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Azobenzenes and catalysis

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Abstract

Azobenzene is the most extensively used class of chromophores in a large variety of applications. Recently, the use of azobenzene derivatives was developed in catalysis especially as promoter. This paper aims to provide a global overview of the main access to the diazo compounds from 2010, as well as their use as a reactant or a promoter in organometallic catalysis.

1. Introduction

Amongst the class of photo-reversible molecules, and the large variety of applications in photoregulation, azobenzene is the most intensively used, and azopolymers\(^1\) can be considered as useful materials for photo-mechanical applications.\(^2\) We propose here in a first part to complete and update the synthetic pathways to azobenzenes. In a second part, the various catalytic transformations of azobenzenes as reactant will be discussed, and finally, the use of diazo compounds as catalytic promoter will be presented.

There are three spectroscopic classes in the diazo compounds: azobenzene (\(R_1\) and \(R_2\) are H, alkynes, alkenes etc...), aminoazobenzene (\(R_1\) or \(R_2\) is \(\text{NH}_2\)), pseudo-stillbene (\(R_1 = \text{EWG}, R_2 = \text{EDG}\)) (Fig. 1a).\(^3\) For the isomerization step, there is two major ways of light-induced switching from trans to cis isomer: \(N=N\) torsion (rotamers) vs \(N\)-inversion (invertomers).\(^4\)-\(^10\) However, according to the literature reviewed by Bandara and Burdette,\(^11\) as an experimental result, if trans-azobenzene isomerization always occurs in the \(S1\) state by an inversion process, regardless of the initial excitemt, some theoretical studies predict isomerization of trans-azobenzene to be multi-dimensional or dominated by rotation. For cis-to-trans fast thermal isomerization, regarding to the azobenzene substituents, two structural features should be present: push-pull electronic distribution; a hydroxy group that allows the keto–enol equilibrium. These two factors permit the azo-dye to
proceed through the rotation pathway, and, consequently, the thermodynamically stable trans form of the azo-dye can be restored very quickly.\textsuperscript{12} If we focus on the azobenzene class, a simplified state model for azobenzene isomerization can be described, leading to the energy that the system needs or release during the transformations (Fig. 1b)\textsuperscript{13} with however a strong dependence of both photoisomerization and thermal isomerization rates on the polarity but not on the viscosity of the solvent.\textsuperscript{13} It is noticeable that a dark-switch can occur when using gold nanoparticles.\textsuperscript{14}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{General classes of diazo compounds. Simplified state model for azobenzene. \(\varepsilon\) = extinction coefficients, \(\Phi\) = quantum yields for the photoisomerization, \(k\) = rate of thermal relaxation.}
\end{figure}

Concerning the azo syntheses, there are several ways to envision the formation and the functionalization of azobenzenes (Fig. 2).\textsuperscript{15}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{General pathways to azobenzene formation or functionalization.\textsuperscript{15}}
\end{figure}

Mills reaction or oxidative/reductive dimerizations can form the N=N bond from their corresponding aniline/nitrobenzene derivatives, whereas diazo coupling are of the best known methods to form the C-N bond. Transpositions can also occur, leading to an azo compound. Finally, cross couplings can modify pre-formed azobenzenes. Some of these reactions, published from 2010, will be discussed here.

\section*{2. General synthetic pathways}

Very few recent reviews dealt with the syntheses of azobenzenes.\textsuperscript{16--18} Part from the reviews, the azobenzenes syntheses are still extensively described. The present review does not aim to list all the occurrences in literature, but to provide a
global overview of the main synthetic pathways from 2010, as well as the catalysis, as a tool for their functionalization, or as 
an application.

2.1. Diazo coupling

Diazo coupling, as an extensively used method to perform azobenzene syntheses with huge application area,\textsuperscript{19–37} implies a 
two steps process: (i) formation of a diazonium salt starting from aniline derivative with or without isolation of the salt and 
(ii) formation of the target azobenzene by coupling the diazonium salt and an electron-rich aromatic core such as phenol or 
aniline derivatives (Scheme 1).

