Review article

Arenediazonium salts transformations in water media: Coming round to origins

Marina E. Trusova [a], Ksenia V. Kutonova [a], Victor V. Kurtukov [b], Victor D. Filimonov [a], Pavel S. Postnikov [b],*

[a] Department of Biotechnology and Organic Chemistry, National Research Tomsk Polytechnic University, 634050 Tomsk, Russia
[b] Department of Technology of Organic Substances and Polymer Materials, National Research Tomsk Polytechnic University, 634050 Tomsk, Russia

Abstract

Aromatic diazonium salts belong to an important class of organic compounds. The chemistry of these compounds has been originally developed in aqueous media, but then chemists focused on new synthetic methods that utilize reactions of diazonium salts in organic solvents. However, according to the principles of green chemistry and resource-efficient technologies, the use of organic solvents should be avoided. This review summarizes new trends of diazonium chemistry in aqueous media that satisfy requirements of green chemistry and sustainable technology.
© 2016 Tomsk Polytechnic University. Production and hosting by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/). Peer review under responsibility of Tomsk Polytechnic University.

Keywords: Diazonium salts; Green chemistry; Arylation; Halogenation; Cross-coupling

Aromatic diazonium salts (ADS) have been recognized as one of the most versatile and valuable reagents in organic synthesis for more than 150 years [1]. From the historical perspective, the chemistry of diazonium salts had been originally developed in aqueous media; however, many reactions had low efficiency because of the instability of diazonium salts and their low solubility in water. The development of stable diazonium salts has become an important achievement in diazonium chemistry. Unfortunately, the conventional stable diazonium salts have a low solubility in water, and therefore, in the second half of 20th century, the chemists have focused on synthetic methodologies that utilize reactions of diazonium salts in organic solvents. These reactions made it possible to develop a range of highly efficient synthetic procedures of C—Heteroatom and C—C bond formations [2–5].

At present, green and sustainable chemistry is one of the most rapidly developing areas of research in organic chemistry and technology. The "green" approach implies the improvement of chemical process, which has a positive effect on the environment by reducing or completely eliminating hazardous and toxic chemicals usage [6]. Over the past 15 years, reactions in aqueous media have become the main trend in diazonium chemistry according to one of the most important principles of green chemistry [7–9]. High reactivity of ADS [2,10,11] and the absence of harmful emissions make them valuable within the concept of sustainable and green chemistry.

1. Carbon—heteroatom bond formation via dediazoniation of aromatic diazonium salts in aqueous media

1.1. C—Halogen bond formation

Dediazoniation reactions of ADS forming a C—Hal bond take a special place in diazonium salts chemistry. Since 1858, when diazonium salts were discovered by Peter Griess [1], reactions of halodediazoniation were the most significant and well-studied ADS transformations as well as azo-coupling. Nevertheless, new methods of ADS halogenation that satisfy the principles of sustainable and green chemistry are being actively developed nowadays.

V.D. Filimonov and co-authors have developed a green one-pot synthetic procedures for the preparation of iodoarenes via diazotization–iodination (Scheme 1) [12–14]:

* Corresponding author. Department of Technology of Organic Substances and Polymer Materials, National Research Tomsk Polytechnic University, 634050 Tomsk, Russian Federation. Tel.: +(3822) 563 861; fax: +(3822) 563 637.
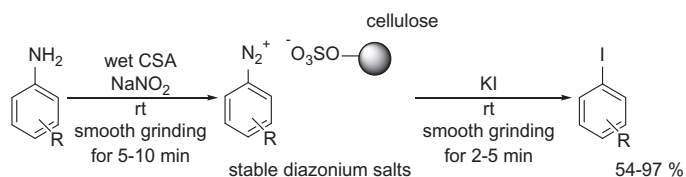E-mail address: postnikov@tpu.ru (P.S. Postnikov).
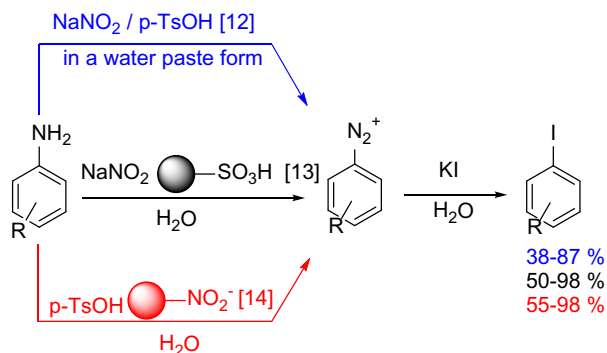
Scheme 1. The green one-pot diazotization–iodination of aromatic amines.
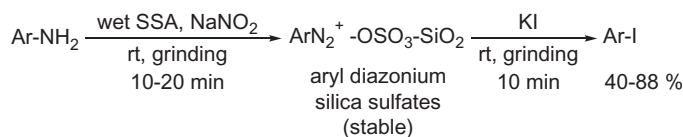
Scheme 2. The one-pot diazotization–iodination of aromatic amines.

Scheme 3. Diazotization–iodination using biodegradable and recyclable sulfonated cellulose.

