

# Photocatalyst-free, single nickel catalysis: a general method to access diverse carbon-heteroatom bonds

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## Article

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# Abstract

State-of-the-art photoredox/nickel dual catalysis is a powerful strategy for the rapid assembly of complex scaffolds but requires expensive and highly reactive photosensitizers to shuttle energy or electrons. Single nickel catalysis, which performs dual roles of light-harvesting and organometallic catalysis, avoids these issues associated with photocatalysts. Herein, we report visible light-promoted single nickel catalysis for diverse carbon-heteroatom couplings under mild conditions. This mild, general, and robust method to couple diverse nitrogen, oxygen, and sulfur nucleophiles with an aryl(heteroaryl)/alkenyl iodides/bromides exhibits a wide range of functional group tolerance and is applicable to late-stage modification of pharmaceuticals and natural products. Based on preliminary mechanistic studies, a  $\text{Ni}^{\text{I}}/\text{Ni}^{\text{III}}$  cycle was proposed via the generation of active  $\text{Ni}^{\text{I}}$  complexes that appear from homolysis of  $\text{Ni}^{\text{II}}\text{-I}$  rather than  $\text{Ni}^{\text{II}}\text{-aryl}$  bond.

## Introduction

Transition-metal catalysis for couplings is a frequently used method of assembling compounds containing heteroatoms<sup>1-3</sup>. Notably, the Buchwald-Hartwig amination reaction can access nearly any type of aniline scaffold for the development of pharmaceuticals<sup>1</sup>. As an alternative or complement to palladium catalysis, cheap and earth-abundant nickel catalysis has been intensively investigated with the renaissance of photochemistry<sup>4-7</sup>. State-of-the-art photoredox/nickel dual catalysis unlocks reductive elimination (RE) to forge diverse carbon-heteroatom bonds via a single electron transfer (SET) or energy transfer (EnT) process under irradiation with visible light<sup>3,4,6-13,14</sup>. Although several reports of visible-light mediated nickel catalysis to access diverse carbon-heteroatom bonds have been disclosed, the previous works mostly required photocatalysts<sup>3,4,6,7</sup>. (Fig. 1a) Single metal catalysis, which performs dual roles of light-harvesting and organometallic catalysis, would provide a good solution to avoid these issues associated with photocatalysts<sup>15,16</sup>. Gratifyingly, photoexcitation of various transition metal complexes/catalysts for diverse chemical transformations has been elegantly studied by Fu, Peter, Norcera, Doyle, and others<sup>3,17-20</sup>. The pioneering work of visible-light-induced nickel catalysis for C-O bond formation was reported by Doyle and their colleagues<sup>21,22</sup>. Subsequently, the application of a similar strategy was extended to photochemical C-N/C-O cross-coupling of chiral amines/amino alcohols/amino acid esters or alcohols with various aryl bromides in the absence of photocatalyst using high energetic UV-light by Xue and their colleagues<sup>23,24</sup>. It is still challenging for the development of visible-light-induced carbon-heteroatom coupling reactions in nickel catalysis. Recently, Thomas, Pieber, and coworkers elegantly installed two carbazole units to bipyridine ligand with the absorption of  $\text{Ni}^{\text{II}}$  species in the range of visible light and succeeded in the coupling of sulfinates, carboxylic acids, and sulfonamides with aryl iodides under mild conditions<sup>25</sup> (Fig. 1b). In addition, Miyake and coworkers reported a different mechanism via direct excitation of nickel-amine complexes by UV light to access C-N cross-coupling<sup>26</sup>. Despite these previous works, there still remains large room to develop visible-light-induced, single nickel catalysis for the construction of diverse carbon-heteroatom bonds. Therefore, the

development of a general synthetically useful method to enable diverse carbon-heteroatom bonds coupling with wide substrates scope, diverse nucleophiles and aryl/alkenyl halides, in broad functional group tolerance is highly desirable. For practical synthetic application, the use of readily available catalyst and visible-light under exogenous photocatalyst-free conditions is desired.

$\text{Ni}^{\text{I}}/\text{Ni}^{\text{III}}$  catalytic cycle, in which  $\text{Ni}^{\text{III}}$  complexes underwent facile reductive elimination to form carbon-heteroatom bonds was widely proposed in nickel/photoredox dual catalysis<sup>3,4,6,7,27,28</sup> and single nickel catalysis<sup>21,22, 23-26</sup>. Aryl-Ni(II)-halide (**1b**) complexes feature the strong absorption in the range of visible light and are likely to generate the active nickel(I) species via homolysis of nickel-aryl bonds in the presence of the light under exogenous photocatalyst-free condition<sup>22</sup> (Fig. 1b). Aryl-Ni(II)-halide (**1b**) complexes should be useful to forge carbon-heteroatom bonds via  $\text{Ni}^{\text{I}}/\text{Ni}^{\text{III}}$  cycle under visible light irradiation, but, unfortunately, successful examples are still very limited compared to dual nickel/photoredox catalysis (Fig. 1a). Therefore, we made effort to expand the utility of single nickel catalysis, which plays the light-harvesting and organometallic catalysis roles to access diverse carbon-heteroatom bonds formation including some examples that were not reported even by using dual nickel/photoredox catalyst.