\textbf{Scheme 1} General scheme of diazo coupling.

Concerning the first step, the main methodologies were the synthesis of diazonium salt in presence of \textit{in-situ} HNO\textsubscript{2}\textsuperscript{38–41} 
or its nitrosylsulfuric acid derivative.\textsuperscript{42} However, depending of the starting materials, other reagents were described for the 
production of diazonium salts such as a mixture of acetic acid/hydrochloric acid/isoamyl nitrite\textsuperscript{43} or a modified 
montmorillonite K-10 clay coupled with sodium nitrite.\textsuperscript{44} Concerning the addition of aromatic core, phenol\textsuperscript{45–51} or its 
derivatives\textsuperscript{52–56} are central molecules (Scheme 2), because of their easiest way of reaction with diazonium salts free in 
solution or blocked on backbone polymer.\textsuperscript{57} This strategy permitted the synthesis of achiral, chiral\textsuperscript{58} target azobenzenes but 
also symmetrical\textsuperscript{59 60} and unsymmetrical\textsuperscript{61 62–65 66 67} ones.
2.2. Reductive and oxidative dimerization

To build up azobenzenes, oxidations of primary aromatic amines or reductions of nitroaryl compounds are well described.

2.2.1. Reduction of nitrobenzene derivatives

To reduce selectively nitro moiety for the production of azobenzene, zinc dust or lead are one of the main reagent used (Scheme 3).

Scheme 3 Example of chemioselective reduction of nitroarene to arylhydroxylamine. 68
However, other reagents were described for the reduction of nitroaromatic derivatives. For example, Nanjundaswamy and co-workers studied the effectiveness of triethylammonium formate (TEAF) in the presence of magnesium for the formation of azo compounds by the reductive coupling of nitroaromatics (Scheme 4).69

\[
2 \begin{array}{c}
  \text{RNO}_2 \\
  \text{Mg/TEAF} \\
  \text{R-N}_2
\end{array} 
\]

\[
R = \text{H, Me, OMe, OEt, Cl}
\]

80% to 93%

Scheme 4 Synthetic pathway for reductive dimerization of nitrobenzenes derivatives.69

Hydrogenations can also lead to azobenzene formation using unsupported ultra-thin platinum nanowires as catalysts for the nitrobenzene hydrogenation under mild conditions (Scheme 5a).70 If the yields are great (with KOH as a base, 89% of azobenzene was obtained), the reaction is not fully selective (under these conditions, 10% of aniline was obtained). Corma’s group described reductive dimerization with gold supported on nanocrystalline cerium oxide.71 The azobenzene adsorption on the catalyst surface seemed to be much weaker than the azoxybenzene one. Consequently, the non-desired hydrogenation of the azobenzene to the aniline only occurred when the azoxybenzene has been completely hydrogenated. However, if conversions are full (excluding nitrophenol and nitroaniline as starting material), selectivities seemed to be strongly dependant on substituents (Scheme 5b).

\[
2 \begin{array}{c}
  \text{RNO}_2 \\
  \text{PtNWs/H}_2/\text{KOH} \\
  \text{N}_2
\end{array} 
\]

90%

\[
R_1 = \text{H or C}_2\text{H}_5
\]

\[
R_2 = \text{CH}_3, \text{Cl, OCH}_3, \text{CO(CO)}_2\text{H, NH}_2, \text{OH}
\]

conv. = 60% to 100%

select. = 0% to 99%

Scheme 5 Reductive dimerizations by hydrogenation.70,71

Part from metallic reductions, symmetrical 4,4'-dihydroxyazobenzene was obtained in 40% yield through the self-condensation of 4-nitrophenol in the presence of potassium hydroxide at high temperature (Scheme 6).72 However, to the best of our knowledge, the mechanistic aspect of the reaction is still not elucidated.
Complex hydrids such as LiAlH₄ might reduce and dimerize nitroaniline derivatives. These hydrids were also used to perform intramolecular reductive dimerization (Scheme 7).

