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Accessing Heteroannular Benzoxazole and Benzimidazole Scaffolds via Carbodiimides Using Azide−Isocyanide Cross-Coupling as Catalyzed by Mesoionic Singlet Palladium Carbene Complexes Derived from a Phenothiazine Moiety

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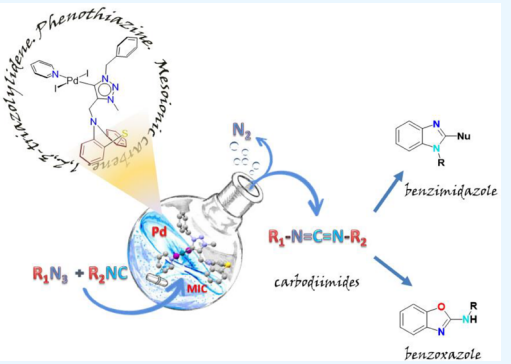
ABSTRACT: The coupling of aryl and aliphatic azides with isocyanides yielding carbodiimides (**8**−**17**) were efficiently catalyzed by well-defined structurally characterized *trans*-(MIC)PdI_2(L) [MIC = 1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazol-5-ylidene, L = NC_5H_5 (**4**), MesNC (**5**)], *trans*-$(MIC)_2PdI_2$ (**6**), and *cis*-(MIC)$Pd(PPh_3)I_2$ (**7**) type palladium complexes, which incidentally mark the first instances of the use of mesoionic singlet palladium carbene complexes for the said application. As observed from the product yields, the catalytic activity varied in the order **4** > **5** ∼ **6** > **7** for these complexes. A detailed mechanistic studies indicated that the catalysis proceeded via a palladium(0) (**4a**−**7a**) species. Using a representative palladium precatalyst (**4**), the azide−isocyanide coupling was successfully extended to synthesizing two different bioactive heteroannular benzoxazole (**18**−**22**) and benzimidazole (**23**−**27**) derivatives, thereby broadening the scope of the catalytic application.



INTRODUCTION

Carbodiimides have long evoked interest for over half a century now, primarily for their diverse range of applications varying from peptide synthesis to phosphorylation reactions to dehydration reactions.[1−3] Their biocompatibility and non-toxicity make them well-suited for peptide synthesis as cross-linkers providing "zero-length" amide linkages between carboxylic and amine groups.[4] In organic synthesis, carbodiimides, belonging to the heterocumulene family of compounds and containing two adjacent C═N bonds, are also of sustained interest as they provide a unique opportunity for synthesizing N-heterocycles, which are known for their pharmaceutical properties.[5,6] The N-heterocycles constitute common fragments in marketed drugs and medicinal chemistry targets as a part of the drug discovery initiatives.[1] Hence, convenient access routes to these important carbodiimide class of compounds are in demand,[7] and catalytically achieving that remains a challenging objective. Carbodiimides, with two adjacent C═N bonds, make synthons for N-heterocycles.[1,5]

A common approach involves the decarboxylative coupling of isocyanates, leading to the elimination of CO_2.[3] The method is primarily restricted to preparing symmetrical carbodiimides, as the selectivity between the homocoupled and heterocoupled products becomes an issue in coupling between different isocyanates. Notably, the syntheses of the more synthetically challenging unsymmetrical carbodiimides are obtained in a stoichiometric fashion by aza-Wittig reactions of phosphinimines with isocyanates[8] and by the Sn-mediated metathesis of isocyanates and silyl amines.[9] Under heterogeneous conditions, the catalytic oxidative coupling of primary amines to isocyanides using gold[10] or $PdCl_2/Ag_2O$[11] produces carbodiimides.

However, an esoteric organometallic approach involving transition metal-mediated nitrene transfer in an azide−isocyanide coupling provides a more efficient atom economic approach to these carbodiimides.[12−14] The appeal of this method resides in the easy and convenient synthetic access available for different azides, the simplicity of the process for preparing the symmetrical and unsymmetrical carbodiimides, and the generation of the environmentally benign dinitrogen as the only byproduct of the reaction.

Judicious exploitation of this method allows for the construction of a variety of bioactive heterocycles[15] like the benzoxazoles known for their antibiotic, antifungal, antiviral, antitumor, antiulcer, antibacterial, anti-inflammatory, antitubercular, and analgesic properties[16,17] that rightfully constitute the core motif of a chiral nonsteroidal anti-inflammatory drug, flunoxaprofen.[18] This approach also allows synthesis of other

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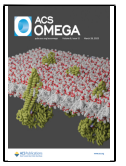


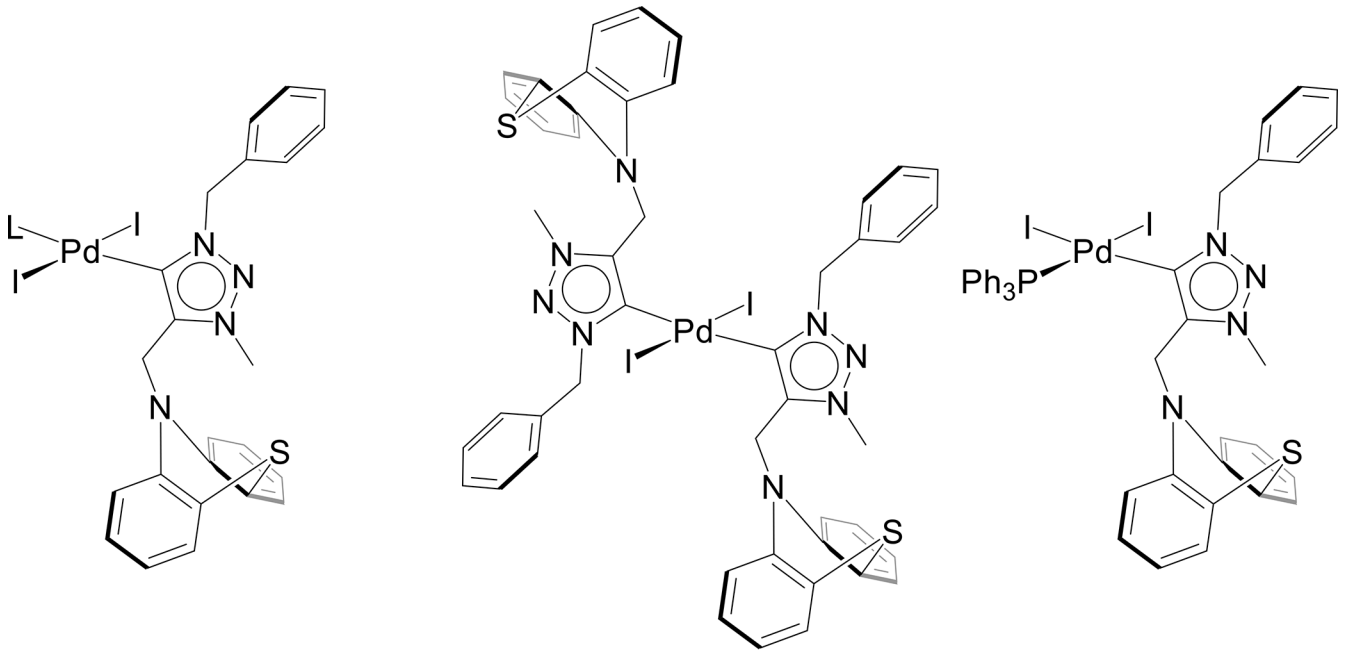
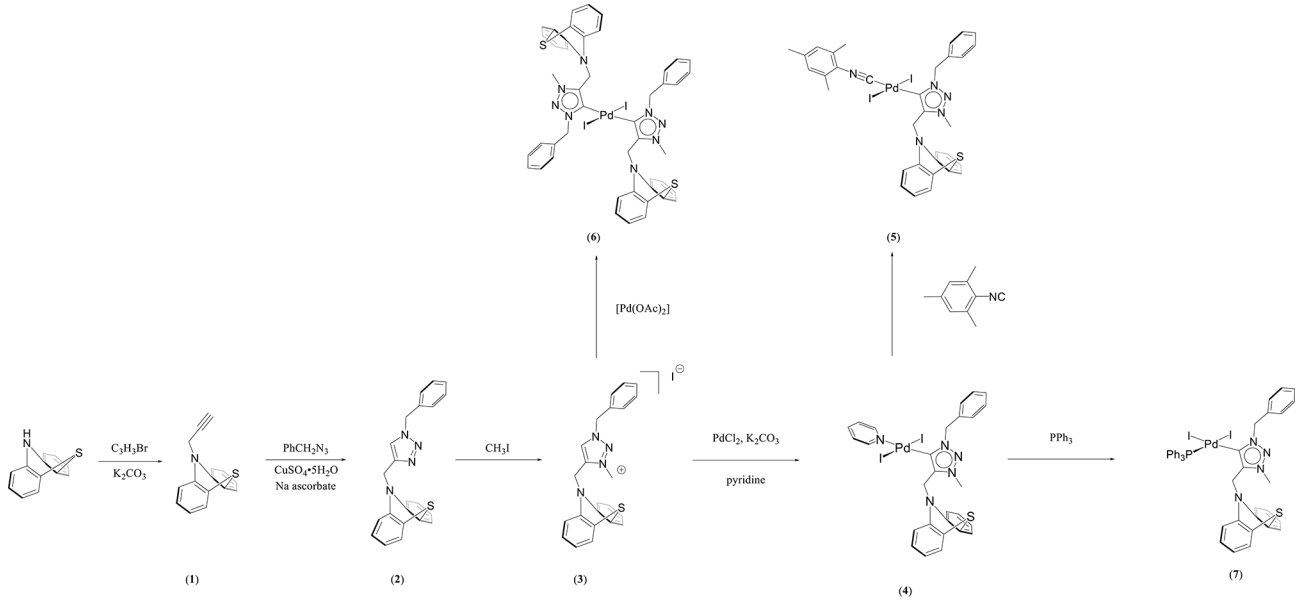


Figure 1. Synthesized phenothiazine-derived mesoionic singlet carbene complexes of palladium (**4**−**7**).

Scheme 1. Synthetic Routes to the Compounds (1−3) and the Phenothiazine-Derived Mesoionic Singlet Carbene Complexes of Palladium (4−7)



important N-heterocycles like the benzimidazoles having pharmaceutical and industrial applications.[19]

With our interest in exploring the potentials of the transition metal complexes of the heteroatom stabilized cyclic and acyclic singlet carbene ligands in homogeneous catalysis[20−25] and in biomedical applications,[26] we study different singlet-carbene ligand classes covering the cyclic normal N-heterocyclic carbenes,[27] abnormal mesoionic carbenes[25,28] the acyclic diaminocarbenes[22,29] and the fused-cyclic ones of the imidazole,[30] benzimidazole,[31] triazole,[23,24,32] oxazolidine,[33] bioxazoline,[34] and triazolooxazine[35] architectures. The mesoionic (MIC) carbenes, featuring less heteroatom stabilization than the more ubiquitous normal N-heterocyclic carbenes,[36] come with specific donors and reactivity properties but surprisingly remain less explored.[37] Because of the reasons mentioned above, we decided to study the catalytic utility of the transition metal complexes of the 1,2,3-triazole-derived mesoionic carbene in the azide−isocyanide coupling reaction for the synthesis of carbodiimides. In this regard, we decided to design a new type of the 1,2,3-triazole-derived mesoionic carbene ligand bearing phenothiazine moiety. Of late, phenothiazine has received attention for its organic light-

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emitting diodes (OLEDs), photovoltaic devices, data storage, sensors, and bioimaging applications but with no footprint in chemical catalysis.[38] Hence, we decided to pursue the potential of the phenothiazine-based 1,2,3-triazole-derived mesoionic carbene stabilized transition metal complexes in the azide−isocyanide coupling reaction.

Here, in the manuscript, we report a convenient synthetic route to various carbodiimide compounds (**8**−**17**) by the azide−isocyanide coupling mediated by palladium complexes (**4**−**7**) (Figure 1) of a new phenothiazine-based 1,2,3-triazole derived mesoionic carbene ligand. Further, we demonstrate their utility in synthesizing two bioactive heteroannular benzoxazole (**18**−**22**) and benzimidazole (**23**−**27**) derivatives.

RESULTS AND DISCUSSIONS

A new phenothiazine-derived mesoionic singlet carbene ligand namely, 1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazol-5-ylidene, was designed primarily for the reasons of exploring its utility in transition metal mediated homogeneous catalysis applications. This new class of phenothiazine functionalized 1,2,3-triazole derived N-heterocyclic carbene ligand was conveniently obtained from its triazolium iodide salt, 1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazolium iodide (**3**), by the alkylation reaction of 10-[(1-benzyl-1*H*-1,2,3-triazol-4-yl)methyl]-10*H*-phenothiazine (**2**) with MeI in *ca.* 99% yield (Scheme 1). The formation of **3** was confirmed by the observation of the characteristic (NCHC) resonance at δ *ca.* 9.52 ppm in the ^{1}H NMR spectrum and at δ *ca.* 143.1 in $^{13}C\{^1H\}$ NMR spectrum (Supporting Information, Figures S13−S16). The corresponding NCH_3 resonance appeared at δ *ca.* 4.26 ppm in ^{1}H NMR, and at δ *ca.* 39.6 ppm in $^{13}C\{^1H\}$ NMR. The Cu mediated click reaction between 10-(prop-2-yn-1-yl)-10*H*-phenothiazine (**1**) and benzyl azide yielded the desired phenothiazine functionalized 1,2,3-triazole derivative (**2**) in *ca.* 65% yield.[39]

The 1,2,3-triazolium iodide salt (**3**) provided a convenient platform for accessing a large number of transition metal complexes. For example, the direct metalation reaction of (**3**) with $PdCl_2$ in pyridine, in the presence of K_2CO_3 as base yielded *trans*-[1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazol-5-ylidene]$PdI_2(NC_5H_5)$ (**4**) complex in 95% yield (Scheme 1). As expected, the *o*-NC_5H_5 resonance of the metal bound pyridine moiety appeared significantly downfield shifted at δ *ca.* 9.05 ppm as opposed to that of δ *ca.* 8.62 ppm for free pyridine in the ^{1}H NMR[40] (Supporting Information, Figures S20 and S21).

Furthermore, the characteristic Pd−$C_{carbene}$ peak at δ *ca.* 139.0 ppm (Supporting Information, Figures S22−S23) in the $^{13}C\{^1H\}$ NMR spectra of (**4**) is comparable to that observed for related *trans*-[1-Ph-3-Me-4-Ph-1,2,3-triazol-5-ylidene]-$PdI_2(NC_5H_5)$ (δ *ca.*139.8 ppm),[41] *trans*-[{(*S*)-7-CH_2Ph-2-Me-6,7-dihydro-4H-[1,2,3]-triazolo[5,1-*c*][1,4]oxazin-3-ylidene}$PdI_2(NC_5H_5)$ (δ *ca.*138.5 ppm)[35] and the other structurally characterized examples known in the literature (Supporting Information, Table S2).

As expected, the molecular structure of **4** (Figure 2 and Supporting Information, Table S1), as determined by the single crystal X-ray diffraction study, exhibited a nonplanar butterfly structure with the S and N heteroatoms occupying the 1,4 apical positions, while the two aromatic rings are pointed outward from the (2,3) and (5,6) positions of a boat confirmation, consistent with commonly observed conformation of a phenothiazine moiety.[42] In agreement with the d^8 configuration of a palladium(II) center, a square planar geometry was

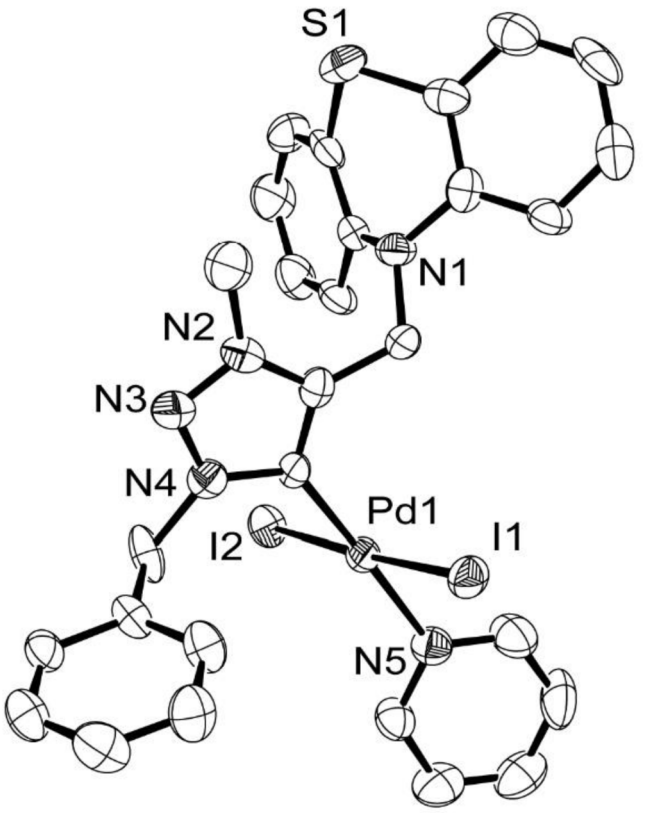

Figure 2. ORTEP diagram of **4** with thermal ellipsoids are shown at the 50% probability level. Selected bond lengths (Å) and angles (deg): Pd(1)−C(1) 1.981(5), Pd(1)−I(1) 2.6069(8), Pd(1)−I(2) 2.6104(8), Pd(1)−N(5) 2.105(7), I(2)−Pd(1)−I(1) 177.06(3), N(5)−Pd(1)−I(1) 90.34(19), N(5)−Pd(1)−I(2) 91.55(19), C(1)−Pd(1)−I(1) 88.0(2), C(1)−Pd(1)−I2 90.2(2), and C(1)−Pd(1)−N(5) 176.9(3).

observed for **4** with the mesoionic 1,2,3-trizole based N-heterocyclic carbene ligand and the "'throwaway'" pyridine moiety disposed at opposite ends of a near linear angle at the metal center [$\angle$C(1)−Pd(1)−N(5) = 176.9(3)°] while two more iodine atoms occupied the other two *trans* positions [$\angle$I(2)−Pd(1)−I(1) = 177.06(3)°].

The Pd−$C_{carbene}$ bond distance of 1.981(8) Å in (**4**) compared well with the representative reported analogues, namely *trans*-[1-Ph-3-Me-4-Ph-1,2,3-triazol-5-ylidene]$PdI_2(NC_5H_5)$ [1.971(6) Å][41] and *trans*-{(S)-7-CH_2Ph-2-Me-6,7-dihydro-4*H*-[1,2,3]-triazolo[5,1-*c*][1,4]oxazin-3-ylidene}$PdI_2(NC_5H_5)$ [1.974(9) Å].[35] (Supporting Information, Table S2).

A rare isocyanide bound palladium complex, *trans*-[1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazol-5-ylidene]PdI_2(CN−Mes) (**5**), was prepared by the treatment of (**4**) with MesNC at ambient temperature in *ca.* 50% yield (Scheme 1). To the best of our knowledge, the palladium complex (**5**) represents the only reported example of a (MIC)PdI_2(CN−R) type complex of a mesoionic 1,2,3-triazole derived N-heterocyclic carbene. However, a handful of related analogues are known for benzimidazole[43,44] and indazole derived N-heterocyclic carbenes.[44] (Supporting Information, Table S3). Given the fact that all of these mixed carbene/isocyanide complexes were synthesized from a dimeric halide-bridged complex by treatment with the aliphatic and aromatic isocyanides,[43,44] the current method for the preparation of **5** offers a new way for accessing these type of mixed carbene/isocyanide complexes.

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Of foremost importance to a mixed carbene/isocyanide themed precatalyst (**5**) is the metal bound isocyanide moiety. The successful coordination of MesNC to the Pd(II) center was evident from the $^{13}C\{^1H\}$ NMR spectra for complex **5**, where the Pd−CN signal appeared as a broad triplet at δ *ca.*138.7 ppm and was significantly downfield shifted ($\Delta\delta$ = *ca.* 14.6 ppm) in comparison to the free MesNC (δ *ca.*124.1 ppm) (Supporting info Figures S29 and S30). An analogue shift of ($\Delta\nu$) *ca.* 73 cm^{-1} was observed for (ν(CN) = 2188 cm^{-1}) in IR spectroscopy with respect to the free MesNC (ν(CN) = 2115 cm^{-1}).[45]

Single-crystal X-ray diffraction study revealed a square planar geometry for complex **5** (Figure 3 and Supporting Information, Table S1) analogous to that of complex **4**. Quite interestingly, an elongation of the Pd−$C_{carbene}$ bond length in **5** [2.002(5) Å] with respect to **4** [1.981(8) Å)], suggests a stronger *trans*-effect of the MesNC moiety in the former than the pyridine moiety in latter. Consistently, the Pd−CNMes bond length in (**5**) [1.970(5) Å] is significantly shorter than the sum of individual covalent radii of Pd and C_{sp} atoms [2.08 Å].[46] This observation is in agreement with a reported mixed indazole-carbene/isocyanide complex, *trans*-[1,2-Me_2-indazol-3-ylidene]PdI_2(CN−Xyl), [*d*/(Pd−$C_{carbene}$) = 2.002(5) Å and *d*/(Pd−CN) = 1.993(5) Å].[44] The benzimidazole derived analogues, *trans*-[1,3-Me_2-benzimidazol-2-ylidene]PdI_2(CN−Xyl)[44] [*d*/(Pd−$C_{carbene}$) = 1.996(3) Å and *d*/(Pd−CN) = 1.986(4) Å], *trans*-[1,3-Me_2-benzimidazol-2-ylidene]PdI_2(CN−Cy), [*d*/(Pd−$C_{carbene}$) = 1.986(4) Å and *d*/(Pd−CN) = 1.993(5) Å],[44] however, do not show such a profound *trans*-effect.