Herein, we describe a general method of visible-light mediated nickel-catalyzed carbon-heteroatom bond formation with an unprecedented broad nucleophile scope using commercially available 4,4'-di-*tert*-butyl-2,2'-bipyridine (dtbbpy) as a ligand (Fig. 1b). Diverse nitrogen, oxygen, and sulfur nucleophiles with a broad *pK<sub>a</sub>* range were successfully coupled with corresponding aryl/alkenyl iodides/bromides under mild conditions without any exogenous photocatalysts. Preliminary mechanistic studies suggested the putative active  $\text{Ni}^{\text{I}}$  complexes in  $\text{Ni}^{\text{I}}/\text{Ni}^{\text{III}}$  cycle were likely from homolysis of the  $\text{Ni}^{\text{II}}\text{-I}$  bond rather than the  $\text{Ni}^{\text{II}}\text{-aryl}$  bond.

## Results And Discussion

**Reaction development and optimization.** We started screening the C-N coupling by using bis(1,5-cyclooctadiene)nickel(0) ( $\text{Ni}(\text{COD})_2$ ) as the nickel(0) source and aryl iodide as the electrophile to form the assumed active aryl-Ni-I complexes (Table S1). After intensive investigation for coupling of aniline **4** with ethyl 4-iodobenzoate **5**, the coupling product **6** was obtained in almost quantitative yield when using simple, commercially available 4,4'-di-*tert*-butyl-2,2'-bipyridine as the ligand, ( $\text{Ni}(\text{COD})_2$ ) and 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) as a base under photo-irradiation with blue light-emitting diodes (LEDs) at 30 °C (Table S1, Entry 2). An air-stable  $\text{NiCl}_2$  salt exhibited comparable reactivity to  $\text{Ni}(\text{COD})_2$  in tetrahydrofuran (THF) (Entry 1). Other air-stable nickel(II) salts also gave product **6**, but in lower yield (Entries 3–5). Subsequently, the  $\text{NiCl}_2$  salt was used in further optimization studies. In contrast to previous photoredox/nickel dual catalysis<sup>3</sup>, high polar solvents were not suitable for the coupling process, probably due to their strong coordination ability to the nickel(II) complex<sup>29</sup>, while a less-polar solvent, toluene, also resulted in lower efficiency than THF (Entries 6–10). The solubility and basicity were considered critical for the deprotonation of anilines on a nickel complex to replace iodine using a suitable

base<sup>30</sup>. Thus, DBU exhibited the best performance among other common organic or inorganic bases (Entries 11–16). The use of proper ligands is key to realizing the visible-light-induced carbon-nitrogen coupling. Ligand screening showed that redox-active bipyridine ligands were required to maintain the reactivity (Entries 17–20). Furthermore, control experiments indicated that visible light, ligand, base, and nickel salt were all essential to achieve the coupling reaction, supporting our assumption that direct photo-excitation of the nickel complex by visible light is required (Entries 21–24). When exposed to air, the process was completely inhibited (Entry 25), indicating that the active nickel catalyst was sensitive to air.

**Substrate scope.** Substrate scope studies for diverse cross-couplings are summarized in Fig. 2 and Fig. 3. Various nitrogen, oxygen, and sulfur nucleophiles with a broad p*K*<sub>a</sub> range successfully afforded coupling products **6–108** from aryl/alkenyl iodides/bromides in good to excellent yields with good functional group tolerance, demonstrating the versatility of the present exogenous photocatalyst-free conditions (Figs. 2 & 3). Arylation of aromatic and alkyl amines gave coupled products (**6–12**, **30–44**) in good to excellent yield, and was scalable to gram scale (**30**, 95% yield). Both electron-donating and electron-withdrawing anilines reacted smoothly (**7**, **8**). Sterically hindered anilines bearing a substitution at the *ortho*-position exhibited good reactivity, delivering diarylamines (**9**, **10**). Notably, an aryl chloride unit remained intact, thus affording the corresponding coupled products in high yield (**12**, **31**, **104**). Interestingly, 2-aminopyridine coupled twice with aryl iodide (**22**). Weakly nucleophilic *N*-reagents such as amides, sulfonamides, sulfoximines, indoles, pyrrole, imine, carbamates, urea, and phosphinic amide smoothly coupled with aryl iodides to afford products (**13–29**) in high yields. *N*-Arylation of indoles, pyrrole, and urea to access structures (**23**, **24**, **28**, **71**, **73**) of pharmaceutical interest were realized for the first time under photo-driven nickel catalysis, thereby providing an efficient alternative to copper catalysis<sup>31,32</sup>.

