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One-pot preparation of azobenzenes from nitrobenzenes by the combination of an indium-catalyzed reductive coupling and a subsequent oxidation

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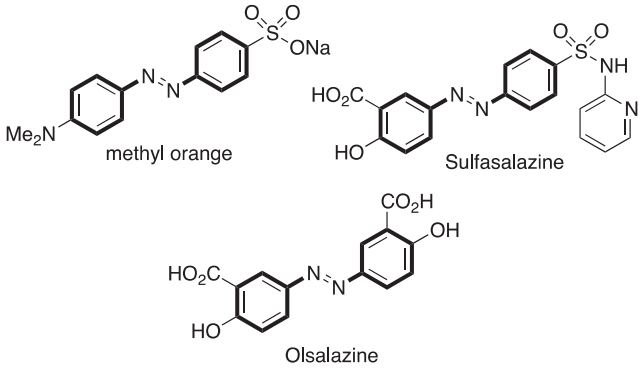
ABSTRACT

We demonstrated how a reduction step with a reducing system comprised of $In(OTf)_3$ and Et_3SiH and a subsequent oxidation that occurred under an ambient (oxygen) atmosphere allowed the highly selective and catalytic conversion of aromatic nitro compounds into symmetrical or unsymmetrical azobenzene derivatives. This catalytic system displayed a tolerance for the functional groups on a benzene ring: an alkyl group, a halogen, an acetyl group, an ester, a nitrile group, an acetyl group, an ester moiety, and a sulfonamide group.

1. Introduction

Azobenzene derivatives constitute important and central building blocks in functional materials, as well as in biologically active substances. For example, aryl azobenzene derivatives, which emit a variety of colors, have been widely utilized as the coloring matters, such as azo dyes or pigments, or as the photoresponsive functional materials, such as liquid crystals.[1] Also, because enzymes, such as azoreductase are known to selectively metabolize an azo moiety on azobenzenes for the release of a selected drug, which may show efficacy as a medicine, an azo moiety is often embedded in the drug structures.[2] Based on this biological action, sulfasalazine,[3] which treats rheumatoid arthritis, and olsalazine,[4] which is effective against inflammatory bowel disease, were developed as prodrugs (Scheme 1). Therefore, the development of a highly selective preparation for aromatic azobenzenes would be as valuable as their functions.

The substitution of diazonium salts with electron-rich benzenes under basic conditions and the coupling reaction of nitrosobenzenes with anilines (Mills reaction)[5] are considered as the classical methods that are used to prepare azobenzenes; along with those, other procedures[6] have also been disclosed.[7] Recently, a catalytic oxidation of anilines with a variety of oxidizing reagents, such as MnO_2 ($KMnO_4$),[8] $KMnO_4$–$CuSO_4 \cdot 5H_2O$,[9] HgO–I_2,[9a,10] or



Scheme 1. Functional materials containing an azobenzene skeleton.

$NaBO_3 \cdot 4H_2O$–$B(OH)_3$,[11] was developed. In their breakthrough study, Corma and Garcia reported that gold nanoparticles immobilized on TiO_2 catalyzed the aerobic oxidative coupling of anilines, producing azobenzenes.[12] Moreover, Jiao and co-workers have reported the development of a Cu(I)–pyridine system under an O_2 atmosphere, and Shi co-workers have detailed the Cu(I)–diaziridinone catalyzed oxidative dehydrogenative coupling of anilines.[13] As a reaction system without a metal catalyst, Minakata and co-workers disclosed that *tert*-butyl hypoiodite (*t*-BuOI) promoted the oxidative dimerization of aromatic amines, leading to a convenient preparation of unsymmetrical azobenzenes.[14]

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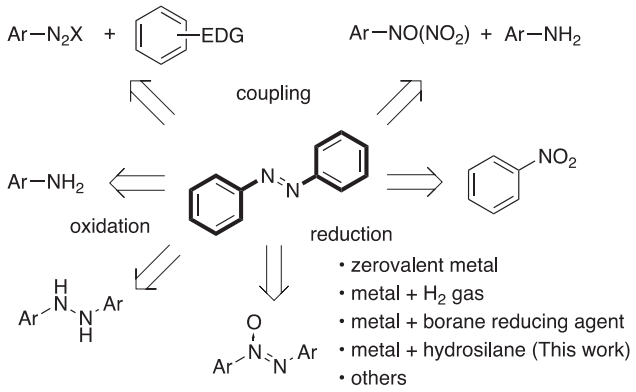
Likewise, the preparation of azobenzenes through a reduction of nitrobenzenes with reducing reagents has also been developed by several groups, but the typical approach was limited to operations that required more than stoichiometric amounts of a metal catalyst either the use of a Zn metal under strong basic conditions[15] or the use of a Pb metal in the presence of HCO_2H and Et_3N.[16] Also, compared with the catalytic preparation of azobenzenes via the oxidation of anilines, the catalytic preparation of azobenzenes by reduction of nitrobenzenes has thus far been limited to specific procedures using hydrogen gas in the presence of either a nano-Pd, a Pt-nanowire, a Ru-nanoparticle,[17] or another system.[18] As far as we could ascertain, the use of a hydrosilane as a reducing source for these transformations is unique (Scheme 2). Thus, the development of a catalytic and simple preparation for azobenzenes via the reduction of aromatic nitro compounds seems to have remained unexplored.