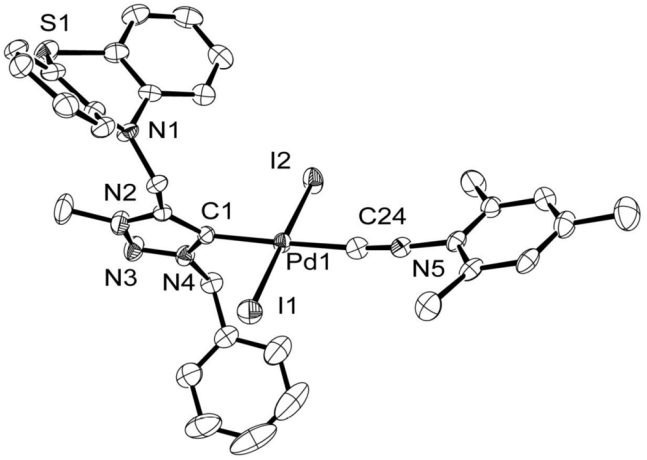


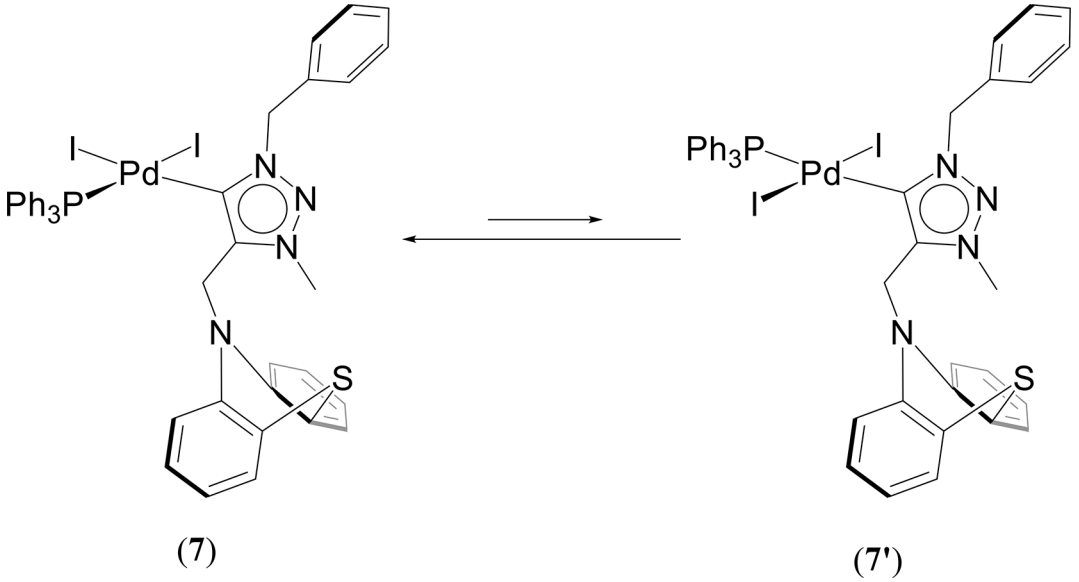
Figure 3. ORTEP diagram of **5** with thermal ellipsoids are shown at the 50% probability level. Selected bond lengths (Å) and angles (deg): Pd(1)−C(1) 2.002(5), Pd(1)−I(1) 2.5892(5), Pd(1)−I(2) 2.6144(5), Pd(1)−C(24) 1.970(5), I(2)−Pd(1)−I(1) 178.11(2), C(24)−Pd(1)−I(1) 89.85(15), C(24)−Pd(1)−I(2) 90.14(15), C(1)−Pd(1)−I(1) 88.07(14), C(1)−Pd(1)−I2 92.07(14), and C(1)−Pd(1)−C(24) 175.6(2).

The complex (**4**), when treated with PPh_3, gave a mixed carbene/PPh_3 type complex *cis*-[1-CH_2Ph-3-Me-4-(CH_2N-$(C_6H_4)_2$S)-1,2,3-triazol-5-ylidene]Pd(PPh_3)I_2 (**7**) in *ca.* 80% yield at ambient temperature (Scheme 1).

Quite interestingly, the ^1H, $^{13}C\{^1H\}$ and $^{31}P\{^1H\}$ NMR, all convincingly pointed at the existence of an equilibrium between *cis*-(**7**) and *trans*-(**7′**) species in solution at ambient temperature (Scheme 2 and Supporting Information, Figures S41−S45). Specifically, in the ^1H NMR spectrum, the NC$\underline{H}_3$ resonance appeared at δ *ca.* 3.71 ppm for *cis*-(**7**) and at δ *ca.* 4.05 ppm for *trans*-(**7′**) in *ca.* 3.4:1 ratio. Indeed, in the variable temperature ^1H NMR experiment, the ratio of the NC$\underline{H}_3$ resonances, one that appeared at δ *ca.* 3.71 ppm for *cis*-(**7**) and the other at δ *ca.* 4.05 ppm for *trans*-(**7′**), changed from *ca.* 3.4:1 at 25 °C to *ca.* 1:1 at 100 °C. (Supporting Information, Figures S219−S220). In the spin saturation ^1H NMR experiment, when the NCH_3 moiety of *cis*-(**7**) was irradiated at δ *ca* 3.71 ppm, the intensity of the NCH_3 moiety of *trans*-(**7′**) at δ *ca.* 4.05 ppm decreased and vice versa, thereby attesting to the equilibrium present between the two species in solution (Supporting Information, Figure S221).

Furthermore, diastereotopic resonances were observed for both the C$\underline{H}_2$Ph and NC$\underline{H}_2$ moieties in *cis*-(**7**), with a doublet pair observed at δ *ca.* 5.94 ppm and δ *ca* 5.07 ppm and at δ *ca.* 5.40 ppm and δ *ca.* 4.19 ppm, exhibiting geminal ($^2J_{HH}$) coupling

Scheme 2. ^1H NMR Analysis Showing Equilibrium between *cis*-(7) and *trans*-(7′) in *ca.* 3.4:1 Ratio in Solution at Room Temperature



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constants of 14 and 15 Hz respectively. In contrast, both the C$\underline{H}_2$Ph and NC$\underline{H}_2$ resonances were singlets at δ *ca.* 5.86 ppm and at δ *ca.* 5.43 ppm respectively for the *trans*-(7′) complex. The $^{13}C\{^1H\}$ NMR of *cis*-(7) too showed the complete set of isomeric peaks due to the presence of the minor isomer *trans*-(7′) in solution. In the $^{31}P\{^1H\}$ NMR, the Pd−$\underline{P}Ph_3$ resonance at δ *ca.* 25.0 ppm was attributed to *cis*-(7), based on the reported examples, *cis*-[1-Et-3-Me-4-$C_{12}H_9$-1,2,3-triazol-5-ylidene]Pd-$(PPh_3)I_2$ (δ ca. 25.8 ppm)[47] and *cis*-[1-CH_2Ph-3-Me-4-Ph-1,2,3-triazol-5-ylidene]Pd$(PPh_3)I_2$ (δ *ca.* 25.2 ppm).[25] (Supporting Information, Table S4), while the other upfield shifted Pd−$\underline{P}Ph_3$ resonance at δ *ca.* 15.9 ppm was assigned to the *trans*-(7′), based on the related analogues, *trans*-[1-CH_2Ph-3-Et-4-C_6H_{10}OH-1,2,3-triazol-5-ylidene]Pd$(PPh_3)I_2$[25] (δ ca. 16.9 ppm) and *trans*-[1-CH_2Ph-3-Me-4-C_6H_{10}OH-1,2,3-triazol-5-ylidene]Pd$(PPh_3)I_2$ (δ ca. 17.0 ppm).[25]

The structural characterization using single crystal X-ray diffraction study revealed a *cis* complex (7) (Figure 4 and

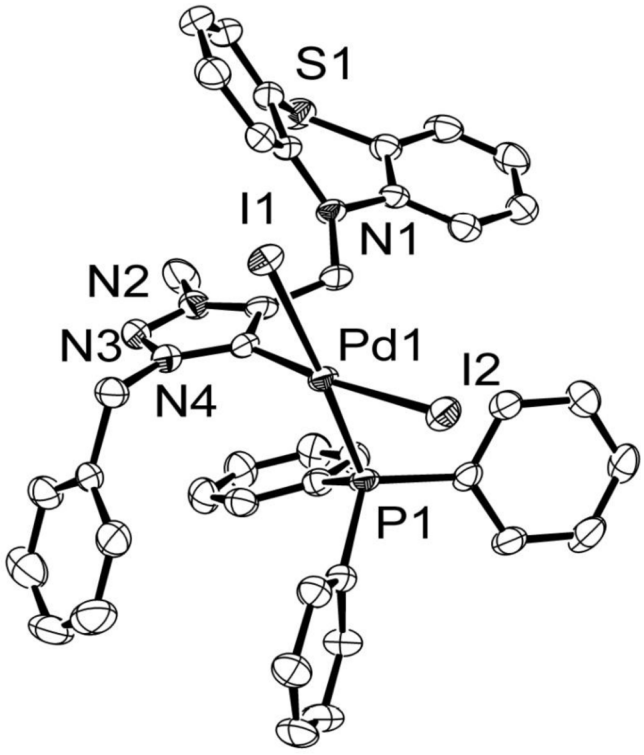

Figure 4. ORTEP diagram of 7 with thermal ellipsoids are shown at the 50% probability level. Selected bond lengths (Å) and angles (deg): Pd(1)−C(1) 2.001(7), Pd(1)−I(1) 2.6381(6), Pd(1)−I(2) 2.6633(7), Pd(1)−P(1) 2.2950(17), I(1)−Pd(1)−I(2) 91.98(2), C(1)−Pd(1)−I(1) 87.18(19), C(1)−Pd(1)−I(2) 174.17(19), C(1)−Pd(1)−P(1) 91.29(19), P(1)−Pd(1)−I2 89.81(5), and P(1)−Pd(1)−I(1) 176.93(5).

Supporting Information, Table S1), in which the mesoionic 1,2,3-trizole based N-heterocyclic carbene ligand and the PPh_3 moieties were in *cis* disposition around the square planar palladium(II) metal center [∠C(1)−Pd(1)−P(1) = 91.29(19)°] with the other two sites occupied by the iodine atoms [∠I(1)−Pd(1)−I(2) = 91.98(2)°]. Furthermore, the Pd−$C_{carbene}$ [2.001(7) Å] and Pd−$P_{phosphine}$ [2.2950(17) Å] bond distances in *cis*-(7) were in good agreement with other related complexes, namely *cis*-[1-Ph-3-Me-4-*n*-Bu-1,2,3-triazol-5-ylidene]Pd$(PPh_3)I_2$ [d/(Pd−$C_{carbene}$) = 2.000(4) Å, d/(Pd−$P_{phosphine}$) = 2.2789(10) Å][48] and *cis*-[1-CH_2Ph −3-Me-4-Ph-1,2,3-triazol-5-ylidene]Pd$(PPh_3)I_2$ [d/(Pd−$C_{carbene}$) = 2.006(6) Å, d/(Pd−$P_{phosphine}$) = 2.2804(17) Å][25] (Supporting Information, Table S4).

The metalation of the triazolium iodide salt (3) with $Pd(OAc)_2$ quantitatively yielded the *trans*-[1-CH_2Ph-3-Me-4-$(CH_2N(C_6H_4)_2S)$-1,2,3-triazol-5-ylidene]$_2PdI_2$ complex (6) in 93% yield (Scheme 1). In this case too, two sets of resonances were observed in both the ^1H and $^{13}C\{^1H\}$ NMR spectra signifying the presence of two conformers *i.e. trans-anti* and *trans-syn* (Supporting Information, Figures S34−S37). In the ^1H NMR spectrum, the sterically favored *trans-anti* isomer appeared in a *ca.* 1.7:1 ratio over the *trans-syn* conformer at 25 °C, which changed to *ca.* 1.5:1 at 50 °C. (Supporting Information, Figure S218).[49] In $^{13}C\{^1H\}$ NMR spectra, two closely spaced Pd−$C_{carbene}$ signals for the *trans-anti* and *trans-syn* conformers of **6** appeared at 156.7 and 156.4 ppm, respectively.

The complex (6) is among the few structurally characterized examples of the $(MIC)_2PdI_2$ type complexes supported over a 1,2,3 triazole-derived mesoionic N-heterocyclic carbene ligand known in the literature (Supporting Information, Table S5). The square planar complex (6) (Figure 5 and Supporting

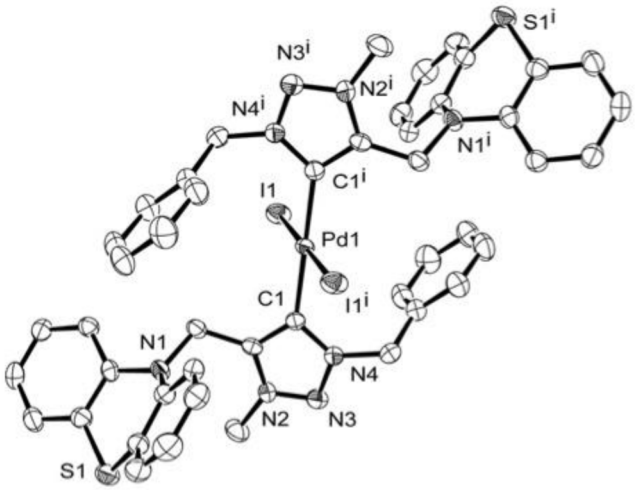

Figure 5. ORTEP diagram of **6** with thermal ellipsoids are shown at the 50% probability level. Selected bond lengths (Å) and angles (deg): Pd(1)−C(1) 2.030(4), Pd(1)−I(1) 2.6107(3), and C(1)−Pd(1)−I(1) 88.66(10).

Information, Table S1) was surrounded by two mesoionic carbene units in [∠C(1)−Pd(1)−C(1^i) = 180.0°], while two iodide atoms occupied the remaining two diametrically opposite sites [∠I(1)−Pd(1)−I(1^i) = 180.0°]. In addition, the observed Pd−$C_{carbene}$ bond distance of 2.030(4)Å and the Pd−I bond distance of 2.6107(3) Å were in close range to that reported for similar complexes, namely, *trans*-[1-Ph-3-Me-4-Ph-1,2,3-triazol-5-ylidene]$_2PdI_2$ [d/(Pd−$C_{carbene}$) = 2.026(6) Å, d/(Pd−I) = 2.6174(5) Å][50] and *trans*-[1-Et-3-Me-4-Ph-1,2,3-triazol-5-ylidene]$_2PdI_2$ [d/(Pd−$C_{carbene}$) = 2.049(3) Å, d/(Pd−I) = 2.6181(3) Å].[51] (Supporting Information, Table S5).

The palladium (4−7) complexes efficiently carried out the coupling of aryl and aliphatic azides with different isocyanides yielding carbodiimides in the presence of a base (Table 1, 2, 3 and Supporting Information, Table S6−S12). A series of optimization experiments on the representative pair of substrates, namely phenyl azide and benzyl isocyanide, with a

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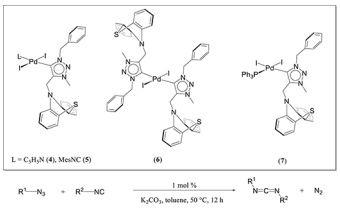
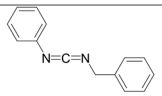
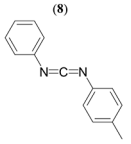
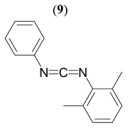
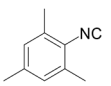
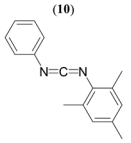
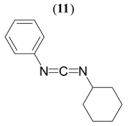
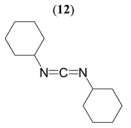
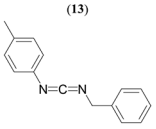
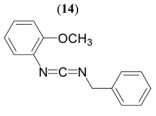
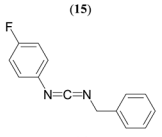
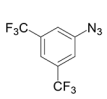
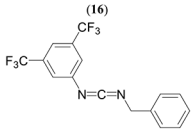
Table 1. Selected Results for Phenothiazine-Derived Mesoionic Singlet Carbene Palladium (4−7) Complexes Catalyzed Azide−Isocyanide Coupling Yielding Carbodiimides[a,b]



S. No.	azide	isocyanide	Product	Pd−MIC (**4**)	Pd−MIC (**5**)	Pd−MIC (**6**)	Pd−MIC (**7**)
				yield[b]	yield[b]	yield[b]	yield[b]
1			 (**8**)	88	79	66	48
2			 (**9**)	94	85	74	52
3			 (**10**)	78	62	50	24
4			 (**11**)	61	53	39	16
5			 (**12**)	94	92	76	32
6			 (**13**)	84	67	54	37
7			 (**14**)	66	54	39	28
8			 (**15**)	56	38	26	12
9			 (**16**)	99	93	80	61
10			 (**17**)	91	75	65	44

[a]Reaction conditions: azide (0.369 mmol), isocyanide (0.443 mmol), complex (**4**/**5**/**6**/**7**) (0.003 mmol, 1 mol %) and K_2CO_3 (1.10 mmol) in 5.0 mL of toluene at 50 °C for 12 h. [b]Isolated yields (%).

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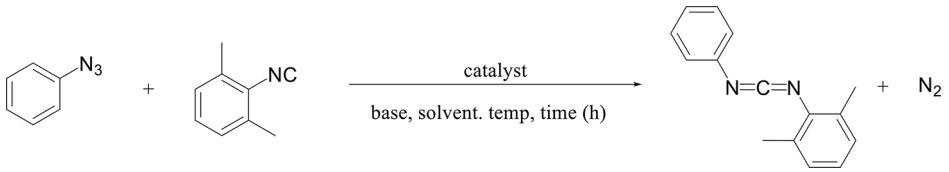
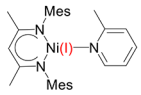
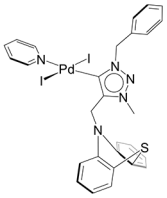
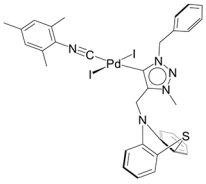
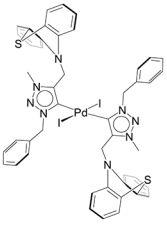
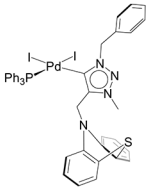
Table 2. Comparison of the Reaction Yield and Turnover Number (TON) Calculated with Respect to the Formation of *N*-[(Xylylimino)methylene]aniline in the Catalyzed Azide−Isocyanide Coupling Reaction of the Representative Phenyl Azide and 2,6-Dimethylphenyl Isocyanide Substrates as Catalyzed by 4−7 and other Transition Metal Complexes Known in the Literature



S. No.	catalyst	base	time (h)	solvent	catalyst loading	temperature	yield (%)	TON	reference
1.	$[Pd(PPh_3)_4]$	-	5	THF	2.5 mol %	room temperature	82 (by ^{1}H NMR)	33	[55]
2.		-	17	Et_2O	5 mol %	−35 °C to room temperature	99 (by ^{1}H NMR)	20	[14]
3.	 (**4**)	K_2CO_3 (3 equiv.)	12	toluene	1 mol %	50 °C	78 (isolated)	78	this work
4.	 (**5**)	K_2CO_3 (3 equiv)	12	toluene	1 mol %	50 °C	62 (isolated)	62	this work
5.	 (**6**)	K_2CO_3 (3 equiv.)	12	toluene	1 mol %	50 °C	50 (isolated)	50	this work
6.	 (**7**)	K_2CO_3 (3 equiv.)	12	toluene	1 mol %	50 °C	24 (isolated)	24	this work

representative precatalyst (**4**) provided the optimal catalysis conditions. As expected, the blank run performed without the precatalyst (**4**) and the base, produced no product for the aforementioned substrates (entry 1, Supporting Information, Table S12). The control run, performed only in the presence of the base K_2CO_3, too yielded no detectable product (entry 2, Supporting Information, Table S12). The control runs performed with the metal precursor $Pd_2(dba)_3$ gave *ca.* 41% product yield (entry 4, Supporting Information, Table S12) and that with **4** yielded no detectable product (entry 9, Supporting Information, Table S12). However, the same run when performed with $Pd_2(dba)_3$ and with **4** in the presence of the base K_2CO_3 produced *N*-[(benzylimino)methylene]aniline (**8**) in *ca.* 37% (entry 5, Supporting Information, Table S12) and *ca.* 88% (entry 10, Supporting Information, Table S12) yields respectively. Additional control runs involving the ligand precursor (**3**) in the presence of K_2CO_3 base showed no detectable product formation, thereby highlighting the significant influence played by the palladium (**4**−**7**) precatalysts in the azide−isocyanide coupling reaction (entry 3, Supporting

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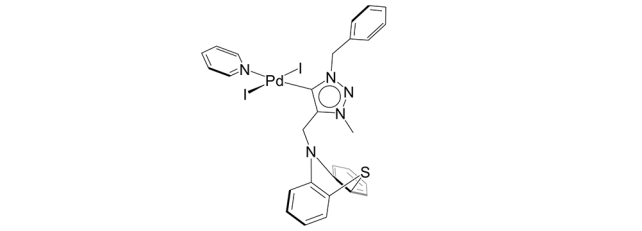
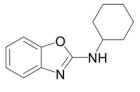
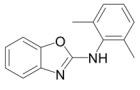
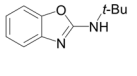
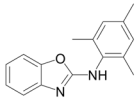
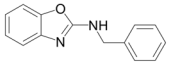
Table 3. Selected Results for a Simple Practical Synthesis of a Variety of Benzoxazole Derivatives Using Azide−Isocyanide Coupling Catalyzed by a Phenothiazine-Derived Mesoionic Singlet Carbene Palladium (4) Complex[a,b]



R = C_6H_{11} (**18**), 2,6-$Me_2C_6H_3$ (**19**), *t*–Bu (**20**), 2,4,6-$Me_3C_6H_2$ (**21**), $CH_2C_6H_5$ (**22**)

S. No.	azide	isocyanide	product	Pd−MIC (4) yield[b]
1			 (**18**)	84
2			 (**19**)	54
3		*t*-BuNC	 (**20**)	89
4			 (**21**)	33
5			 (**22**)	59

[a]Reaction conditions: azide (0.369 mmol), isocyanide (0.443 mmol), complex **4** (0.003 mmol, 1 mol %), and K_2CO_3 (1.10 mmol) in 5.0 mL of toluene at 50 °C for 12 h. [b]Isolated yields (%).

