3. Introduction:

In the modern premises of exploration of science, the nitrogen containing organic compounds find special interest in the field of synthetic organic chemistry, owing to their exciting and diverse biological activities. These compounds have widespread applications [1] in pharmaceuticals, organic materials, natural products and catalysis (**Fig. 1**).

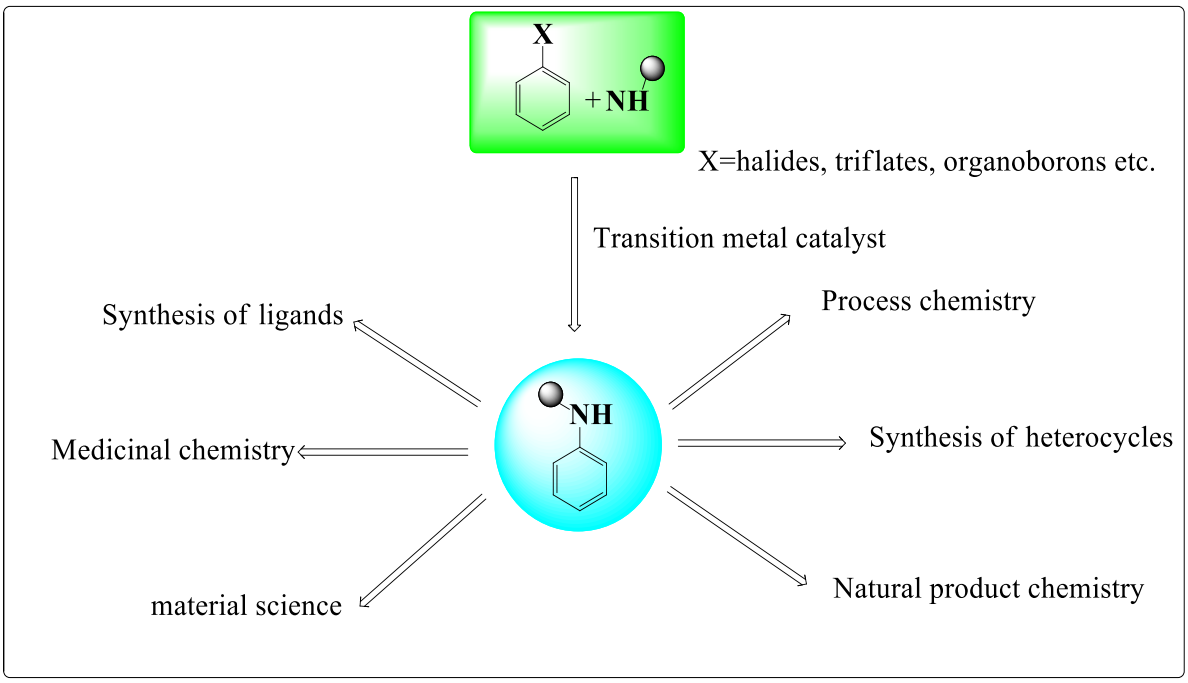


Fig. 1: Fields of applications of C-N bond formation reaction

Despite of numerous significant developments, the exercise for the construction of C-N bond still remains a challenging area. It is mainly due to the involvement of harsh reaction conditions in addition to unfavorable and expensive catalysts in most of the cases. **Fig. 2** shows some important compounds via C-N bond formation reaction.

Here, in the present thesis, we present two major C-N bond formation reactions, *viz. N*-arylation and nitration of aromatic compounds.

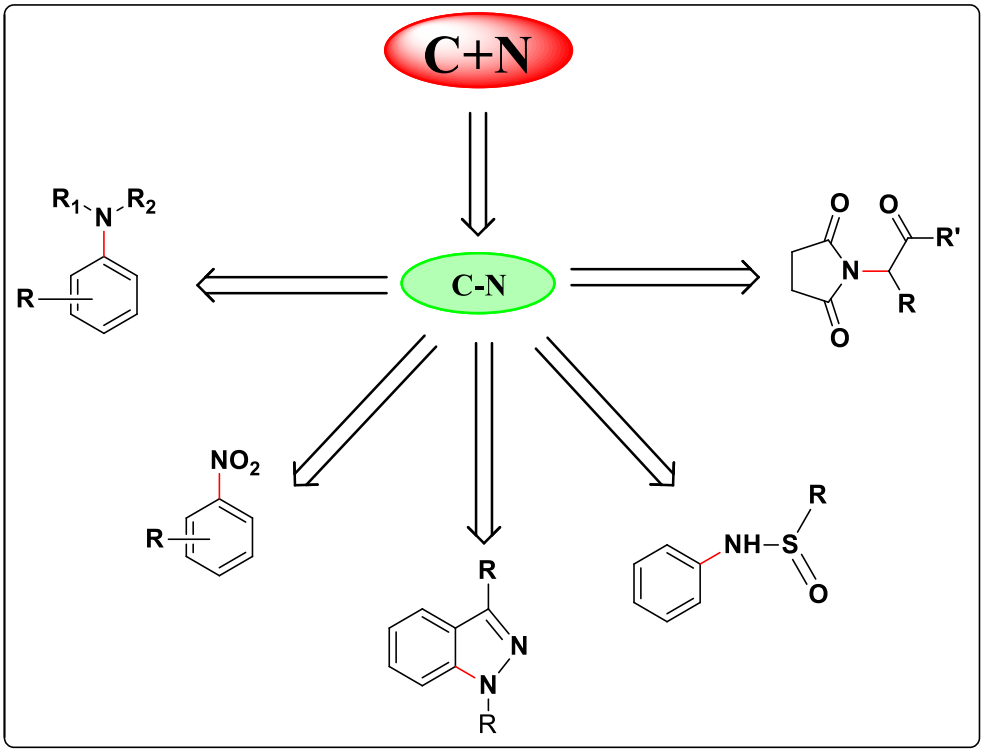


Fig. 2: C-N bond containing some organic compounds

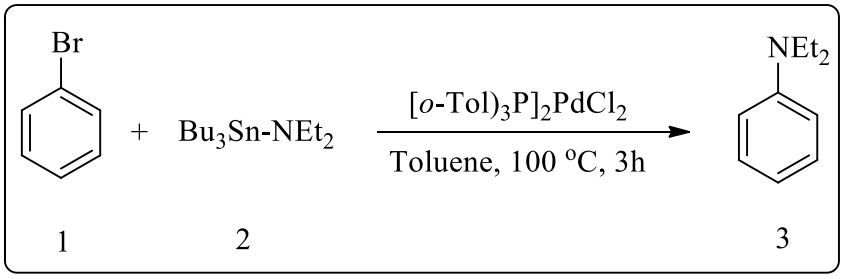
_N_-arylation of amines and _N_-heterocycles:

A metal catalyzed reaction between aryl halide and nitrogen nucleophile leading to a newly formed carbon-nitrogen linkage is often expressed as *N*-arylation reaction. The classical *N*-arylation reactions were performed with Pd and Cu catalyst.