The authors have developed a range of methods for diazotization of aromatic amines by $NaNO_2$ in the presence of p-TsOH [12] or cationic-exchange resins [13]. Using polymer-supported nitrite in the presence of p-TsOH has also proved effective [14]. Simple addition of KI to the reaction mixture led to the formation of aryl iodides in modest to high yields. These approaches allow avoiding the use of organic solvents and volatile inorganic acids.

Moreover, the ion-exchange resins of both types can be easily recycled. While polymer-supported reagents increase the time of diazotization in comparison to conventional procedures, the simplicity of separation and recycling, as well as absence of acidic waste, turn such methods into prominent examples of green iodoarenes synthesis.

Polymer-immobilized acid was also used by Zarei group [15] under solvent-free conditions. The authors used silica-sulfuric acid (SSA) as a convenient proton source for ADS preparation (Scheme 2). Then the iodoarenes were formed via simple grinding of the obtained ADS and dry KI.

F. Nemati and co-authors developed an environmentally-friendly and convenient approach to the preparation of iodoarenes using biodegradable and recyclable sulfonated cellulose (CSA) as an acid source (Scheme 3) [16].

P. Tundo's group described another methodology for ArI synthesis that follows the principles of green chemistry (Scheme 4) [17]. The possibility of diazotization using CO_2/

H_2O system as acid has been proved by the authors. The CO_2/H_2O system has sufficient acidity for the desired ADS formation but, unfortunately, it does not fully suppress side reactions of triazens formation. Hence, the yields of target ArI were significantly decreased.

It should be noted that the substitution of diazo-group by bromide required an addition of copper catalyst decreasing the synthetic value of this method.

Ki-Whan Chi and his group [18,19] described a new convenient procedure for the preparation of aryl halides via dediazoniation of arenediazonium tosylates and camphor-sulfates under solvent-free conditions (Scheme 5).

It has been shown that the halogen source strongly affects the yields of desired products in the bromination of arenediazonium tosylates [18]. For example, NaBr is less reactive in comparison with Bu_4NBr: the yields of corresponding ArBr are 0–65% and 45–87%, respectively.
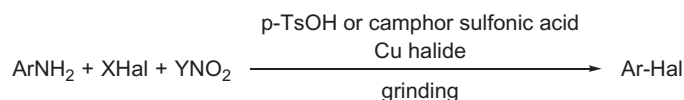
Later, the authors demonstrated that using copper salts as halogen source significantly increases the yields of the target products in reaction with arenediazonium camphor-sulfates [19].

1.2. C—nitrogen bond formation

Organic azides are valuable reagents, which are widely used in biochemistry [20], pharmacology [21] and organic synthesis [22].

While aliphatic azides can be easily obtained via reaction of the azide anion source with electrophiles [23], the synthesis of aromatic azides is a more complicated task. Diazonium salts are the most promising substrates for green synthesis of aryl azides. For example, ADS can be used as a substrate for the preparation of aryl azides in ionic liquids [24,25]. Such methods can be characterized as green, but in our review we will focus on describing a synthetic procedures utilizing water as a solvent.

A vivid example of ADS azidation in aqueous media was described by Filimonov et al. [26]. The authors developed a new
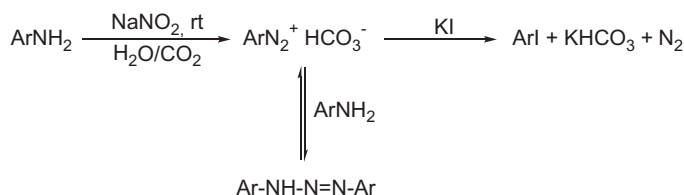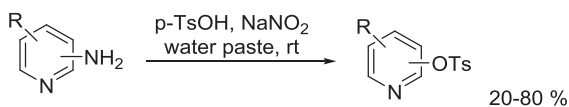

Scheme 4. Proposed pathway for the formation of diazonium salt and its reaction with KI in CO_2/H_2O system.
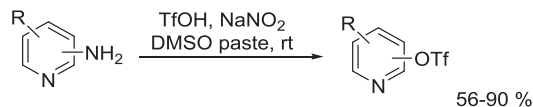

XHal = $Bu_4N^+Br^-$, $BnEt_3N^+Cl^-$
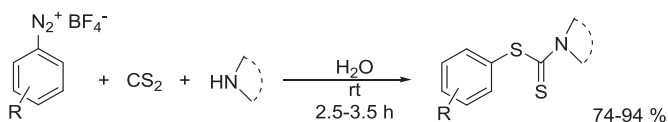YNO_2 = t-BuONO, $NaNO_2$
Cu halide = $CuBr_2$, $CuCl_2$

Scheme 5. The preparation of aryl halides via dediazoniation of arenediazonium tosylates and camphor-sulfates under solvent-free conditions.