Information, Table S12). Notably, the significant enhancement in the product yield by *ca.* 51% in case of complex **4**, in comparison to $Pd_2(dba)_3$, highlights the favorable influence of the mesoionic 1,2,3-triazole derived N-heterocyclic carbene ligand in catalyzing the coupling of phenyl azide and benzyl isocyanide. The Hg drop experiment bore testimony toward the homogeneous nature of the catalysis as near equal yield of *ca.* 83% was found in the presence of mercury as opposed to 88% in absence of it (entries 10 and 11, Supporting Information, Table S12).

Furthermore, the base variation study suggested K_2CO_3 (Supporting Information, Table S6) and the solvent variation study suggested toluene for optimal catalysis conditions (Supporting Information, Table S7). The variation of the molar ratio of the optimal base K_2CO_3 with the substrate phenyl azide produced highest yield at *ca.* 1:3 ratio (Supporting Information, Table S9). A catalysis reaction temperature of 50 °C (entry 2, Supporting Information, Table S8) and a catalyst loading of 1 mol % were found to be suitable based on the temperature dependence and the catalyst loading variation studies (entry 3, Supporting Information, Table S10).

The temperature dependence study with complex **4** showed that the product yield decreased with temperature, which can be attributed to the thermal decomposition of the azide moiety.[52] Similar observation was made for the said azide−isocyanide coupling reaction mediated by Cr,[13] as starting materials were decomposed, when the reaction mixture was heated beyond 60 °C.

In line with this investigation, the XPS analysis of the **4**−**7** complexes, before and after heating in toluene at 100 °C for 24 h, were performed. No trace of Pd leaching was observed in that process, and peaks corresponding to Pd(0) was also absent in the data. (Supporting Information, Figures S238−S246). Additionally, the temperature dependent ^{1}H NMR were also analyzed for complexes **4**−**7**, and in this case too, no signature of decomposed peaks were found. (Supporting Information, Figures S216−S220). These experiments clearly showed that these (**4**−**7**) catalysts were stable during the catalysis conditions, and the decomposition of the azide substrates at the catalysis temperature was more dominant. It is worth noting that in long reaction time and under prolonged heating, carbodiimides tend to decompose or polymerize.[12,53]

The time dependence study yielded 12 h to be the optimum reaction time as per the product yield (entry 4, Supporting Information, Table S11). Hence based on the aforementioned results, the catalysis conditions for the azide−isocyanide coupling that were chosen for the further substrate scope studies were at 1 mol % of the catalyst loading in the presence of the 3 equiv of K_2CO_3 in toluene at 50 °C for 12 h of the reaction time.

It is noteworthy to mention, all of the (**4**−**7**) complexes successfully carried out the azide−isocyanide coupling of different aryl azides ranging from phenyl azide to 4-methylphenyl azide, to 2-methoxyphenyl azide to 4-fluorophenyl azide to 3,5-bis(trifluoromethyl)phenyl azide to eventually an aliphatic azide, namely cyclohexyl azide with a host of isocyanides, namely, benzyl isocyanide, 4-methylphenyl isocyanide, 2,6-dimethylphenyl isocyanide, 2,4,6-trimethylphenyl isocyanide, and cyclohexyl isocyanide under the optimized catalysis conditions. Quite expectedly, with the increase in sterics, on going from 4-methylphenyl isocyanide to 2,6-dimethylphenyl isocyanide to 2,4,6-trimethylphenyl isocyanide, a steady decrease in the catalysis yield was observed for all the four (**4**−**7**) precatalysts when coupled with phenyl azide (entries 2−4, Table 1). Again, for the same isocyanide, i.e. benzyl isocyanide, the electron deficient 4-fluorophenyl azide and 3,5-bis(trifluoromethyl)phenyl azide performed consistently better than the corresponding electron rich 4-methylphenyl azide for all the (**4**-**7**) precatalysts (entries 7, 9, and 10, Table 1). Similar instances of higher reactivity of the electron deficient azides have been reported for an Fe catalyst and has been rationalized as a consequence of metal to azide π-back bonding that stabilizes the metal bound azide species.[54] For the coupling with cyclohexyl isocyanide higher yield was consistently observed with phenyl azide compared to its aliphatic counterpart cyclohexyl azide for all the four (**4**−**7**) precatalysts.

A careful scrutiny of the substrate scope study brings out an interesting trend of the catalyst reactivity observed along the line, **4** > **5** ∼ **6** > **7**, thereby implying that the pyridine bound Pd

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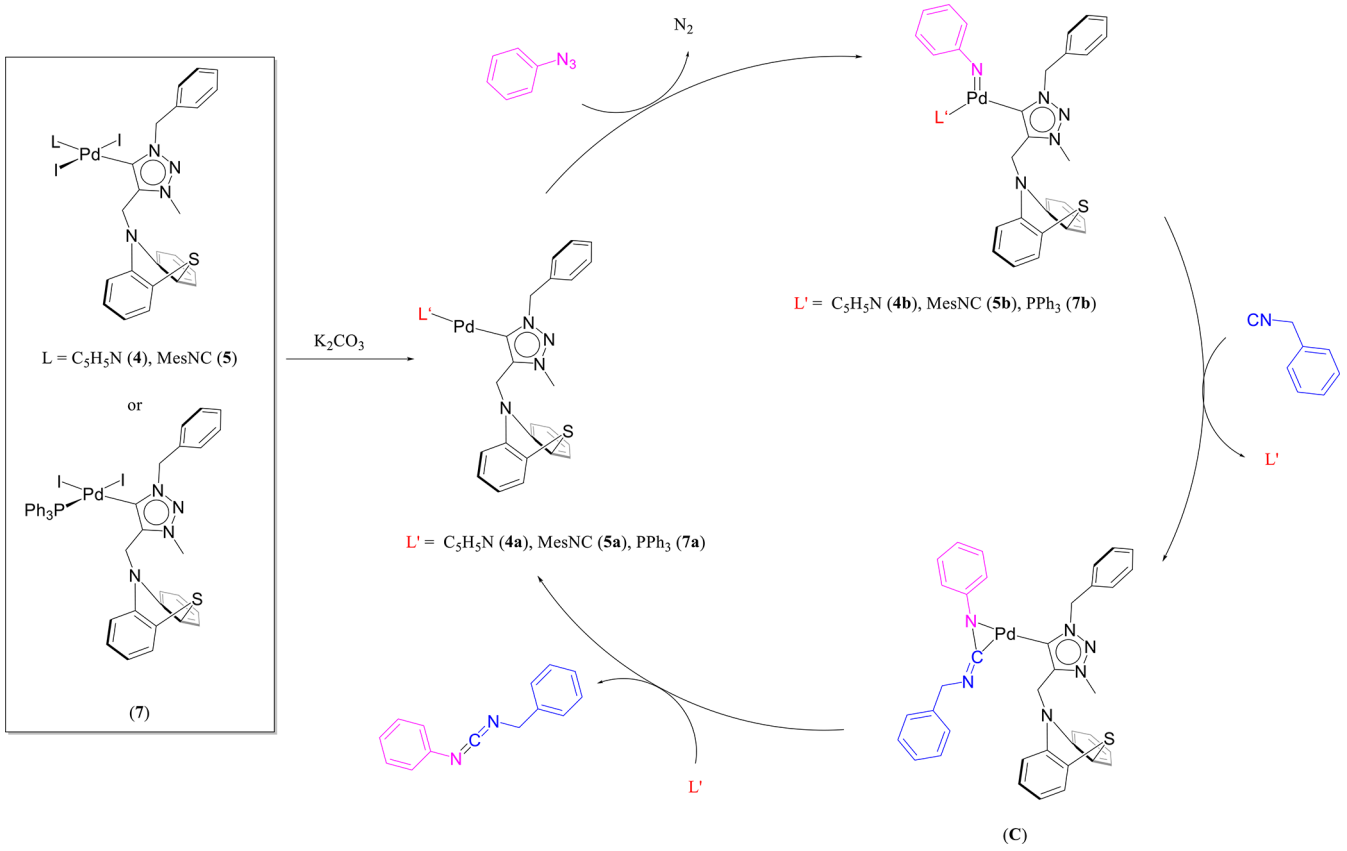
Scheme 3. Proposed Mechanism Showing the Intermediates 4a,b, 5a,b, 6a,b, and C for the Azide−Isocyanide Coupling as Catalyzed by Phenothiazine-Derived Mesoionic Singlet Carbene Palladium (4, 5, 7) Complexes for the Representative Substrates, Namely Phenyl Azide and Benzyl Isocyanide



complex (**4**) is the most effective, while the PPh_3 bound Pd complex (**7**) is the least effective of all the ten substrates studied for the azide−isocyanide coupling reaction. The other two precatalysts, i.e., the isocyanide bound Pd complex (**5**) and the *bis*-mesoionic 1,2,3-triazole based NHC complex (**6**), lie in between the highly active (**4**) and the least active (**7**) precatalysts, and are comparable to each other in terms of the catalysis product yield.

We are not aware of any other structurally characterized molecular palladium catalysts reported for the azide-iscocyanide coupling barring $[Pd(PPh_3)_4]$.[55] Additionally, there exists only one other structurally characterized Ni(I) complex, namely $(MesNCHCH_3CH_2CHCH_3NMes)Ni(2\text{-picoline})$[14] for the azide−isocyanide coupling of the phenyl azide and 2,6-dimethylphenyl isocyanide pair of substrates, similar to that reported for our palladium complexes (**4**−**7**) (Table 2). Though the $[Pd(PPh_3)_4]$[55] complex reported a higher conversion of *ca.* 82% based on ^{1}H NMR at 5 h of reaction time at room temperature but at higher catalyst loading of 2.5 mol % in comparison to that of 1 mol % of the catalyst loading for our palladium complexes (**4**−**7**) showing moderate to good isolated yields of *ca.* 24−78% at 50 °C after 12 h of reaction time (Table 2). The Ni(I) complex, namely $(MesNCHCH_3CH_2CHCH_3NMes)Ni(2\text{-picoline})$[14] exhibited quantitative conversion by ^{1}H NMR at a longer reaction time of 17 h and also at a higher catalyst loading of 5 mol % at temperatures ranging from −35 °C to room temperature (Table 2). In light of these studies, the catalysis yields exhibited by our palladium (**4**−**7**) complexes are indeed promising and would usher further research into the area.

Moreover, in the absence of any prior report of Pd-NHC complex catalyzing the said reaction, a comparison with a benchmark PEPPSI catalyst namely, *trans*-$[1,3\text{-}(2,6\text{-}(i\text{-}Pr)_2C_6H_3)_2\text{-imidazol-2-ylidene}]PdCl_2(NC_5H_5)$,[56] was made with the palladium (**4**−**7**) complexes under analogous catalysis conditions. Specifically, the benchmark PEPPSI complex, *trans*-$[1,3\text{-}(2,6\text{-}(i\text{-}Pr)_2C_6H_3)_2\text{-imidazol-2-ylidene}]PdCl_2(NC_5H_5)$ was synthesized according to the literature procedure,[56] and when used to carry out the same catalysis, (entry 7, Supporting Information, Table S12) exhibited inferior performance in comparison to our (**4**−**7**) catalysts. Another triazolylidene based palladium complex *trans*-$[1\text{-Ph-3-Me-4-}CH_2\text{Ph-1,2,3-triazol-5-ylidene}]PdI_2(NC_5H_5)$,[25] having a phenyl group rather phenothiazine, too exhibited inferior activity than the (**4**−**7**) catalysts (entry 8, Supporting Information, Table S12). The study further highlights the significance of these MIC based (**4**−**7**) catalysts in the azide−isocyanide coupling reaction.

A unified mechanism involving redox palladium (0/II) oxidation states have been proposed for the (**4**−**7**) complexes catalyzing the azide−isocyanide coupling in case of the two representative substrates, phenyl azide and benzyl isocyanide, (Scheme 3 and Supporting Information, Scheme S1 and Figures 6, 7, 8, and S222−S237).[55] The proposed catalysis initiates with the formation of the Pd(0) species **4a**, **5a**, and **7a** (Scheme 3) and **6a** (Supporting Information, Scheme S1) from the respective Pd(II) (**4**−**7**) complexes with the reduction of the metal center occurring in the presence of the base K_2CO_3.[57]

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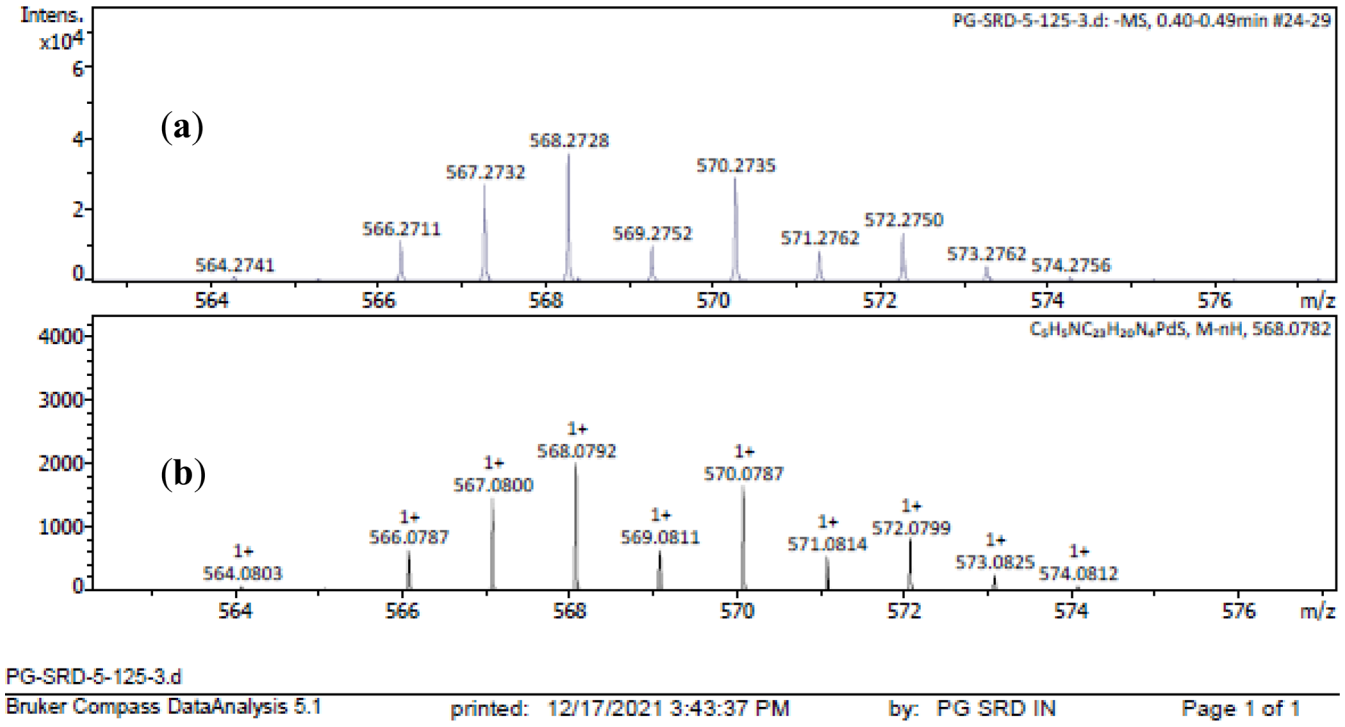

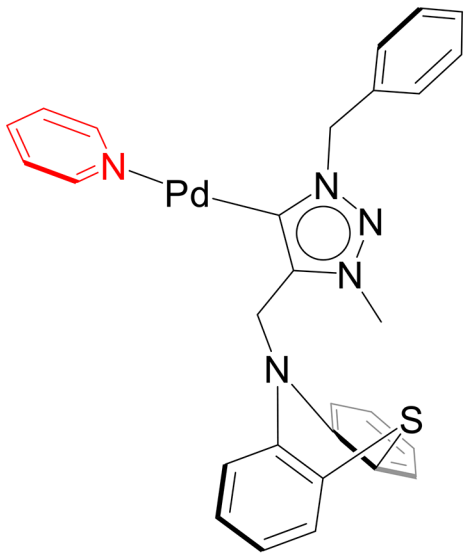

(4a)

Figure 6. Expanded ESI-MS data consistent with the proposed Pd (0) species [1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazol-5-ylidene]Pd-(NC_5H_5) (**4a**), $[M-H]^-$ detected in the reaction mixture of K_2CO_3, 3 mmol and 1 mol % of catalyst (**4**) in 5.0 mL of toluene heated at 50 °C for 30 min [(a) experimental and (b) simulated pattern of ESI-MS data].

With 3 equiv of K_2CO_3, the catalysis yield was found to be the maximum according to the base and base equivalence variation studies (Supporting Information, Tables S8 and S11), which can be attributed to the fact that K_2CO_3, being a weak inorganic base, has less solubility in an organic solvent like toluene.[58] Quite significantly mass evidence are consistent with the proposed **4a** (Figure 6 and Supporting Information, Figure S222), **7a** (Supporting Information, Figured S230 and S231) and **6a** (Supporting Information, Figures S234 and S235). Upon reaction with phenyl azide, the Pd bound nitrene species, **4b**, **5b**, and **7b** (Scheme 3) and **6b** (Supporting Information, Scheme S1) are formed with the elimination of N_2, and of which **4b** (Figure 7 and Supporting Information, Figure S223) **5b** (Supporting Information, Figures S226 and S227) have been observed by mass spectrometry. Subsequently, the insertion of benzyl isocyanide into the Pd−nitrene species **4b**, **5b**, and **7b**

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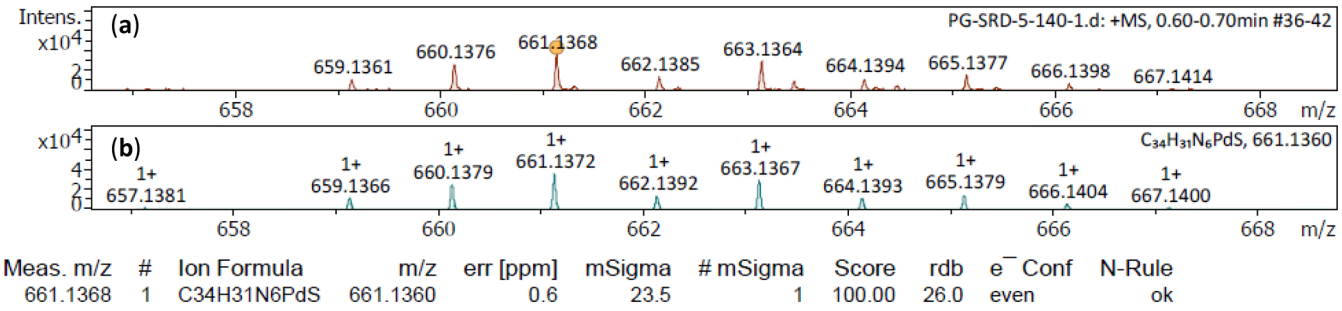

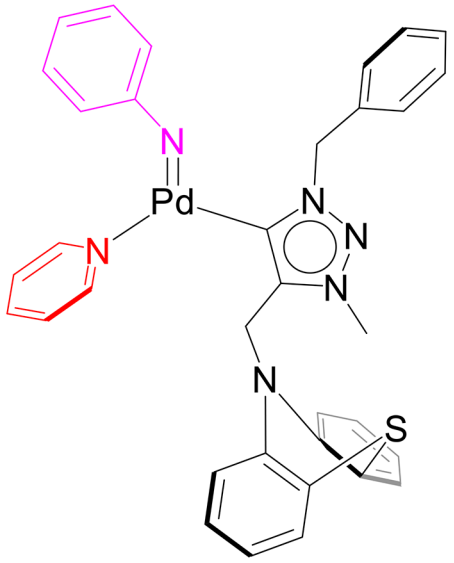

(4b)

Figure 7. Expanded ESI-MS data consistent with the proposed Pd bound nitrene species [1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazol-5-ylidene]Pd(=NC_6H_5)(NC_5H_5) (**4b**), $[M + H]^+$ detected in the reaction mixture of phenyl azide, 1 mmol of K_2CO_3, 3 mmol, 1 mol % of catalyst (**4**), 5.0 mL of toluene at 50 °C for 1 h [(a) experimental and (b) simulated pattern of ESI-MS data].