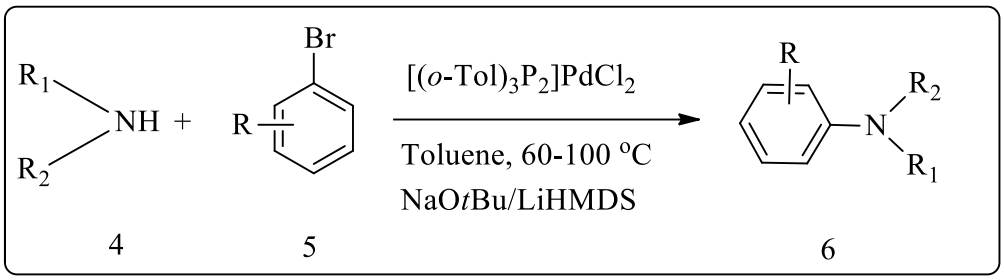
Pd catalyzed _N_-arylation:

Migita and Kosugi [2] first reported the palladium catalyzed C(Sp^2)-N bond formation process in 1983 (**Scheme 1**) using bromo benzene (**1**) and tin amide (**2**) to form *N*,*N*'-diethyl aniline (**3**). But, its practical applicability was found less owing to the use of stoichiometric quantity of a moisture sensitive and toxic tin reagent.

In the mid 1990s, Buchwald and Hartwig [3] reported an efficient *N*-arylation of secondary amine (**4**) by aryl bromide (**5**) catalyzed by Pd complex in the presence of a base like NaO*t*Bu or LiHMDS providing tertiary aryl amine (**6**) with excellent yields (**Scheme 2**), where these limitations were trounced.



Scheme 1: First Pd catalyzed *N*-arylation reaction



Scheme 2: Buchwald-Hartwig amination

Buchwald and Hartwig proposed a mechanism for the reaction (**Fig. 3**); the first step involves oxidative addition of aryl halide to palladium species forming an intermediate **A**. Consequently, the amine attacks on the intermediate A and generates another intermediate **B** which undergoes deprotonation and reductive elimination to afford the desired coupling product and renders regeneration of the catalyst. Post modification of this protocol disclose that the coupling protocol undergo transformation with numerous *N*-nucleophiles like amides [4], amine [5], nitrogen containing heterocycles [2, 6] etc.

Subsequently, different ligand assisted protocols were developed for the same titled reaction to improve the efficiency.

In 2000, Buchwald and Wolf [7] reported BINAP promoted *N*-arylation of amine (**Scheme 3**) with different substituted aryl, alkyl bromides in presence of $Pd(OAc)_2$.

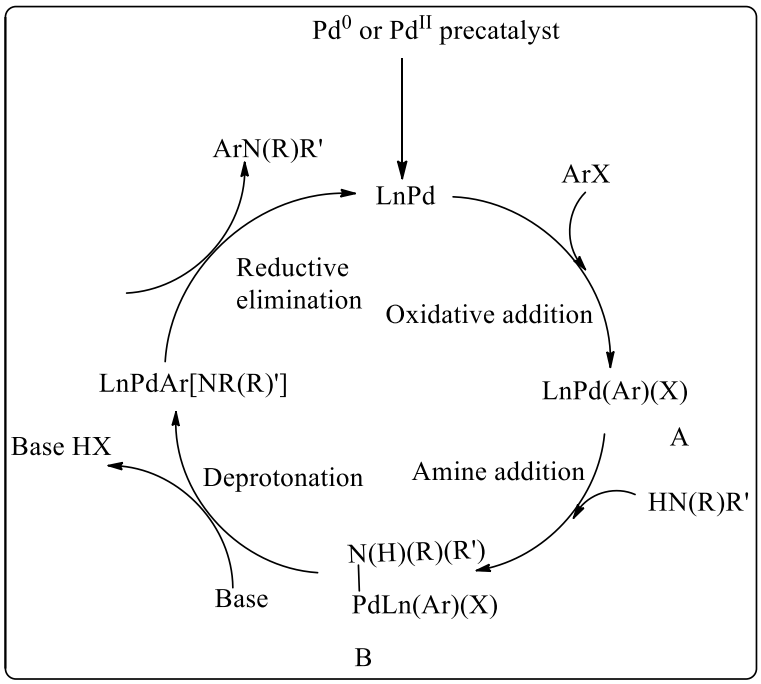
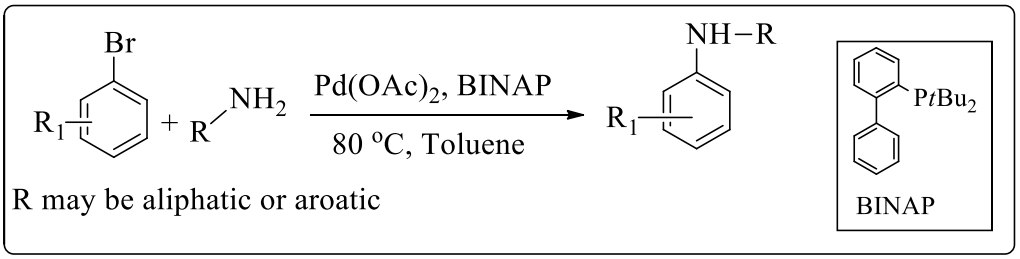


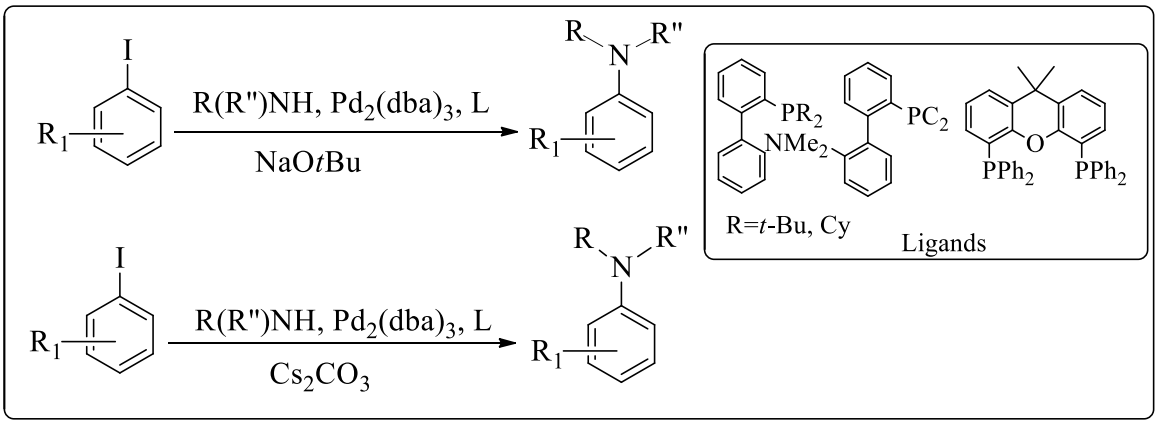
Fig. 3: Proposed mechanism for Buchwald-Hartwig amination