Sakai and co-workers demonstrated how a reduction step with a system comprised of In(OTf)₃ and Et₃SiH allowed the reductive dimerization of nitrobenzene derivatives to the corresponding azobenzene. The possible pathway was also described (Scheme 8).

**Scheme 8** Plausible pathway for the formation of azobenzene.

### 2.2.2. Oxidation of aniline derivatives

Oxidative coupling of aniline is usually performed using KMnO₄/CuSO₄ in good yield (Scheme 9).
Scheme 9 Oxidative coupling of aniline.$^{76,77}$

It was noticeable that symmetrical ortho-thioether substituted azobenzenes were obtained in only 2% yield when iron sulfate was used instead of copper sulfate.$^{78}$ MnO$_2$, a weaker oxidative agent than KMnO$_4$ allowed also the formation of azobenzenes in 87% (Scheme 10).$^{79}$

Scheme 10 Oxidative dimerization with MnO$_2$.$^{79}$

A simplest way of oxidative dimerization consists in the use of air or dioxygen.$^{80,81}$ Recently, Commins and Garcia-Garibay synthesized a photochromic molecular gyroscope using this method of copper-catalysed air-oxidative dimerization of aminotoluene into its corresponding azobenzene (Scheme 11).$^{82}$ Red copper was also successfully used with dioxygen to afford symmetrical azobenzenes from aniline.$^{83}$

Scheme 11 Copper-catalysed air-oxidative dimerization of methylaniline.$^{82}$

An oxidative one-pot route to $N$-substituted sulfonamidic azobenzene derivatives as protected aniline was recently reported.$^{84}$ A part from CF$_3$ substituent which did not afford the desired product, the method gave yields from 19 to 75% (Scheme 12).

Scheme 12 mCPBA oxidation of dihydrobenzothiadiazines.$^{84}$
After the formation of several lanthanide complexes of Pr(III), Sm(III), Gd(III), Tb(III), Er(III) and Yb(III) with the sodium salt of the Schiff base, the Gd(III) complex formed was applied to the oxidative dimerization of anilines with yields between 12 and 88% (Scheme 13).

Scheme 13 Lanthanide complexes applied to oxidative dimerization of aniline.

Usually, the trans-azobenzene is the major isomer obtained during its formation. But surprisingly, by an oxidative dimerization of 4-bromo-2,3,5,6-tetrafluoroaniline to its corresponding azobenzene, Friščić and co-workers managed to isolate cis form as major isomer after flash silica column (Scheme 14). However, the long half-lives of cis-azobenzenes are in agreement with the literature as o-fluorinated azobenzenes can exhibit significantly separated trans- and cis-form n–π* absorption maxima leading to long cis-isomer half-lives.

Scheme 14 Cis and trans azobenzene formation.

2.3. Mills reaction

Equivalent to oxidative dimerization mechanistically speaking, Mills reaction differs in leading to the possibility to obtain unsymmetrical products. However, only few oxidants were recently reported for the formation of nitroso compounds from their corresponding anilines: Oxone (2KHSO₅.KHSO₄.K₂SO₄, Scheme 15), or m-CPBA.
2.4. Rearrangements

As triazene rearrangement is one of the intramolecular possibilities to obtain azobenzenes from triazene, there are other rearrangements published recently, such as urea or Wallach ones.

Triazene rearrangement is an intramolecular reaction performed in acidic conditions, and leads to two products (para position as major one) in three steps. However, when another electron-rich arene is present in the media, its coupling with the ionic or radical rearrangement of triazene (leading to the diazonium salt/radical formed) allowed the formation of the corresponding azobenzene (Scheme 16).
Scheme 16 Triazene rearrangement or decomposition for the formation of azobenzene.94-97

Another important rearrangement in azobenzene formation is the Wallach transformation. For example, in 2013, Wallach rearrangement permitted the preparation of \( p \)-hydroxyazobenzocrown ethers starting from different azoxybenzocrowns as substrates with yields between 30% and 78% (Scheme 17).98