(Scheme 3) yields a common intermediate (**C**) (Figure 8 and Supporting Information, Figures S224, S225, S228, S229, S232, and S233), while **6b** generates the intermediate **6c** (Supporting Information, Scheme S1 and Figures S236 and S237), and both **C** and **6c** have also been observed by mass spectrometry. Finally, a reductive elimination step regenerates the Pd(0) species **4a**, **5a**, and **7a** (Scheme 3) and **6a** (Supporting Information, Scheme S1) along with the elimination of the free carbodiimide product (**8**).

In this regard, it is noteworthy that ESI-MS studies[59] have been routinely used for screening short-lived, low concentration intermediate species of several homogeneous metal-catalyzed transformations.[60] However, since the information about the charged state of a metal, if obtained from the ESI-MS technique, remains inconclusive,[61] and so such efforts demands further validation by other experimental techniques. In the present study such validation regarding the oxidation state of the metal center has been obtained using X-ray photoelectron spectroscopy as discussed below.

Additional corroboration of the proposed mechanism came from the X-ray photoelectron spectroscopy studies. In particular, the X-ray photoelectron spectroscopy (XPS) analysis of complexes **4**−**7** showed the presence of palladium, iodine, nitrogen, sulfur, and carbon in the precatalysts. As expected for the molecular complexes, the binding energies of Pd confirm its +2 oxidation state.[62] A comparative XPS analysis of complexes **4**−**7** after heating in toluene at 100 °C for 24 h showed that the characteristic core level peaks of Pd 3d, I 3d, N 1s, S 2p, and C 1s are at the same binding energies as for the molecular complexes (Figure 9 and see Supporting Information, Table S13 and Figures S238−S246). The 3d core-level palladium of complex **4** was fitted with two main peaks, the peak for Pd $3d_{5/2}$ at 341.7 eV and for Pd $3d_{3/2}$ at 336.4 eV, which were assignable to the Pd(II) oxidation state.[62,63] To characterize the intermediate species generated during the azide−isocyanide coupling reaction X-ray photoelectron spectroscopy (XPS) study was inspected of the reaction mixture using phenyl azide, benzyl isocyanide and complex **4**. Two different new peaks at 335.5 and 340.9 eV, attributed to Pd $3d_{5/2}$ and Pd $3d_{3/2}$ peaks of Pd(0) species,

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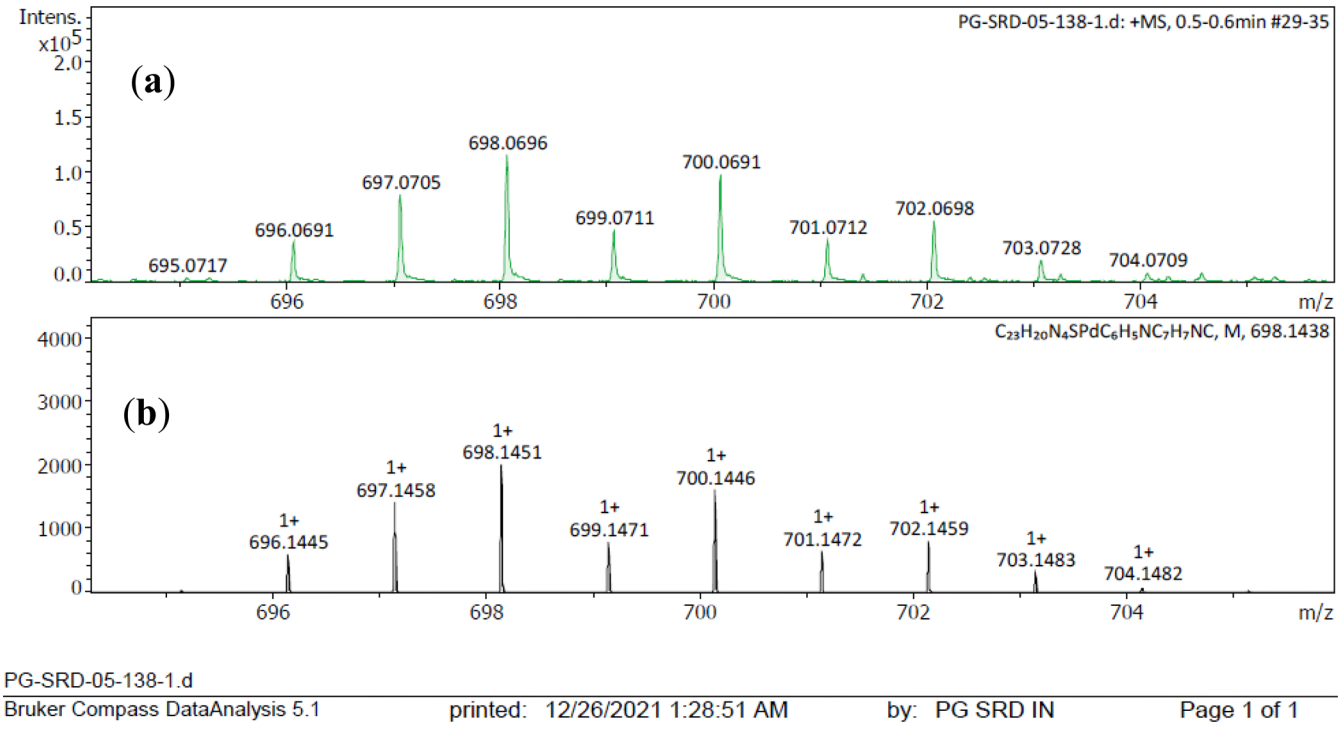

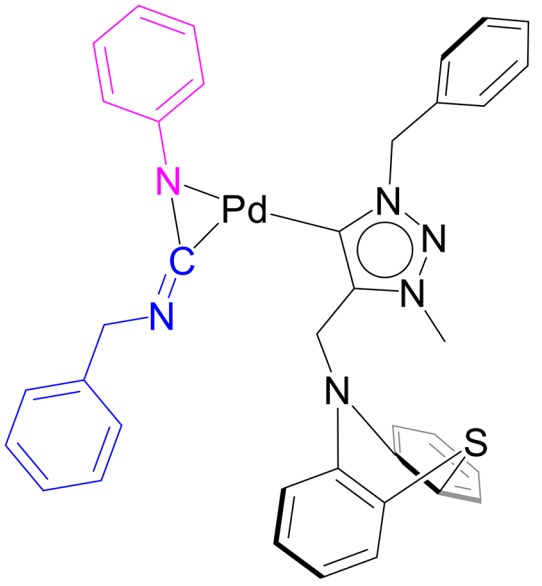

(C)

Figure 8. Expanded ESI-MS data consistent with the proposed species [1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazol-5-ylidene]Pd[η^2-(Ph)*N*=C(NCH_2Ph)] (**C**), $[M]^+$ detected in the reaction mixture of phenyl azide, 1 mmol of benzyl isocyanide, 1.2 mmol of K_2CO_3, 3 mmol, 1 mol % of catalyst (**4**), 5.0 mL of toluene at 50 °C for 1.5 h [(a) experimental and (b) simulated pattern of ESI-MS data].

appeared in the analysis.[62,63] These peaks confirmed that both Pd(II) and Pd(0) species were involved during the catalytic cycle.

As part of our ongoing efforts to synthesize bioactive heterocycles in a tandem fashion,[21,22,24] the azide−isocyanide cross-coupling was extended to accessing benzoxazole motifs from the reaction of *o*-functionalized aryl azides with different isocyanides. Specifically, the representative catalyst (**4**) successfully catalyzed the coupling and the cyclization sequence steps producing the 2-aminobenzoxazole derivatives (**18**−**22**) from the reaction of 2-azido alcohol and R−NC [R = Cy (**18**), 2,6-$Me_2C_6H_3$ (**19**), *t*-Bu (**20**), 2,4,6-$Me_3C_6H_2$ (**21**), $CH_2C_6H_5$ (**22**)] under optimal catalysis conditions in moderate to excellent yields of 54−89% (Table 3). It is needless to mention that the benzoxazole rings are important for their antimicrobial, anticonvulsant, anti-inflammatory and anticancer properties and

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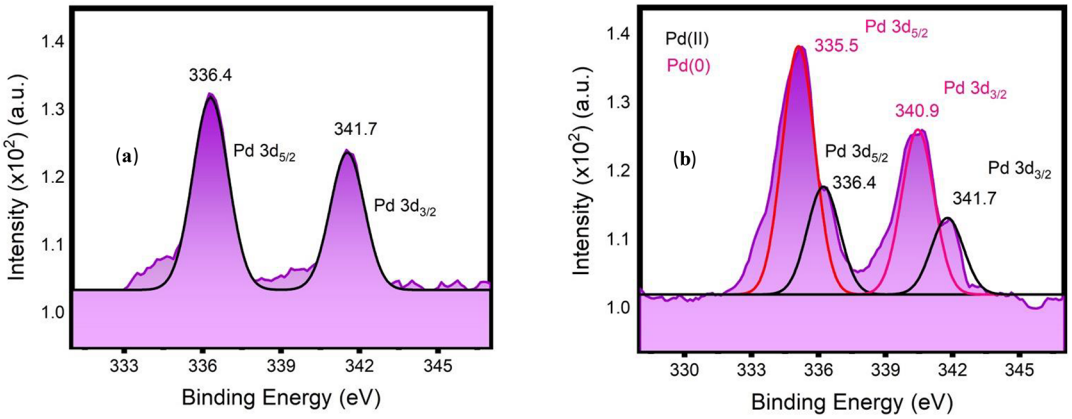

Figure 9. XPS analysis of the 3d core level peaks of level of Pd 3d: Pd(II) (black), Pd(0) (pink), (a) precatalyst **4**, and (b) precatalyst **4** after treatment with PhN_3, $PhCH_2NC$, and K_2CO_3 for 12 h in 5 mL of toluene at 50 °C.

are also studied for their DNA topoisomerase inhibitor and cholesterol ester transfer protein (CETP) inhibitor activities.[16,64]

A similar coupling/cyclization sequence were extended for synthesizing various bioactive 2-substituted benzimidazoles.[65] In particular, the representative precatalyst (**4**) coupled the 2-halidophenyl azide with benzyl and cyclohexyl isocyanides yielding the corresponding *o*-haloarylcarbodiimides, followed by a cascade cyclization process in the presence of another Cu(I) catalyst in one pot and without the need for isolation of the intermediate to give the N-substituted 2-heterobenzimidazoles derivatives (**23**−**27**) in good yields using different N-heterocycles as nucleophiles (Table 4).

CONCLUSION

In conclusion, several late transition metal complexes of palladium (**4**−**7**) were stabilized over a new class of phenothiazine derived mesoionic 1,2,3-triazole based carbene (MIC) ligand (**3**), thereby highlighting the versatility of this kind of MIC ligand for synthesizing different metal complexes. Significantly enough, the mixed carbene/isocyanide complex (**5**) represents the only structurally characterized example known until date of a (MIC)PdI_2(CN−R) type complex, supported over a mesoionic 1,2,3-triazole derived carbene. The palladium (**4**−**7**) complexes efficiently catalyzed the azide−isocyanide coupling reaction yielding various symmetrical and unsymmetrical carbodiimides (**8**−**17**). More importantly, the (MIC)$PdI_2(NC_5H_5)$ type complex (**4**) beats out all other palladium complexes (**5**−**7**) in terms of catalysis performance, while the PPh_3 bound *cis*-(MIC)$Pd(PPh_3)I_2$ type complex (**7**) was found to be the least active one. The remaining two complexes, i.e., the mixed carbene/isocyanide (MIC)-PdI_2(CN−R) type complex (**5**) and the *trans*−$(MIC)_2PdI_2$ type complex (**6**) exhibited comparable catalytic activities. The mechanistic study performed on two representative substrates, i.e. the phenyl azide and benzyl isocyanide revealed that the catalysis proceeds through the formation of palladium(0) species of the type (MIC)Pd(L) [L = NC_5H_5, MesNC, MIC, PPh_3] and the palldium bound nitrene species (MIC)]Pd-(=NC_6H_5)(L) [L = NC_5H_5, MesNC, PPh_3, MIC], and of which the following species (**4a**, **6a**, **7a**, **4b**, and **5b**) have been characterized by mass spectrometry. The scope of the azide−isocyanide coupling was successfully extended by demonstrating its application in the formation of different derivatives of two bioactive heteroannular ring systems namely, 2-aminobenzoxazole (**18**−**22**) and the N-substituted 2-heterobenzimidazole (**23**−**27**). As the **4**−**7** complexes represent a rare class of well-defined palladium based molecular catalyst for the azide−isocyanide coupling reaction yielding various carbodiimide compounds, the study will provide further impetus to the development of the area.

EXPERIMENTAL SECTION

General Procedures. All manipulations were carried out using standard Schlenk techniques. Solvents were purified and degassed by standard procedures. Benzyl bromide, sodium azide, and methyl iodide were purchased from Spectrochem Chemicals and phenothiazine and propargyl bromide were purchased from Sigma-Aldrich Chemicals and used without any further purification. ^{1}H NMR and ^{13}C{^{1}H} NMR spectra were recorded on Bruker 400 MHz and Bruker 500 MHz NMR spectrometer. ^{1}H NMR peaks are labeled as singlet (s), doublet (d), triplet (t), quartet (q), doublet of doublet (dd), doublet of triplets (dt), triplets of doublets (td), doublet of triplets of triplets (dtd), and multiplet (m). Variable temperature dependent ^{1}H NMR for complexes **4**−**6** were recorded on a JEOL ECZR Series 600 MHz NMR spectrometer. Variable Temperature dependent ^{1}H NMR and spin saturation transfer (SST) ^{1}H NMR for complex 7 were recorded on a Bruker 400 MHz spectrometer. The 10-(prop-2-yn-1-yl)-10H-phenothiazine was synthesized by modification of procedures reported in literature.[66] The benchmark PEPPSI complex [*trans*-[1,3-(2,6-(*i*-Pr)$_2$C$_6$H$_3$)$_2$-imidazol-2-ylidene]$PdCl_2(NC_5H_5)$,] was made according to the literature procedure.[56] High-resolution mass spectrometry measurements were done on a Micromass Q−Tof spectrometer and a Bruker maxis impact spectrometer. Infrared spectra were recorded on a PerkinElmer Spectrum One FT-IR spectrometer. Elemental Analysis was carried out on Thermo Quest FLASH 1112 SERIES (CHNS) Elemental Analyzer. X-ray photoelectron spectra were acquired on ULVAC-PHI/PHI 5000 VersaProbe-II spectrometer with a monochromatic Al Kα X-ray source (1486.6 eV) using a pass energy of 58.7 eV. X-ray diffraction data were collected for compounds (**4**−**7**) on a Bruker D8 QUEST single crystal diffractometer with Mo Ka (k = 0.71073 Å) radiation. The Bruker D8 QUEST single-crystal X-ray diffractometer were equipped with an Oxford liquid nitrogen cryostream. Crystals were mounted on a nylon loop with paraffin oil. The structures were solved via direct methods using SHELXT and refined via the full matrix least-squares method with SHELXL-2018/3, refining on F^2.[67] Crystal data collection

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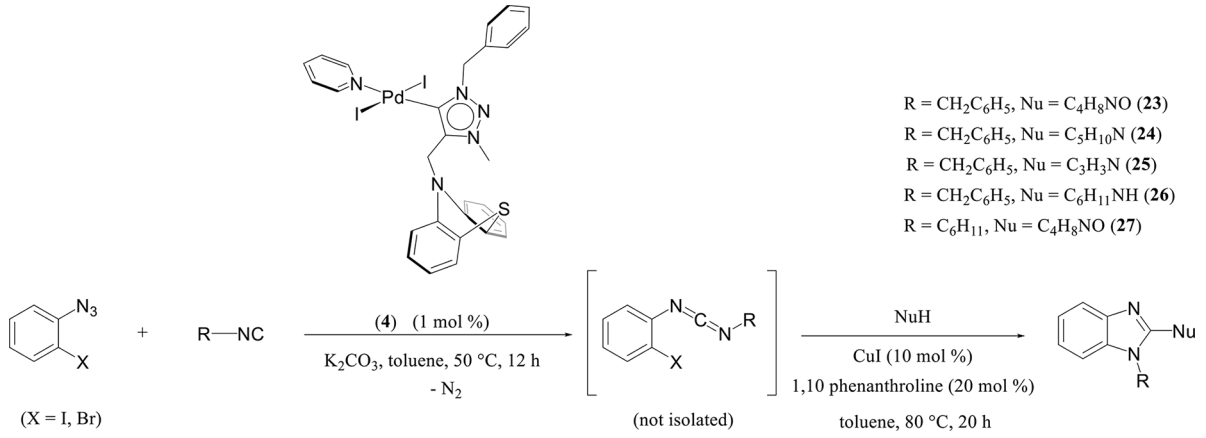
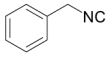
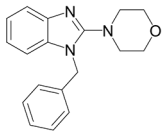
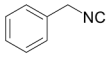
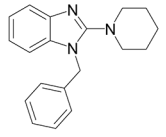
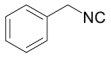
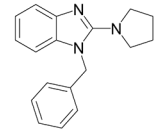
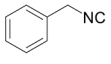
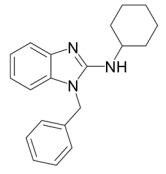
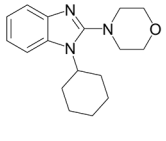
Table 4. Selected Results for a Simple Practical Synthesis of a Variety of Benzimidazole Derivatives Using Azide−Isocyanide Coupling Catalyzed by a Phenothiazine-Derived Mesoionic Singlet Carbene Palladium (4) Complex[a,b]



S. No.	azide	isocyanide	nucleophile	product	Pd−NHC (4) yield[b]
1				 (23)	64
2				 (24)	68
3				 (25)	48
4				 (26)	55
5				 (27)	72

[a]Reaction conditions: azide (0.369 mmol), isocyanide (0.443 mmol), complex **4** (0.003 mmol, 1 mol %), and K_2CO_3 (1.10 mmol) in 5.0 mL of toluene at 50 °C for 12 h. Reaction mixture was cooled to room temperature and then CuI (0.100 mmol, 10 mol %), 1,10-phenanthroline (0.200 mmol, 20 mol %), Cs_2CO_3 (2.00 mmol), and N-heterocycle (1.10 mmol) were added to it and heated at 80 °C for 20 h. [b]Isolated yields (%).

and refinement parameters were summarized in Supporting Information, Table S1. CCDC-2041824 (for **4**), CCDC-2060553 (for **5**), CCDC-2123529 (for **6**), and CCDC-2069000 (for **7**), contain the supplementary crystallographic data for this paper. These data can be obtained free of charge

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from the Cambridge Crystallographic Data center via www.ccdc.cam.ac.uk/data_request/cif.

Synthesis of 10-(Prop-2-yn-1-yl)-10*H*-phenothiazine (1).[66] A mixture of phenothiazine (5.00 g, 25.0 mmol) and Na_2CO_3 (3.98 g, 37.5 mmol) in *ca.* 50 mL of anhydrous toluene was stirred at room temperature for 30 min, followed by the dropwise addition of propargyl bromide (80 wt % in toluene, 5.57 g, 37.5 mmol). The reaction mixture was refluxed for 24 h, after which it was evaporated *in vacuo*. The resultant residue was dissolved in *ca.* 100 mL of CH_2Cl_2, filtered and washed with water (*ca.* 2 × 50 mL). The collected organic layer was dried over anhydrous Na_2SO_4 and evaporated *in vacuo*. The crude product was further purified by column chromatography using silica gel as the stationary phase and by elution with petroleum ether to obtain a white solid (**1**) (2.12 g, 35%). ^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.22 (dd, 2H, $^3J_{HH}$ = 8 Hz, $^4J_{HH}$ = 1 Hz, $C_{12}\underline{H}_8NS$), 7.18 (td, 2H, $^3J_{HH}$ = 7 Hz, $^4J_{HH}$ = 1 Hz, $C_{12}\underline{H}_8NS$), 7.13 (dd, 2H, $^3J_{HH}$ = 7 Hz, $^4J_{HH}$ = 1 Hz, $C_{12}\underline{H}_8NS$), 6.95 (td, 2H, $^3J_{HH}$ = 7 Hz, $^4J_{HH}$ = 1 Hz, $C_{12}\underline{H}_8NS$), 4.52 (d, 2H, $^4J_{HH}$ = 2 Hz, $NC\underline{H}_2C{\equiv}CH$), 2.46 (t, 1H, $^4J_{HH}$ = 2 Hz, $NCH_2C{\equiv}C\underline{H}$). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz, 25 °C): δ 144.1 ($\underline{C}_{12}H_8NS$), 127.5 ($\underline{C}_{12}H_8NS$), 127.1 ($\underline{C}_{12}H_8NS$), 123.4 ($\underline{C}_{12}H_8NS$), 123.0 ($\underline{C}_{12}H_8NS$), 114.8 ($\underline{C}_{12}H_8NS$), 79.3 ($NCH_2\underline{C}{\equiv}CH$), 74.5 ($NCH_2C{\equiv}\underline{C}H$), 38.5 ($N\underline{C}H_2CCH$). HRMS (ESI): calcd for $[C_{15}H_{11}NS + K]^+$, 276.0244; found, 276.0239.