The protocol was applicable for coupling with diverse *O*-nucleophiles as well, including alcohols, carboxylic acids<sup>12,33</sup>, phenol, water, and oxime, to deliver *O*-arylation products (**45–62**) in good yield. Electron-rich and electron-poor aromatic or aliphatic carboxylic acids were successfully used in the esterification with aryl iodides (**57–60**). It is particularly noteworthy that the hydroxylation of aryl halides with water under exogenous photocatalyst-free conditions gave the products (**62**, **85**, **86**) in good yields<sup>34</sup>. Substrates containing terminal alkynyl groups, such as propargylamine and pent-4-yn-1-ol, are rarely used as coupling partners in nickel catalysis, but were applicable in this system (**43** and **52**). Intramolecular C–O coupling also proceeded smoothly (**56**). Thiocarboxylic acids coupled with aryl/heteroaryl iodides (**63** & **90**). As shown in footnote *a* of Fig. 2, reactions with weak *O*-nucleophiles proceeded well just by using a nickel(0) source instead of a nickel(II) salt.

Aryl iodides with diverse functional groups such as halides, trifluoromethoxy, trifluoromethyl, acyl, formyl, nitriles, esters, and alkynyl groups at the *para*, or *meta*-position readily undergo coupling to afford O/*N*-arylation products (**66–70**, **73**, **75–77**, **80**, **85**, **88**). Electron-rich aryl iodides showed similarly high reactivity, giving products (**64**, **65**, **70**, **72**) in high yields. The protocol was also applicable to sterically hindered *ortho*-substituted aryl iodides, affording the products in good yield (**78** and **79**, 85% and 61% respectively). Five- or six-membered heterocycles were well adapted to efficiently generate C–N, C–O and C–

S coupled products (**74**, **81**, **82**, **87–89**, **90**). To expand the utility of this protocol, we also investigated the substrate scope of aryl bromides. It is pleasing to find that the aryl bromides also smoothly coupled with *N,O*-nucleophiles to afford the final products in good yields under slightly modified conditions (**91–95**). Some alkenyl iodides, which are rarely used as coupling partners in photoredox/nickel dual catalysis, possibly due to their incompatibility with highly reactive photocatalysts, were also applicable under the present protocol, efficiently forging C-N/C-O bonds (**96–100**). The widespread application of the photo-driven single nickel catalysis was showcased by late-stage modification of pharmaceuticals and natural products (**101–108**). Interestingly, the triflate group remained intact, affording **108** and **107'**, the isomer of the coupled product (**107**), in 95% yield and 60% yield respectively.

**Mechanistic investigations.** To gain insight into the supposed Ni<sup>I</sup>/Ni<sup>III</sup> catalytic cycle of this single nickel catalysis (Fig. 1b), several experiments were run as summarized in Fig. 4 and in supplementary information. Based on Doyle's proposed Ni<sup>I</sup>/Ni<sup>III</sup> catalytic cycle, we initially supposed that the activated Ni<sup>I</sup> can be generated via homolysis of Ni<sup>I</sup>-aryl bond. The supposed homolysis of Ni<sup>I</sup>-aryl bond should then generate small amount of dehalogenated arene and corresponding dimerized biphenyl. In Fig. 4a, however, such side adducts were not detected with gas chromatography-mass spectrometry (GC-MS) analysis under our standard conditions using either NiCl<sub>2</sub> or Ni(COD)<sub>2</sub> and DBU base in THF. In Fig. 4b-(1), competition experiments using ethyl 4-iodobenzoate (1 equiv) and 2-iodotoluene (1 equiv) as competing electrophiles and hexan-1-amine as a nucleophile (0.8 equiv) gave **34** as a sole product in 79% yield. The result indicated that 2-iodotoluene remains intact in the presence of more reactive ethyl 4-iodobenzoate. On the other hand, in Fig. 4b-(2), when using a sub-stoichiometric amount of pre-formed Ni<sup>II</sup> complex **109** as a catalyst, compound **78** was observed in 7% together with **34**. Even in this case, neither toluene nor its dimer was detected by GC-MS. In Fig. 4b-(2), we also detected 2-iodotoluene by GC-MS, which is ascribed to reductive elimination from Ni<sup>III</sup> complexes to form carbon-iodide bond<sup>35,36</sup>. These results indicated that the active Ni<sup>I</sup> species under our reaction conditions is less likely to be generated via homolysis of Ni-aryl bond. As shown in Fig S5, we assume that the active Ni<sup>I</sup> complexes were generated via homolysis of Ni-I bond of complex **109** under visible light irradiation<sup>37</sup>, then the second complex **109** was oxidized by iodine radical to form Ni<sup>III</sup> complex **S-II**, which underwent facile reductive elimination to deliver 2-iodotoluene or ligand exchange with nucleophiles to deliver coupling product **78** as detected in Fig. 4b-(2). In addition, the formation of coupled product **78** can be obtained from **109** by stoichiometric studies in which the yield of **78** increased with increasing amounts of hexan-1-amine along with some 2-iodotoluene as well, which is consistent with ligand exchange in the presence of excess nucleophile (Fig. S6).