Scheme 17 Wallach rearrangement on various azoxybenzocrowns.98
3. Catalytic transformations involving azobenzene as reactant

3.1. Metal complexation using azobenzene

Azobenzene with its two aromatic rings and its two nitrogen atoms can undergo a complexation with a metal (Scheme 18). For example, pallado-complexes syntheses were already reviewed by Ghedini and co-workers, centered on five-membered “(C,N)Pd” metallacycle and some representative examples of complexes featuring a useful set of physical properties. They were selected and divided into different classes (depending on the nature of the ligands). Some recent interesting examples of metallo complexes of azobenzenes bearing palladium, nickel or rhodium are presented.

Examples of azobenzene metallacycles can be found on diazo compounds bearing various heteroatoms, such as sulphur, nitrogen and/or oxygen. In the case of sulfur atom, the reliability of auxiliary C-H---S synthons is investigated in dictating the crystal packing of the synthesized molecules. In the case of nitrogen and/or oxygen atoms, an unexpected migration or elimination of the ortho moiety bound by the azo compound was studied. It is also noticeable that keto/enol isomerization of azonaphtols can lead to isomer palladacycles (Scheme 18).
It is however important to notice that when competing 3d metals(II) such as Ni, Co, Mn, with palladium(II), 3d-metals turned to be inactive in ortho-metallation and transform into the corresponding M(II) acetates, although nickel(II) is known to be a historical good metalling agent for azobenzene. Another point is that heterometallic complexes react with azo compound much easier than homometallic ones (Scheme 19).

Scheme 18 Azobenzene complexations.

Scheme 19 Homo- vs heterometallic complexes reaction with azobenzene.
Other ortho C-H activations were also related with for example C,N-chelated stannylene\textsuperscript{107} or N-heterocyclic chlorosilylene\textsuperscript{108} with azobenzene. Recently, Rh(III)-catalyzed formation of cinnolines and cinnolinium salts\textsuperscript{109} or selenylation of arenes including azobenzenes was described.\textsuperscript{110} Moreover, with push-pull (and so dissymmetrical) azobenzenes, mechanochemistry with liquid-assisted grinding played an important role in regioselective ortho C-H activation.\textsuperscript{111} Then, direct ortho-hydroxylation with dioxane as source of hydroxyl radical was published.\textsuperscript{112}

\textbf{Scheme 20} Recent ortho C-H activations

When azobenzene is transformed into its anion radical with potassium graphite previously to the complexation, the treatment with a stable Ni complex can afford a substitution in 84\% overall yield (Scheme 21).\textsuperscript{113}
3.2. Palladium catalysis

In literature, palladium-catalyzed reaction and complexations involving azobenzenes are the most important. In 2013, acylation of azobenzenes at the 2-position through a Pd-catalyzed C-H functionalization was performed in yields from 54 to 86% with various benzaldehydes (Scheme 22a). \(^{114}\) They also performed these acylation with α-oxocarboxylic acids (Scheme 22b). \(^{115}\)

Scheme 22 Direct access to acylated azobenzenes via Pd-Catalyzed C-H functionalization.

A procedure to afford mono- and diacrylazobenzene via Pd-catalyzed oxidative C-H bond activation from toluene was reported and permitted to control mono- and diacylated products by the oxidant loading tert-butylhydroperoxide (TBHP) (Scheme 23). \(^{116}\) Indeed, adding 4 equivalents of oxidant led to the mono functionalization, whereas 15 equivalents allowed the bis-coupling to occur.
Scheme 23 Oxidative C-H bond activation of azobenzene.\textsuperscript{116}

With the rediscovery of the Staudinger reaction as a mild and highly selective method for bioconjugation, Saxon and Bertozzi led access to various applications in chemical biology.\textsuperscript{117} Feringa’s group studied the possibility of using the Staudinger–Bertozzi ligation, making the aromatic moiety used in this reaction a part of the chromophore system of the molecular photoswitch ligation.\textsuperscript{118} The reactant was synthesized by diazo coupling followed by the bromo-PEG3 substitution on the aromatic ring, and finally the palladed phosphination was performed (Scheme 24).