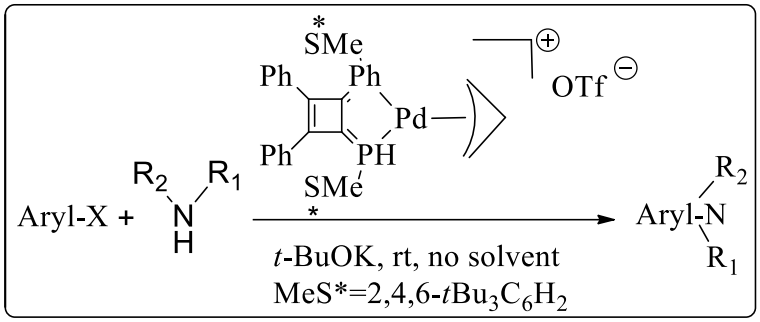
Scheme 3: BINAP enhanced *N*-arylation

A catalytic system comprising of monophosphinobiphenyl ligands [8] and $Pd(OAc)_2$, was successfully employed towards *N*-arylation of amines with aryl iodides, was reported by Ali and Buchwald in 2001(**Scheme 4**).

Gajare [9] *et al*. (2004) and Tewari [10] *et al*. (2005) developed diphosphinidenecyclobutene and phosphonium salts of alkyl-di-(1-adamantyl)phosphines respectively as ligands for efficient Pd catalyzed *N*-arylation of amines (**Schemes 5 and 6**).

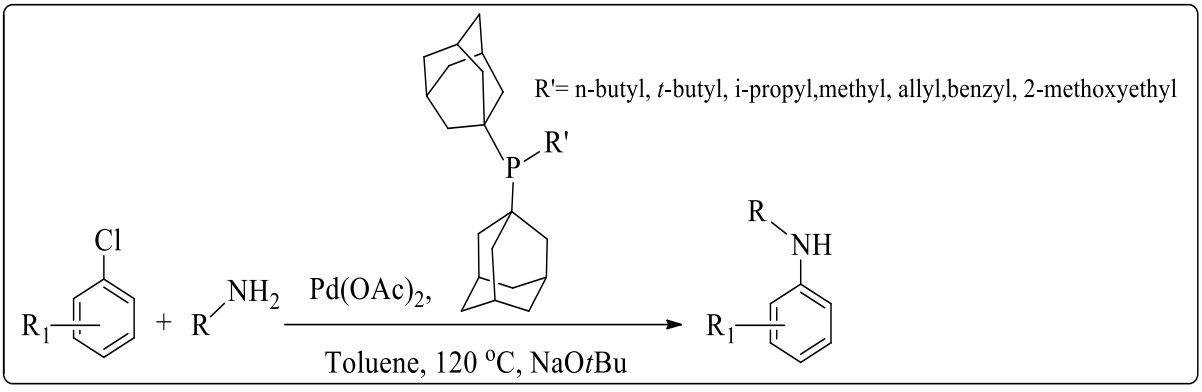


Scheme 4: Buchwald and Ali's method



Scheme 5: Gajare's method

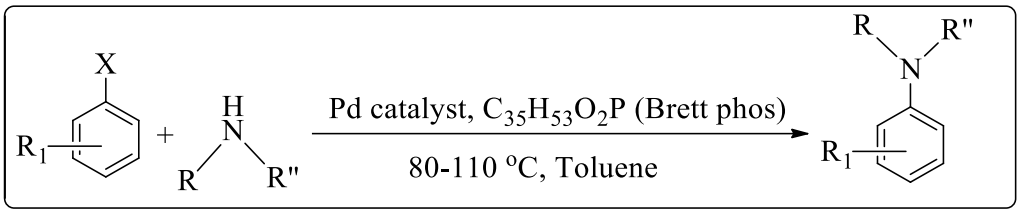
Hill [11] *et al.* demonstrated that di(*tert*-butyl) neopentylphosphine (DTBNpP) sources provided better activity for amination of aryl bromides than tri(*tert*-butyl)phosphine (TTBP) in combination with Pd under mild conditions.



Scheme 6: Tewari's *N*-arylation protocol

Reddy [12] *et al*. established a Pd catalyzed amination of aryl halides via (*t*-Bu)$_2$PNP(*i*BuNCH$_2$CH$_2$)$_3$N as ligand source.

In 2008, the cross-coupling of primary nitrogen nucleophiles and aryl halide [13] was carried out using the Pd complex, (CyPF*t*Bu)PdCl$_2$, which was recognized as highly efficient catalyst with low catalyst loading. The catalytic activity of Pd(II) complexes carrying saturated NHC-*N*,*N*'-dimethyl biphenylamine (DMBPA) palladacycle [14] complexes was evaluated for *N*-arylation reaction. The biphenyl ligand used in the palladacycles synthesis was produced using Suzuki-Miyaura cross-coupling reaction. Fors *et al.* illustrated the amination reactions of aryl iodides via Pd catalyst system involved with Brett Phos ligand [15] (**Scheme 7**).



Scheme 7: Brett phos in *N*-arylation reaction

The overall efficiency in the coupling reaction was improved assuming that the use of ligand could slow down the formation of the bridging dimmers. The Pd catalyzed Buchwald-Hartwig amination reaction was also investigated [16] using biarylphosphine ligand Me$_3$(OMe)*t*BuXPhos. The ligand was prepared from inexpensive and readily available 2,3,6-trimethylphenol.

Cu catalysis in *N*-arylation reaction:

The first *N*-arylation reaction was reported more than 100 years ago by using Cu catalyst; however the beauty of the reaction was recognized in the later part of the 20th century. Several experiments were done for proper choice of effective Cu source and it was revealed that almost all Cu sources could be used for the reaction but, higher activity was found with Cu(I) salts. After several mechanistic investigations to identify the proper oxidation state of the active Cu species it was proposed that the actual catalytic species in the reaction is Cu(I) species. Whenever Cu(II) source were employed, cupric ion was reduced, attributing the catalytic activity to Cu(I) species. At the same time,

different *N*- and *O*- donor bidented ligands were designed (**Fig. 4**) for perfect amination of aryl halides. In 2001, Buchwald [17] and his co-worker designed diamines (L1-L5) as ligands for the *N*-arylation which were compatible with a number of functional groups like aryl chloride, secondary amine, indoles etc.