Based on experimental results (Fig. 4(a), (b)), we tentatively propose a Ni<sup>I</sup>/Ni<sup>III</sup> catalytic cycle depicted in Fig. 4c. The nickel(0) species **I** is oxidized by aryl iodide to form aryl-Ni<sup>II</sup>-I complex **II**, which exhibits some absorption in the range of visible-light (Fig. S8 & S9). Then the aryl-Ni<sup>II</sup>-I complex **II** or its possible related five coordinated complexes with DBU or nucleophiles as the fifth ligand was excited by the visible light and underwent homolysis of Ni<sup>II</sup>-I bond to deliver iodine radical and Ni<sup>I</sup> complex **III**. Subsequently, iodine

radical was rebounded to the second aryl-Ni<sup>II</sup>-I complex **II** to afford complex **IV**, followed by ligand exchange and reductive elimination to afford active Ni<sup>I</sup> complex **VI** and coupling product. This process always requires visible-light irradiation (Fig. S4), probably due to the disproportionation of gradually accumulated Ni<sup>I</sup> complex **III** and **VI** to form Ni<sup>0</sup> complex **I** and Ni<sup>II</sup> complex **II** again. Some other control experiments using pre-formed Ni<sup>I</sup> complex or generated in situ also were run as well<sup>25,28</sup>; however, we did not observe coupling products (Fig. S3 & Table S2). Therefore, we can not exclude other possibilities, such as Ni<sup>0</sup>/Ni<sup>II</sup>/\*Ni<sup>II</sup> catalytic cycle<sup>38,39</sup> (Fig. S7) at the moment.

## Conclusions

We developed visible-light-induced single nickel catalysis to achieve cross-coupling of aryl/alkenyl iodides/bromides with diverse nitrogen, oxygen, and sulfur nucleophiles under mild conditions. Importantly, the combination of commercially available nickel salt, ligand, and organic base showed excellent generality, robustness, and practicality as demonstrated by the broad substrate scope, late-stage functionalization of complex pharmaceuticals/natural products, and a gram scale reaction. We anticipate these discoveries would be widely useful for arylation/alkenylation of diverse nucleophiles under mild conditions for rapid assembly of valuable chemicals. Further investigations into the utility of single nickel catalysis as well as mechanistic studies are ongoing.

## Methods

**General procedure for the visible-light-induced nickel catalysis for C-N, C-O, or C-S cross-coupling.** To an oven-dried 10 mL reaction tube were added NiCl<sub>2</sub> or Ni(COD)<sub>2</sub> (0.01 mmol, 5 mol%), dtbbpy (0.01 mmol, 5 mol%), and anhydrous THF (1 mL) in a nitrogen-filled glove box. The resulting mixture was stirred for 5 min, followed by adding aryl or alkenyl iodides/bromides (0.2 mmol, 1.0 equiv), *N*, *O* or *S*-nucleophiles (0.24 mmol, 1.2 equiv), and 1,8-Diazabicyclo[5.4.0]undec-7-ene (DBU) (0.3 mmol, 1.5 equiv) in sequence, and sealed with a screwed cap. The sealed tube was placed on a photo-reactor under irradiation with blue LEDs (455 nm, 6 W) and kept stirring at 30 °C for 36 h. The mixture was quenched with H<sub>2</sub>O, and extracted with ethyl acetate. The combined organic layers were dried over anhydrous Na<sub>2</sub>SO<sub>4</sub>, concentrated in vacuo. The crude product was purified by silica gel column chromatography to afford the coupled product.

## Declarations

### Data availability

All data are available in the paper or its supplementary information.

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### Author contributions:

H. L. contributed to optimizing the coupling reactions and mechanistic studies. H.L (C-N, O, S couplings), G. W. (C-N coupling), Y. M. (C-O coupling), and K. L (C-O coupling) performed and analyzed the coupling reactions and characterized the products. Y. F made contributions to the arylation of amines by using aryl bromides. W. Z. made some alkenyl iodides for couplings. L.L. conceived the original idea. M.S. and L.L. supervised the research. H.L, M.S, and L.L prepared the manuscript. All authors contributed to discussions and commented on the manuscript.