Synthesis of 10-((1-Benzyl-1*H*-1,2,3-triazol-4-yl)-methyl)-10*H*-phenothiazine (2). 10-(Prop-2-yn-1-yl)-10*H*-phenothiazine (**1**) (0.478 g, 2.01 mmol), benzyl azide (0.322 g, 2.41 mmol), $CuSO_4{\cdot}5H_2O$ (0.604 g, 2.41 mmol), and sodium ascorbate (0.479 g, 2.41 mmol) were mixed together in 10 mL of DMF and refluxed for 24 h. The reaction mixture was diluted with *ca.* 50 mL of CH_2Cl_2 and *ca.* 150 mL of water and stirred vigorously at room temperature for 30 min. Subsequent separation of the organic layer, followed by repeated washing with water (*ca.* 3 × 100 mL), drying over anhydrous Na_2SO_4, and finally evaporating the volatiles *in vacuo* gave the crude product, which was further purified by column chromatography using silica gel as the stationary phase and by elution with CH_2Cl_2 to get a white solid (**2**) (0.485 g, 65%). ^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.21−7.17 (m, 4H, $C_2\underline{H}N_3$ and $CH_2C_6\underline{H}_5$), 7.01 (dd, 2H, $^3J_{HH}$ = 7 Hz, $^4J_{HH}$ = 1 Hz, $C_{12}\underline{H}_8NS$), 7.00−6.99 (m, 2H, $CH_2C_6\underline{H}_5$), 6.95 (td, 2H, $^3J_{HH}$ = 7 Hz, $^4J_{HH}$ = 1 Hz, $C_{12}\underline{H}_8NS$), 6.80 (td, 2H, $^3J_{HH}$ = 7 Hz, $^4J_{HH}$ = 1 Hz, $C_{12}\underline{H}_8NS$), 6.67 (dd, 2H, $^3J_{HH}$ = 7 Hz, $^4J_{HH}$ = 1 Hz, $C_{12}\underline{H}_8NS$), 5.36 (s, 2H, $C\underline{H}_2C_6H_5$), 5.11 (s, 2H, $NC\underline{H}_2$). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz, 25 °C): δ 145.3 ($\underline{C}_{12}H_8NS$), 144.2 ($\underline{C}_2HN_3$), 134.6 ($CH_2\underline{C}_6H_5$), 129.0 ($CH_2\underline{C}_6H_5$), 128.5 ($CH_2\underline{C}_6H_5$), 127.5 ($\underline{C}_{12}H_8NS$), 127.3 ($CH_2\underline{C}_6H_5$), 127.1 ($\underline{C}_{12}H_8NS$), 124.0 ($\underline{C}_{12}H_8NS$), 122.8 ($\underline{C}_{12}H_8NS$), 122.5 ($\underline{C}_2HN_3$), 115.3 ($\underline{C}_{12}H_8NS$), 54.1 ($N\underline{C}H_2$), 45.0 ($\underline{C}H_2C_6H_5$). IR data (cm^{-1}) KBr pellet: 3445 (m), 3121 (m), 3062 (m), 2946 (m), 1571 (m), 1495 (s), 1440 (s), 1357 (s), 1286 (s), 1251 (s), 1210 (s), 1122 (s), 1050 (s), 857 (s), 749 (s), 718 (s), 643 (s), 616 (s). HRMS (ESI): calcd for $[C_{22}H_{18}N_4S + H]^+$, 371.1325; found, 371.1323. Anal. Calcd for $C_{22}H_{18}N_4S$: C, 71.33; H, 4.90; N, 15.12; S, 8.65. Found: C, 71.21; H, 4.58; N, 14.80; S, 8.93%.

Synthesis of 1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazolium Iodide (3). 10-((1-Benzyl-1H-1,2,3-triazol-4-yl)-methyl)-10*H*-phenothiazine (**2**) (0.400 g, 1.07 mmol), and MeI (1.53 g, 10.8 mmol) were mixed in 10 mL of CH_3CN and refluxed for 24 h. The reaction mixture was then cooled to room temperature and all the volatiles were evaporated in *vaccuo*. The crude product thus obtained was further purified through column chromatography using silica gel as the stationary phase and by elution with $CHCl_3$/MeOH (95:5 *v*/*v*) mixture to get the product as a yellow solid (**3**) (0.548 g, 99%). ^{1}H NMR ($CDCl_3$, 500 MHz, 25 °C): δ 9.52 (s, 1H, NC$\underline{H}$C of $C_2\underline{H}N_3$), 7.35−7.27 (m, 5H, $C_{12}\underline{H}_8NS$ and $CH_2C_6\underline{H}_5$), 7.14 (t, 2H, $^3J_{HH}$ = 7 Hz, $CH_2C_6\underline{H}_5$), 7.08 (d, 4H, $^3J_{HH}$ = 8 Hz, $C_{12}\underline{H}_8NS$), 6.89 (t, 2H, $^3J_{HH}$ = 8 Hz, $C_{12}\underline{H}_8NS$), 5.73 (s, 2H, $C\underline{H}_2C_6H_5$), 5.57 (s, 2H, $NC\underline{H}_2$), 4.26 (s, 3H, $NC\underline{H}_3$). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 125 MHz, 25 °C): δ 143.1 ($\underline{C}_2HN_3$), 139.8 ($\underline{C}_{12}H_8NS$), 131.6 ($\underline{C}_2HN_3$), 131.1 ($CH_2\underline{C}_6H_5$), 129.8 ($CH_2\underline{C}_6H_5$), 129.4 ($CH_2\underline{C}_6H_5$), 129.1 ($CH_2\underline{C}_6H_5$), 128.2 ($\underline{C}_{12}H_8NS$), 127.8 ($\underline{C}_{12}H_8NS$), 125.7 ($\underline{C}_{12}H_8NS$), 124.0 ($\underline{C}_{12}H_8NS$), 116.7 ($\underline{C}_{12}H_8NS$), 57.5 ($N\underline{C}H_2$), 41.8 ($\underline{C}H_2C_6H_5$), 39.6 ($N\underline{C}H_3$). IR data (cm^{-1}) KBr pellet: 3433 (m), 3061 (w), 2924 (w), 2851 (w), 1589 (s), 1572 (w), 1485 (w), 1461 (s), 1352 (m), 1320 (m), 1285 (m), 1254 (m), 1224 (m), 1160 (w), 1079 (w), 933 (m), 854 (m), 754 (s), 643 (s), 572 (w), 512 (w), 473 (w). HRMS (ESI): calcd for $[C_{23}H_{21}N_4S]^+$, 385.1481; found, 385.1482. Anal. Calcd for $C_{23}H_{21}N_4IS$: C, 53.91; H, 4.13; N, 10.93; S, 6.26. Found: C, 53.94; H, 4.42; N, 10.54; S, 6.62%.

Synthesis of *trans*-[1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazol-5-ylidene]$PdI_2(NC_5H_5)$ (4). A mixture of 1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazolium iodide (**3**) (0.250 g, 0.487 mmol), $PdCl_2$ (0.086 g, 0.487 mmol), K_2CO_3 (0.337 g, 2.43 mmol), and NaI (0.365 g, 2.43 mmol) was refluxed in pyridine (5 mL, 63.0 mmol) for 16 h. The reaction mixture was cooled to room temperature, diluted with $CHCl_3$ (*ca.* 50 mL), filtered and subsequently washed with saturated aqueous $CuSO_4$ solution (*ca.* 3 × 50 mL) and water (*ca.* 100 mL). The organic layer was separated and dried over anhydrous Na_2SO_4 and filtered. The filtrate was concentrated under vacuum to give a sticky, brown residue. The residue thus obtained was further triturated using hexane and EtOAc to give the product (**4**) as a yellow solid (0.381 g, 95%). ^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 9.05 (d, 2H, $^3J_{HH}$ = 5 Hz, $NC_5\underline{H}_5$), 7.75 (t, 1H, $^3J_{HH}$ = 7 Hz, $NC_5\underline{H}_5$), 7.63 (dd, 2H, $^3J_{HH}$ = 7 Hz, $^4J_{HH}$ = 2 Hz, $C_{12}\underline{H}_8NS$), 7.44−7.39 (m, 3H, $CH_2C_6\underline{H}_5$), 7.35 (t, 2H, $^3J_{HH}$ = 7 Hz, $CH_2C_6\underline{H}_5$), 7.31−7.29 (m, 4H, $C_{12}\underline{H}_8NS$ and $NC_5\underline{H}_5$), 7.22 (d, 2H, $^3J_{HH}$ = 7 Hz, $^4J_{HH}$ = 2 Hz, $C_{12}\underline{H}_8NS$), 7.03−6.99 (m, 2H, $C_{12}\underline{H}_8NS$), 5.96 (s, 2H, $C\underline{H}_2C_6H_5$), 5.54 (s, 2H, $NC\underline{H}_2$), 4.00 (s, 3H, $NC\underline{H}_3$). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz, 25 °C): δ 153.7 ($N\underline{C}_5H_5$), 143.6 ($\underline{C}_{12}H_8NS$), 139.0 (Pd-$\underline{C}$), 137.3 ($N\underline{C}_5H_5$), 134.8 ($CH_2\underline{C}_6H_5$), 133.3 ($\underline{C}_2N_3$), 129.8 ($CH_2\underline{C}_6H_5$), 128.6 ($CH_2\underline{C}_6H_5$), 128.5 ($CH_2\underline{C}_6H_5$), 128.2 ($\underline{C}_{12}H_8NS$), 127.4 ($\underline{C}_{12}H_8NS$), 125.0 ($\underline{C}_{12}H_8NS$), 124.2 ($\underline{C}_{12}H_8NS$), 123.4 ($N\underline{C}_5H_5$), 117.0 ($\underline{C}_{12}H_8NS$), 59.5 ($N\underline{C}H_2$), 45.3 ($\underline{C}H_2C_6H_5$), 37.8 ($N\underline{C}H_3$). IR data (cm^{-1}) KBr pellet: 3439 (s), 3031 (w), 2954 (w), 2922 (w), 2851 (w), 2602 (w), 1732 (w), 1602 (w), 1457 (s), 1446 (s), 1364 (m), 1325 (m), 1258 (m), 1225 (m), 1213 (m), 1153 (w), 1129 (w), 1105 (w), 1070 (w), 956 (s), 865 (m), 753 (s), 618 (w), 580 (w), 498 (w). HRMS (ESI): calcd for $[C_{28}H_{25}N_5I_2PdS{-}C_5H_5N{-}I]^+$, 616.9483; found, 616.9487. Anal. Calcd for $C_{28}H_{25}N_5I_2PdS$: C, 40.82; H, 3.06; N, 8.50; S, 3.89. Found: C, 40.59; H, 3.06; N, 7.95; S, 3.30%.

Synthesis of *trans*-[1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazol-5-ylidene]PdI_2(CN−Mes) (5). A mixture of [1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazol-5-ylidene]-$PdI_2(NC_5H_5)$ (**4**) (0.340 g, 0.413 mmol) and MesNC (0.090 g, 0.619 mmol) was dissolved in a mixed solvent medium of dry toluene (*ca.* 5 mL) and dry THF (*ca.* 5 mL) and stirred at room temperature for 24 h. The solvent was evaporated and the crude

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product thus obtained was further purified by column chromatography using silica gel as stationary phase and by elution with petroleum ether/ethyl acetate (90:10 *v*/*v*) mixture to get a yellow solid (**5**) (0.161 g, 50%). ^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.56 (d, 2H, $^3J_{HH}$ = 7 Hz, $C_{12}\underline{H}_8NS$), 7.39−7.35 (m, 3H, $CH_2C_6\underline{H}_5$), 7.28 (t, 2H, $^3J_{HH}$ = 7 Hz, $CH_2C_6\underline{H}_5$), 7.22 (t, 4H, $^3J_{HH}$ = 7 Hz, $C_{12}\underline{H}_8NS$), 7.00 (t, 2H, $^3J_{HH}$ = 7 Hz, $C_{12}\underline{H}_8NS$), 6.93 (s, 2H, 2,4,6-$(CH_3)_3C_6\underline{H}_2$), 5.85 (s, 2H, $C\underline{H}_2C_6H_5$), 5.45 (s, 2H, $NC\underline{H}_2$), 4.01 (s, 3H, $NC\underline{H}_3$), 2.55 (s, 6H, 2,4,6-$(C\underline{H}_3)_3C_6H_2$), 2.32 (s, 3H, 2,4,6-$(C\underline{H}_3)_3C_6H_2$). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz, 25 °C): δ 147.2 (Pd-$\underline{C}$), 143.7 ($\underline{C}_{12}H_8NS$ and 2,4,6-$(CH_3)_3\underline{C}_6H_2$), 140.2 ($\underline{C}_2N_3$), 139.8 (2,4,6-$(CH_3)_3\underline{C}_6H_2$), 138.7 (N$\underline{C}$), 136.2 (2,4,6-$(CH_3)_3\underline{C}_6H_2$), 133.6 ($CH_2\underline{C}_6H_5$), 129.8 ($CH_2\underline{C}_6H_5$), 128.8 ($CH_2\underline{C}_6H_5$), 128.7 ($CH_2\underline{C}_6H_5$), 128.4 ($\underline{C}_{12}H_8NS$), 127.6 ($\underline{C}_{12}H_8NS$), 125.3 ($\underline{C}_{12}H_8NS$), 123.6 ($\underline{C}_{12}H_8NS$), 117.3 ($\underline{C}_{12}H_8NS$), 59.6 (N$\underline{C}H_2$), 45.0 ($\underline{C}H_2C_6H_5$), 37.8 (N$\underline{C}H_3$), 21.3 (2,4,6-$(\underline{C}H_3)_3C_6H_2$), 19.0 (2,4,6-$(\underline{C}H_3)_3C_6H_2$). IR data (cm^{-1}) KBr pellet: 3854(w), 3747 (w), 3444 (m), 3058 (w), 3031 (w), 2950 (w), 2919 (w), 2359 (w), 2188 (s), 1604 (w), 1571 (w), 1455 (s), 1371 (m), 1326 (m), 1284 (w), 1256 (w), 1224 (m), 1140 (w), 1104 (w), 1082 (w), 1038 (w), 933 (w), 889 (w), 837 (w), 757 (s), 708 (w), 645 (w), 597 (w), 524 (w). HRMS (ESI): calcd for $[C_{33}H_{31}N_5I_2PdS-I]^+$, 762.0374; found, 762.0383. Anal. Calcd for $C_{33}H_{31}N_5I_2PdS$: C, 44.54; H, 3.51; N, 7.87; S, 3.60. Found: C, 45.27; H, 3.57; N, 7.49; S, 2.86%.

Synthesis of *trans*-[1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazol-5-ylidene]$_2$PdI$_2$ (6). 1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazolium iodide (**3**) (0.256 g, 0.500 mmol) and $Pd(OAc)_2$ (0.056 g, 0.250 mmol) were dissolved in *ca.* 15 mL of 1,4-dioxane and then refluxed for 24 h. The resulting reaction mixture was filtered through Celite and further purified by column chromatography with silica gel as the stationary phase and by elution with petroleum ether/ethyl acetate (80:20 *v*/*v*) mixture to get the product as a yellow solid (**6**) (0.261 g, 93%). Both the ^{1}H NMR and ^{13}C{^{1}H} NMR spectra showed the presence of two isomers, *trans-anti* and *trans-syn*, in *ca.* 1.7:1 ratio, respectively. ^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C) (major): δ 7.46 (d, 4H, $^3J_{HH}$ = 7 Hz, $C_{12}\underline{H}_8NS$), 7.35−7.31 (m, 2H, $CH_2C_6\underline{H}_5$), 7.21−7.13 (m, 5H, $C_{12}\underline{H}_8NS$ and $CH_2C_6\underline{H}_5$), 7.01 (t, 2H, $^3J_{HH}$ = 8 Hz, $C_{12}\underline{H}_8NS$), 6.04 (s, 2H, $C\underline{H}_2C_6H_5$), 5.27 (s, 2H, $NC\underline{H}_2$), 4.03 (s, 2H, $NC\underline{H}_3$). (Minor) δ 7.39 (d, 4H, $^3J_{HH}$ = 7 Hz, $C_{12}\underline{H}_8NS$), 7.31−7.29 (m, 2H, $CH_2C_6\underline{H}_5$), 7.26−7.21 (m, 5H, $C_{12}\underline{H}_8NS$ and $CH_2C_6\underline{H}_5$), 6.97 (t, 2H, $^3J_{HH}$ = 8 Hz, $C_{12}\underline{H}_8NS$), 5.85 (s, 2H, $C\underline{H}_2C_6H_5$), 5.64 (s, 2H, $NC\underline{H}_2$), 4.01 (s, 2H, $NC\underline{H}_3$). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz, 25 °C): (major) δ 156.4 (Pd-$\underline{C}$), 143.7 ($\underline{C}_{12}H_8NS$), 140.5 ($\underline{C}_2N_3$), 134.4 ($CH_2\underline{C}_6H_5$), 128.9 ($CH_2\underline{C}_6H_5$), 128.7 (2 $CH_2\underline{C}_6H_5$), 128.3 ($\underline{C}_{12}H_8NS$), 127.5 ($\underline{C}_{12}H_8NS$), 125.0 ($\underline{C}_{12}H_8NS$), 123.4 ($\underline{C}_{12}H_8NS$), 117.5 ($\underline{C}_{12}H_8NS$), 58.7 (N$\underline{C}H_2$), 45.3 ($\underline{C}H_2C_6H_5$), 37.4 (N$\underline{C}H_3$). (Minor) δ 156.7 (Pd-$\underline{C}$), 143.9 ($\underline{C}_{12}H_8NS$), 140.1 ($\underline{C}_2N_3$), 134.5 ($CH_2\underline{C}_6H_5$), 129.1 ($CH_2\underline{C}_6H_5$), 128.6 (2 $CH_2\underline{C}_6H_5$), 128.3 ($\underline{C}_{12}H_8NS$), 127.7 ($\underline{C}_{12}H_8NS$), 125.1 ($\underline{C}_{12}H_8NS$), 123.4 ($\underline{C}_{12}H_8NS$), 117.2 ($\underline{C}_{12}H_8NS$), 59.0 (N$\underline{C}H_2$), 45.5 ($\underline{C}H_2C_6H_5$), 37.5 (N$\underline{C}H_3$). IR data (cm^{-1}) KBr pellet: 3451(m), 3058 (m), 2927 (m), 2851 (w), 2728 (w), 2581 (w), 1943 (w), 1738 (w), 1591 (m), 1571 (m), 1484 (m), 1453 (s), 1369 (m), 1330 (m), 1286 (m), 1257 (w), 1224 (m), 1153 (w), 1105 (w), 1072 (w), 1038 (w), 930 (w), 844 (w), 753 (s), 733 (s), 614 (w), 526 (w), 500 (w). HRMS (ESI): calcd for $[C_{46}H_{40}I_2N_8PdS_2-I]^+$, 1001.0891; found, 1001.0906. Anal. Calcd for $C_{46}H_{40}I_2N_8PdS_2$: C, 48.93; H, 3.57; N, 9.92; S, 5.68. Found: C, 48.84; H, 3.20; N, 9.62; S, 5.18%.