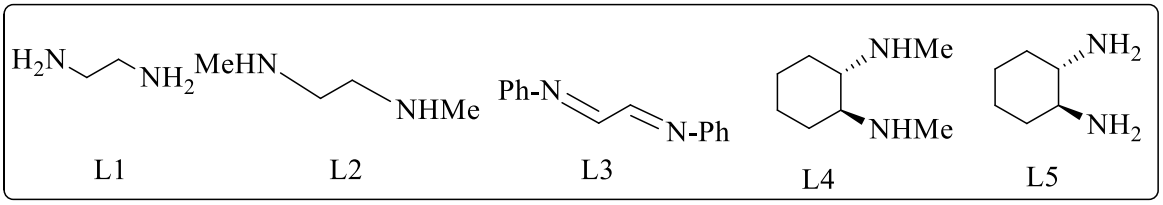


Fig. 4: *N*-containing ligands in Cu catalyzed *N*-arylation reaction

Similarly, Goodbrand explicated 1,10-phenanthroline [18] (L6) as efficient ligand system for Cu catalyzed amination of aryl halides. Later on, it was proved by Buchwald and Altmann [19] that substituted phenanthroline (4,7-dimethoxyphenanthroline, L7) was more effective for the *N*-arylation of *N*-heterocycles like imidazoles. In the last few decades, various *N*-donor ligands were found to be effective for the *N*-aryation reaction, *viz.* 4,7-dichlorophenanthroline [20] (L8), 2-aminopyrimidine-4,6-diol [21] (L9), azajulodine [22] (L10), 3,4,7,8–tetramethyl-1,10-phenanthroline [23] (L11), bis-iminopyridin [24] (L12), bis-pyridineimine [25] (L13), 2-amino-4,6-dimethoxypyridine [26] (L14) etc. All the stated examples are shown in the **Fig. 5**.

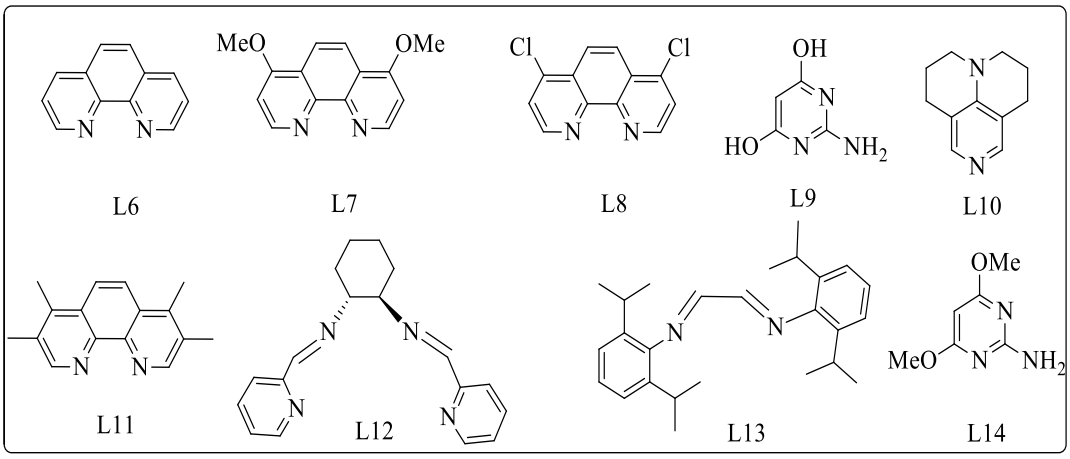


Fig. 5: *N*-containing ligands in Cu catalyzed *N*-arylation reaction

In addition, *O*,*O*-bidented ligands like *β*-keto ester [27] (L15), ethanediol [28] (L16), diketones [29] (L17-L18), diethylsalicylamide [30] (L19), binol [31] (L20), 1,1,1 –tris(hydroxymethyl)ethane [32] (L21) were also found to deliver satisfying results for the amination of aryl halide. The exampled ligands are exposed in **Fig. 6**.

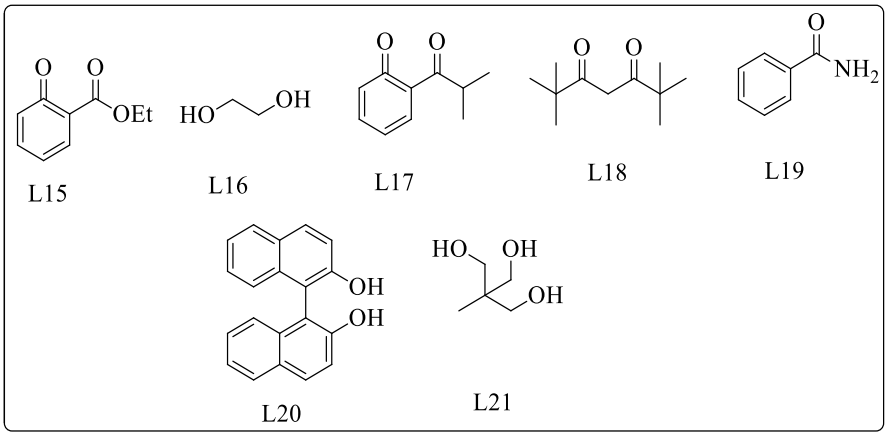


Fig. 6: *O*-donor ligands for *N*-arylation.

An array of both *N*- and *O*- donor ligands were also successfully employed such as amino acid derivatives [33] (L22-L26), aminophosphonate [34] (L27-L28), oxime hydroxide [35] (L29-L30), oximephosphine oxides [36] (L31) aminoalcohols [37] (L32), 8-hydroxyquinoline [38] (L33) etc as shown in **Fig. 7**.

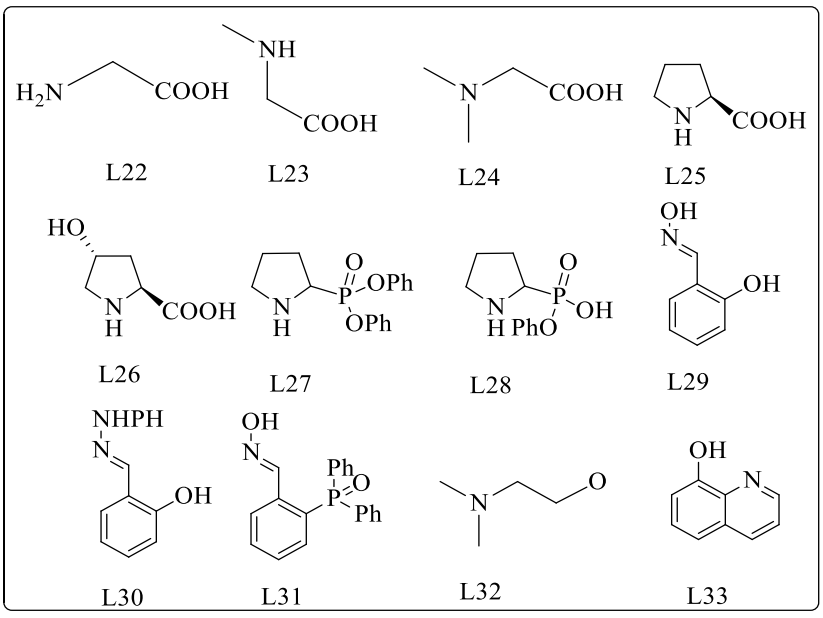
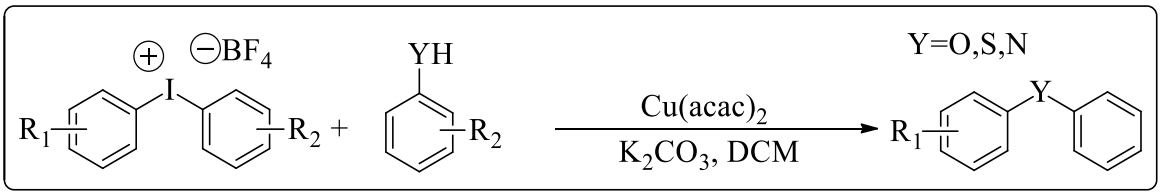


Fig. 7: Both *O*- and *N*-donor ligands for *N*-arylation

Apart from ligand diversity, substrates variations were also investigated for the *N*-arylation of amines. Further, the scope of the protocol was explored introducing new organometallic species as coupling partner. Beringer and Kang successfully applied aryl iodonium salt [39] as productive coupling partner for the *N*-, *S*- and *O*-arylation (**Scheme 8**).