$$ArN_2^+ OTs^- \xrightarrow[\substack{H_2O \\ rt}]{NaN_3} ArN_3 \qquad (a)$$

~100 %

$$ArNH_2 \xrightarrow[\substack{H_2O \\ rt}]{\substack{p\text{-}TsOH \\ NaNO_2}} \left[ArN_2^+ OTs^- \right] \xrightarrow[\substack{H_2O \\ rt}]{NaN_3} ArN_3 \qquad (b)$$

80-98 %

Scheme 6. (a) The synthesis of ArN$_3$ using water-soluble arenediazonium tosylates and NaN$_3$. (b) The one-pot synthesis of aromatic azides from anilines.

$$Ar\text{-}NH_2 \xrightarrow[\substack{[P_4\text{-}VP]N_3, \text{ Grinding (30-60 min)}}]{p\text{-}TsOH, NaNO_2, \text{water (0.2 ml)}} Ar\text{-}N_3$$

Scheme 7. One-pot method for diazotization–azidation of aromatic amines using [P$_4$-VP]N$_3$.

Scheme 8. The synthesis of arylazides using sulfonated cellulose as proton source.

effective procedure for the synthesis of ArN$_3$ using water-soluble arenediazonium tosylates and NaN$_3$ as an azide source (Scheme 6a). The one-pot synthesis of aromatic azides from anilines (Scheme 6b) via simple sequence of diazotization–azidation reactions is particularly useful.

The reactions with sodium azide were carried out at room temperature in water solution. The full conversion of starting substrates was achieved within 20–60 minutes. This method is applicable for the preparation of aromatic and some heterocyclic azides.

Immobilized reagents are widely used in azidodediazoniation reactions [13,14] and iododediazoniation

reactions as shown above. The use of such reagents allows to carry out a process in aqueous media or even under solvent-free conditions.

Thus, poly-(4-vinylpyridine)-supported azide [P$_4$-VP]N$_3$ has been used for preparation of aryl azides from anilines via one-pot generation of arenediazonium tosylates under solvent-free conditions (Scheme 7) [27].

F. Nematti and A. Elhampour described a synthetic procedure utilizing sulfonated cellulose as an alternative proton source for diazotization of aromatic amines (Scheme 8) [28].

The authors proved that sulfonated cellulose can be recycled and used at least five times without significant loss of activity. Thus, the yields of desired product decreased approximately by 5% per cycle.

Arenediazonium silica sulfates can be used as conventional diazonium salts in azidodediazoniation reactions with cheap NaN$_3$ as azide source [29]. Complete conversion of starting material was achieved after 10–15 minutes with yields of desired products around 65–90%.

Aromatic azides are widely used as substrates in copper-catalyzed click-reaction with acetylenes. For this reason, a simple method of a one-pot click-reaction utilizing the in situ azidodediazoniation of arenediazonium silica sulfates was described. The reaction was carried out in water with sodium ascorbate at room temperature (Scheme 9) [30]. It was shown that microwave irradiation allows to decrease reaction time with the same yields of desired products (Scheme 9) [31].

The application of *in situ* generated aryl azides in a ternary click-reaction, catalyzed by nanosized copper on activated carbon, was described (Scheme 10) [32]. The ArN$_3$ can be obtained from isolated ADS or from anilines via one-pot diazotization process.

1.3. C—Chalcogens bond formation

Reactions of unstable aromatic diazonium salts in water often lead to phenol formation due to nucleophilic substitution of diazo group [1]. Such examples of dediazoniation followed by C—O bond formation were described long ago, but they do

Scheme 9. One-pot click-reaction utilizing the in situ azidodediazoniation of arenediazonium silica sulfates in water and microwave irradiation.

Scheme 10. *In situ* generated aryl azides in a ternary click-reaction.

Scheme 11. Diazotization of aminopyridines in water paste in presence of p-TsOH with formation of pyridyltosylates.

Scheme 12. Diazotization of aminopyridines in DMSO/H$_2$O paste in presence of TfOH with formation of pyridyl triflates.

Scheme 13. Synthesis of aryl dithiocarbamates in water media.

not have high synthetic applicability. This review describes synthetic procedures for preparation of O-substituted phenol compounds. Ionic liquids [33,34] may be used as media for C—O bond formation but these transformations will not be discussed in the frame of this review.

Synthesis of pyridyl tosylates and triflates under solvent-free conditions was described by E.A. Krasnokutskaya et al. (Schemes 11 and 12) [35,36]. The authors developed a convenient procedure for diazotization of aminopyridines in water paste in presence of p-TsOH (Scheme 11) with formation of pyridyltosylates instead of diazonium salts via spontaneous diazo-group substitution.

The use of this procedure for the synthesis of pyridyl triflates was not successful. The desired pyridyl triflates were formed only with yields below 20%. As expected, hydroxypyridines were the major products of this transformation. The simple replacement of water with DMSO dramatically increased the yields of desired pyridyl triflates up to 90% (Scheme 12).

Sulfur compounds are often used as biologically active substances and for designing composite materials [37]. Therefore, the development of new synthetic procedures for preparation of sulphur-substituted arenes is an important objective.