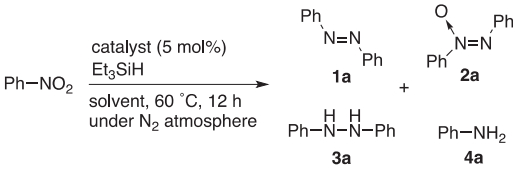
Scheme 2. Diverse approaches to azobenzenes.

We have reported that a reducing system comprised of an indium (III) compound and a hydrosilane was highly effective for the reduction of reducible agents, such as an aldehyde, a ketone, an acetal, and a carboxylic acid.[19,20] However, the conversion from a nitrobenzene to an azobenzene in our previous work was limited to several substituents.[21] Herein, we report the full details of the catalytic and reductive preparation of azobenzenes from a variety of nitrobenzenes via the $In(OTf)_3$—Et_3SiH reducing system. We also detail how this system was applied in the preparation of asymmetrical azobenzene derivatives and in an intramolecular manner.

2. Results/discussion

Based on our previous study,[21] when we initially examined the reduction of nitrobenzene with $InBr_3$ and Et_3SiH under $CHCl_3$ reflux conditions, most of the nitrobenzene was recovered, and four types of reductive products involving azobenzene (**1a**), azoxybenzene (**2a**), hydrazobenzene (**3a**), and aniline (**4a**) were formed with low selectivity (entry 1 in Table 1). Thus, to improve the product selectivity, the effect from relatively high polar solvents, such as THF, MeOH, and DMF, was investigated. As a result, THF and MeOH selectively gave azoxybenzene (**2a**) and hydrazobenzene (**3a**), respectively (entries 2 and 3). Also, when DMF was used, the corresponding hydrazobenzene was obtained in an almost quantitative yield (entry 4). Then, when the effect of a counterion on the indium compound in DMF was tested, neither $InCl_3$ nor $In(OAc)_3$ improved either the reactivity or the selectivity, but $InCl_3$ gave a small amount of azobenzene (entries 5 and 6). It is noteworthy that when the equivalent of Et_3SiH was reduced to 3 equiv in the presence of $InBr_3$ in DMF, the yield of azobenzene (**1a**) was increased to a 59% yield (entry 7). This was probably due to controlling the over-reduction of the azobenzene. Moreover, $In(OTf)_3$ further improved both the chemical yield and the product selectivity (entry 8). After several optimizations of the reaction conditions, we finally settled on the following procedure. The mixtures that involved azobenzene (**1a**) and hydrazobenzene (**3a**) that were produced by the first reduction step, were treated with oxidation under an ambient atmosphere to directly convert the corresponding azobenzene derivative (entry 9). When the second oxidation step was carried out under an O_2 atmosphere, the reaction time was drastically shortened (entry 10). During the search for optimal conditions, we also found that the indium compound catalyzed the dehydrogenate conversion from a hydrazobenzene to an azobenzene.[22] However, the use of other group 13 metals, such as $AlCl_3$ and $GaCl_3$, did not catalyze the reduction as well as $In(OTf)_3$, and neither did $ZnCl_2$ nor $BiCl_3$ (entries 11–14).

Table 1
Examinations of reaction conditions

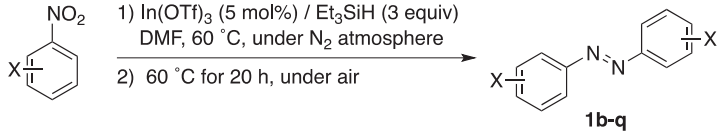


Entry	InX_3	Silane (equiv)	Solv	Yield (%)[a]			
				1a	**2a**	**3a**	**4a**
1	$InBr_3$	4	$CHCl_3$	2	15	10	9
2	$InBr_3$	4	THF	Trace	96	Trace	ND
3	$InBr_3$	4	MeOH	Trace	ND	75	ND
4	$InBr_3$	4	DMF	ND	ND	94	ND
5	$InCl_3$	4	DMF	19	2	65	ND
6	$In(OAc)_3$	4	DMF	ND	48	ND	4
7	$InBr_3$	3	DMF	59	12	20	ND
8	$In(OTf)_3$	3	DMF	66	Trace	25	ND
9[b]	$In(OTf)_3$	3	DMF	(81)	ND	Trace	Trace
10[c]	$In(OTf)_3$	3	DMF	84	ND	Trace	Trace
11	$AlCl_3$	4	DMF	ND	ND	ND	ND
12	$GaCl_3$	4	DMF	3	34	Trace	3
13	$BiCl_3$	4	DMF	ND	ND	ND	ND
14	$ZnCl_3$	4	DMF	ND	ND	ND	ND