Scheme 8: Aryl iodonium salt as a coupling partner

Other organometallic coupling partners like aryl bismuth [40], aryl lead [41], aryl siloxane [42], aryl stannane [43] etc. were also tested for the mentioned reaction. But, most of the protocols were ligand associated and found to be expensive which on scale up invited the problem of waste disposal (**Fig. 8**).

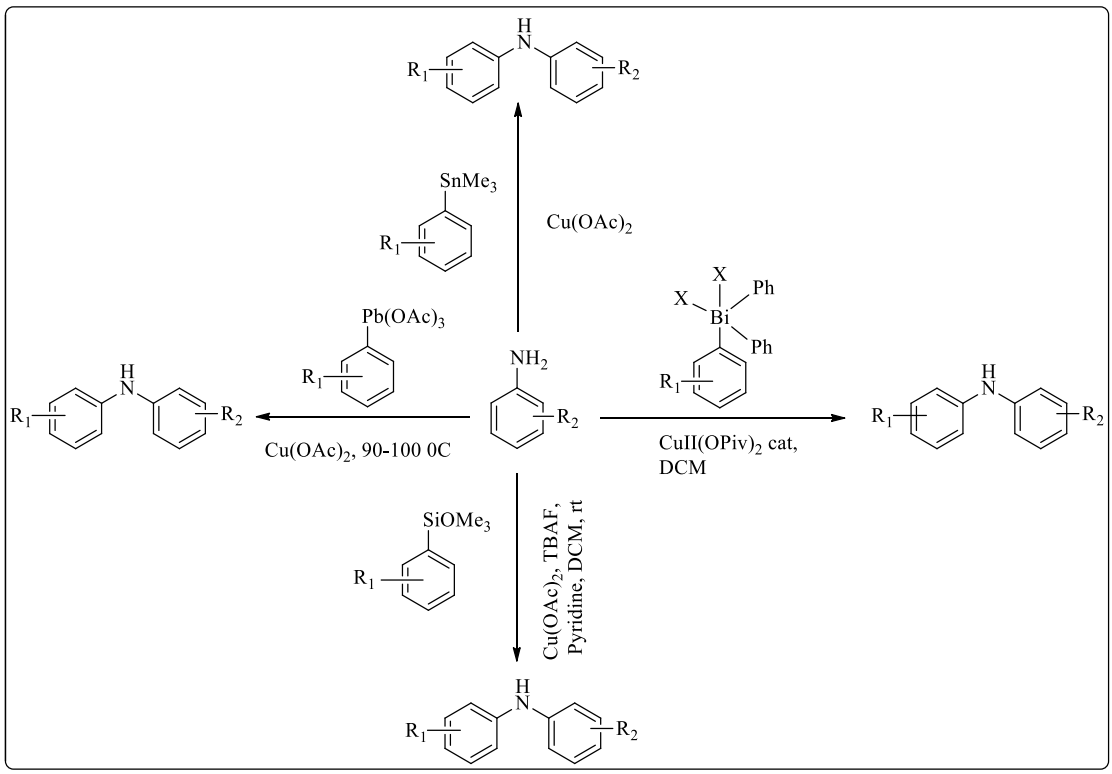
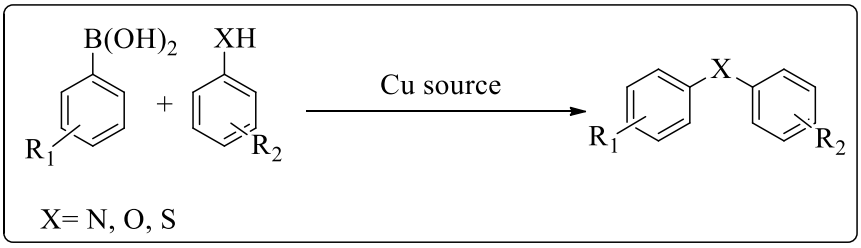


Fig. 8: Different organometallic coupling partners for *N*-arylation

In addition, use of high temperature is a basic need for the discussed reaction protocols and it drifts the protocols from green chemistry postulates. On the other hand, the coupling partner aryl halides react sluggishly and also considered as pollutant.

Though organometallic coupling partners are also used for the reactions which are more reactive than the halides, yet they are toxic in nature and integrated with imperfect functional group tolerance.

Dedicating subsequent efforts towards the *N*-arylation reaction, in 1998, Chan and Lam [44] established another Cu mediated reaction protocol for C-N bond formation reaction (**Scheme 9**) which was able to overcome several drawbacks related to the issues like stability, toxicity, lack of functional group tolerance of the coupling partner, high reaction temperature etc. The reaction was performed in DCM at room temperature using stoichiometric Cu(II) acetate, arylboronic acids and several nucleophilic counterparts including anilines, amides, imides, carbamates, ureas, sulphonamides, *N*-heterocycles etc.



Scheme 9: Cu-catalyzed Chan-Lam reaction

Additionally, it was applicable towards C-O and C-S bond formation reactions. Arylboronic acid is a profound organometallic species having wide applicability in organic synthesis owing to their structural diversity, moisture resistance and lower toxicity properties. So, arylboronic acids hold a superior position among all the other organometallic counterparts. As a result, Chan-Lam cross-coupling reaction has stood out as a standard procedure for *N*-arylation of amines and *N*-heterocycles. The exact mechanism of the reaction still in dispute though Chan-Lam proposed a mechanistic pathway for the reaction. The proposed mechanism given by Chan-Lam is shown in the **Fig. 9** which involves four major steps *viz*. oxidation, ligand exchange, transmetallation and reductive elimination.