Synthesis of *cis*-[1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazol-5-ylidene]Pd(PPh_3)I$_2$ (7). A mixture of [1-CH_2Ph-3-Me-4-($CH_2N(C_6H_4)_2S$)-1,2,3-triazol-5-ylidene]-$PdI_2(NC_5H_5)$ (**4**) (0.300 g, 0.367 mmol) and PPh_3 (0.114 g, 0.437 mmol) was dissolved in dry CH_2Cl_2 (*ca.* 15 mL) and stirred at room temperature for 16 h. The solvent was evaporated and the crude product thus obtained was further purified by column chromatography using silica gel as stationary phase and by elution with petroleum ether/ethyl acetate (90:10 *v*/*v*) mixture to get a yellow solid (**7**) (0.293 g, 80%). Both the ^{1}H NMR and ^{13}C{^{1}H} NMR spectra showed the presence of two isomers, *cis* and *trans* in *ca.*3.7:1 ratio. ^{1}H NMR (DMSO-d_6, 400 MHz, 25 °C) (major): δ 7.63−7.48 (m, 15H, P($C_6\underline{H}_5$)$_3$), 7.33 (d, 2H, $^3J_{HH}$ = 7 Hz, $CH_2C_6\underline{H}_5$), 7.28−7.19 (m, 7H, $C_{12}\underline{H}_8NS$ and $CH_2C_6\underline{H}_5$), 7.04 (t, 4H, $^3J_{HH}$ = 7 Hz, $C_{12}\underline{H}_8NS$), 5.94 (d, 1H, $^2J_{HH}$ = 14 Hz, $C\underline{H}_2C_6H_5$), 5.40 (d, 1H, $^2J_{HH}$ = 15 Hz, $NC\underline{H}_2$), 5.07 (d, 1H, $^2J_{HH}$ = 14 Hz, $C\underline{H}_2C_6H_5$), 4.19 (d, 1H, $^2J_{HH}$ = 15 Hz, $NC\underline{H}_2$), 3.71 (s, 3H, $NC\underline{H}_3$). (minor): δ 7.63−7.48 (m, 15H, P($C_6\underline{H}_5$)$_3$), 7.35 (d, 2H, $^3J_{HH}$ = 7 Hz, $CH_2C_6\underline{H}_5$), 7.28−7.19 (m, 7H, $C_{12}\underline{H}_8NS$ and $CH_2C_6\underline{H}_5$), 7.04 (t, 4H, $^3J_{HH}$ = 7 Hz, $C_{12}\underline{H}_8NS$), 5.86 (s, 2H, $C\underline{H}_2C_6H_5$), 5.43 (s, 2H, $NC\underline{H}_2$), 4.05 (d, 3H, $^4J_{HH}$ = 6 Hz, $NC\underline{H}_3$). ^{13}C{^{1}H} NMR (DMSO-d_6, 100 MHz, 25 °C) (major): δ 155.1 (Pd-$\underline{C}$), 144.2 ($\underline{C}_2N_3$), 143.7 ($\underline{C}_{12}H_8NS$), 137.5 (P($\underline{C}_6H_5$)$_3$), 134.8 (P($\underline{C}_6H_5$)$_3$), 133.4 (P($\underline{C}_6H_5$)$_3$), 131.5 (P($\underline{C}_6H_5$)$_3$), 131.1 ($CH_2\underline{C}_6H_5$), 130.1 ($CH_2\underline{C}_6H_5$), 129.2 ($CH_2\underline{C}_6H_5$), 128.9 ($CH_2\underline{C}_6H_5$), 128.4 ($\underline{C}_{12}H_8NS$), 127.9 ($\underline{C}_{12}H_8NS$), 124.8 ($\underline{C}_{12}H_8NS$), 124.1 ($\underline{C}_{12}H_8NS$), 117.9 ($\underline{C}_{12}H_8NS$), 58.6 (N$\underline{C}H_2$), 43.1 ($\underline{C}H_2C_6H_5$), 38.5 (N$\underline{C}H_3$). (Minor): δ 155.1 (Pd-$\underline{C}$), 144.1 ($\underline{C}_2N_3$), 143.6 ($\underline{C}_{12}H_8NS$), 137.5 (P($\underline{C}_6H_5$)$_3$), 135.2 (P-($\underline{C}_6H_5$)$_3$), 132.5 (P($\underline{C}_6H_5$)$_3$), 132.0 (P($\underline{C}_6H_5$)$_3$), 130.6 ($CH_2\underline{C}_6H_5$), 129.6 ($CH_2\underline{C}_6H_5$), 129.1 ($CH_2\underline{C}_6H_5$), 128.8 ($CH_2\underline{C}_6H_5$), 128.3 ($\underline{C}_{12}H_8NS$), 127.9 ($\underline{C}_{12}H_8NS$), 124.9 ($\underline{C}_{12}H_8NS$), 123.8 ($\underline{C}_{12}H_8NS$), 117.6 ($\underline{C}_{12}H_8NS$), 59.1 (N$\underline{C}H_2$), 44.6 ($\underline{C}H_2C_6H_5$), 38.0 (N$\underline{C}H_3$). ^{31}P{^{1}H} NMR ($CDCl_3$, 162 MHz, 25 °C) (Major): δ 25.0 (Pd−$\underline{P}$). (Minor): δ 15.9 (Pd−$\underline{P}$) IR data (cm^{-1}) KBr pellet: 3450(s), 3052 (w), 2967 (w), 2925 (w), 1633 (m), 1480 (w), 1456 (s), 1435 (s), 1370 (w), 1314 (m), 1257 (m), 1223 (w), 1159 (w), 1093 (w), 1072 (w), 999 (w), 952 (w), 899 (w), 836 (w), 815 (w), 753 (s), 697 (s), 663 (w), 618 (w), 527 (m), 512 (m). HRMS (ESI): calcd for $[C_{41}H_{35}I_2N_4PPdS-I]^+$, 879.0394; found, 879.0409. Anal. Calcd for $C_{41}H_{35}I_2N_4PPdS$: C, 48.90; H, 3.50; N, 5.56; S, 3.18. Found: C, 49.05; H, 3.66; N, 5.72; S; 3.30%.

General Procedure for the Synthesis of Carbodimides Using Azide−Isocyanide Cross-Coupling as Catalyzed by Phenothiazine-Derived Mesoionic Singlet Carbene Palladium (4−7) Complexes (Table 1, Entries 1−10). In a typical catalysis run, a 20 mL reaction vial was charged with a mixture of palladium complex **4**/**5**/**6**/**7** (0.003 mmol, 1 mol %) and K_2CO_3 (1.10 mmol), and then PhN_3 (0.369 mmol) and $PhCH_2NC$ (0.443 mmol) were added to it, followed by 5 mL of toluene, and the reaction mixture was heated at 50 °C for 12 h. Then it was cooled to room temperature, filtered, and subsequently purified by column chromatography using silica gel (neutralized by triethylamine) as the stationary phase and by elution with a mixed medium of petroleum ether/EtOAc to give the desired product, as characterized by ^{1}H and ^{13}C{^{1}H} NMR spectroscopy, GC−MS, and elemental analysis data.

General Procedure for the Blank Experiment. In a typical blank catalysis run, a mixture of PhN_3 (0.369 mmol),

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$PhCH_2NC$ (0.443 mmol) in toluene (*ca.* 5 mL) was heated for 12 h at 50 °C. The reaction mixture was then cooled to room temperature, and the volatiles were evaporated. The crude product thus obtained was analyzed by ^1H NMR spectroscopy and GC−MS (entry 1, Supporting Information, Table S12).

General Procedure for the Control Experiment. The following different control runs were performed.

(i) A mixture of PhN_3 (0.369 mmol), $PhCH_2NC$ (0.443 mmol), and K_2CO_3 (1.10 mmol) in toluene (*ca.* 5 mL) was heated for 12 h at 50 °C. The crude product thus obtained was analyzed by ^1H and $^{13}C\{^1H\}$ NMR spectroscopy, and GC−MS (entry 2, Supporting Information, Table S12).

(ii) A mixture of PhN_3 (0.369 mmol), $PhCH_2NC$ (0.443 mmol), ligand **3** (0.003 mmol, 1 mol %), and K_2CO_3 (1.10 mmol) was heated for 12 h at 50 °C. The crude product thus obtained was analyzed by ^1H and $^{13}C\{^1H\}$ NMR spectroscopy, and GC−MS (entry 3, Supporting Information, Table S12).

(iii) A mixture of PhN_3 (0.369 mmol), $PhCH_2NC$ (0.443 mmol), and $[Pd_2(dba)_3]$ (1 mol %) in toluene (*ca.* 5 mL) was heated for 12 h at 50 °C. The crude product thus obtained was purified by column chromatography using silica gel (neutralized by triethylamine) as the stationary phase and by elution with a mixed medium of petroleum ether/EtOAc to give the desired product, as characterized by ^1H and $^{13}C\{^1H\}$ NMR spectroscopy, GC−MS, and elemental analysis data (entry 4, Supporting Information, Table S12).

(iv) A mixture of PhN_3 (0.369 mmol), $PhCH_2NC$ (0.443 mmol), $[Pd_2(dba)_3]$ (1 mol %), and K_2CO_3 (1.10 mmol) in toluene (*ca.* 5 mL) was heated for 12 h at 50 °C. The crude product thus obtained was purified by column chromatography using silica gel (neutralized by triethylamine) as the stationary phase and by elution with a mixed medium of petroleum ether/EtOAc to give the desired product, as characterized by ^1H and $^{13}C\{^1H\}$ NMR spectroscopy, GC−MS, and elemental analysis data (entry 5, Supporting Information, Table S12).

(v) A mixture of PhN_3 (0.369 mmol), $PhCH_2NC$ (0.443 mmol), $[(CH_3CN)_2PdCl_2]$ (1 mol %), and K_2CO_3 (1.10 mmol) in toluene (*ca.* 5 mL) was heated for 12 h at 50 °C. The crude product thus obtained was purified by column chromatography using silica gel (neutralized by triethylamine) as the stationary phase and by elution with a mixed medium of petroleum ether/EtOAc to give the desired product, as characterized by ^1H and $^{13}C\{^1H\}$ NMR spectroscopy, GC−MS, and elemental analysis data (entry 6, Supporting Information, Table S12).

(vi) A mixture of PhN_3 (0.369 mmol), $PhCH_2NC$ (0.443 mmol), [*trans*-[1,3-(2,6-(*i*-Pr)$_2$C$_6$H$_3$)$_2$-imidazol-2-ylidene]$PdCl_2(NC_5H_5)$] (1 mol %), and K_2CO_3 (1.10 mmol) in toluene (*ca.* 5 mL) was heated for 12 h at 50 °C. The crude product thus obtained was purified by column chromatography using silica gel (neutralized by triethylamine) as the stationary phase and by elution with a mixed medium of petroleum ether/EtOAc to give the desired product, as characterized by ^1H and $^{13}C\{^1H\}$ NMR spectroscopy, GC−MS, and elemental analysis data (entry 7, Supporting Information, Table S12).

(vii) A mixture of PhN_3 (0.369 mmol), $PhCH_2NC$ (0.443 mmol), *trans*-[1-Ph-3-Me-4-CH_2Ph-1,2,3-triazol-5-ylidene]$PdI_2(NC_5H_5)$ (0.003 mmol, 1 mol %), and K_2CO_3 (1.10 mmol) in toluene (*ca.* 5 mL) was heated for 12 h at 50 °C. The crude product thus obtained was purified by column chromatography using silica gel (neutralized by triethylamine) as the stationary phase and by elution with a mixed medium of petroleum ether/EtOAc to give the desired product, as characterized by ^1H and $^{13}C\{^1H\}$ NMR spectroscopy, GC−MS, and elemental analysis data (entry 8, Supporting Information, Table S12).

(viii) A mixture of PhN_3 (0.369 mmol), $PhCH_2NC$ (0.443 mmol), and complex **4** (0.003 mmol, 1 mol %) was heated for 12 h at 50 °C. The crude product thus obtained was analyzed by ^1H and $^{13}C\{^1H\}$ NMR spectroscopy and GC−MS (entry 9, Supporting Information, Table S12).

(ix) A mixture of PhN_3 (0.369 mmol), $PhCH_2NC$ (0.443 mmol), complex **4** (0.003 mmol, 1 mol %), and K_2CO_3 (1.10 mmol) was heated for 12 h at 50 °C. The crude product thus obtained was purified by column chromatography using silica gel (neutralized by triethylamine) as the stationary phase and by elution with a mixed medium of petroleum ether/EtOAc to give the desired product, as characterized by ^1H and $^{13}C\{^1H\}$ NMR spectroscopy, GC−MS and elemental analysis data (entry 10, Supporting Information, Table S12).

General Procedure for the Hg Drop Test.

(i). In a typical Hg drop catalysis run, a mixture of PhN_3 (0.369 mmol), $PhCH_2NC$ (0.443 mmol), and catalyst **4** (0.003 mmol, 1 mol %), K_2CO_3 (1.10 mmol) and excess Hg^0 in toluene (*ca.* 5 mL) was heated for 12 h at 50 °C. The reaction mixture was then cooled to room temperature, and the volatiles were evaporated. The crude product thus obtained was purified by column chromatography using silica gel (neutralized by triethylamine) as the stationary phase and by elution with a mixed medium of petroleum ether/EtOAc to give the desired product, as characterized by ^1H and $^{13}C\{^1H\}$ NMR spectroscopy, GC−MS and elemental analysis data (entry 11, Supporting Information, Table S12).

(ii). In a typical Hg drop catalysis run, a mixture of PhN_3 (0.369 mmol), $PhCH_2NC$ (0.443 mmol), and catalyst **5** (0.003 mmol, 1 mol %), with K_2CO_3 (1.10 mmol) and excess Hg^0 in toluene (*ca.* 5 mL) was heated for 12 h at 50 °C. The reaction mixture was then cooled to room temperature, and the volatiles were evaporated. The crude product thus obtained was purified by column chromatography using silica gel (neutralized by triethylamine) as the stationary phase and by elution with a mixed medium of petroleum ether/EtOAc to give the desired product, as characterized by ^1H and $^{13}C\{^1H\}$ NMR spectroscopy, GC−MS and elemental analysis data (entry 12, Supporting Information, Table S12).

(iii). In a typical Hg drop catalysis run, a mixture of PhN_3 (0.369 mmol), $PhCH_2NC$ (0.443 mmol), and catalyst **6** (0.003 mmol, 1 mol %), with K_2CO_3 (1.10 mmol) and excess Hg^0 in toluene (*ca.* 5 mL) was heated for 12 h at 50 °C. The reaction mixture was then cooled to room temperature, and the volatiles were evaporated. The crude product thus obtained was purified by column chromatography using silica gel (neutralized by triethylamine) as the stationary phase and by elution with a mixed medium of petroleum ether/EtOAc to give the desired product, as

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characterized by ^{1}H and $^{13}C\{^{1}H\}$ NMR spectroscopy, GC−MS and elemental analysis data (entry 13, Supporting Information, Table S12).

(iv). In a typical Hg drop catalysis run, a mixture of PhN_3 (0.369 mmol), $PhCH_2NC$ (0.443 mmol), and catalyst **7** (0.003 mmol, 1 mol %), with K_2CO_3 (1.10 mmol) and excess Hg^0 in toluene (*ca.* 5 mL) was heated for 12 h at 50 °C. The reaction mixture was then cooled to room temperature, and the volatiles were evaporated. The crude product thus obtained was purified by column chromatography using silica gel (neutralized by triethylamine) as the stationary phase and by elution with a mixed medium of petroleum ether/EtOAc to give the desired product, as characterized by ^{1}H and $^{13}C\{^{1}H\}$ NMR spectroscopy, GC−MS and elemental analysis data (entry 14, Supporting Information, Table S12).

General Procedure for the Mass Experiment. In a typical mass experiment run, a mixture of catalyst **4**−**7** (0.01 mmol, 1 mol %) and K_2CO_3 (3 mmol) in 5.0 mL of toluene was heated at 50 °C for 30 min, and then an aliquot from the reaction mixture was analyzed by ESI-MS, where the Pd(0) species **4a** (Figure 6 and Supporting Information, Figure S222), **6a** (Supporting Information, Figures S234 and S235), and **7a** (Supporting Information, Figures S230 and S231) were detected.

In a typical mass experiment run, a mixture of PhN_3 (1 mmol), catalyst **4**−**7** (0.01 mmol, 1 mol %), and K_2CO_3 (3 mmol) in 5.0 mL of toluene was heated at 50 °C for 30 min, and then an aliquot from the reaction mixture was analyzed by ESI-MS, where the Pd bound nitrene species **4b** (Figure 7 and Supporting Information, Figure S223) and **5b** (Supporting Information, Figures S226 and S227) were detected.

In a typical mass experiment run, a mixture of PhN_3 (1 mmol), $PhCH_2NC$ (1.2 mmol), catalyst **4**−**7** (0.01 mmol, 1 mol %), and K_2CO_3 (3 mmol) in 5.0 mL of toluene was heated at 50 °C for 1.5 h, and then an aliquot from the reaction mixture was analyzed by ESI-MS, where the species **C** (Figure 8 and Supporting Information, Figures S224, S225, S228, S229, S232, and S233) and **6c** (Supporting Information, Figure S236 and S237) were detected.

General Procedure for the XPS Experiment. The following different XPS runs were performed.

(i) Complex **4** (0.030 mmol) was heated for 24 h in 5 mL of toluene at 100 °C, and then the solvent was evaporated and dried. The crude product thus obtained was analyzed by XPS (Supporting Information, Figure S239).

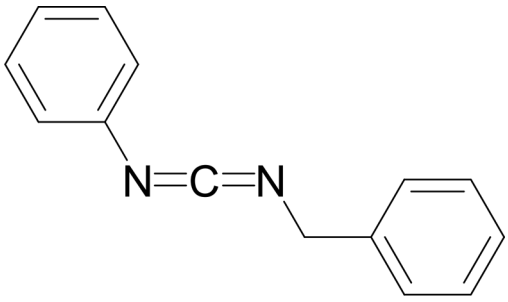
(ii) Complex **5** (0.030 mmol) was heated for 24 h in 5 mL of toluene at 100 °C, and then the solvent was evaporated and dried. The crude product thus obtained was analyzed by XPS (Supporting Information, Figure S241).

(iii) Complex **6** (0.030 mmol) was heated for 24 h in 5 mL of toluene at 100 °C, and then the solvent was evaporated and dried. The crude product thus obtained was analyzed by XPS (Supporting Information, Figure S243).

(iv) Complex **7** (0.030 mmol) was heated for 24 h in 5 mL of toluene at 100 °C, and then the solvent was evaporated and dried. The crude product thus obtained was analyzed by XPS (Supporting Information, Figure S245).

(v) A mixture of PhN_3 (0.369 mmol), $PhCH_2NC$ (0.443 mmol), complex **4** (0.030 mmol, 10 mol %), and K_2CO_3 (1.10 mmol) was heated for 12 h in 5 mL of toluene at 50 °C, and then the solvent was evaporated and dried. The crude product thus obtained was analyzed by XPS (Supporting Information, Figure S246).

Synthesis of *N*-((Benzylimino)methylene)aniline (8).[68]

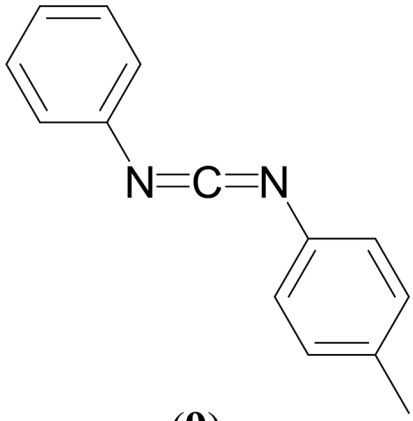


(8)

Yields: 0.068 g, 88% (**4**), 0.060 g, 79% (**5**), 0.051 g, 66% (**6**), 0.036 g, 48% (**7**).

^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.42−7.40 (m, 4H, $CH_2C_6\underline{H}_5$), 7.36−7.33 (m, 1H, $CH_2C_6\underline{H}_5$), 7.28 (t, 2H, $^{3}J_{HH}$ = 7 Hz, $C_6\underline{H}_5$), 7.13 (t, 1H, $^{3}J_{HH}$ = 7 Hz, $C_6\underline{H}_5$), 7.03 (d, 2H, $^{3}J_{HH}$ = 7 Hz, $C_6\underline{H}_5$), 4.60 (s, 2H, $C\underline{H}_2C_6H_5$). $^{13}C\{^{1}H\}$ NMR ($CDCl_3$, 100 MHz, 25 °C): δ 140.0 ($\underline{C}_6H_5$), 137.8 ($CH_2\underline{C}_6H_5$), 137.3 (N$\underline{C}$N), 129.3 ($\underline{C}_6H_5$), 128.8 ($\underline{C}_6H_5$), 127.8 ($\underline{C}_6H_5$), 127.4 ($CH_2\underline{C}_6H_5$), 124.9 ($CH_2\underline{C}_6H_5$), 123.6 ($CH_2\underline{C}_6H_5$), 50.5 ($\underline{C}H_2C_6H_5$). GC−MS (ESI): m/z = 208 $[M]^+$. Anal. Calcd for $C_{14}H_{12}N_2$: C, 80.74; H, 5.81; N, 13.45. Found: C, 80.08; H, 5.74; N, 13.05%.

Synthesis of *N*-((Tolylimino)methylene)aniline (9).[69]



(9)

Yields: 0.072 g, 94% (**4**), 0.065 g, 85% (**5**), 0.055 g, 74% (**6**), 0.040 g, 52% (**7**).

^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.33 (t, 2H, $^{3}J_{HH}$ = 7 Hz, $C_6\underline{H}_5$), 7.19 (d, 3H, $^{3}J_{HH}$ = 7 Hz, $C_6\underline{H}_5$), 7.14 (d, 2H, $^{3}J_{HH}$ = 8 Hz, $C_6\underline{H}_4CH_3$), 7.09 (d, 2H, $^{3}J_{HH}$ = 8 Hz, $C_6\underline{H}_4CH_3$), 2.34 (s, 3H, $C_6H_4C\underline{H}_3$). $^{13}C\{^{1}H\}$ NMR ($CDCl_3$, 100 MHz, 25 °C): δ 138.7 ($\underline{C}_6H_5$), 135.6 (N$\underline{C}$N), 135.5 ($\underline{C}_6H_4CH_3$), 130.1 ($\underline{C}_6H_5$), 129.5 ($\underline{C}_6H_5$), 125.5 ($\underline{C}_6H_5$), 124.2 ($\underline{C}_6H_4CH_3$), 124.1 ($\underline{C}_6H_4CH_3$), 123.9 ($\underline{C}_6H_4CH_3$), 21.0 ($C_6H_4\underline{C}H_3$). GC−MS (ESI): m/z = 208 $[M]^+$. Anal. Calcd for $C_{14}H_{12}N_2$: C, 80.74; H, 5.81; N, 13.45. Found: C, 80.19; H, 5.96; N, 13.54%.

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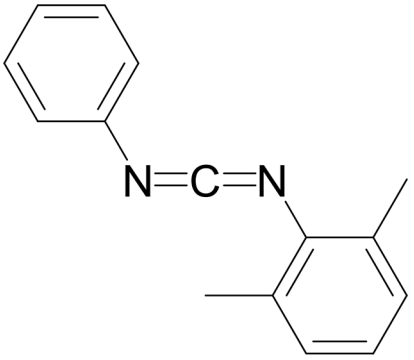
Synthesis of *N*-((Xylylimino)methylene)aniline (10).[14]

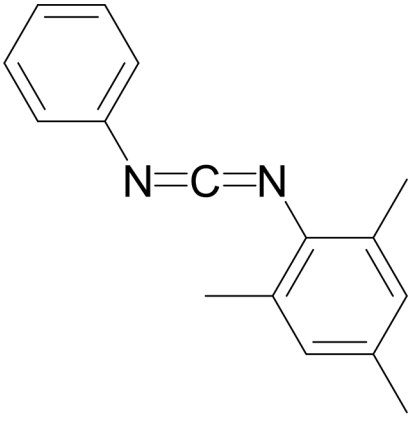


(10)

Yields: 0.064 g, 78% (**4**), 0.051 g, 62% (**5**), 0.041 g, 50% (**6**), 0.019 g, 24% (**7**).

