–7.11 (m, 1H), 7.06 (s, 1H), 2.44 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 138.9, 137.1, 134.1, 129.9, 129.3, 129.1, 128.4, 126.4, 122.4, 121.9, 119.8, 119.2, 112.5, 110.7, 9.9; IR (KBr): ν = 3053, 2919, 2855, 1615, 1591, 1454, 737 cm^{-}1; HR-MS: m/z = 285.0153, calcd. for $C_{15}H_{12}NBr$ (M+H$^+$): 285.0153.

1-(4-Methoxyphenyl)-2-methyl-1*H*-indole (10e):[56] The product was obtained as white needles; (DCM/ether); yield: 172.9 mg (73%); mp 63–65 °C; ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.58–7.54 (m, 1H), 7.28–7.23 (m, 2H), 7.12–7.05 (m, 4H), 7.02 (d, J = 2.1 Hz, 1H), 6.37 (s, 1H), 3.89 (s, 3H), 2.27 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 159.0, 138.5, 137.4, 130.6, 129.2, 128.0, 120.8, 119.8, 119.5, 114.6, 110.0, 100.7, 55.5, 13.3; HR-MS: m/z = 237.1154, calcd. for $C_{16}H_{15}NO$ (M+H$^+$): 237.1154.

1-(2-Bromophenyl)-1*H*-pyrrole (10f):[57] The product was obtained as a colourless oil; yield: 163.5 mg (74%); ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.71 (dd, J = 1.0 and 6.9 Hz, 1H), 7.42–7.34 (m, 2H), 7.25 (dd, J = 2.0 and 6.0 Hz, 1H), 6.90 (t, J = 2.0 Hz, 2H), 6.37 (t, J = 2.0 Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 140.5, 133.9, 128.9, 128.4, 128.3, 122.4, 120.0, 109.3; HR-MS: m/z = 220.9840, calcd. for $C_{10}H_8BrN$ (M+H$^+$): 220.9840.

Bis(4-methoxyphenyl)amine (10g):[58] The product was obtained as colourless needles (ether/hexane); yield: 121.4 mg (53%); mp 97–98 °C; ^{1}H NMR (400 MHz, DMSO-d_6): δ = 7.52 (brs, 1H), 6.90 (d, J = 8.1 Hz, 4H), 6.81–6.78 (m, 4H), 3.67 (S, 6H); ^{13}C NMR (100 MHz, DMSO-d_6): δ = 152.8, 138.0, 118.1, 114.5, 55.2; IR (KBr): ν = 3421, 2958, 2937, 2914, 2839, 1510, 1298, 1240, 1221, 1180, 829, 816, 762 cm^{-1}; HR-MS: m/z = 229.1108, calcd. for $C_{14}H_{15}NO_2$ (M+H$^+$): 229.1103.

General Procedure for the S-Arylation Reaction (12a–f)

To a round-bottomed flask containing 1.0 mmol of ArX 1, 1.4 mmol of KO-*t*-Bu, 1.0 mol% of $Pd(OAc)_2$ and 1.0 mol% of **L4**, 2.0 mL of solvent were added under a nitrogen atmosphere. After that thiophenol (**11**) 1.0 equiv. was added in the reaction mixture, which was stirred vigorously for 12 h at 100 °C. After the completion of reaction, ethyl acetate was added to the reaction mixture and the whole washed with water. The organic layer was collected, dried over Na_2SO_4, evaporated under vacuum, and the residue was purified by column chromatography to afford the desired product (ethyl acetate/hexane).

(4-Methoxyphenyl)(*p*-tolyl)sulfane (12a):[59] The product was obtained as a colourless oil; yield: 215.1 mg (94%); ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.29–7.24 (m, 4H), 6.87–6.83 (m, 4H), 3.78 (s, 3H), 2.44 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 158.1, 130.1, 128.7, 114.6, 55.3, 18.0; IR (KBr): ν = 3003, 2936, 2835, 1590, 1491, 1475, 1288, 1247, 1172, 1030, 825, 636, 622 cm^{-1}; HR-MS: m/z = 230.0765, calcd. for $C_{14}H_{14}OS$ (M+H$^+$): 230.0765.