Ranu and co-authors developed a new procedure for synthesis of aromatic sulfur compounds in water media (Scheme 13) [8]. It was shown that the one-pot condensation of arenediazonium tetrafluoroborates, carbon disulfide and amine in water led to formation of valuable S-aryl dithiocarbamates.

This reaction proceeds smoothly under mild conditions (room temperature, absence of transition metals). The authors carried out a detailed evaluation of the reaction mechanism (Scheme 14). Thus, in the first stage, carbon disulfide reacts with piperidine forming hexahydropyridine-1-dithiocarbamic acid which can be individually purified and characterized. Further S$_N$Ar reaction between the acid and diazonium salt leads to final product.

F. Nemati group used a similar procedure for arenediazonium sulfates immobilized on magnetic nanoparticles as substrates (ArN$_2^+$ $^-$O$_3$S-SiO$_2$@Fe$_3$O$_4$) [38].

Recently, ADS was applied in preparation of the chalcogen derivatives containing C—S, C—Te, C—Se bonds (Scheme 15) [39]. The reactions were carried out in a ball mill under solvent-free conditions with neutral alumina Al$_2$O$_3$ and KOH. The authors proved that the method is applicable for a wide range of aryl chalcogenides syntheses.

### 1.4. Arenediazonium salts as substrates in green methods of C—C bond formation

Since 1977, when Matsuda group discovered a new method of Pd-catalyzed olefin arylation, applicability of diazonium salts has significantly expanded [40]. Their "superelectrophilic" properties allowed to develop new mild methods of Heck [10], Suzuki [41], Stille [42–44] and Hiyama coupling reactions [45]. Diazonium salts are the most promising reagents for these reactions in comparison to halides, triflates and tosylates. For this reason, the amount of synthetic methods utilizing ADS as substrates for C—C bond formation has dramatically increased. Recently, the development of new green methods of Pd-catalyzed C—C coupling became a new trend in diazonium chemistry.
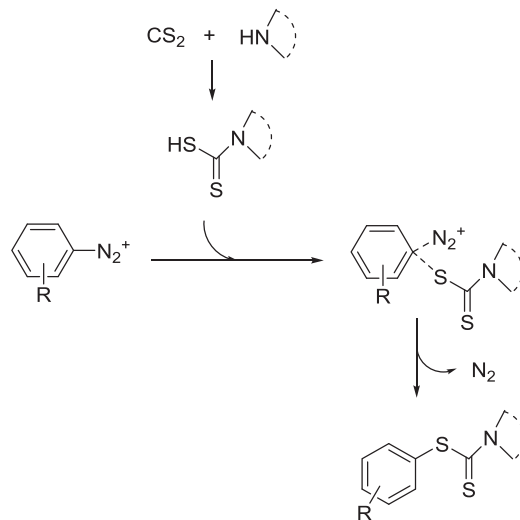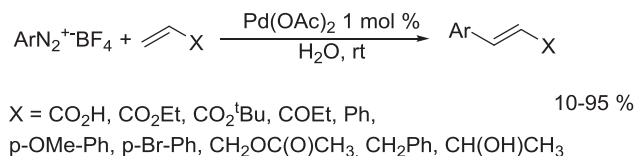

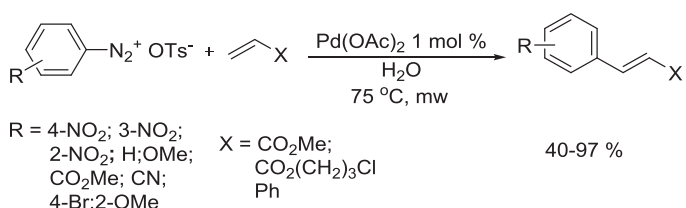Scheme 14. The mechanism of the formation of S-aryl dithiocarbamates.
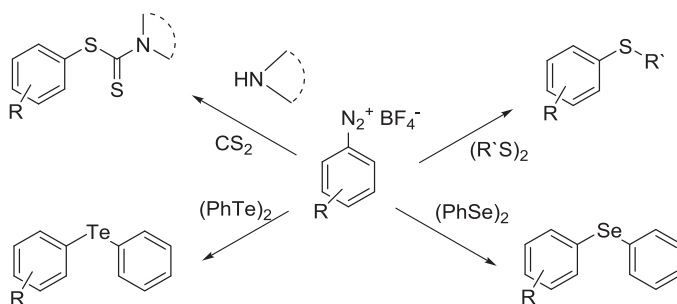
Scheme 15. Synthesis of arylchalcogenides via arenediazonium tetrafluoroborates.

$ArN_2^{+-}OSO_3\text{-}SiO_2$ + alkene-X → Ar-CH=CH-X

Pd(OAc)₂ 4 mol %, H₂O, rt

X = CO₂Me, Ph, CO₂H   80-89 %
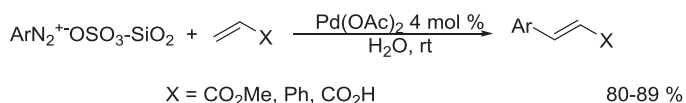
Scheme 16. Heck–Matsuda reactions with arenediazonium silica sulfates in water in the presence of Pd(OAc)₂.