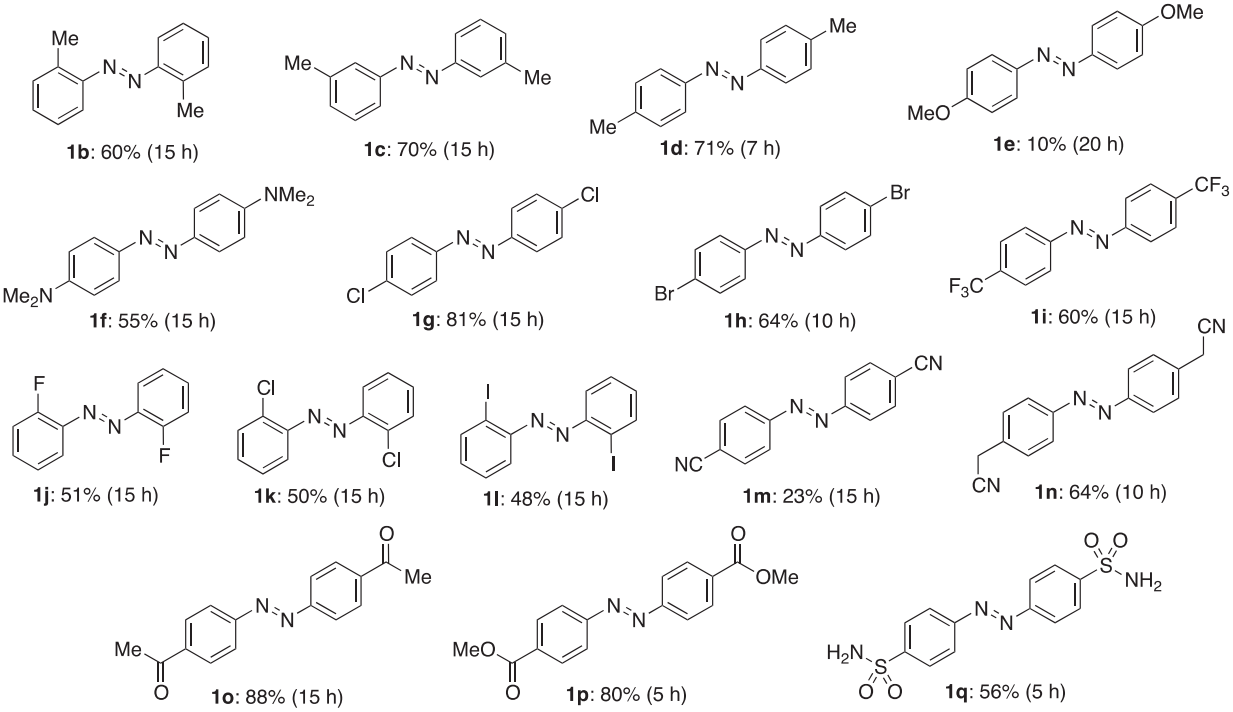
[a] GC (Isolated) yield.
[b] After the first reduction, the resultant mixture was stirred for 20 h under an ambient atmosphere.
[c] After the first reduction, the resultant mixture was stirred for 3 h under an O_2 atmosphere.

With the optimal conditions in hand, the generality of this coupling was examined using a variety of nitrobenzenes (Table 2).[23] The use of a substrate with a methyl group, with no relation to the location, afforded the desired azobenzene derivatives **1b**–**d** in moderate to good yields. However, when the reaction was carried out using a nitrobenzene with a methoxy group, the azobenzene **1e** was obtained in only a 10% yield, and most of the starting nitrobenzene was recovered. This was probably due to the fact that the indium catalyst coordinated the methoxy group rather than the nitro group. Unexpectedly, the substrate with a dimethylamino group produced the azobenzene derivative **1f** in a practical yield, and seemed to more strongly coordinate with the indium catalyst than the substrate with a methoxy group. The use of nitrobenzenes, which have a halogen atom and a trifluoromethyl group at the *para* position, underwent the coupling reaction to give the corresponding azobenzene derivatives **1g**–**i** in relatively good yields. In contrast, using nitrobenzenes with an *ortho*-substituted halogen atom gave the azobenzenes **1j**–**l** in moderate yields, which was probably caused by a steric repulsion. Also, a cyano group, which directly bonded to a benzene ring, was sensitive to this reducing system, leading to a decrease in the yield. However, when using the substrate with a cyano group, which sandwiched a methylene chain, the corresponding azobenzene **1n** was obtained in a relatively good yield. It is worth noting that the nitrobenzenes with either an acetyl

Table 2
One-pot synthesis of a variety of azobenzene derivatives from monosubstituted nitrobenzenes[a,b]



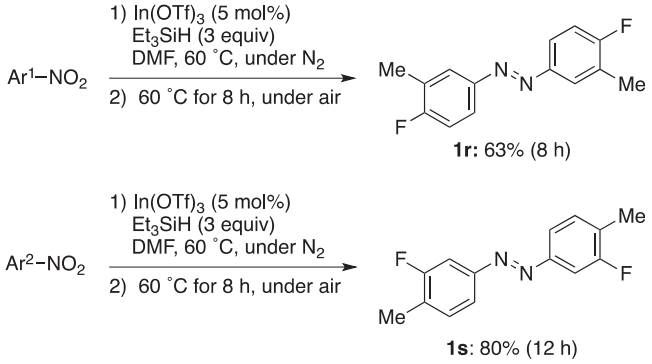
1b-q



[a] Reaction conditions: nitrobenzene (1 mmol), catalyst (0.05 mmol), silane (3 mmol) in DMF (1 mL) at 60 °C.
[b] Time denotes the reaction time in the first step.

group or an ester group, which are sensitive to a common reducing reagent, were successfully converted to the azobenzene derivatives **1o** and **p** in good yields. When the reaction was carried out using the substrate with a sulfonamide group, the nitrobenzene was completely consumed, and the corresponding azobenzene **1q** was obtained. As an extension, when a similar reaction was performed using disubstituted nitrobenzene derivatives including both a fluoro group and a methyl group, the expected azobenzene derivatives **1r** and **s** were obtained in good yields (Scheme 3).