**Competing interests:** Authors declare no competing interests.

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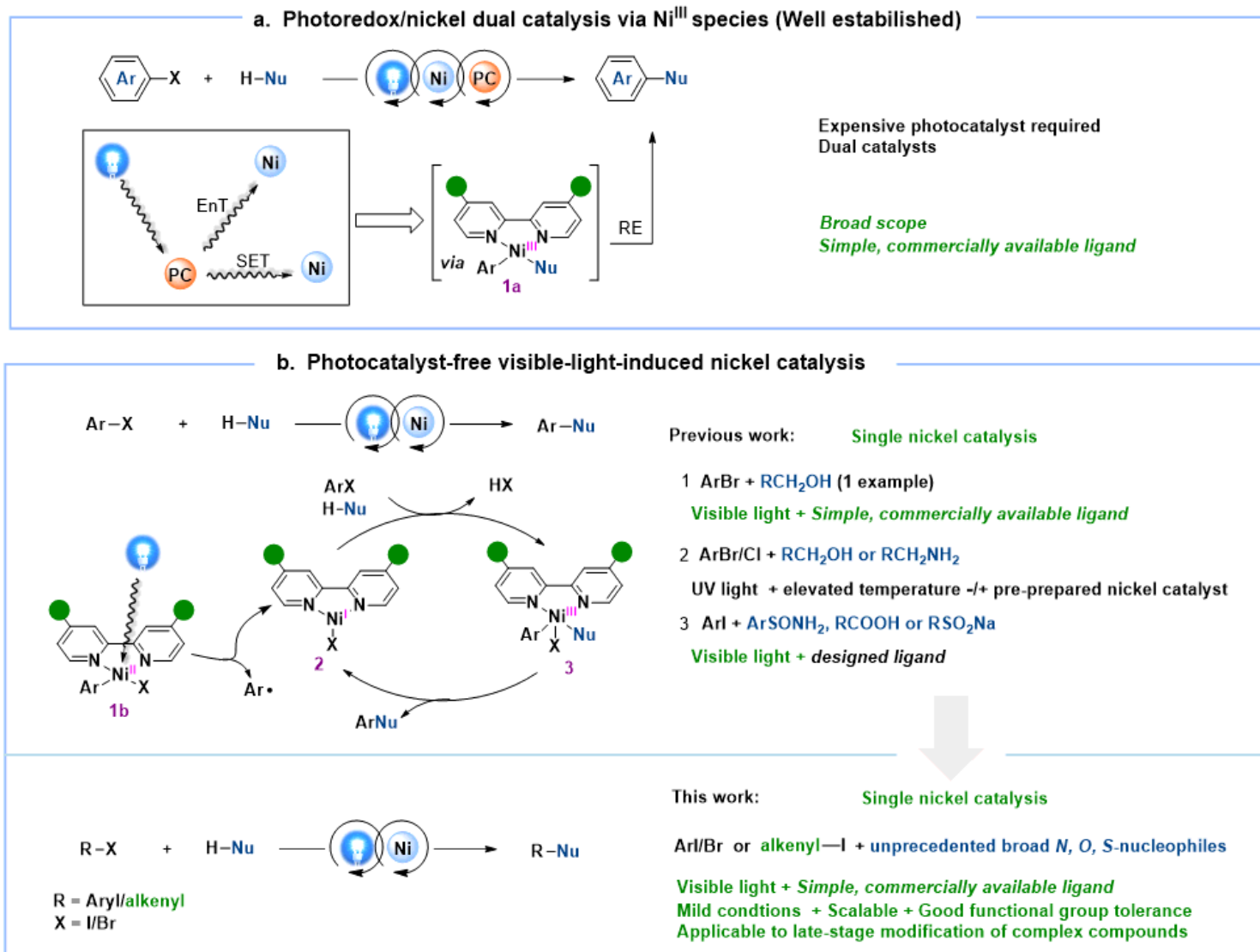
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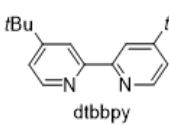
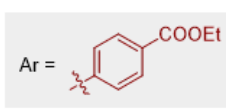
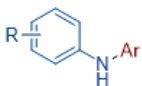
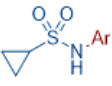
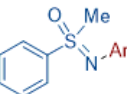
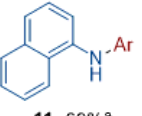
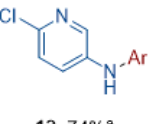
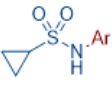
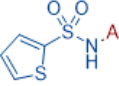
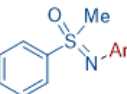
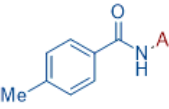
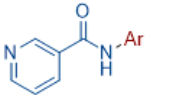
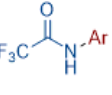
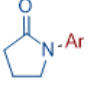
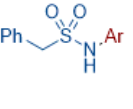
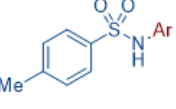
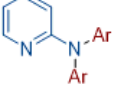
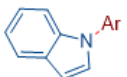