Scheme 24 Reactant synthesis for Staudinger-Bertozzi ligation.\textsuperscript{118}

Numerous simple Suzuki condensation using iodo- or bromoazobenzene derivatives and an arylboronic acid in a presence of Pd(PPh\textsubscript{3})\textsubscript{4}/sodium (hydrogeno)carbonate,\textsuperscript{119–123} or Pd(OAc)\textsubscript{2}/sodium carbonate\textsuperscript{114,125} were successfully achieved in organic or organic/water solvents. For example, azobenzene derivatives possessing terminal phenylenebiuret hydrogen-bonding groups including Suzuki reaction as the final synthetic step were described (Scheme 25).\textsuperscript{126}

Scheme 25 Suzuki coupling for the azobenzene phenylenebiuret synthesis.\textsuperscript{126}
Another example is the applications in vivo, where substitution in all four diazo-ortho-position allowed the isomerization with red light, and so the better penetrating of light for photoisomerization through tissues. This compound synthesized via Suzuki reaction (Fig. 3) underwent slow reduction by reduced glutathione, meaning that only extracellular or short-term intracellular use were possible in vivo.\textsuperscript{127}

![Fig. 3 Red-shifted azobenzene molecules.](image)

When two chromophores with different light-induced isomerization are included in one molecule, it can lead to light-motioned molecule as will. For example, the rotaxane described by Tian and co-workers possessed an azobenzene moiety with a E→Z isomerization wavelength of 380 nm (Z→E at 450 nm) whereas the stilbene had a E→Z isomerization wavelength of 280 nm (Z→E at 313 nm).\textsuperscript{128} The link between the two moieties (Fig. 4 labeled in grey) was obtained by Suzuki coupling (Pd(OAc)\textsubscript{2}, Na\textsubscript{2}CO\textsubscript{3}).

![Fig. 4 Rotaxane synthesis.](image)

When dihalogenoazobenzenes are involved, polymers or macrocycles can be synthesized by pallado-coupling method. For example, in 2000, Masuda’s group reported the synthesis of polymers having azobenzene units in the main chain by utilizing the Pd-catalyzed Suzuki coupling (Scheme 26a).\textsuperscript{129} The conjugated polymers were prepared by coupling 1,3-
propanediol diesters of 1,4-phenylenediboronic acids with 4,4′-diiodoaobzenes in quantitative yields. Another example is the formation of macromolecular “ accordions” by Suzuki coupling (Scheme 26b).  

![Scheme 26 Suzuki coupling for the polymerization of azobenzene.](image)

Still in the polymer domain, a fluorene- and azobenzene-containing conjugated polymer has been successfully synthesized using Suzuki polycondensation (Scheme 27a black and grey resp.). One year later, monodisperse conjugated polymer particles with incorporated light-switchable azobenzene moieties using a Suzuki-Miyaura dispersion polymerization under sonication and heating were described (Scheme 27b). After a classical dibromoazobenzene formation by Mills reaction, the Suzuki-Miyaura coupling was performed with diboronic acid propandiol ester of fluorene derivative and Pd[P(Ph)3]4 with PVPVA/Triton X45. This surfactant was used to disperse the particles properly.
Dihalogenated azobenzene can also lead to self-assemble macrocycle, as described by Yamamura, Okazaki and Nabeshima.\textsuperscript{134} Suzuki coupling led the authors to obtain the desired azobenzene-linked biscatecholate ligand (Scheme 28). This ligand in presence of boron or titanium entities gave ring- and cage-shaped complexes.