This reaction system was then applied to the one-pot preparation of unsymmetrical azobenzene derivatives (Table 3). From the results shown in Scheme 1, an acetyl group showed a tolerance to this reducing system, so that the control of selectivity using a molar



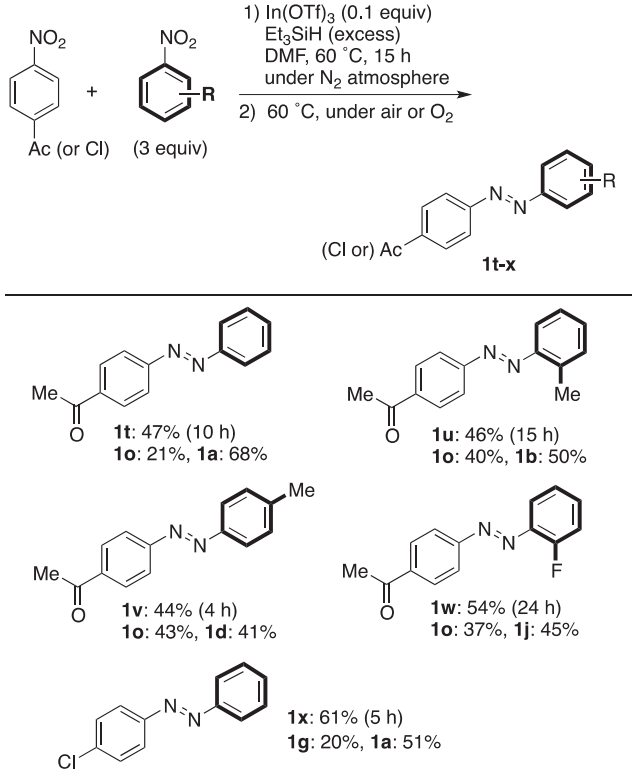
Scheme 3. One-pot synthesis of azobenzene derivatives from disubstituted nitrobenzenes.

ratio of a nitrobenzene and *p*-nitroacetophenone was attempted. For example, when the reaction was carried out using 3 equiv of nitrobenzene and *p*-nitroacetophenone under conditions that consisted of 0.1 equiv of $In(OTf)_3$ and an excess amount (12 equiv) of Et_3SiH, after the usual column separation, the expected unsymmetrical azobenzene **1t** could be isolated in a 47% yield from two homo-coupling azobenzenes. In a similar manner, the use of nitrobenzene having either an electron-donating or -withdrawing group also produced the corresponding unsymmetrical azobenzenes **1u**–**w** in moderate yields. The cross-coupling of *p*-chloronitrobenzene with nitrobenzene (3 equiv) also gave the desired unsymmetrical azobenzene derivative **1x** in a practical yield.

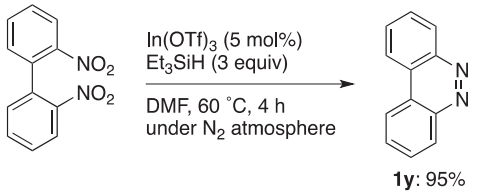
Then, we applied the present method to an intramolecular ring-closing reaction of 2,2′-dinitrobiphenyl. As shown in Scheme 4, the dinitro compound was treated with 5 mol % of $In(OTf)_3$ and 3 equiv of Et_3SiH in DMF at 60 °C for 4 h to isolate the intramolecular coupling product, benzo[*c*]cinnoline (**1y**) in an excellent yield. Because aromatization of the formed hydrazine ring worked as a driving force, this procedure needed no oxidative conversion process from the formed hydrazine derivative to the corresponding cyclic azobenzene under an ambient atmosphere.

We anticipated the possibility that nitrosobenzene would be one of the intermediates in the conversion series, and then performed several control experiments (Scheme 5). When nitrosobenzene was directly conducted with 2 equiv of Et_3SiH under our standard conditions, as expected, the corresponding azobenzene was selectively obtained in a 71% yield. Also, when a similar reaction was carried out in the absence of $In(OTf)_3$, the formation of only azoxybenzene **2a**, which was reductively prepared from the

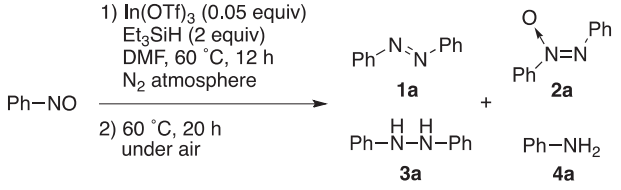
Table 3
One-pot synthesis of unsymmetrical azobenzene derivatives[a–c]



[a] Reaction conditions: nitrobenzene (1 mmol), catalyst (0.1 mmol), silane (12 mmol) in DMF (1 mL) at 60 °C, under an air atmosphere in the second oxidation step. Time denotes the reaction time in the second step.
[b] Reaction conditions: nitrobenzene (1 mmol), catalyst (0.1 mmol), silane (12 mmol) in DMF (1 mL) at 60 °C, under an O_2 atmosphere in the second oxidation step.
[c] Reaction conditions: nitrobenzene (1 mmol), catalyst (0.1 mmol), silane (10 mmol) in DMF (1 mL) at 60 °C, under an O_2 atmosphere in the second oxidation step.



Scheme 4. Intramolecular reductive ring-closing reaction of the dinitro compound.

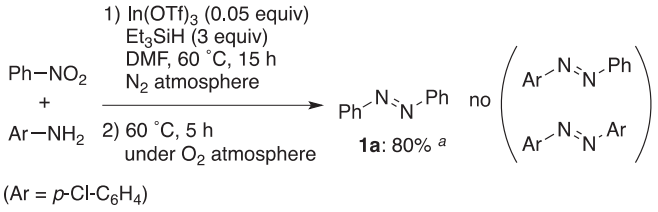


$In(OTf)_3$ + Et_3SiH	**1a**: 71%[a]	(**2a**: 11%, **3a**: trace, **4a**: trace)[a]
only Et_3SiH	**1a**: ND[a]	(**2a**: 43%, **3a**: trace, **4a**: trace)[a]
only $In(OTf)_3$	**1a**: ND[a]	(**2a**: 20%, **3a**: ND, **4a**: ND)[a]

[a] GC yield.