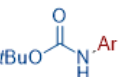

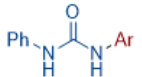
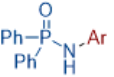
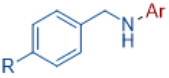
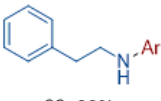
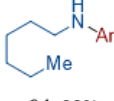
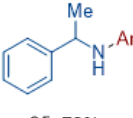
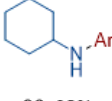
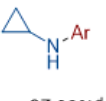
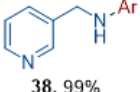
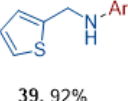
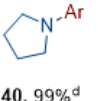
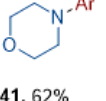
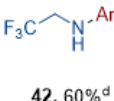
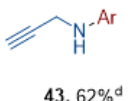
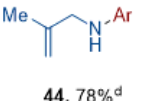

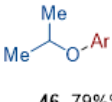
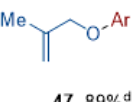
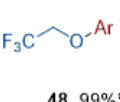
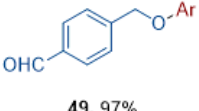
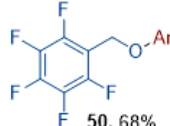
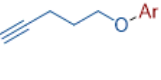
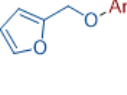
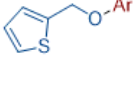
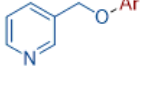
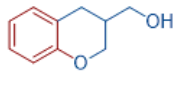
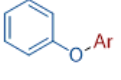
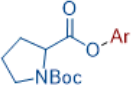
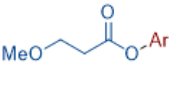
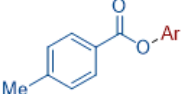
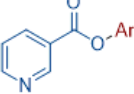
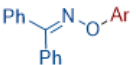

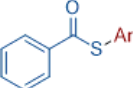
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## Figures