$ArN_2^{+-}BF_4$ + alkene-X → Ar-CH=CH-X

Pd(OAc)₂ 1 mol %, H₂O, rt

X = CO₂H, CO₂Et, CO₂ᵗBu, COEt, Ph,   10-95 %
p-OMe-Ph, p-Br-Ph, CH₂OC(O)CH₃, CH₂Ph, CH(OH)CH₃

Scheme 17. Heck–Matsuda reaction of arenediazonium salts in water in the presence of 1 mol % Pd(OAc)₂.

R-Ar-N₂⁺ OTs⁻ + alkene-X → R-Ar-CH=CH-X

Pd(OAc)₂ 1 mol %, H₂O, 75 °C, mw

R = 4-NO₂; 3-NO₂;   X = CO₂Me;   40-97 %
2-NO₂; H;OMe;   CO₂(CH₂)₃Cl
CO₂Me; CN;   Ph
4-Br;2-OMe

Scheme 18. Heck–Matsuda reaction of arenediazonium tosylates in water under microwave irradiation.

The first synthetic method of C—C coupling reactions with ADS in neat water was described in 2011 by Zarei group. The authors demonstrated that arenediazonium silica sulfates have a high reactivity in olefin arylation in the presence of Pd(OAc)₂ (Scheme 16) [46]. The derivatives of methyl cinnamate, stilbene and cinnamic acid were obtained with high yields.

Later Valriberra group managed to decrease Pd(OAc)₂ loading to 1 mol% in the reaction of olefines with arenediazonium tetrafluoroborates as electrophilic reagents (Scheme 17) [47].

It should be noted that only ethyl acrylate and ethyl vinyl ketone demonstrate high reactivity under these conditions. Arylation of other alkenes (acrylic acid and *tert*-butyl acrylate, styrene and its derivatives, allyl acetate, allylbenzene, 3-butene-2-ol) was not as successful. The desired products were formed with low to moderate yields. It is noteworthy that the authors used only arenediazonium tetrafluoroborates with electron-donating substituents, except 4-bromobenzenediazonium tetrafluoroborate.

V.D. Filimonov and his research group demonstrated the possibility of alkene arylation by arenediazonium tosylates in neat water (Scheme 18) [48]. The reaction proceeds smoothly in the presence of 1 mol%. Pd(OAc)₂ under microwave irradiation.

The authors mentioned that high reactivity of arenediazonium tosylates in this method is associated with its good solubility in aqueous media.

The immobilized Pd catalysts are widely used in C—C coupling reactions with diazonium salts due to the possibility of their recyclization [49]. For example, the *in situ* formed palla-

dium nanoparticles were used as a catalyst for arylation of alkenes by arenediazonium tetrafluoroborates (Scheme 19) [50].
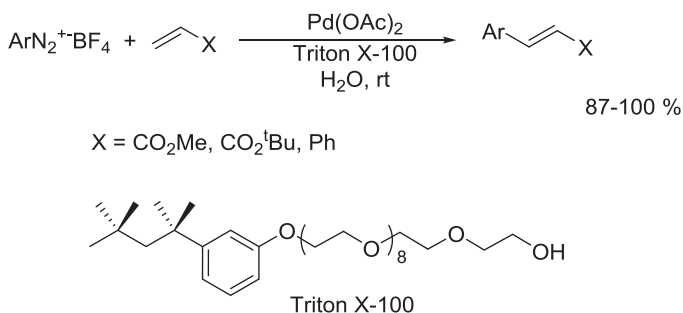
The Gholinejad's group utilized the palladium nanoparticles on agarose for Matsuda–Heck and Suzuki–Miyaura reactions [51]. Ethyl cinnamates and stilbenes were prepared with high yields in presence of only 0.0026 mol % Pd-catalyst (Scheme 20).

It was shown that the nature of solvents influenced the yields of desired products. The higher yields of arylated alkenes were achieved using neat water as solvent in contrast to organic solvents or methanol–water mixture. On the contrary, the use of methanol–water mixture instead of neat water allowed to sufficiently increase the yields of target biphenyls in Suzuki–Miyaura reaction.
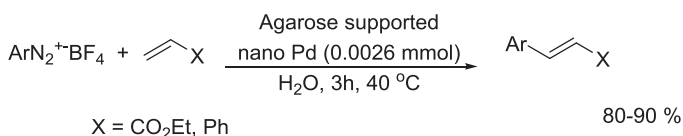
A method for biphenyl preparation using arenediazonium tetrafluoroborates and potassium aryl trifluoroborates in water was described by S. Cacchi et al. (Scheme 21) [9].