Scheme 28 Suzuki coupling for the formation of biscatecholate ligand.\textsuperscript{135}

In cross-coupling reactions, azobenzenes therefore usually act as electrophiles, which greatly limits the scope of the reaction. But the boronic moiety can be also hold by the chromophore. For example, pallado-coupling to synthesize several tripod-shaped oligo(p-phenylene)s with legs composed of two phenylene units was reported. An azobenzene chromophore group was present on the functional arm.\textsuperscript{135} To accomplish the synthesis of one of the tripod desired, they prepared the
paranitroazo derivative. And the coupling of this boronic ester with the precursor was carried out in presence of Pd(PPh$_3$)$_4$ as catalyst and Na$_2$CO$_3$ as the base (Scheme 29).

![Scheme 29](image)

**Scheme 29** Tripod-shaped oligo(p-phenylene) synthesis containing an azo moiety.\(^{135}\)

Competing Knoevenagel reaction (route 2) to Suzuki route (route 1) to obtain their dendron precursor (Scheme 30), Müllen and co-workers found that the palladium-catalyzed coupling sequence furnished pure product in good yield (93% vs 53%) because it avoided the production of a large number of side-products.\(^ {136}\)

![Scheme 30](image)

**Scheme 30** Suzuki route vs Knoevenagel reaction to obtain dendron precursor.\(^ {136}\)
Instead of a boronic acid, Suzuki coupling reaction can employ an azobenzene trifluoroborate. This method was applied for attaching an azobenzene moiety onto aryl and vinyl iodides. After an azobenzene boronic ester converted into its trifluoroborate derivative, the Suzuki cross coupling was performed yielding the reached compound in 59% (Scheme 31). It is noticeable that to map the functional group compatibility of this reaction they have employed the azobenzene trifluoroborate with a variety of vinylic and aromatic iodides yielding the corresponding products in 41 to 72% yield.

![Scheme 31](image)

**Scheme 31** Suzuki coupling on azobenzene trifluoroborate derivative.

Stille coupling was described very few times on azobenzenes. We can cite the study of Staubitz and co-workers on stannylated azobenzenes showing that these molecules can be used as nucleophilic components in Stille cross-coupling reactions with aryl bromides in yields from 70 to 93% (Scheme 32).

![Scheme 32](image)

**Scheme 32** Stille Coupling with azobenzene as nucleophile.

A part from Suzuki and Stille couplings, Sonogashira coupling can be performed when a halogen is held by the aromatic ring. And among reactants, trimethylsilyl- or triisopropylsilylacetylene is a useful tool for the Sonogashira cross-coupling functionalization of azobenzenes. However 2,2-methylbut-3-yn-2-ol followed by a deprotection step is also described in literature as in the following example (Scheme 33).
More complex alkynes can also be used. For example, Zarwell and Rück-Braun synthesized a tripod azobenzene-linker-conjugate by cross coupling, using tetrakis triphenylphosphine palladium (Pd\(^0\)) and copper iodide with triethylamine, a commonly used base in 61% yield (Scheme 34). It is noticeable that in some conditions, the coupling and reduction of azobenzene can furnish hydrazines, the acetylene acting as a proton donor.

Complexity can be also held by the azobenzene reactant. Almost none of the azobenzene emit light because of a radiationless deactivation process such as photoisomerization, Kano, Kawashima and co-workers have synthesized borylazobenzene and reported the intense fluorescence properties upon irradiation. Fluorescent borylazobenzene constructions went through Sonogashira coupling (Scheme 35).

Other bases than triethylamine can also be used. Thus, Mohamed Ahmed and Mori described a Sonogashira coupling with aqueous ammonia (Scheme 36), a base which is tolerable for the reaction of aryl iodides or terminal alkynes bearing an
azobenzene group.\textsuperscript{151} It is noticeable that without ammonia, the reaction failed, suggesting that the presence of an amino group on the aryl halide could not substitute the ammonia.

\[
\begin{array}{c}
R = \text{CH}_2\text{Si} - 4\text{NC}_6\text{H}_4 \quad \text{HBr} - \text{C}_6\text{H}_{13} \\
X = \text{C}_6\text{H}_{15} \quad \text{H}
\end{array}
\]

\begin{align*}
\text{R} - \equiv + \quad & \text{Scheme 36 Sonogashira coupling with aqueous ammonia.}\textsuperscript{151} \\
& \text{Sonogashira coupling with aqueous ammonia.}\textsuperscript{151}
\end{align*}

Dihalogeno-compounds can be used as reactant, as Tanaka's group functionalized an azobenzene to a chromogenic host compound (Fig. 5a),\textsuperscript{152} or Reed, Tour and co-workers for their oligomers precursors (Fig. 5b).\textsuperscript{153} It is important to note that none of the hydrazo product was obtained.