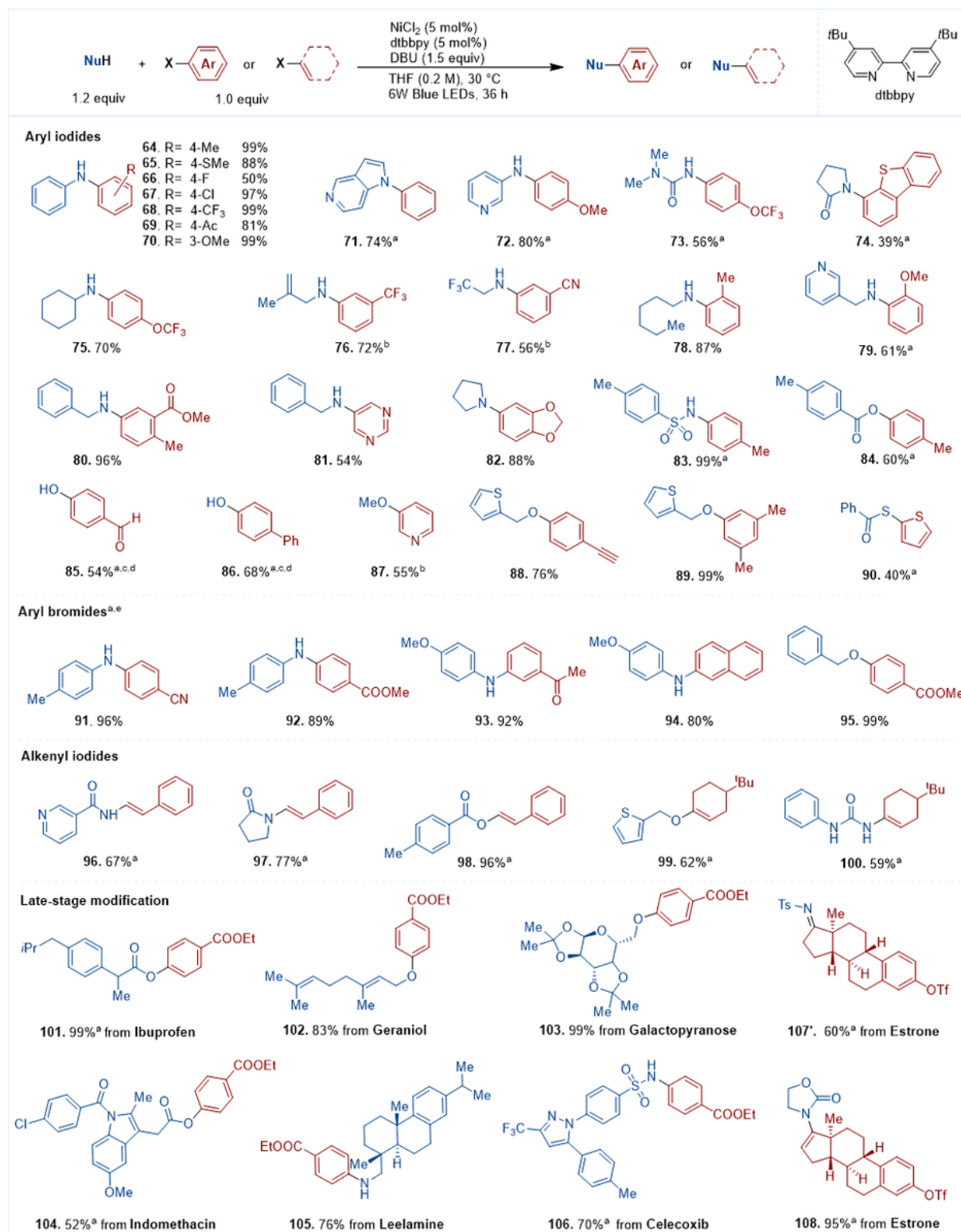
**Figure 1**

**Diverse strategies of visible-light promoted carbon-heteroatom couplings. a**, Photoredox/nickel dual catalysis for diverse carbon-heteroatom couplings. **b**, Photoexcitation of nickel catalysis to form carbon-heteroatom bonds under exogenous photocatalyst-free conditions.

$\text{NuH} + \text{I}-\text{Ar} \xrightarrow[\text{THF (0.2 M), 30 }^\circ\text{C, 6W Blue LEDs, 36 h}]{\text{NiCl}_2 \text{ (5 mol\%)} \atop \text{dtbbpy (5 mol\%)} \atop \text{DBU (1.5 equiv)}} \text{Nu}-\text{Ar}$							
1.2 equiv	1.0 equiv						
<b>Anilines</b>		<b>Sulfamides</b>	<b>Sulfoximine</b>				
	6. R = 4-H 98% 7. R = 4-F 94% 8. R = 4-OMe 79% 9. R = 2-Me 85% 10. R = 2-OMe 88%						
	11. 69% <sup>a</sup>		12. 74% <sup>a</sup>				
<b>Amides</b>			13. 98% <sup>a</sup>				
	14. 90% <sup>a</sup>						
		15. 86% <sup>a</sup>		16. 93% <sup>a</sup>			
	17. 99% <sup>a</sup>		18. 95% <sup>a</sup>				
		19. 99% <sup>a</sup>		20. 95% <sup>a</sup>			
		22. 65% <sup>a</sup>	<b>Pyridinamine</b>				
		23. 84% <sup>a</sup>			24. 99% <sup>a</sup>		
		25. 78% <sup>a</sup>			26. 64% <sup>a</sup>		
		27. 87% <sup>a</sup>			28. 71% <sup>a</sup>		
		29. 81% <sup>a</sup>	<b>Phosphamide</b>				
		30. R = H 97% 30. R = H 95% (Gram scale) <sup>c</sup> 31. R = Cl 78% 32. R = OMe 84%			33. 99%		
		34. 99%			35. 72%		
		36. 92%			37. 93% <sup>d</sup>		
		38. 99%			39. 92%		
		40. 99% <sup>d</sup>			41. 62%		
		42. 60% <sup>d</sup>			43. 62% <sup>d</sup>		
		44. 78% <sup>d</sup>	<b>Primary and secondary alcohols<sup>b</sup></b>				
		45. 86% <sup>d</sup>			46. 79% <sup>d</sup>		
		47. 89% <sup>d</sup>			48. 99% <sup>d</sup>		
		49. 97%			50. 68%		
		51. 94%			52. 99%		
		53. 99%			54. 97%		
		55. 92% <sup>a</sup>			56. 96%		
<b>Carboxylic acids</b>		<b>Oxime</b>		<b>Water</b>	<b>Thiocarboxylic acid</b>		
	57. 89% <sup>a</sup>			58. 65% <sup>a</sup>		59. 98% <sup>a</sup>	
		60. 74% <sup>a</sup>			61. 51% <sup>a</sup>		62. 98% <sup>a,b,e</sup>
		63. 73% <sup>a</sup>					