Scheme 5. Conversion from nitrosobenzene to azobenzene **1a**.

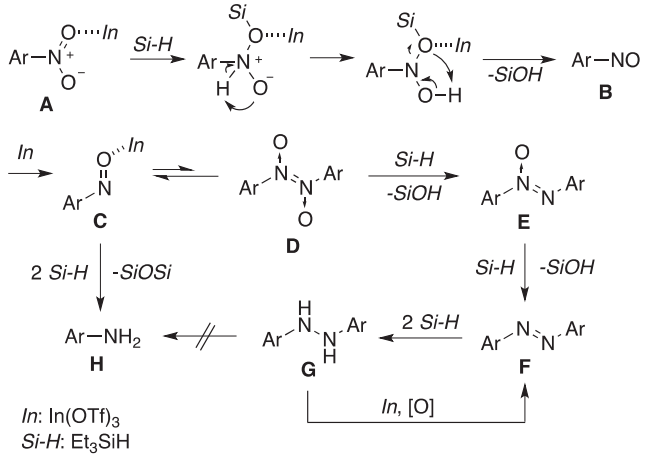
dimerization of nitrosobenzene, was observed in a 43% GC yield with the recovery (50% GC yield) of the starting nitrosobenzene. Moreover, running with only $In(OTf)_3$ led to a drastic decrease in the yield of the azoxybenzene **2a** with the recovery (80% GC yield) of nitrosobenzene. Consequently, these results show that nitrosobenzene occupies one of the key intermediates of the reduction series and implies that the indium catalyst strongly activated the starting nitro group rather than the formed nitroso group, and did not produce an indium hydride that may be derived from an indium catalyst and a hydrosilane when using this system. Moreover, the crossed reaction of nitrobenzene with *p*-chloroaniline yielded only azobenzene **1a** in an 80% yield and produced neither the crossed azobenzene derivative nor the homo-coupling azobenzene derived from *p*-chloroaniline (Scheme 6). Thus, these results strongly support the theory that it is the generation of a nitrosobenzene derivative rather than an aniline, that is, essential for the reductive coupling of nitrobenzene derivatives.



[a] GC yield.

Scheme 6. Examination of the cross-coupling from nitrobenzene and *p*-chloroaniline.

Based on the control experiments, to arrive at a plausible mechanism for the present coupling reaction, we assumed that the conversion proceeds through the following path as shown in Scheme 7. A hydrosilane initially reduces the nitrobenzene **A**, that is, activated by the indium catalyst to produce nitrosobenzene **B**. Then, the activated nitrosobenzene **C** undertakes dimerization to form an azobenzene dioxide **D**, which is known to principally exist as a monomer in solution,[24] and a subsequent second reduction to produce azoxybenzene **E**. Reduction of the azoxybenzene occurs, finally leading to the formation of both the corresponding azobenzene **F** and the further reduced hydrazobenzene **G**. The hydrazobenzene **G** was converted back to azobenzene **F** through a subsequent oxidation reaction. Also, we anticipated that aniline **H** would be formed via double reduction of nitrosobenzene **C**, rather than being produced through the reductive cleavage of hydrazobenzene **G**.



Scheme 7. Plausible reaction path from nitrobenzenes to azobenzenes.

3. Conclusions

In conclusion, we demonstrated that a reduction step composed of $In(OTf)_3$ and Et_3SiH with a subsequent oxidation step enabled a highly selective and a catalytic conversion of aromatic nitro compounds into azobenzenes. We also found that the reducing system enabled the direct one-pot preparation of unsymmetrical azobenzenes. Moreover, we disclosed that this simple catalytic system appears to be remarkably tolerant of a variety of functional groups. The present method using $In(OTf)_3$ and Et_3SiH provided a simpler and more convenient alternative to traditional methods.

4. Experimental section

4.1. General

All manipulations were carried out under N_2 atmosphere, unless otherwise noted. Dimethylformamide (DMF) was distilled over CaH_2. All indium salts, metal catalysts, and nitrobenzenes were commercially available and were used without further purification. Triethylsilane or other hydrosilanes were used without further purification. Reactions were monitored by TLC analysis of the reaction aliquots. Thin-layer chromatography (TLC) was effected on silica gel 60 F_{254}, and components were located by observation under UV light. Column chromatography was performed using silica gel. ^1H NMR spectra were measured at 500 (or 300) MHz using tetramethylsilane as an internal standard. ^{13}C NMR spectra were measured at 125 (or 75) MHz using the center peak of chloroform (77.0 ppm) as an internal standard. High resolution mass spectra were measured using NBA (3-nitrobenzylalcohol) as a matrix.

4.2. General procedure for indium-catalyzed reductive synthesis of azobenzene compounds

To a 5 mL screw vial under N_2 containing a freshly distilled DMF (0.6 mL) were successively added aromatic nitro compound (0.60 mmol), $In(OTf)_3$ (0.030 mmol, 17 mg), and Et_3SiH (1.80 mmol, 287 μL). The resulting mixture was stirred at 60 °C (bath temperature), and monitored by TLC analysis. After completion of the reaction, the resultant mixture was further stirred under either an ambient or an O_2 atmosphere during the corresponding reaction time. The reaction was quenched with H_2O (6 mL). The aqueous layer was extracted with AcOEt (6 mL×3), the combined organic phases were dried over anhydrous Na_2SO_4, filtered, and evaporated under reduced pressure. The crude product was purified by recrystallization from the solvent (hexane/chloroform) or silica gel column chromatography (hexane/AcOEt) to afford the corresponding azobenzene derivatives.