The Pd-nanoparticles immobilized on a polysaccharide matrix were utilized as the water-dispersible catalytic system. The authors noticed that the proposed catalyst had high activity and recyclability at least 8 times without sufficient deactivation. The described procedure allows to prepare a wide range of mono- and di-substituted biphenyls with high yields.
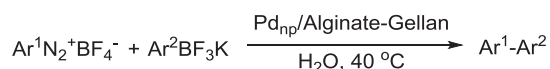
Zinc-ferrite nanoparticles coated by palladium (Pd-ZnFe₂O₄) were used as a catalyst in C—C and C—O coupling by the A.S. Singh's group [52]. The authors proved that such type of nano-sized catalyst had high activity in Sonogashira and Suzuki coupling as well as C—O coupling of aryl halides. The particularly important application of this catalytic system is in

$ArN_2^{+-}BF_4$ + alkene-X → Ar-CH=CH-X

Pd(OAc)₂, Triton X-100, H₂O, rt   87-100 %

X = CO₂Me, CO₂ᵗBu, Ph

Triton X-100

Scheme 19. The *in situ* formed palladium nanoparticles as a catalyst for Heck–Matsuda reaction.

$ArN_2^{+-}BF_4$ + alkene-X → Ar-CH=CH-X

Agarose supported nano Pd (0.0026 mmol), H₂O, 3h, 40 °C

X = CO₂Et, Ph   80-90 %

Scheme 20. The Pd-economy Heck–Matsuda reaction in neat water.

$Ar^1N_2^+BF_4^-$ + Ar^2BF_3K → Ar^1-Ar^2

Pd$_{np}$/Alginate-Gellan, H₂O, 40 °C

Scheme 21. The preparation of biphenyls in the presence of Pd-nanoparticles immobilized on a polysaccharide matrix in water.
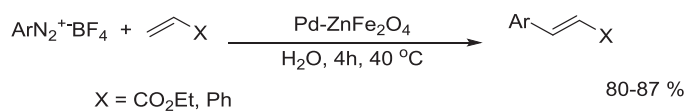
Scheme 22. Heck–Matsuda reaction in the presence of the superparamagnetic Pd-catalyst in water.
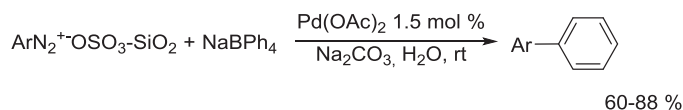
Scheme 23. Suzuki–Miyaura reaction of arenediazonium silica sulfates in presence of 1.5 mol % Pd(OAc)$_2$ in water.
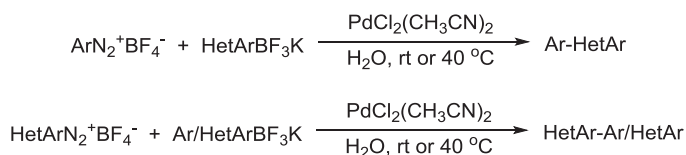
Scheme 24. The reaction between potassium trifluoroborates and ASD in aqueous media with PdCl$_2$(CH$_3$CN)$_2$ as catalyst.

Heck–Matsuda reactions between arenediazonium tetrafluoroborates and olefins (ethyl acrylate, styrene).

It should be noted that only reactions with diazonium salts were successfully carried out in neat water (Scheme 22). Superparamagnetic nanoparticles simplified isolation and purification of desired products due to enhanced magnetic properties. The authors proved that activity of catalyst did not decrease for at least 3 cycles of recyclization.

The reactivity of arenediazonium silica sulfates in Suzuki–Miyaura reaction was evaluated by A. Zarei [53]. The authors prepared a range of mono-substituted biphenyls via interaction of sodium tetraphenylborate and corresponding ADS in presence of 1.5 mol % Pd(OAc)$_2$ (Scheme 23).

The described method cannot be applied to preparation of biphenyls containing strong electron-donating groups (4-OMe, 2-OMe). Satisfactory yields were achieved only in microwave reactor at 60 °C. A significant disadvantage of described procedure of Suzuki–Miyaura coupling is low atomic efficiency due to usage of NaBPh$_4$ as reagent.
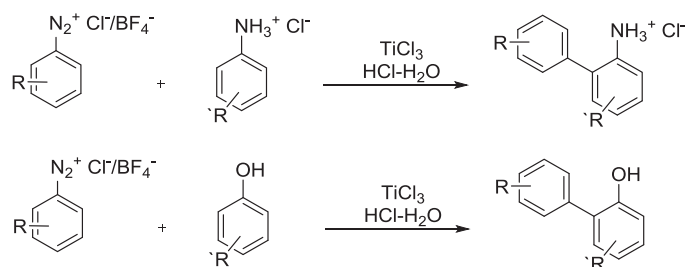
Scheme 25. Homberg–Bachmann reaction in neat water using arenediazonium chlorides generated in situ.

Roglans' group described a synthesis of bis-heteroarenes and arylated heterocycles via Suzuki–Miyaura reaction. The reaction between potassium trifluoroborates and diazonium tetrafluoroborates proceed in aqueous media with PdCl$_2$(CH$_3$CN)$_2$ as catalyst (Scheme 24) [54].

Such procedure is applicable to the synthesis of various arylated thiophene, benzothiophene and benzofuran derivatives in moderate to high yields. It should be noted that full conversion of starting materials is in need of a relatively high Pd-catalyst loading (5–10 mol %).