Since, multi Sonogashira couplings can lead to oligomers or polymers. For example, ethynyl-linked azobenzene molecular wires were reported (Fig. 6).\textsuperscript{154}

In 2013, synthesis and photoresponse of helically folded polymers bearing an azobenzene moiety in the main chain was successfully performed by Sonogashira coupling polymerization of d-hydroxyphenylglycine-derived monomer with 3,3′- and 4,4′-diethynylazobenzenes (Scheme 37).\textsuperscript{155} Same manipulation have already been performed by the same group in 2011 but
with the cross coupling on meta-position of the same aromatic ring.\textsuperscript{156} Again, the diethynylazobenzenes involved were synthesized by Sonogashira coupling with trimethylsilylacetylene followed by deprotection.

\textbf{Scheme 37} Sonogashira coupling for the formation of helical polymer.\textsuperscript{155,156}

3.3. Rhodium catalysis

For the formation of benzotriazole derivatives, a sequential rhodium-catalyzed amidation and oxidation in one pot was described. The best first step of the synthesis was achieved using tosyl azide in the presence of \([\text{Cp}^*\text{RhCl}_2]_2\) with AgNTf\textsubscript{2} \textsuperscript{157} (Scheme 38) or AgSbF\textsubscript{6}.\textsuperscript{158} Same year, Jia and Han did the same manipulation demonstrating the ortho regioselectivity of the reaction and the plausible reaction mechanism was published.\textsuperscript{158,159}
Another example is the formation of indazoles by reaction of azobenzene with rhodium catalyst $[\text{Cp*RhCl}_2]^2$ and AgSbF$_6$. The proposed reaction pathway for 2H-indazole synthesis is given below (Scheme 39). It begins with the C-H activation of azobenzene, followed by the addition of the aldehyde. Nucleophilic substitution followed by the aromatization gave the authors their reached product.
3.4. Nickel catalysis

Part from complexation, only reductive cleavage of azobenzene into its aniline or derivative by Raney nickel or porous nickel was described in literature and especially concerning kinetics.\textsuperscript{161,162} Diphenylhydrazine can also be obtained depending on the temperature set to the reaction.\textsuperscript{163} Instead of Raney nickel, silica gel supported nickel\textsuperscript{164} or nickel-containing mesoporous silicate molecular sieve catalyst can be used.\textsuperscript{165} Furthermore, the NiMCM-41 catalyst tested was also found to be reusable with keeping good to very good yields of the reaction. As an example, azobenzene was cleaved into aniline in 91% yield -1\textsuperscript{st} run- to 89% yield -6\textsuperscript{th} run- (Scheme 40).

\[ R = R_1 = H, 4-\text{Cl, Br, 3-CH}_3, 4-\text{CH}_3, 4-\text{OCH}_3 \]

\[ R = H, R_1 = 4-\text{NH}_2 \]

\[ R = H, R_1 = 3-\text{CH}_3 \]

\textbf{Scheme 40} Mesoporous silicate molecular sieve catalysis.\textsuperscript{165}

4. Catalytic transformations involving azobenzene as promoter

4.1. Catalytic transformation involving azobenzene as promoter

Even if papers have been published on the synthesis of azo-containing phosphanes as potential catalytic promoters, few described their application in organometallic catalysis,\textsuperscript{166,167} organocatalysis or on their catalytic application in water.