**Figure 2**

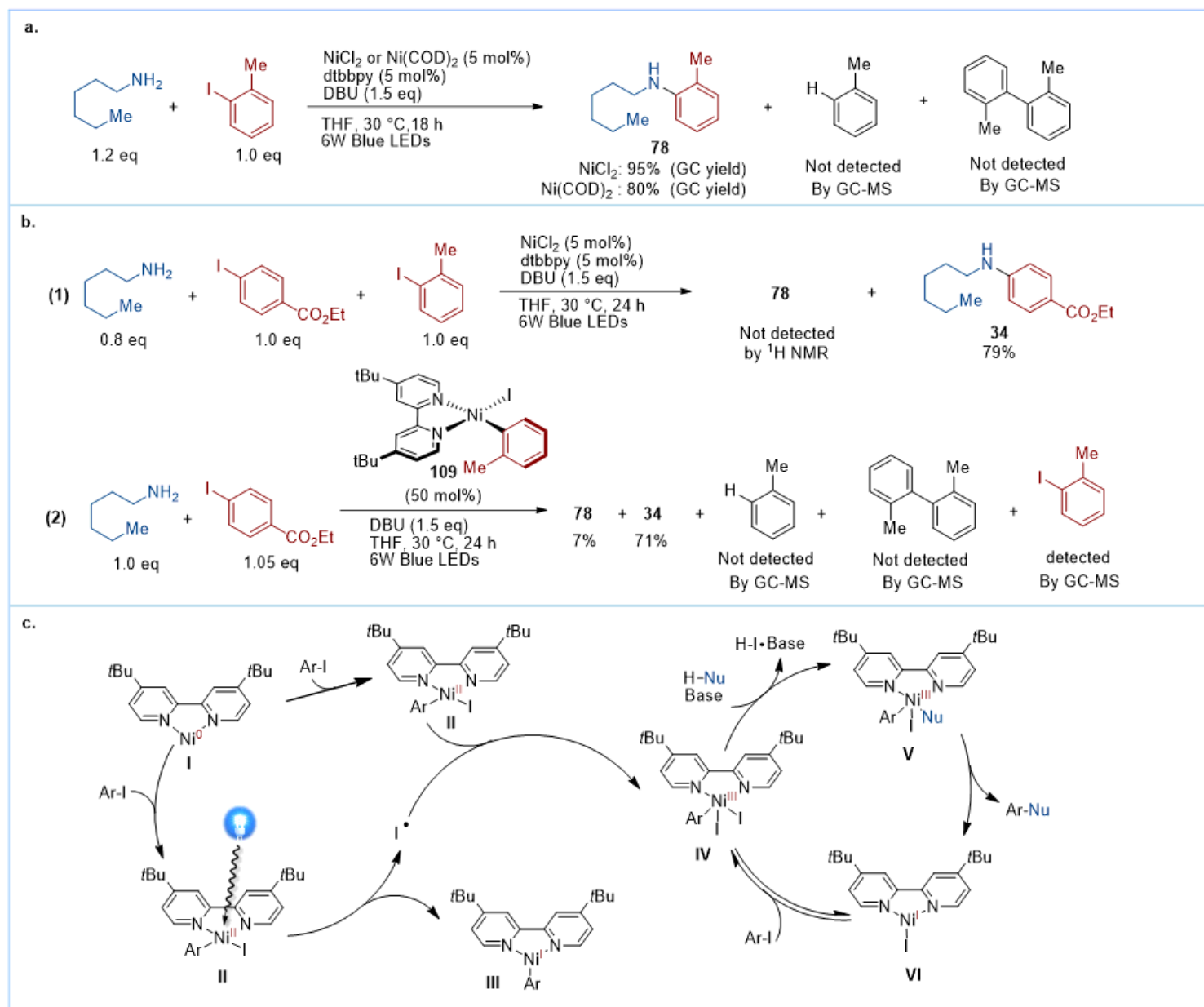
**Photo-driven nickel catalysis for carbon-heteroatom couplings:** substrate scope of *N*, *O*, and *S* nucleophiles. Standard conditions as shown in Table S1 (0.2 mmol scale; isolated yield) unless otherwise noted. <sup>a</sup>Ni(COD)<sub>2</sub> was used, <sup>b</sup>18 h, <sup>c</sup>5.0 mmol scale, <sup>d</sup>1.5 equiv of *N*/*O*-nucleophiles, <sup>e</sup>5.0 equiv of H<sub>2</sub>O.



**Figure 3**

**Photo-driven nickel catalysis for carbon-heteroatom couplings.** Substrate scope of aryl/alkenyl halides and late-stage modification of pharmaceuticals and natural products. Standard conditions as shown in Table S1 (0.2 mmol scale; isolated yield), aryl iodides were used unless otherwise noted. <sup>a</sup>Ni(COD)<sub>2</sub> was used, <sup>b</sup>1.5 equiv of N/O-nucleophiles, <sup>c</sup>18 h, <sup>d</sup>5.0 equiv of H<sub>2</sub>O, <sup>e</sup>Ar-Br (0.24 mmol, 1.2 equiv), N/O-

nucleophiles (0.2 mmol, 1 equiv) and 2-methyltetrahydrofuran (2 mL) as solvent were used under irradiation with 10W blue LEDs.



**Figure 4**

**Mechanistic investigation.** **a.** Gas chromatographymass spectrometry analysis for C-N coupling. **b.** Competing experiments. **c.** Proposed mechanism. The yield was determined by  $^1\text{H}$ -Nuclear magnetic resonance analysis using 1,3,5-Trimethoxybenzene as an internal standard unless otherwise noted.

## Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryInformation.pdf](#)