4.2.1. Azobenzene[13b] (***1a***). 81% yield (88 mg); an orange solid; mp 65.0–66.0 °C; IR (KBr): ν=3062, 1580, 1482, 1452, 1070, 775, 689 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.46–7.54 (m, 3H), 7.92–7.93 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 122.8, 129.1, 131.0, 152.7; MS (FAB): *m*/*z* 183 (M^++H), 154 (M^+-N_2 100%).

4.2.2. 2,2′-Dimethylazobenzene[13b] (***1b***). 60% yield (76 mg); a red solid; mp 53.0–54.0 °C; IR (KBr): ν=3452, 2913, 1471, 1113, 1047, 768, 717 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 2.74 (s, 6H), 7.25 (m, 2H), 7.33 (m, 4H), 7.61–7.64 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.6, 115.8, 126.3, 130.7, 131.2, 138.0, 151.1; MS (EI): *m*/*z* 210 (M^+, 100%).

4.2.3. 3,3′-Dimethylazobenzene[13b] (***1c***). 70% yield (88 mg); a dark orange solid; mp 50.3–51.6 °C; IR (KBr): ν=2920, 1604, 1467, 1251, 794, 698 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 2.46 (s, 6H), 7.28–7.29 (m, 2H), 7.39–7.42 (m, 2H), 7.72 (m, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.4, 120.4, 122.9, 128.9, 131.7, 139.0, 152.8; MS (EI): *m*/*z* 210 (M^+, 100%).

4.2.4. 4,4′-Dimethylazobenzene[13b] (***1d***). 71% yield (89 mg); a pale orange solid; mp 145.0–146.0 °C; IR (KBr): ν=3416, 2911, 1598, 1485, 1141, 823, 702 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 2.43 (s, 6H), 7.30 (d, *J*=8.0 Hz, 4H), 7.81 (d, *J*=8.0 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 21.5, 122.7, 129.7, 141.2, 150.8; MS (EI): *m*/*z* 210 (M^+, 100%).

4.2.5. 4,4′-Dimethoxyazobenzene[14] (***1e***). 10 % yield (15 mg); a brown solid; mp 149.8–151.6 °C; IR (KBr): ν=3092, 2843, 1588, 1573, 1499, 1241, 841 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 3.89 (s, 6H), 7.00 (d, 4H, *J*=9.0 Hz), 7.88 (d, 4H, 9.0 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 55.6, 114.2, 124.3, 147.1, 161.6; MS (FAB): *m*/*z* 242 (M^+).

4.2.6. 4,4′-Bis(dimethylamino)azobenzene[17a] (***1f***). 45% yield (72 mg); an orange powder; mp 256.7–258.3 °C; IR (KBr): ν=2928, 2784, 1601, 1511, 1367, 1148, 809 cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 6.76 (d, *J*=9.0 Hz, 4H), 7.81 (d, *J*=9.0 Hz, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 40.4, 111.7, 124.0, 144.0, 151.5; MS (FAB): *m*/*z* 268 (M^+).

4.2.7. 4,4′-Dichloroazobenzene[14] (***1g***). 81% yield (121 mg); an orange needles; mp 184.5–185.5 °C; IR (KBr): ν=3449, 1568, 1475, 1080, 1000, 843 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.49 (d, *J*=8.5 Hz, 4H), 7.86 (d, *J*=8.5 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 124.2, 129.4, 137.2, 150.8; MS (ESI): *m*/*z* 250 (M^+, 100%), 252 (M^++2).

4.2.8. 4,4′-Dibromoazobenzene[14] (***1h***). 64% yield (130 mg); an orange powder; mp 203.0–204.5 °C; IR (KBr): ν=3452, 1571, 1475, 1394, 1067, 835 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.65 (d, *J*=9.0 Hz, 4H), 7.79 (d, *J*=9.0 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 124.4, 125.8, 132.4, 151.2; MS (ESI): *m*/*z* 338 (M^+, 51%), 340 (M^++2, 100%), 342 (M^++4, 49%).

4.2.9. 4,4′-Di(trifluoromethyl)azobenzene[13b] (***1i***). 60% yield (114 mg); an red solid; mp 97.3–99.1 °C; IR (KBr): ν=2924, 1611, 1412, 1320, 1160, 1100, 849 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.80 (d, *J*=8.4 Hz, 4H), 8.03 (d, *J*=8.4 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 123.3, 123.8 (q, J_{C-F}=272.4 Hz), 126.4 (q, J_{C-F}=3.7 Hz), 133.0 (q, J_{C-F}=32.6 Hz), 154.1; MS (FAB): *m*/*z* 318 (M^+, 100%).

4.2.10. 2,2′-Difluoroazobenzene[25] (***1j***). 51% yield (67 mg); an orange solid; mp 99.6–101.0 °C; IR (KBr): ν=1589, 1483, 1263, 1110, 856 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.26 (m, 4H), 7.48 (m, 2H), 7.80 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 117.1 (d, J_{C-F}=20.2 Hz), 117.9, 124.4 (d, J_{C-F}=3.8 Hz), 133.0 (d, J_{C-F}=8.2 Hz), 140.8 (d, J_{C-F}=3.8 Hz), 160.4 (d, J_{C-F}=258.6 Hz); MS (FAB) *m*/*z* 218 (M^+).