In 2008 Heinrich group proposed a new method for Homberg–Bachmann reaction in neat water using arenediazonium chlorides generated in situ (Scheme 25) [55]. The reaction can be used for coupling of anilines and hydroquinones soluble in HCl. TiCl$_3$ was used as an initiator of radical reaction that produced target biphenyls in moderate yields.

The authors proved that electron-rich anilines had a greater activity than electron-deficient anilines, which allowed them to make a conclusion about S$_{RN}$1 reaction mechanism.

Felpin group has recently modified a classic method for Meerwein reaction [56].

The authors demonstrated that diazonium methanesulfonates have a high reactivity in benzoquinone arylation in neat water without any organic co-solvents (Scheme 26). The aryl benzoquinones were prepared in moderate to high yields. This synthetic procedure is one of the most prominent examples of C—C coupling reactions in green chemistry. The advantages of described method include the absence of Pd-catalyst, the relatively low loading of acid and the recyclability of CuO catalyst.
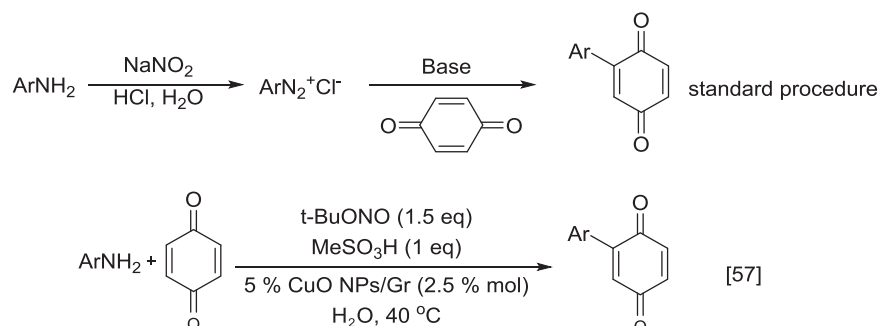
Scheme 26. New method for Meerwein arylation in neat water.

Summary

In this review we described and discussed modern synthetic methods of new carbon—heteroatom and carbon—carbon bonds formation using aromatic diazonium salts in aqueous media. In general, the use of diazonium chemistry in water is an important trend of contemporary organic synthesis. Nowadays, diazonium salts are widely used as one of the most promising substrates in green organic synthesis.