4.1.1. Organo-catalysis

As organocatalysis application, azobenzene-based thiourea catalysts can control the catalytic activity by the use of light. The conceptual design of the systems relies on the inactivation by an intramolecular hydrogen bonding, only on the \textit{cis}-form.\textsuperscript{168} Organo-catalysis proved to be more efficient in the dark (96% yield vs 21% at 365 nm), as expected by the authors (Scheme 41).
Another example is given by Viehmann and Hecht who synthesized a photoswitchable guanidine catalyst (Fig. 7), beginning with the azobenzene formation from Mills reaction with Oxone®. However, if the catalyst underwent reversible photochromic properties it seemed to be inactive in the Ring Opening Polymerization of lactide. 

\[
\text{Scheme 41 ON-OFF organo-catalysis.}^{168}
\]

\[
\text{Fig. 7 Photoswitchable guanidine catalyst.}^{89}
\]

### 4.1.2. Micellar catalysis

Surfactant can enhance the reactivities in water,\textsuperscript{169} azobenzene ones could have the same properties but with a synthetic product recovery facilitated. For example, our group performed micellar catalysis using an azobenzenic surfactant and applied this to the Pd-catalyzed Tsuji–Trost reaction in water (Scheme 42).\textsuperscript{170} Same organopalladed reaction was performed with a mixture of amphiphilic phosphanes (Scheme 42)\textsuperscript{171} with or without randomly-modified β-cyclodextrins (RAME-β-CD). Without cyclodextrins, heptane/water was used for the reaction, whereas with these macromolecules, the reaction was performed in pure water. The addition of cyclodextrins in the aqueous compartment improved the phosphane-based aggregate dynamics, resulting in an increase in the catalytic performances.\textsuperscript{172}
Another example was described as a new azobenzene, also used to enhance the yield the model reaction tested (Scheme 43). BABTGA was then synthesized in 12 steps, beginning with a Mills reaction of butylaniline, followed by a Sonogashira coupling, a click reaction and an oxidation of the D-glucose moiety to its corresponding glucuronic acid. If aniline acetylation works in water, the recovery of the product, as well as the yields obtained are not as good as in the presence of the surfactant. Moreover, and most importantly, we demonstrated the impact of the surfactant isomerization on the good recovery of the acetanilides formed.

Scheme 43 Aniline acetylation in water enhanced by BABTGA.

5. Conclusion

Azobenzene family is still extensively used in various applications such as light-controlled molecular brake, molecular electronic devices, or even photoswitching azo compounds in vivo with red light. Most of the strategies employed to obtain azobenzene derivatives via diazo coupling used phenol derivatives as electron-donner moieties. However,
substitution of in-situ HNO$_2$ was reported for the syntheses of diazo compounds. Reductive dimerization was described starting from nitroaryls in presence of various reductants: Zn, Mg, H$_2$/Pt or H$_2$/Au, KOH and complex hydrides. Moreover, oxidative dimerizations were reported starting from anilines using conventional oxidants such as KMnO$_4$/CuSO$_4$, MnO$_2$, air or O$_2$, m-CPBA.

Part from diazo syntheses, metal complexations for the preparation of azobenzene metallocycles were studied including Pd, Ni or Rh atoms. Pallado-catalysis using azobenzenes as reactant was the most developed in literature. Amongst the various works, Pd-catalysed C-H functionalization, phosphorylation, Suzuki, Stille or Sonogashira couplings were described. In the case of Suzuki reaction, azobenzene derivatives were used both as halogenated compounds or as borates. Moreover, rhodium and nickel catalysis were reported in few papers, including 1,2-addition and azobenzene clivage into aniline.

Finally, azobenzene was also used as core for reaction promoter, especially in photochromic micellar catalysis in water. In this topic, all the works were reported by our group, and concerned Tsuji-Trost catalysis or amidation.

In the future, new methodologies for azobenzene production and especially with green reactants, solvents, or alternative technologies will be a challenge for synthetic organic chemists. Application of azobenzenes either as reactant or promoter will allow paving the way for catalysis, science and technology.

References

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