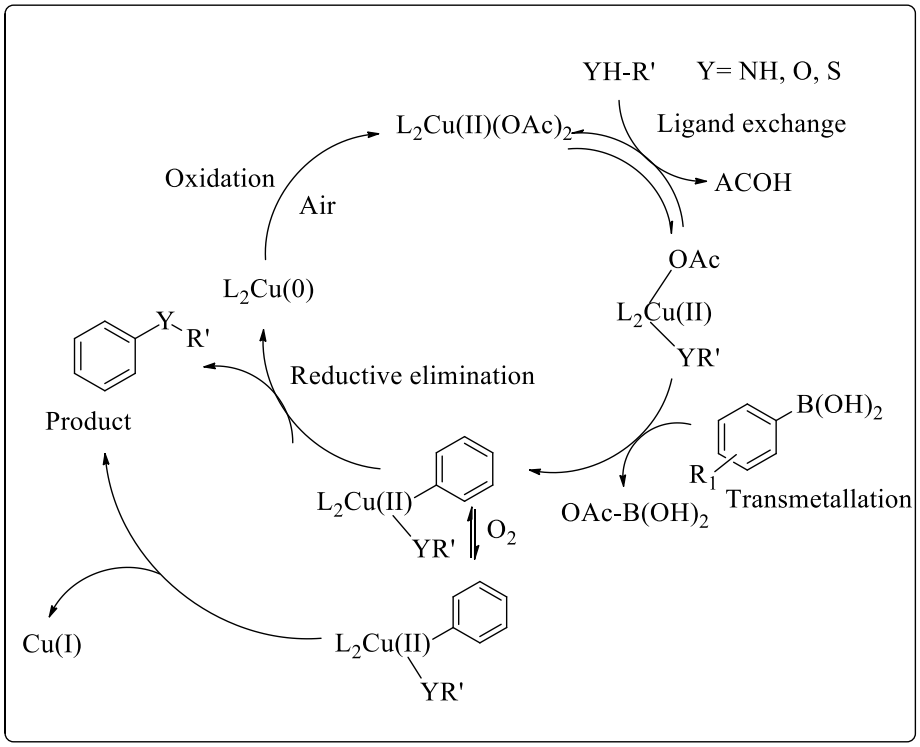
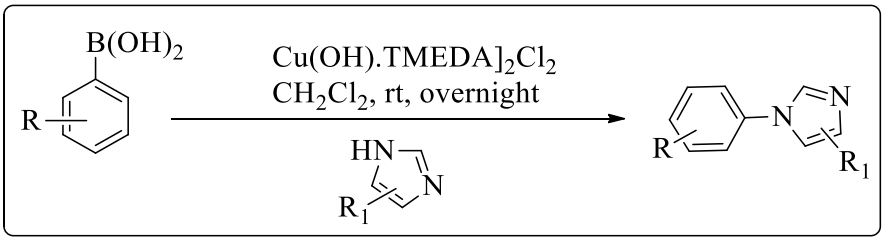


Fig. 9: Proposed mechanism for Chan-Lam cross-coupling reaction

But, the classical Chan-Lam coupling reaction also associated with some demerits owing to the use of stoichiometric amount of copper salt, excess of arylboronic acids and requirement of long reaction time. The problem regarding use of stoichiometric amount of Cu salt was first solved by using an *in-situ* generated Cu catalyst $[Cu(OH).TMEDA]_2Cl_2$ reported by Collman and Zhong [45] in an *N*-arylation reaction of imidazole (**Scheme 10**).

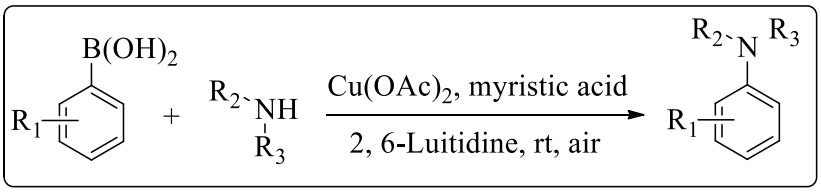


Scheme 10: Collmann and Zhong method

Later, the same author reported an *N*-arylation reaction taking imidazole as *N*-coupling partner in aqueous medium. But, to obtain higher yield in the reaction, it was mandatory to keep the reaction medium at neutral pH value. Collmann and his co-

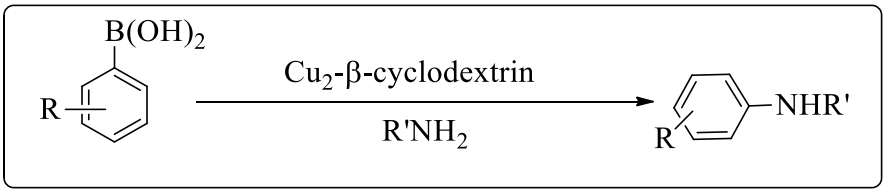
workers revisited [46] the protocol and designed more efficient catalyst μ–hydroxo Cu(II) complex. In the complex, the metal is linked with nitrogen chelating bidentate ligands. The catalyst was prepared by using different Cu salts like CuCl, CuBr, CuI, CuOTf and several bidentate ligands under oxygen atmosphere in water. After investigation it was found that TMEDA [47] was the most efficient ligand although all ligands afforded acceptable yields. It was Lam [48] who reported that *N*-arylation reaction could also be catalyzed in presence of 10 mol% of $Cu(OAc)_2$ aided by variety of oxidants like molecular oxygen, pyridine-*N*-oxide, TEMPO etc. Myristic acid [49] was also employed as ligand by Buchwald and co-workers for an effective *N*-arylation of aniline with boronic acid in presence $Cu(OAc)_2$ as catalyst and 2,6-lutidine as base and the protocol was able to manage admirable yields (**Scheme 11**).

At the same time, Batey and co-workers [50] developed another protocol utilizing 10 mol% of $Cu(OAc)_2 \cdot H_2O$, oxygen atmosphere and molecular sieves. Use of molecular sieves showed the potentiality to enhance the reaction yields.



Scheme 11: Myristic acid promoted *N*-arylation

Yokomatsu [51] and his co-worker reported a method to produce *N*-arylated product of different aliphatic and aromatic amines using Cu_2β-cyclodextrin as catalyst at room temperature in water (**Scheme 12**).



Scheme 12: Cu_2β-cyclodextrin catalyzed reaction

In 2006, Laxmi kantam [52] and her group disclosed a heterogeneous catalyst copper fluoroapatite (CuFAP) for effective *N*-arylation of *N*-nucleophiles at room temperature. They succeed to reuse the catalyst for several times with constant activity even after fourth run.

A unique base free, *N*-arylation of anilines and imidazoles was reported by Islam [53] and co workers using polymer supported Cu catalyst in MeOH.

Microwave assisted reaction protocol [54] was also reported by Singh *et al*. for the concerned reaction which utilized $Cu(OAc)_2$, Et_3N and pyridine.

Our group [55] also established an efficient Cu salen complex catalyzed methodology for *N*-arylation of anilines and imidazole in aqueous solvent.

Very recently, Phukon and co-workers [56] reported a DMAP/ Cu promoted quick Chan-Lam reaction.

During the last few decades, the reaction protocol was further explored with other organoboron coupling partner like triphenyl boroxine [57], aryl boronate ester [58], aryltriolborates [59] etc.

Nevertheless, various methods have been established for the Chan-Lam coupling reaction; still the development of more efficient protocol eliminating all the drawbacks, continues to be significant among research community.