^{1}H NMR ($CDCl_3$, 500 MHz, 25 °C): δ 7.33 (t, 2H, $^3J_{HH}$ = 7 Hz, $C_6\underline{H}_5$), 7.18 (d, 2H, $^3J_{HH}$ = 7 Hz, $C_6\underline{H}_5$), 7.14 (t, 1H, $^3J_{HH}$ = 7 Hz, 2,6-$(CH_3)_2C_6\underline{H}_3$), 7.05 (d, 2H, $^3J_{HH}$ = 7 Hz, 2,6-$(CH_3)_2C_6\underline{H}_3$), 7.00 (t, 1H, $^3J_{HH}$ = 7 Hz, $C_6\underline{H}_5$), 2.40 (s, 6H, 2,6-$(C\underline{H}_3)_2C_6H_3$). ^{13}C{^{1}H} NMR ($CDCl_3$, 125 MHz, 25 °C): δ 139.8 ($\underline{C}_6H_5$), 134.9 (2,6-$(CH_3)_2\underline{C}_6H_3$), 132.8 (2,6-$(CH_3)_2\underline{C}_6H_3$), 131.5 (N$\underline{C}$N), 129.5 ($\underline{C}_6H_5$), 128.2 ($\underline{C}_6H_5$), 125.1 ($\underline{C}_6H_5$), 124.7 (2,6-$(CH_3)_2\underline{C}_6H_3$), 123.7 (2,6-$(CH_3)_2\underline{C}_6H_3$), 19.0 (2,6-$(\underline{C}H_3)_2C_6H_3$). GC−MS (ESI): m/z = 222 $[M]^+$. Anal. Calcd for $C_{15}H_{12}N_2$: C, 81.05; H, 6.35; N, 12.60. Found: C, 81.71; H, 6.60; N, 12.37%.

Synthesis of *N*-((Mesityimino)methylene)aniline (11).[70]

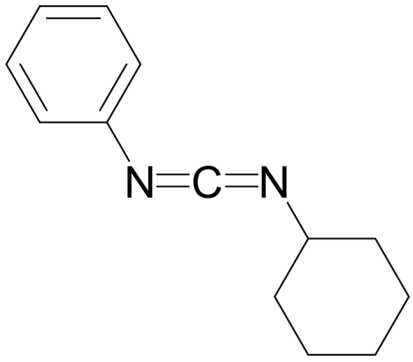


(11)

Yields: 0.053 g, 61% (**4**), 0.046 g, 53% (**5**), 0.034 g, 39% (**6**), 0.014 g, 16% (**7**).

^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.32 (t, 2H, $^3J_{HH}$ = 7 Hz, $C_6\underline{H}_5$), 7.18−7.11 (m, 3H, $C_6\underline{H}_5$), 6.87 (s, 2H, 2,4,6-$(CH_3)_3C_6\underline{H}_2$), 2.36 (s, 6H, 2,4,6-$(C\underline{H}_3)_3C_6H_2$), 2.27 (s, 3H, 2,4,6-$(C\underline{H}_3)_3C_6\underline{H}_2$). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz, 25 °C): δ 140.2 ($\underline{C}_6H_5$), 134.9 (2,4,6-$(CH_3)_3\underline{C}_6H_2$), 132.7 (2,4,6-$(CH_3)_3\underline{C}_6H_2$), 132.1 (2,4,6-$(CH_3)_3\underline{C}_6H_2$), 131.8 (N$\underline{C}$N), 129.4 ($\underline{C}_6H_5$), 128.9 ($\underline{C}_6H_5$), 124.6 ($\underline{C}_6H_5$), 123.6 (2,4,6-$(CH_3)_3\underline{C}_6H_2$), 20.8 (2,4,6-$(C\underline{H}_3)_3C_6H_2$), 18.9 (2,4,6-$(C\underline{H}_3)_3C_6H_2$). GC−MS (ESI): m/z = 236 $[M]^+$. Anal. Calcd for $C_{16}H_{16}N_2$: C, 81.32; H, 6.82; N, 11.85. Found: C, 81.31; H, 6.74; N, 11.68%.

Synthesis of *N*-((Cyclohexyimino)methylene)aniline (12).[71]

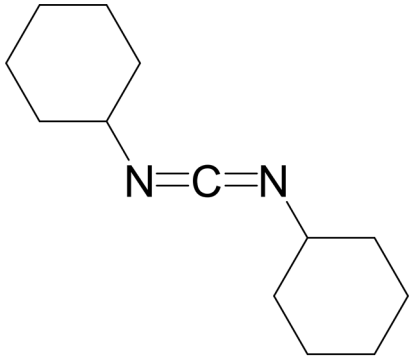


(12)

Yields: 0.069 g, 94% (**4**), 0.068 g, 92% (**5**), 0. 056 g, 76% (**6**), 0.023 g, 32% (**7**).

^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.31 (t, 2H, $^3J_{HH}$ = 7 Hz, $C_6\underline{H}_5$), 7.13−7.10 (m, 3H, $C_6\underline{H}_5$), 3.53−3.46 (m, 1H, $C_6\underline{H}_{11}$), 2.06−2.01 (m, 2H, $C_6\underline{H}_{11}$), 1.83−1.77 (m, 2H, $C_6\underline{H}_{11}$), 1.66−1.47 (m, 3H, $C_6\underline{H}_{11}$), 1.42−1.28 (m, 3H, $C_6\underline{H}_{11}$). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz, 25 °C): δ 140.9 ($\underline{C}_6H_5$), 136.2 (N$\underline{C}$N), 129.3 ($\underline{C}_6H_5$), 124.5 ($\underline{C}_6H_5$), 123.3 ($\underline{C}_6H_5$), 56.6 ($\underline{C}_6H_{11}$), 34.9 ($\underline{C}_6H_{11}$), 25.3 ($\underline{C}_6H_{11}$), 24.3 ($\underline{C}_6H_{11}$). GC−MS (ESI): m/z = 200 $[M]^+$. Anal. Calcd for $C_{13}H_{16}N_2$: C, 77.96; H, 8.05; N, 13.99. Found: C, 78.73; H, 8.28; N, 13.20%.

Synthesis of *N*-((Cyclohexylimino)methylene)-cyclohexylamine (13).[71]



(13)

Yields: 0.064 g, 84% (**4**), 0.051 g, 67% (**5**), 0.041 g, 54% (**6**), 0.028 g, 37% (**7**).

^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 3.20−3.14 (m, 1H, $C_6\underline{H}_{11}$), 1.91−1.89 (m, 2H, $C_6\underline{H}_{11}$), 1.73−1.70 (m, 2H, $C_6\underline{H}_{11}$), 1.57−1.53 (m, 1H, $C_6\underline{H}_{11}$), 1.35−1.16 (m, 5H, $C_6\underline{H}_{11}$). ^{13}C{^{1}H} NMR ($CDCl_3$, 125 MHz, 25 °C): δ 139.8 (N$\underline{C}$N), 55.7 ($\underline{C}_6H_{11}$), 34.9 ($\underline{C}_6H_{11}$), 25.4 ($\underline{C}_6H_{11}$), 24.7 ($\underline{C}_6H_{11}$). GC−MS (ESI): m/z = 206 $[M]^+$. Anal. Calcd for $C_{13}H_{22}N_2$: C, 75.68; H, 10.75; N, 13.58. Found: C, 76.19; H, 10.75; N, 13.56%.

https://doi.org/10.1021/acsomega.2c07875
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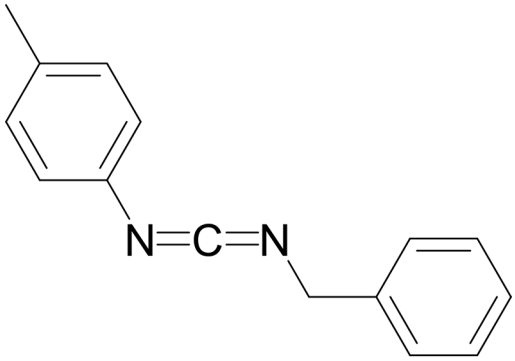
Synthesis of *N*-((Tolylimino)methylene)-cyclohexylamine (14).[72]

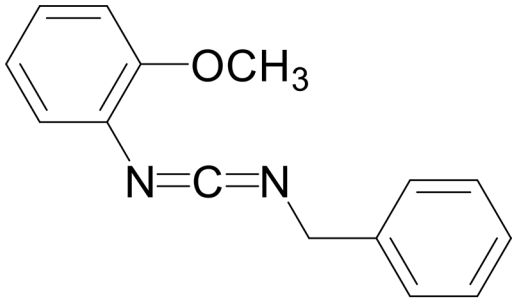


(14)

Yields: 0.054 g, 66% (**4**), 0.043 g, 52% (**5**), 0. 032 g, 39% (**6**), 0.023 g, 28% (**7**).

^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.37−7.36 (m, 4H, $CH_2C_6\underline{H}_5$), 7.32−7.29 (m, 1H, $CH_2C_6\underline{H}_5$), 7.04 (d, 2H, $^3J_{HH}$ = 8 Hz, $C_6\underline{H}_4CH_3$), 6.88 (d, 2H, $^3J_{HH}$ = 8 Hz, $C_6\underline{H}_4CH_3$), 4.55 (s, 2H, $C\underline{H}_2C_6H_5$), 2.29 (s, 3H, $C_6H_4C\underline{H}_3$). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz, 25 °C): δ 137.9 ($\underline{C}_6H_4CH_3$), 137.8 (N$\underline{C}$N), 137.0 $CH_2\underline{C}_6H_5$), 134.6 ($\underline{C}_6H_4CH_3$), 129.9 ($\underline{C}_6H_4CH_3$), 128.7 ($\underline{C}_6H_4CH_3$), 127.7 ($CH_2\underline{C}_6H_5$), 127.4 ($CH_2\underline{C}_6H_5$), 123.4 ($CH_2\underline{C}_6H_5$), 50.5 ($\underline{C}H_2C_6H_5$), 20.9 ($C_6H_4\underline{C}H_3$). GC−MS (ESI): m/z = 222 [M]$^+$. Anal. Calcd for $C_{15}H_{14}N_2$: C, 81.05; H, 6.35; N, 12.60. Found: C, 79.80; H, 6.32; N, 12.20%.

Synthesis of *N*-((Tolylimino)methylene)-cyclohexylamine (15).

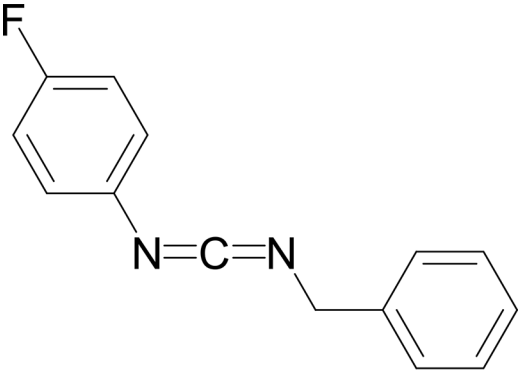


(15)

Yields: 0.049 g, 56% (**4**), 0.033 g, 38% (**5**), 0. 023 g, 26% (**6**), 0.010 g, 12% (**7**).

^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.41−7.34 (m, 4H, $CH_2C_6\underline{H}_5$), 7.31−7.28 (m, 1H, $CH_2C_6\underline{H}_5$), 7.06 (td, 1H, $^3J_{HH}$ = 8 Hz, $^4J_{HH}$ = 2 Hz, $C_6\underline{H}_4OCH_3$), 6.99 (d, 2H, $^3J_{HH}$ = 8 Hz, $C_6\underline{H}_4OCH_3$), 6.85 (t, 1H, $^3J_{HH}$ = 8 Hz, $C_6\underline{H}_4OCH_3$), 6.84 (d, 2H, $^3J_{HH}$ = 8 Hz, $C_6\underline{H}_4OCH_3$), 4.58 (s, 2H, $C\underline{H}_2C_6H_5$), 3.76 (s, 3H, $C_6H_4OC\underline{H}_3$). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz, 25 °C): δ 154.0 ($\underline{C}_6H_4OCH_3$), 138.1 ($CH_2\underline{C}_6H_5$), 128.6 ($\underline{C}_6H_4OCH_3$), 128.4 (N$\underline{C}$N), 127.5 ($CH_2\underline{C}_6H_5$), 127.4 (2 $\underline{C}_6H_4OCH_3$), 125.6 ($CH_2\underline{C}_6H_5$), 124.7 ($CH_2\underline{C}_6H_5$), 120.9 ($\underline{C}_6H_4OCH_3$), 111.0 ($\underline{C}_6H_4OCH_3$), 55.8 ($C_6H_4O\underline{C}H_3$), 50.6 ($\underline{C}H_2C_6H_5$). GC−MS (ESI): m/z = 238 [M]$^+$. Anal. Calcd for $C_{15}H_{14}N_2O$: C, 75.61; H, 5.92; N, 11.76. Found: C, 75.26; H, 5.84; N, 11.45%.

Synthesis of *N*-((4-Fluorophenylimino)methylene)-cyclohexylamine (16).

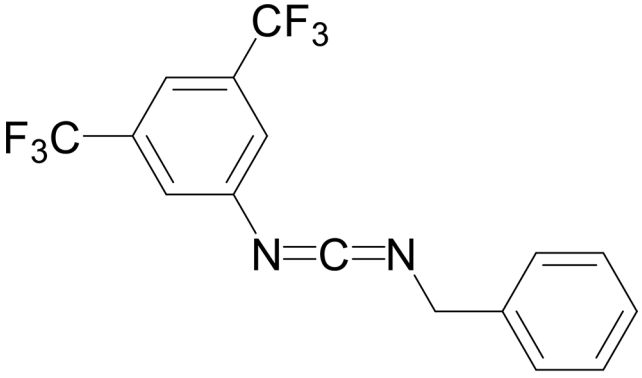


(16)

Yields: 0.082 g, 99% (**4**), 0.077 g, 93% (**5**), 0. 067 g, 80% (**6**), 0.050 g, 61% (**7**).

^{1}H NMR (C_6D_6, 400 MHz, 25 °C): δ 7.05−7.04 (m, 3H, $CH_2C_6\underline{H}_5$), 7.03−6.94 (m, 2H, $CH_2C_6\underline{H}_5$), 6.75−6.71 (m, 2H, $C_6\underline{H}_4F$), 6.60−6.56 (m, 2H, $C_6\underline{H}_4F$), 4.00 (s, 2H, $C\underline{H}_2C_6H_5$). ^{13}C{^{1}H} NMR (C_6D_6, 100 MHz, 25 °C): δ 161.1 (d, $^1J_{CF}$ = 244 Hz, $\underline{C}_6H_4F$), 137.9 ($CH_2\underline{C}_6H_5$), 137.1 (N$\underline{C}$N), 132.0 ($CH_2\underline{C}_6H_5$), 131.4 (d, $^4J_{CF}$ = 4 Hz, $\underline{C}_6H_4F$), 128.5 ($CH_2\underline{C}_6H_5$), 127.2 ($CH_2\underline{C}_6H_5$), 124.8 (d, $^3J_{CF}$ = 8 Hz, $\underline{C}_6H_4F$), 115.9 (d, $^2J_{CF}$ = 23 Hz, $\underline{C}_6H_4F$), 49.9 ($\underline{C}H_2C_6H_5$). ^{19}F{^{1}H} NMR (C_6D_6, 376 MHz, 25 °C): δ − 117.71 ($C_6H_4\underline{F}$). GC−MS (ESI): m/z = 226 [M]$^+$. Anal. Calcd for $C_{14}H_{11}N_2F$: C, 74.32; H, 4.90; N, 12.38. Found: C, 75.31; H, 5.12; N, 11.74%.

Synthesis of *N*-((3,5-Bis(trifluoromethyl)-phenylimino)methylene)cyclohexylamine (17).



(17)

Yields: 0.115 g, 91% (**4**), 0.095 g, 75% (**5**), 0. 082 g, 65% (**6**), 0.050 g, 44% (**7**).

^{1}H NMR (C_6D_6, 400 MHz, 25 °C): δ 7.37 (s, 1H, $C_6\underline{H}_3(CF_3)_2$), 7.08 (s, 2H, $C_6\underline{H}_3(CF_3)_2$), 7.06−7.01 (m, 3H, $CH_2C_6\underline{H}_5$), 6.95 (d, 2H, $^3J_{HH}$ = 7 Hz, $CH_2C_6\underline{H}_5$), 3.86 (s, 2H, $C\underline{H}_2C_6H_5$). ^{13}C{^{1}H} NMR (C_6D_6, 100 MHz, 25 °C): δ 143.1 ($\underline{C}_6H_3(CF_3)_2$), 137.3 ($CH_2\underline{C}_6H_5$), 134.6 (N$\underline{C}$N), 132.4 (q, $^2J_{CF}$ = 33 Hz, $\underline{C}_6H_3(CF_3)_2$), 131.7 ($CH_2\underline{C}_6H_5$), 128.8 ($CH_2\underline{C}_6H_5$), 127.1 ($CH_2\underline{C}_6H_5$), 123.4 (d, $^4J_{CF}$ = 3 Hz, $\underline{C}_6H_3(CF_3)_2$), 123.1 (q, $^1J_{CF}$ = 273 Hz, $C_6H_3(\underline{C}F_3)_2$), 117.5 (quin, $^3J_{CF}$ = 4 Hz, $\underline{C}_6H_3(CF_3)_2$), 49.7 ($\underline{C}H_2C_6H_5$). ^{19}F{^{1}H} NMR ($C_6D_6$, 376 MHz, 25 °C): δ − 62.86 ($C_6H_3(C\underline{F}_3)_2$). GC−MS (ESI): m/z = 344 [M]$^+$. Anal. Calcd for $C_{16}H_{10}N_2F_6$: C, 55.82; H, 2.93; N, 8.14. Found: C, 55.54; H, 3.79; N, 8.98%.

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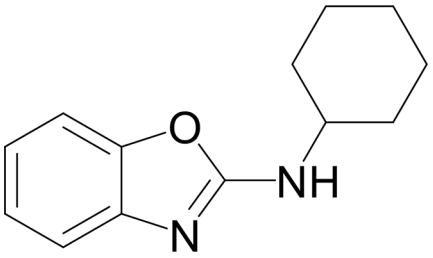
General Procedure for the Synthesis of Benzoxazole Derivatives Using Azide and Isocyanide Cross-Coupling as Catalyzed by a Phenothiazine-Derived Mesoionic Singlet Carbene Palladium (4) Complex (Table 3, Entries 1−5). In a typical catalysis run, a 20 mL reaction vial was charged with a mixture of palladium complex **4** (0.01 mmol, 1 mol %) and K_2CO_3 (3.00 mmol), and then the corresponding azide (1.00 mmol) and isocyanide (1.20 mmol) were added to it, followed by 5 mL of toluene, and the reaction mixture was heated at 50 °C for 12 h. The reaction mixture was cooled to room temperature, filtered, and subsequently purified by column chromatography using silica gel as a stationary phase and by elution with a mixed medium of petroleum ether/EtOAc to give the desired product, as characterized by ^{1}H and ^{13}C{^{1}H} NMR spectroscopy, GC−MS, and elemental analysis data.

Synthesis of *N*-Cyclohexylbenzooxazol-2-amine (18).[73]

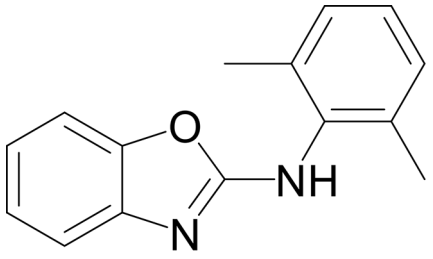


(18)

Yield: 0.181 g, 84% (**4**).

^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.35 (d, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 7.22 (d, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 7.14 (t, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 7.00 (t, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 5.08 (br, 1H, N$\underline{H}$), 3.80−3.71 (m, 1H, $C_6\underline{H}_{11}$), 2.14−2.11 (m, 2H, $C_6\underline{H}_{11}$), 1.79−1.74 (m, 2H, $C_6\underline{H}_{11}$), 1.67−1.62 (m, 1H, $C_6\underline{H}_{11}$), 1.48−1.38 (m, 2H, $C_6\underline{H}_{11}$), 1.34−1.25 (m, 3H, $C_6\underline{H}_{11}$). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz, 25 °C): δ 161.4 (O$\underline{C}$N of C_7H_4NO), 148.3 ($\underline{C}_6H_4$ of C_7H_4NO), 143.1 ($\underline{C}_6H_4$ of C_7H_4NO), 123.8 ($\underline{C}_6H_4$ of C_7H_4NO), 120.6 ($\underline{C}_6H_4$ of C_7H_4NO), 116.2 ($\underline{C}_6H_4$ of C_7H_4NO), 108.6 ($\underline{C}_6H_4$ of C_7H_4NO), 52.0 ($\underline{C}_6H_{11}$), 33.4 ($\underline{C}_6H_{11}$), 25.4 ($\underline{C}_6H_{11}$), 24.7 ($\underline{C}_6H_{11}$). GC−MS (ESI): m/z = 216 $[M]^+$. Anal. Calcd for $C_{13}H_{16}N_2O$: C, 72.19; H, 7.46; N, 12.95. Found: C, 72.34; H, 7.08; N, 12.87%.

Synthesis of *N*-(2,6-dimethylphenyl)lbenzooxazol-2-amine (19).[74]

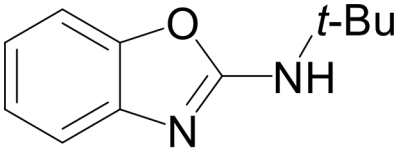


(19)

Yield: 0.128 g, 54% (**4**).