Acknowledgments

References

[1] H. Zollinger, Diazo Chemistry, Weinheim, New York, Basel, Cambridge, Tokyo, 1994.
[2] F. Mo, G. Dong, Y. Zhang, J. Wang, Org. Biomol. Chem. 11 (2013) 1582.
[3] H.H. Hodgson, Chem. Rev. 40 (1947) 251.
[4] A. Roglans, A. Pla-Quintana, M. Moreno-Mañas, Chem. Rev. 11 (2006) 4622.
[5] Y. He, H. Wu, F.D. Toste, Chem. Sci. 6 (2015) 1194.
[6] P.T. Anastas, J.C. Warner, Green Chemistry: Theory and Practice, Oxford University Press, New York, 1998.
[7] B. Basu, K. Biswas, S. Kundu, S. Ghosh, Green Chem. 12 (2010) 1734.
[8] T. Chatterjee, S. Bhadra, B.C. Ranu, Green Chem. 13 (2011) 1837.
[9] S. Cacchi, E. Caponetti, M.A. Casadei, A. Di Giulio, G. Fabrizi, G. Forte, et al., Green Chem. 14 (2012) 317.
[10] J.G. Taylor, A.V. Moro, C.R.D. Correia, Eur. J. Org. Chem. 8 (2011) 1403.
[11] A. Honraedt, F. Le Callonnec, E. Le Grognec, V. Fernandez, F.-X. Felpin, J. Org. Chem. 78 (2013) 4604.
[12] D.A. Gorlushko, V.D. Filimonov, E.A. Krasnokutskaya, N.I. Semenischeva, B.S. Go, H.Y. Hwang, et al., Tetrahedron Lett. 49 (2008) 1080.
[13] V.D. Filimonov, N.I. Semenischeva, E.A. Krasnokutskaya, A.N. Tretyakov, Y.H. Ho, K.W. Chi, Synthesis 185 (2008).
[14] M.E. Trusova, E.A. Krasnokutskaya, P.S. Postnikov, Y. Choi, K.W. Chi, V.D. Filimonov, Synthesis 2154 (2011).
[15] A. Zarei, A.R. Hajipour, L. Khazdoozd, Synthesis 941 (2009).
[16] F. Nemati, A. Elhampour, Sci. Iran. 19 (2012) 1594.
[17] P. Tundo, A. Loris, M. Selva, Green Chem. 9 (2007) 777.
[18] M.E. Moon, Y. Choi, Y.M. Lee, V. Vajpayee, M. Trusova, V.D. Filimonov, et al., Tetrahedron Lett. 51 (2010) 6769.
[19] V. Vajpayee, M.E. Moon, S. Lee, S. Ravikumar, H. Kim, B. Ahn, et al., Tetrahedron 69 (2013) 3511.
[20] M.D. Best, Biochemistry 48 (2009) 6571.
[21] C. Piantadosi Jr., C.J. Marasco, S.L. Morris-Natschke, K.L. Meyer, F. Gumus, J.R. Surles, et al., J. Med. Chem. 34 (1991) 1408.
[22] S. Brase, C. Gil, K. Knepper, V. Zimmermann, Angew. Chem. Int. Ed. 44 (2005) 5188.
[23] B.E. Blass, K.R. Coburn, A.L. Faulkner, W.L. Seibela, A. Srivastava, Tetrahedron Lett. 44 (2003) 2153.
[24] A. Hubbard, T. Okazaki, K.K. Laali, J. Org. Chem. 73 (2008) 316.
[25] A.R. Hajipour, F. Mohammadsaleh, Org. Prep. Proced. Int. 43 (2011) 451.
[26] K.V. Kutonova, M.E. Trusova, P. Postnikov, V.D. Filimonov, J. Parello, Synth 45 (2013) 2706.
[27] M.A.K. Zarchi, R. Nabaei, J. Appl. Polym. Sci. 124 (2012) 2362.
[28] F. Nemati, A. Elhampour, J. Chem. Sci. 124 (2012) 889.
[29] A. Zarei, A.R. Hajipour, L. Khazdooz, H. Aghaei, Tetrahedron Lett. 50 (2009) 4443.
[30] A. Zarei, Tetrahedron Lett. 53 (2012) 5176.
[31] A. Zarei, L. Khazdooz, A.R. Hajipour, H. Aghaei, G. Azizi, Synth 44 (2012) 3353.
[32] F. Alonso, Y. Moglie, G. Radivoy, M. Yus, Org. Biomol. Chem. 9 (2011) 6385.
[33] K.K. Laali, V.J. Gettwert, J. Fluor. Chem. 107 (2001) 31.
[34] K.K. Laali, T. Okazaki, S.D. Bunge, J. Org. Chem. 72 (2007) 6758.
[35] A.N. Tretyakov, E.A. Krasnokutskaya, D.A. Gorlushko, V.D. Ogorodnikov, V.D. Filimonov, Tetrahedron Lett. 52 (2011) 85.
[36] E.A. Krasnokutskaya, A.Z. Kassanova, M.T. Estaeva, V.D. Filimonov, Tetrahedron Lett. 55 (2014) 3771.
[37] T. Kondo, T. Mitsudo, Chem. Rev. 100 (2000) 3205.
[38] F. Nemati, A. Elhampour, S. Zulfaghari, Phosphorus Sulfur Silicon Relat. Elem. 10 (2015) 1692.
[39] N. Mukherjee, T. Chatterjee, B.C. Ranu, J. Org. Chem. 78 (2013) 11110.
[40] K. Kikukawa, T. Matsuda, Chem. Lett. 2 (1977) 159.
[41] H. Bonin, E. Fouquet, F.X. Felpin, Adv. Synth. Catal. 353 (2011) 3063.
[42] K. Kikukawa, K. Kono, F. Wada, T. Matsuda, J. Org. Chem. 48 (1983) 1333.
[43] N.A. Bumagin, L.I. Sukhomlinova, T.P. Tolstaya, I.P. Beletskaya, Russ. J. Org. Chem. 30 (1994) 1605.
[44] S. Dughera, Synthesis 7 (2006) 1117.
[45] K. Ikenaga, K. Kikukawa, T. Matsuda, J. Chem. Soc., Perkin Trans. 1 (1986) 1959.
[46] A. Zarei, L. Khazdooz, A. Pirisedigh, A.R. Hajipour, H. Seyedjamali, H. Aghaei, Tetrahedron Lett. 52 (2011) 4554.
[47] J. Salabert, R.M. Sebastiớn, A. Vallribera, J.F. Civicos, C. Najera, Tetrahedron 69 (2013) 2655.
[48] K.V. Kutonova, M.E. Trusova, A.V. Stankevich, P.S. Postnikov, V.D. Filimonov, Beilstein J. Org. Chem. 11 (2015) 358.
[49] A. Molnar, Chem. Rev. 111 (2011) 2251.
[50] D.S. Gaikwad, D.M. Pore, Synlett 23 (2012) 2631.
[51] M. Gholinejad, Appl. Organomet. Chem. 27 (2013) 19.
[52] A.S. Singh, S.S. Shendage, J.M. Nagarkar, Tetrahedron Lett. 54 (2013) 6319.
[53] A. Zarei, L. Khazdooz, A.R. Hajipour, F. Rafiee, G. Azizi, F. Abrishami, Tetrahedron Lett. 53 (2012) 406.
[54] O. El Bakouri, M. Fernớndez, S. Brun, A. Pla-Quintana, A. Roglans, Tetrahedron 69 (2013) 9761.
[55] A. Wetzel, V. Ehrhardt, M.R. Heinrich, Angew. Chemie – Int. Ed. 47 (2008) 9130.
[56] A. Honraedt, F. Le Callonnec, E. Le Grognec, V. Fernandez, F.X. Felpin, J. Org. Chem. 78 (2013) 4604.