Nitration of aromatic compounds:

Aromatic nitro compounds are considered as resourceful building blocks in the domain of synthetic organic chemistry. Over the years, they have been extensively consumed as explosives and precursors for azo dyes. Moreover, they exist in a range of fields such as pharmaceuticals, dyes and plastic materials [60]. This crucial significance in organic synthesis may be attributed to their ease of availability, easy transformation to other functional groups and the ability of nitroarenes in imparting tunable physical and chemical nature to numerous structurally targeted organic moieties. The traditional nitration method generally requires the employment of an excess of nitric acid, sulfuric acid or dinitrogen pentoxide and carcinogenic starting material benzene. These reactions are plagued by difficulties like poor regioselectivity and defective functional group tolerance. Additionally, the same are considered as environmentally unfavorable process due to the involvement of strong acid and high temperature. As a result, much interest has been drawn towards the development of practical methods for the synthesis of

aromatic nitro compounds. The classical electrophilic nitration of aromatic compounds is probably one of the most extensively studied organic reactions and an immensely important industrial process. Although much advancement have been made for the perfection of their preparation method, still there is a great need for new nitration methodology that can overcome such problems. In past years, various efforts have been devoted to introduce new nitrating agents avoiding conc. nitric acid. Some of the nitrate salts aided catalytic systems for nitration of different functionalized arenes as shown in the **Fig. 10**.

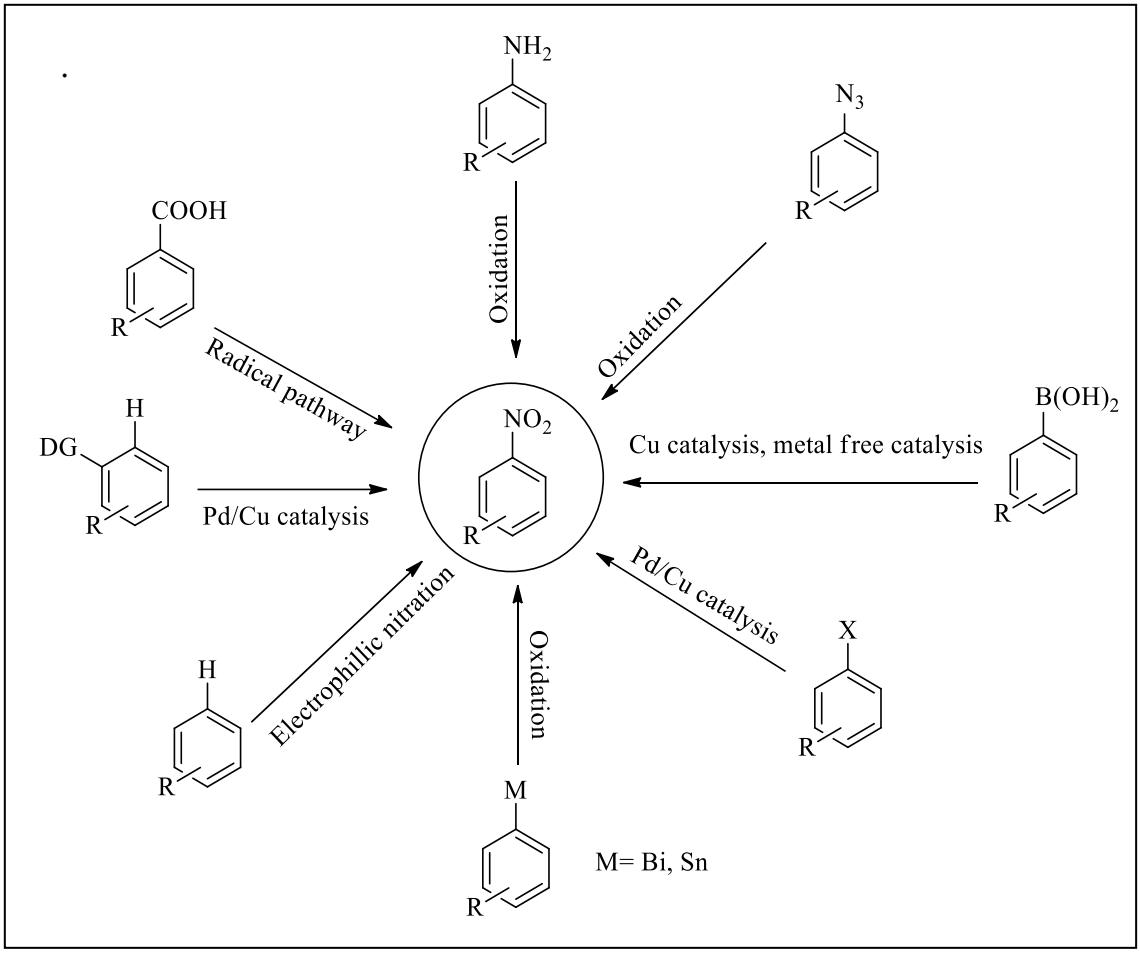
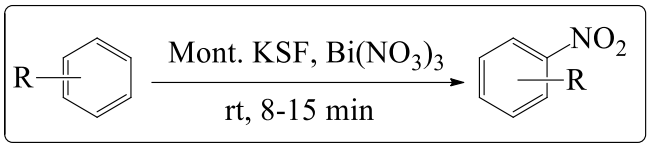


Fig. 10: Pathways to synthesize nitroarenes using nitrate salts

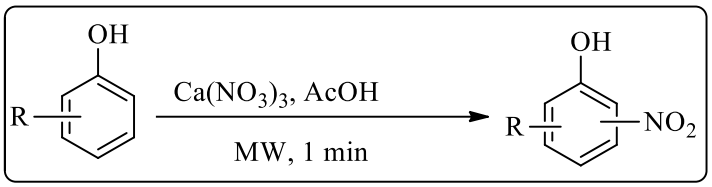
In 2000, Banik and co-workers [61] accounted a solid phase rapid and convenient method for nitration of aromatic compounds using bismuth nitrate supported on montmorillonite at room temperature (**Scheme 13**).

The supremacy of this method over others includes broad substrates scope, readily accessible nitrating agent and fast reaction with high yields as well as strong acid free condition.



Scheme 13: Solid phase nitration of aromatic hydrocarbon

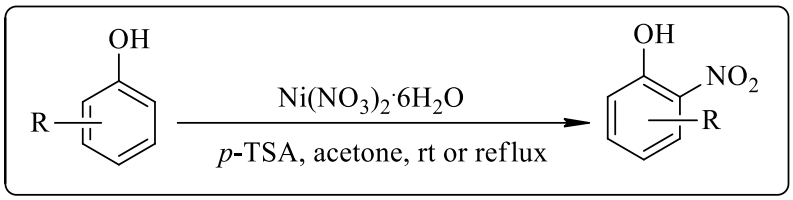
In the past few years, microwave-assisted organic reaction became flourished in both academic and industrial purposes. In 2006, Bose [62] and co-workers investigated a microwave promoted nitration of phenolic compounds using a mixture of calcium nitrate and acetic acid producing calcium acetate as byproduct (**Scheme 14**).