4.2.11. 2,2′-Dichloroazobenzene[8b] (***1k***). 50% yield (65 mg); an orange solid; mp 137.4–138.7 °C; IR (KBr): ν=3056, 1592, 1521, 1462, 1241, 1084, 1057, 950, 762 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.38 (m, 4H), 7.56 (m, 2H), 7.70 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 118.1, 127.4, 130.7, 132.2, 135.8, 148.8; MS (FAB) *m*/*z* 218 (M^+).

4.2.12. 2,2′-Diiodoazobenzene[8b] (***1l***). 48% yield (63 mg); a red needle; mp 155.8–156.6 °C; IR (KBr): ν=1561, 1455, 1245, 1037, 1014, 766 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.19 (m, 2H), 7.46 (m, 2H), 7.76 (m, 2H), 8.04 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 103.2, 118.3, 129.0, 132.8, 139.9, 150.9; MS (FAB) *m*/*z* 218 (M^+).

4.2.13. 4,4′-Dicyanoazobenzene[14] (***1m***). 23% yield (32 mg); a red solid; mp 234.6–235.2 °C; IR (KBr): ν=2921, 2223, 1485, 1404, 1298, 1098, 1012, 854, 836 cm^{-1}; ^1H NMR (500 MHz, $CDCl_3$) δ 7.86 (d,

J=8.0 Hz, 4H), 8.04 (d, J=8.0 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 115.2, 118.1, 123.7, 133.4, 154.0; MS (EI): m/z 232 (M^+, 100%).

4.2.14. 4,4′-Di(cyanomethyl)azobenzene[17a] (***1n***). 64% yield (100 mg); a yellow solid; mp 195.5–197.0 °C; IR (KBr): ν=2916, 2242, 1610, 1429, 1109, 821 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.86 (s, 4H), 7.50 (d, J=8.5 Hz, 4H), 7.94 (d, J=8.5 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 23.6, 117.3, 123.7, 128.8, 132.9, 152.1; MS (FAB): m/z 261 (M^++H, 7%), 154 (100%).

4.2.15. 4,4′-Diacethylazobenzene[14] (***1o***). 88% yield (140 mg); a pale red powder; mp 208.5–209.8 °C; IR (KBr): ν=1674, 1466, 1252, 1229, 1102, 963, 835 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.68 (s, 6H), 8.01 (d, J=8.0 Hz, 4H), 8.13 (d, J=8.0 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 26.8, 123.2, 129.4, 138.9, 154.8, 197.3; MS (FAB): m/z 267 (M^++H), 73 (100%).

4.2.16. Dimethylazobenzene-4,4′-dicarboxylate[21] (***1p***). 85% yield (152 mg); an orange powder; mp 223.1–224.4 °C; IR (KBr): ν=2916, 1734, 1478, 1292, 1116, 873, 775 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 3.97 (s, 6H), 7.99 (d, J=8.0 Hz, 4H), 8.21 (d, J=8.0 Hz, 4H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 52.4, 122.9, 130.7, 132.4, 154.9, 166.4; MS (EI): m/z 298 (M^+, 100%).

4.2.17. 4,4′-Azobenzenedisulfonamide[26] (***1q***). This compound could be isolated by a silica gel column chromatography (eluent: THF); 53% yield (108 mg); a beige powder; decomposed 385 °C, IR (KBr): ν=3587, 3363, 3272, 3080, 1604, 1546, 1346, 1162, 856, 702 cm^{-1}; ^{1}H NMR; (300 MHz, DMSO-d_6) δ 7.60 (s, 2H), 8.03–8.11 (m, 4H); ^{13}C NMR; (75 MHz, DMSO-d_6) δ 124.0, 127.2, 146.6, 153.2; MS (ESI): m/z 340 (M^+, 100%); HRMS (ESI-TOF): Calcd for $C_{12}H_{11}N_4O_4S_2$: 339.0222, Found: 339.0214.

4.2.18. Bis(4-fluoro-3-methylphenyl)diazene[27] (***1r***). 63% yield (93 mg); a yellow needle; mp 163.1–164.5 °C; IR (KBr): ν=2935, 1579, 1487, 1409, 1248, 1195, 1097, 903, 822 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.36 (s, 6H), 7.33 (dd, 2H, J=7.5, 7.5 Hz), 7.56 (d, 2H, J=8.7 Hz), 7.66 (d, 2H, J=8.1 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.7 (d, J_{C-F}=3.2 Hz), 115.6 (d, J_{C-F}=23.9 Hz), 122.6 (d, J_{C-F}=8.9 Hz), 125.4 (d, J_{C-F}=6.3 Hz), 125.8 (d, J_{C-F}=19.0 Hz), 148.8 (d, J_{C-F}=2.3 Hz), 162.9 (d, J_{C-F}=250.7 Hz); MS (EI): m/z 246 (M^+, 5%), 68 (100%); HRMS (FAB-Magnetic Sector): Calcd for $C_{14}H_{12}F_2N_2$: 246.0969, Found: 246.0994.