Phenyl(*o*-tolyl)sulfane (12b):[60] The product was obtained as a colourless oil; yield: 86.1 mg (93%); ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.51–7.48 (m, 2H), 7.32–7.27 (m, 5H), 7.26–7.22 (m, 1H), 7.19–7.11 (m, 1H), 2.48 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 137.5, 137.0, 132.2, 131.2, 130.0, 129.7, 128.9, 126.3, 21.0; HR-MS: m/z = 200.0661, calcd. for $C_{13}H_{12}S$ (M+H$^+$): 200.0660.

2-(*p*-Tolylthio)pyridine (12c):[61] The product was obtained as a colourless oil; yield: 185.0 mg (92%); ^{1}H NMR (300 MHz, $CDCl_3$): δ = 8.41 (dd, J = 2.4 and 3.6 Hz, 1H), 7.51–7.47 (m, 2H), 7.42 (dt, J = 5.7 and 1.8 Hz, 1H), 7.26–7.23 (m, 2H), 6.99–6.94 (m, 1H), 6.83 (d, J = 6.0 Hz, 1H), 2.39 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 162.2, 149.5, 139.4, 136.6, 135.2, 130.4, 127.2, 120.8, 119.6, 21.3; HR-MS: m/z = 201.0612, calcd. for $C_{12}H_{11}NS$ (M+H$^+$): 201.0612.

2,3,4,5-Tetrakis(4-methoxyphenylthio)thiophene (12d): The product was obtained as a colourless oil; yield: 527.9 mg (83%); ^{1}H NMR (400 MHz, $CDCl_3$): δ = 7.40–7.37 (m, 3H), 7.29–7.25 (m, 5H), 6.85–6.79 (m, 8H), 3.78 (s, 3H), 3.75 (s, 9H); ^{13}C NMR (100 MHz, $CDCl_3$): δ = 160.5, 159.6, 158.7, 148.6, 136.0, 135.3, 132.7, 131.1, 129.3, 125.8, 124.9, 123.9, 122.8, 115.1, 114.8, 114.5, 55.3 (2C), 55.2 (2C); IR (KBr): ν = 3001, 2936, 2834, 1590, 1572, 1492, 1461, 1289, 1247, 1172, 1030, 825, 798 cm^{-1}; HR-MS: m/z = 636.0589, calcd. for $C_{32}H_{28}O_4S_5$ (M+H$^+$): 636.0591.

(2-Methoxyphenyl)(*o*-tolyl)sulfane (12e):[62] The product was obtained as a colourless oil; yield: 199.1 mg (87%); ^{1}H NMR (300 MHz, $CDCl_3$): δ = 7.34 (d, J = 7.2 Hz, 1H), 7.27–7.13 (m, 4H), 6.78–6.72 (m, 3H), 3.74 (s, 3H), 2.38 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$): δ = 160.0, 140.3, 137.6, 133.4, 133.2, 130.6, 129.9, 128.1, 126.7, 121.5, 114.8, 111.9, 55.2, 20.6; HR-MS: m/z = 230.0765, calcd. for $C_{14}H_{14}OS$ (M+H$^+$): 230.0765.

(4-Methoxyphenyl)(octyl)sulfane(12f):[62] The product was obtained as a yellow oil; yield: 168.9 mg (67%); ^{1}H NMR (400 MHz, $CDCl_3$): $\delta = 7.34$ (dd, $J = 6.6$ and 2.2 Hz, 2H), 6.77 (dd, $J = 6.6$ and 2.2 Hz, 2H), 3.72 (s, 3H), 2.74 (t, $J = 7.3$ Hz, 2H), 2.43–2.41 (m, 2H), 1.55–1.46 (m, 6H), 1.32–1.28 (m, 2H), 1.21–1.18 (m, 2H), 0.82–0.78 (m, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): $\delta = 158.7$, 132.9, 126.9, 114.4, 55.3, 35.8, 34.3, 31.8, 29.1, 28.8, 22.6, 15.5, 14.1; IR (KBr): $\nu = 2954$, 2925, 2854, 1593, 1493, 1463, 1284, 1245, 1035, 826, 638 cm^{-1}; HR-MS: $m/z = 252.1550$, calcd. for $C_{15}H_{24}OS$ ($M + H^+$): 252.1548.

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