^{1}H NMR (DMSO-d_6, 400 MHz, 25 °C): δ 9.58 (br, 1H, N$\underline{H}$), 7.39 (d, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 7.22 (d, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 7.17−7.10 (m, 4H, $C_7\underline{H}_4NO$ and 2,6-$(CH_3)_2C_6\underline{H}_3$), 7.01 (t, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 2.20 (s, 6H, 2,6-$(C\underline{H}_3)_2C_6H_3$). ^{13}C{^{1}H} NMR (DMSO-d_6, 100 MHz, 25 °C): δ 160.3 (O$\underline{C}$N of C_7H_4NO), 148.0 ($\underline{C}_6H_4$ of C_7H_4NO), 142.8 ($\underline{C}_6H_4$ of C_7H_4NO), 135.6 (2,6-$(CH_3)_2\underline{C}_6H_3$), 134.9 (2,6-$(CH_3)_2\underline{C}_6H_3$), 128.2 (2,6-$(CH_3)_2\underline{C}_6H_3$), 126.9 (2,6-$(CH_3)_2\underline{C}_6H_3$), 123.8 ($\underline{C}_6H_4$ of C_7H_4NO), 120.6 ($\underline{C}_6H_4$ of C_7H_4NO), 115.7 ($\underline{C}_6H_4$ of C_7H_4NO), 108.8 ($\underline{C}_6H_4$ of C_7H_4NO), 17.9 (2,6-$(\underline{C}H_3)_2C_6H_3$). GC−MS (ESI): m/z = 238 $[M]^+$. Anal. Calcd for $C_{15}H_{14}N_2O$: C, 75.61; H, 5.92; N, 11.76. Found: C, 75.28; H, 6.59; N, 11.43%

Synthesis of *N*-*tert*-Butylbenzooxazol-2-amine (20).[74]

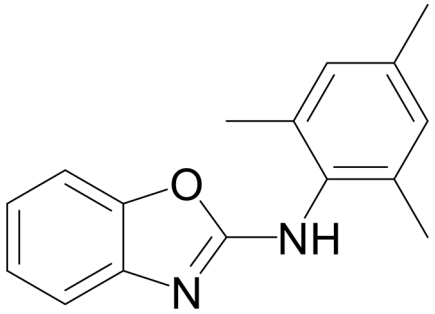


(20)

Yield: 0.169 g, 89% (**4**).

^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.39 (d, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 7.27 (d, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 7.18 (t, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 7.04 (t, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 5.46 (br, 1H, N$\underline{H}$), 1.52 (s, 9H, $C(C\underline{H}_3)_3$). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz, 25 °C): δ 160.8 (O$\underline{C}$N of C_7H_4NO), 148.0 ($\underline{C}_6H_4$ of C_7H_4NO), 142.5 ($\underline{C}_6H_4$ of C_7H_4NO), 123.8 ($\underline{C}_6H_4$ of C_7H_4NO), 120.7 ($\underline{C}_6H_4$ of C_7H_4NO), 116.2 ($\underline{C}_6H_4$ of C_7H_4NO), 108.6 ($\underline{C}_6H_4$ of C_7H_4NO), 52.1 ($\underline{C}(CH_3)_3$), 29.2 ($C(\underline{C}H_3)_3$). GC−MS (ESI): m/z = 190 $[M]^+$. Anal. Calcd for $C_{11}H_{14}N_2O$: C, 69.45; H, 7.42; N, 14.73. Found: C, 68.76; H, 6.54; N, 14.37%.

Synthesis of *N*-Mesiylbenzooxazol-2-amine (21).



(21)

Yield: 0.083 g, 33% (**4**).

^{1}H NMR (DMSO-d_6, 400 MHz, 25 °C): δ 9.03 (br, 1H, N$\underline{H}$), 6.91 (s, 2H, 2,4,6-$(CH_3)_3C_6\underline{H}_2$), 6.71 (dd, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 6.64 (dd, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 6.57 (td, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 6.43 (td, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 2.26 (s, 6H, 2,4,6-$(C\underline{H}_3)_3C_6H_2$), 2.22 (s, 3H, 2,6-$(C\underline{H}_3)_3C_6H_2$). ^{13}C{^{1}H} NMR (DMSO-d_6, 100 MHz, 25 °C): δ 167.8 (O$\underline{C}$N of C_7H_4NO), 144.5 ($\underline{C}_6H_4$ of C_7H_4NO), 139.2 ($\underline{C}_6H_4$ of C_7H_4NO), 136.9 (2,4,6-$(CH_3)_3\underline{C}_6H_2$), 134.4 (2,4,6-

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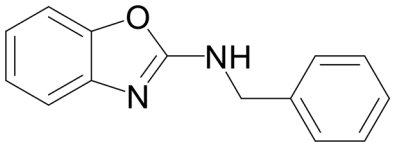
(CH_3)$_3$$\underline{C}_6H_2$), 128.8 2,4,6-($CH_3$)$_3$$\underline{C}_6H_2$), 123.7 (2,4,6-($CH_3$)$_3$$\underline{C}_6H_2$), 120.0 ($\underline{C}_6H_4$ of C_7H_4NO), 117.0 ($\underline{C}_6H_4$ of C_7H_4NO), 115.0 ($\underline{C}_6H_4$ of C_7H_4NO), 114.8 ($\underline{C}_6H_4$ of C_7H_4NO), 21.1 (2,4,6-($\underline{C}H_3$)$_3$$C_6H_2$), 18.6 (2,4,6-($\underline{C}H_3$)$_3$$C_6H_2$). GC−MS (ESI): m/z = 252 $[M]^+$. Anal. Calcd for $C_{16}H_{16}N_2O$: C, 76.16; H, 6.39; N, 11.10. Found: C, 76.47; H, 6.59; N, 10.20%.

Synthesis of *N*-Benzylbenzooxazol-2-amine (22).[75]



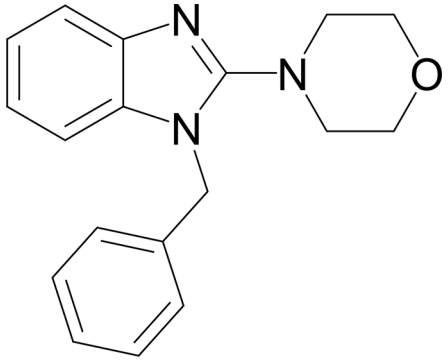
(22)

Yield: 0.162 g, 72% (**4**).

^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.41−7.24 (m, 6H, $C_7\underline{H}_4NO$ and $CH_2C_6\underline{H}_5$), 7.16 (t, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 7.03 (t, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4NO$), 5.98 (br, 1H, N$\underline{H}$), 4.67 (s, 9H, $C\underline{H}_2C_6H_5$). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz, 25 °C): δ 162.1 (O$\underline{C}$N of C_7H_4NO), 148.5 ($\underline{C}_6H_4$ of C_7H_4NO), 142.7 ($\underline{C}_6H_4$ of C_7H_4NO), 137.7 ($CH_2\underline{C}_6H_5$), 128.8 ($CH_2\underline{C}_6H_5$), 127.8 ($CH_2\underline{C}_6H_5$), 127.6 ($CH_2\underline{C}_6H_5$), 124.0 ($\underline{C}_6H_4$ of C_7H_4NO), 120.9 ($\underline{C}_6H_4$ of C_7H_4NO), 116.3 ($\underline{C}_6H_4$ of C_7H_4NO), 108.8 ($\underline{C}_6H_4$ of C_7H_4NO), 47.0 ($\underline{C}H_2C_6H_5$). GC−MS (ESI): m/z = 224 $[M]^+$. Anal. Calcd for $C_{14}H_{12}N_2O$: C, 74.98; H, 5.39; N, 12.49. Found: C, 74.30; H, 5.68; N, 13.38%.

General Procedure for the Synthesis of Benzimidazole Derivatives Using Azide and Isocyanide Cross-Coupling as Catalyzed by a Phenothiazine-Derived Mesoionic Singlet Carbene Palladium (4) Complex (Table 4, Entries 1−5). In a typical catalysis run, a 20 mL reaction vial was charged with a mixture of palladium complex **4** (0.01 mmol, 1 mol %) and K_2CO_3 (3.00 mmol), and then the corresponding azide (1.00 mmol) and isocyanide (1.20 mmol) were added to it, followed by 5 mL of toluene, and the reaction mixture was heated at 50 °C for 12 h. The reaction mixture was cooled to room temperature, CuI (0.100 mmol, 10 mol %), 1,10-phenanthroline (0.200 mmol, 20 mol %), Cs_2CO_3 (2.00 mmol), and N-heterocycle (1.1 mmol) were added to it and heated at 80 °C for 20 h. Then it was filtered, the solvent was evaporated, and the result was subsequently purified by column chromatography using silica gel as the stationary phase and by elution with a mixed medium of petroleum ether/EtOAc to give the desired product, as characterized by ^{1}H and $^{13}C\{^1H\}$ NMR spectroscopy, GC−MS, and elemental analysis data.

Synthesis of 4-(1-Benzyl-1*H*-benzimidazol-2-yl)-morpholine (23).[76]

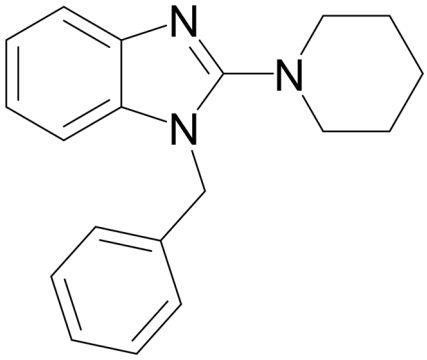


(23)

Yield: 0.187 g, 64% (**4**).

^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.65 (d, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4N_2$), 7.34−7.29 (m, 3H, $CH_2C_6\underline{H}_5$), 7.19 (td, 1H, $^3J_{HH}$ = 8 Hz, $^4J_{HH}$ = 1 Hz, $C_7\underline{H}_4N_2$), 7.14 (d, 2H, $^3J_{HH}$ = 7 Hz, $CH_2C_6\underline{H}_5$), 7.09 (td, 1H, $^3J_{HH}$ = 8 Hz, $^4J_{HH}$ = 1 Hz, $C_7\underline{H}_4N_2$), 7.02 (d, 1H, $^3J_{HH}$ = 7 Hz, $C_7\underline{H}_4N_2$), 5.23 (s, 2H, $C\underline{H}_2C_6H_5$), 3.79 (t, 4H, $^3J_{HH}$ = 5 Hz, $NC_4\underline{H}_8O$), 3.24 (t, 4H, $^3J_{HH}$ = 5 Hz, $NC_4\underline{H}_8O$). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz, 25 °C): δ 157.6 (N$\underline{C}$N of $C_7H_4N_2$), 141.3 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 136.0 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 135.3 ($CH_2\underline{C}_6H_5$), 128.9 ($CH_2\underline{C}_6H_5$), 127.6 ($CH_2\underline{C}_6H_5$), 125.9 ($CH_2\underline{C}_6H_5$), 122.0 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 121.5 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 118.1 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 109.3 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 66.4 ($N\underline{C}_4H_8O$), 50.8 ($N\underline{C}_4H_8O$), 47.4 ($\underline{C}H_2C_6H_5$). GC−MS (ESI): m/z = 293 $[M]^+$. Anal. Calcd for $C_{18}H_{19}N_3O$: C, 73.69; H, 6.53; N, 14.32. Found: C, 73.55; H, 6.02; N, 14.02%.

Synthesis of 1-Benzyl-2-(piperidin-1-yl)-1*H*-benzimidazole (24).[77]



(24)

Yield: 0.197 g, 68% (**4**).

^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.63 (d, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4N_2$), 7.34−7.27 (m, 3H, $CH_2C_6\underline{H}_5$), 7.18 (d, 2H, $^3J_{HH}$ = 7 Hz, $CH_2C_6\underline{H}_5$), 7.17 (t, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4N_2$), 7.06 (t, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4N_2$), 6.98 (d, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4N_2$), 5.20 (s, 2H, $C\underline{H}_2C_6H_5$), 3.20 (t, 4H, $^3J_{HH}$ = 5 Hz, $NC_5\underline{H}_{10}$), 1.67−1.60 (m, 6H, $NC_5\underline{H}_{10}$). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz, 25 °C): δ 159.0 (N$\underline{C}$N of $C_7H_4N_2$), 141.6 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 136.4 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 135.3 ($CH_2\underline{C}_6H_5$), 128.8 ($CH_2\underline{C}_6H_5$), 127.5 ($CH_2\underline{C}_6H_5$), 126.1 ($CH_2\underline{C}_6H_5$), 121.7 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 121.1 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 117.8 ($\underline{C}_6H_4$ of

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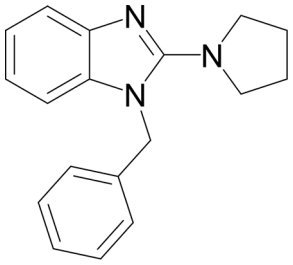
$C_7H_4N_2$), 109.2 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 51.8 ($N\underline{C}_5H_{10}$), 47.6 ($\underline{C}H_2C_6H_5$), 25.6 ($N\underline{C}_5H_{10}$), 24.1 ($N\underline{C}_5H_{10}$). GC−MS (ESI): m/z = 291 $[M]^+$. Anal. Calcd for $C_{19}H_{21}N_3$: C, 78.32; H, 7.26; N, 14.42. Found: C, 78.78; H, 7.37; N, 14.50%.

Synthesis of 1-Benzyl-2-(pyrrolidin-1-yl)-1*H*-benzimidazole (25).[76]

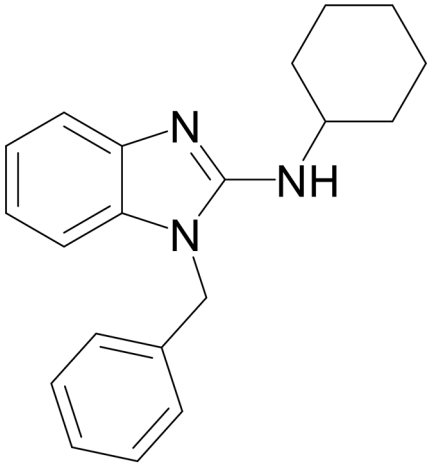


(25)

Yield: 0.083 g, 33% (**4**).

^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.55 (d, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4N_2$), 7.34−7.27 (m, 4H, $C_7\underline{H}_4N_2$ and $CH_2C_6\underline{H}_5$), 7.55 (d, 2H, $^3J_{HH}$ = 7 Hz, $CH_2C_6\underline{H}_5$), 7.01 (t, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4N_2$), 6.97 (d, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4N_2$), 5.28 (s, 2H, $C\underline{H}_2C_6H_5$), 3.58 (br, 4H, $NC_4\underline{H}_8$), 1.91 (br, 4H, $NC_4\underline{H}_8$). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz, 25 °C): δ 161.0 ($N\underline{C}N$ of $C_7H_4N_2$), 141.6 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 138.6 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 136.7 ($CH_2\underline{C}_6H_5$), 128.9 ($CH_2\underline{C}_6H_5$), 127.5 ($CH_2\underline{C}_6H_5$), 125.7 ($CH_2\underline{C}_6H_5$), 122.0 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 120.3 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 116.5 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 108.4 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 50.6 ($N\underline{C}_4H_8$), 47.9 ($\underline{C}H_2C_6H_5$), 25.6 ($N\underline{C}_4H_8$). GC−MS (ESI): m/z = 277 $[M]^+$. Anal. Calcd for $C_{18}H_{19}N_3$: C, 77.95; H, 6.90; N, 15.15. Found: C, 78.21; H, 6.95; N, 14.68%.

Synthesis of 1-Benzyl-*N*-cyclohexyl-1*H*-benzimidazol-2-amine (26).[78]

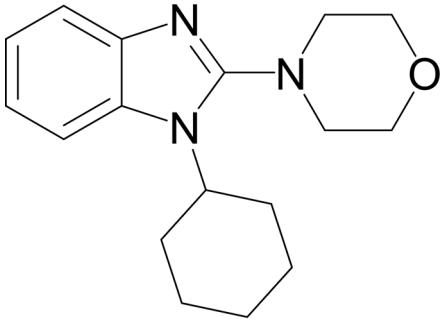


(26)

Yield: 0.168 g, 55% (**4**).

^{1}H NMR ($CDCl_3$, 400 MHz, 25 °C): δ 7.81 (d, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4N_2$), 7.37−7.30 (m, 4H, $CH_2C_6\underline{H}_5$), 7.30−7.27 (m, 1H, $CH_2C_6\underline{H}_5$), 7.25 (t, 1H, $^3J_{HH}$ = 8 Hz, $^4J_{HH}$ = 1 Hz, $C_7\underline{H}_4N_2$), 6.96 (d, 1H, $^3J_{HH}$ = 8 Hz, $^4J_{HH}$ = 1 Hz, $C_7\underline{H}_4N_2$), 6.70 (t, 1H, $^3J_{HH}$ = 7 Hz, $C_7\underline{H}_4N_2$), 4.40 (s, 2H, $C\underline{H}_2C_6H_5$), 3.14 (br, 1H, $C_6\underline{H}_{11}$), 1.96−1.93 (m, 3H, $C_6\underline{H}_{11}$), 1.62−1.59 (m, 3H, $C_6\underline{H}_{11}$), 1.28−1.27 (m, 2H, $C_6\underline{H}_{11}$), 1.12−1.06 (m, 2H, $C_6\underline{H}_{11}$). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz, 25 °C): δ 150.9 ($N\underline{C}N$ of $C_7H_4N_2$), 139.3 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 138.6 ($CH_2\underline{C}_6H_5$), 129.3 ($CH_2\underline{C}_6H_5$), 128.9 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 128.8 ($CH_2\underline{C}_6H_5$), 127.6 ($CH_2\underline{C}_6H_5$), 127.4 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 124.0 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 123.8 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 50.4 ($\underline{C}_6H_{11}$), 46.1 ($\underline{C}H_2C_6H_5$), 33.7 ($\underline{C}_6H_{11}$), 25.4 ($\underline{C}_6H_{11}$), 24.6 ($\underline{C}_6H_{11}$). GC−MS (ESI): m/z = 305 $[M]^+$. Anal. Calcd for $C_{20}H_{23}N_3$: C, 78.65; H, 7.59; N, 13.76. Found: C, 77.72; H, 8.47; N, 13.06%.

Synthesis of 4-(1-Cyclohexyl-1*H*-benzimidazol-2-yl)-morpholine (27).



(27)

Yield: 0.205 g, 72% (**4**).

^{1}H NMR ($CDCl_3$, 500 MHz, 25 °C): δ 7.80 (d, 1H, $^3J_{HH}$ = 8 Hz, $C_7\underline{H}_4N_2$), 7.26 (t, 1H, $^3J_{HH}$ = 8 Hz, $^4J_{HH}$ = 1 Hz, $C_7\underline{H}_4N_2$), 6.91 (d, 1H, $^3J_{HH}$ = 8 Hz, $^4J_{HH}$ = 1 Hz, $C_7\underline{H}_4N_2$), 6.74 (t, 1H, $^3J_{HH}$ = 7 Hz, $C_7\underline{H}_4N_2$), 3.73 (t, 4H, $^3J_{HH}$ = 5 Hz, $NC_4\underline{H}_8O$), 3.34 (t, 4H, $^3J_{HH}$ = 5 Hz, $NC_4\underline{H}_8O$), 3.14 (br, 1H, $C_6\underline{H}_{11}$), 1.90−1.88 (m, 2H, $C_6\underline{H}_{11}$), 1.65−1.62 (m, 2H, $C_6\underline{H}_{11}$), 1.54−1.51 (m, 1H, $C_6\underline{H}_{11}$), 1.24−1.18 (m, 3H, $C_6\underline{H}_{11}$), 1.07−1.05 (m, 2H, $C_6\underline{H}_{11}$). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 125 MHz, 25 °C): δ 155.2 ($N\underline{C}N$ of $C_7H_4N_2$), 139.3 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 129.2 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 124.4 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 123.0 ($\underline{C}_6H_4$ of $C_7H_4N_2$), 66.5 ($N\underline{C}_4H_8O$), 53.7 ($\underline{C}_6H_{11}$), 48.5 ($N\underline{C}_4H_8O$), 34.0 ($\underline{C}_6H_{11}$), 25.2 ($\underline{C}_6H_{11}$), 25.0 ($\underline{C}_6H_{11}$). GC−MS (ESI): m/z = 285 $[M]^+$. Anal. Calcd for $C_{17}H_{23}N_3O$: C, 71.55; H, 8.12; N, 14.72;. Found: C, 72.20; H, 9.07; N, 13.74%.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.2c07875. CCDC-2041824 (for **4**), CCDC-2060553 (for **5**), CCDC- 2123529 (for **6**), and CCDC-2069000 (for **7**) contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data center via www.ccdc.cam.ac.uk/data_request/cif

^{1}H NMR, $^{13}C\{^1H\}$ NMR, IR, HRMS, and elemental analysis data of precarbene ligands (**1**−**3**), ^{1}H NMR, $^{13}C\{^1H\}$ NMR, IR, HRMS, elemental analysis, and XPS data of palladium carbene complexes (**4**−**7**), and ^{1}H NMR, $^{13}C\{^1H\}$ NMR, GC−MS chromatograms, and elemental analysis data of the catalysis products (**8**−**17**), the benzoxazole derivatives (**18**−**22**), and the guanidine derivatives (**23**−**27**) (PDF)

X-ray crystallographic data of palladium carbene complexes (**4**−**7**) (CIF)

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Notes

The authors declare no competing financial interest.

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