4.2.19. Bis(4-methyl-3-fluorophenyl)diazene[27] (***1s***). 80% yield (118 mg); an orange needle; mp 97.8–100 °C; IR (KBr): ν=1579, 1493, 1409, 1253, 1185, 1096, 949, 874 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.37 (s, 6H), 7.13 (m, 2H), 7.75 (m, 4H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 14.8 (d, J_{C-F}=3.2 Hz), 107.5 (d, J_{C-F}=23.9 Hz), 120.5 (d, J_{C-F}=3.2 Hz), 128.4 (d, J_{C-F}=18.2 Hz), 131.6 (d, J_{C-F}=5.5 Hz), 152.1, 161.6 (d, J_{C-F}=246.6 Hz); MS (EI): m/z 246 (M^+, 45%), 109 (100%); HRMS (FAB-Magnetic Sector): Calcd for $C_{14}H_{12}F_2N_2$: 246.0969, Found: 246.0992.

4.2.20. 4-Acetoazobenzene[14] (***1t***). 43% yield (58 mg); a red solid; mp 101.9–103.9 °C; IR (KBr): ν=2922, 1679, 1354, 1252, 969, 835, 776 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.67 (s, 3H), 7.52–7.56 (m, 2H), 7.96 (d, J=7.0 Hz, 2H), 7.98 (d, J=8.5 Hz), 8.12 (d, J=8.5 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 26.8, 122.9, 123.1, 129.2, 129.4, 131.8, 138.4, 152.5, 155.0, 197.5; MS (FAB): m/z 225 (M^++H, 58%), 73 (100%).

4.2.21. 4-Acetyl-2′-methylazobenzene (***1u***). 46% yield (66 mg); mp 101.8–105.2 °C; IR (KBr): ν=3342, 2959, 1682, 1595, 1472, 1354, 1256, 959, 851, 774 cm^{-1}; ^{1}H NMR (500 MHz, $CDCl_3$) δ 2.67 (s, 3H), 2.75 (s, 3H), 7.28 (dd, 1H, J=8.0, 8.0 Hz), 7.37 (d, 1H, J=7.0 Hz), 7.41 (dd, 1H, J=7.5, 6.5 Hz), 7.66 (d, 1H, J=8.0 Hz), 7.97 (d, 2H, J=8.5 Hz), 8.11 (d, 2H, J=8.5 Hz); ^{13}C NMR (125 MHz, $CDCl_3$) δ 17.5, 26.8, 115.3, 122.9, 126.5, 129.4, 131.4, 131.8, 138.1, 139.0, 150.6, 155.3, 197.5; MS (FAB): m/z 239 (M^++H, 15%), 73 (100%); HRMS (FAB-Magnetic Sector): Calcd for $C_{15}H_{14}N_2O$: 238.1106, Found: 238.1081.

4.2.22. 4-Acethyl-4′-methylazobenzene[14] (***1v***). 44% yield (63 mg); a red solid; mp 106.1–109.5 °C; IR (KBr): ν=1673, 1597, 1356, 1265, 1001, 969, 854, 826, 702 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.45 (s, 3H), 2.67 (s, 3H), 7.34 (d, 2H, J=8.4 Hz), 7.87 (d, 2H, J=8.1 Hz), 7.95 (d, 2H, J=8.7 Hz), 8.10 (d, 2H, J=8.7 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 21.6, 26.9, 122.8, 123.2, 129.4, 129.9, 138.1, 142.6, 150.7, 155.2, 197.5; MS (FAB): m/z 238 (M^+, 10%), 83 (100%).

4.2.23. 4-Acetyl-2′-fluorolazobenzene (***1w***). 54% yield (78 mg); a red solid; mp 112.6–114.6 °C; IR (KBr): ν=3335, 3014, 1675, 1591, 1480, 1351, 1219, 959, 850, 771 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 2.67 (s, 3H), 7.27 (m, 2H), 7.51 (m, 1H), 7.79 (dd, 1H, J=7.8, 7.8 Hz), 8.00 (d, 2H, J=8.7 Hz), 8.11 (d, 2H, J=8.4 Hz); ^{13}C NMR (75 MHz, $CDCl_3$) δ 26.9, 117.2 (d, J_{C-F}=19.9 Hz), 117.6, 123.2, 124.4 (d, J_{C-F}=4.0 Hz), 129.4, 133.4 (d, J_{C-F}=8.7 Hz), 138.7, 140.6 (d, J_{C-F}=6.9 Hz), 155.1, 160.5 (d, J_{C-F}=259.0 Hz), 197.4; MS (FAB): m/z 243 (M^++H, 33%), 73 (100%). HRMS (FAB-Magnetic Sector): Calcd for $C_{14}H_{11}FN_2O$: 242.0855, Found: 242.0876.

4.2.24. 4-Chloroazobenzene[21] (***1x***). 62% yield (79.1 mg); an orange solid; IR (KBr): ν=2966, 2925, 1636, 1381, 1268, 1085, 1025, 802 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.45–7.54 (m, 5H), 7.85–7.92 (m 4H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 122.9, 124.1, 129.1, 129.3, 131.3, 136.9, 150.9, 152.4; MS (FAB): m/z 216 (M^+, 100%).

4.2.25. Benzo[c]cinnoline[18b] (***1y***). 95% yield (102 mg); a pale yellow crystal; mp 155.5–156.1 °C; IR (KBr): ν=3056, 1611, 1431, 1353, 1117, 1082, 759 cm^{-1}; ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.90–7.94 (m, 4H), 8.57–8.60 (m, 2H), 8.74–8.77 (m, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 120.9, 121.4, 129.2, 131.3, 131.5, 145.3; MS (FAB): m/z 181 (M^++H).

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Supplementary data

^{1}H and ^{13}C NMR spectra of the azobenzenes prepared using this method. Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.tet.2014.01.048.

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