Scheme 14: Microwave accelerated nitration of phenolic compounds

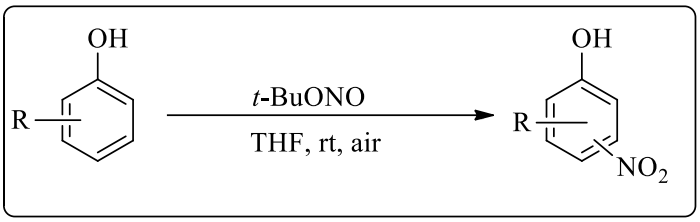
Although, this procedure is compatible from the green chemistry prospect, yet it could not get rid of poor regioselectivity problem because, phenolic substrates produce dinitro derivatives and mixtures of products. During the last few years, *ipso*-nitration has appeared as an attractive method to synthesize aromatic nitro compounds which can resolve the problems of regioselectivity. Till date, many *ipso*-nitration protocols have been developed from different functionalized arenes as shown in the **Fig. 10**. Furthermore, considerable improvements have also been made in transition-metal-catalysis for *ipso*-nitration of aryl halides, arylboronic acids and aromatic hydrocarbons.

Nickel nitrate mediated [63] a regiospecific nitration of phenolic compounds was reported by Rao and co-workers catalyzed by *p*-toluenesulfonic acid (*P*-TSA) (**Scheme 15**) furnishing exclusively mono-nitration products with excellent isolated yields.



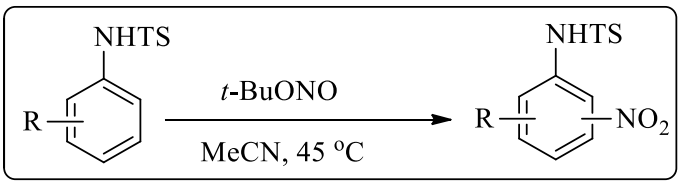
Scheme 15: Regiospecific nitration of phenolic compound

In 2009, Savinov and co-workers [64] introduced a novel nitrating agent, *tert*-butyl nitrite (*t*-OBuNO) for regio-selective mono-nitration of phenols (**Scheme 16**).



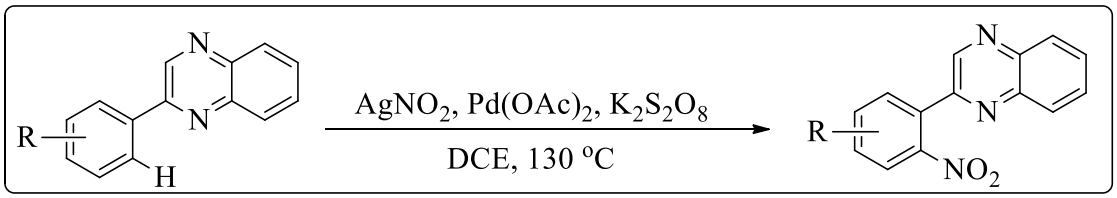
Scheme 16: Nitration of phenolic compounds using *tert*-butyl nitrite

Recently, Arns and co-workers [65] reported the application of *tert*-butyl nitrite as a nitrating agent for the selective nitration of sulfonamides (**Scheme 17**).



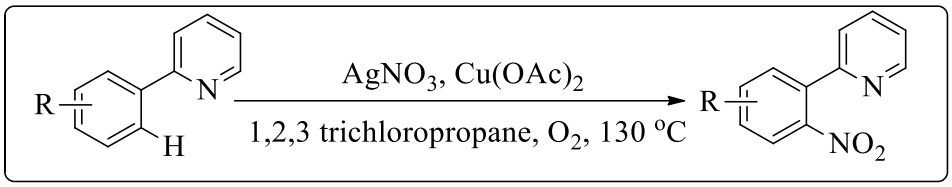
Scheme 17: Nitration of sulfonamide using *tert*-butyl nitrite

This protocol could tolerate a wide diversity of functional groups and displayed high chemoselectivity for sulfonamide. In 2010, Liu and co-workers [66] explained the first palladium-catalyzed radical *ortho*-nitration of aromatic C–H bonds using $AgNO_2$ as a nitrating species (**Scheme 18**). This approach has several advantages, such as extensive functional group tolerance, substrate compatibility and high selectivity towards mono-nitration etc.



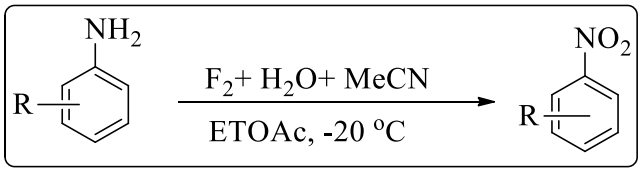
Scheme 18: Nitration via C-H activation

Based on this influential publication, Bi and co-workers stated another chelation-assisted Cu-catalyzed radical *ortho*-nitration of aromatic C–H bonds utilizing $AgNO_3$ [67] as a nitrating agent and dioxygen as oxidant (**Scheme 19**). The use of 1,2,3-trichloropropane as solvent is essential to accomplish high conversion in the reaction.



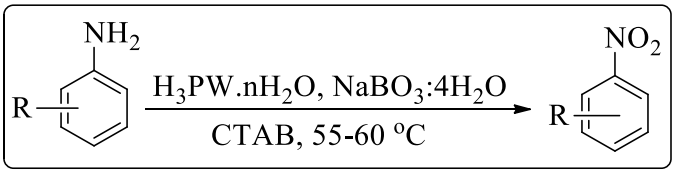
Scheme 19: $AgNO_3$/Cu(II) promoted nitration via C-H activation

Oxidation of primary aromatic amines into nitro compounds is considered as one of a constructive method for synthesis of nitro compounds. However, due to uncontrolled oxidation some other products such as oxime, azo and azoxy, hydroxylamine, nitroso, nitro, compounds also observed along with the desired nitro products. Therefore, effective control over selectivity is of great importance in such reactions. In 2000, Tour and co-workers [68] developed an oxidation method for electron-deficient anilines using *in-situ* generated HOF (hypofluorous acid), (**Scheme 20**). The extremely rapid oxidation and high yields made HOF as a practical oxidant for this purpose.



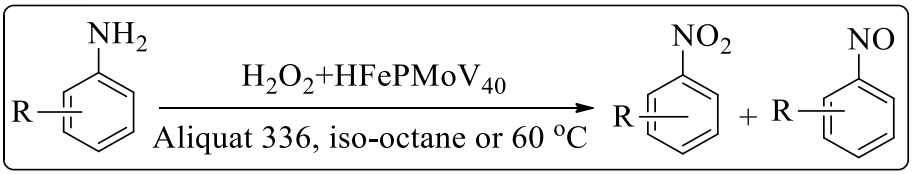
Scheme 20: Oxidation of amines using *in-situ* generated HOF

In 2001, Firouzabadi and co-workers [69] reported an oxidation of aromatic amines catalyzed by tungstophosphoric acid with sodium perborate (**Scheme 21**).



Scheme 21: Rapid oxidation of amines using HOF as oxidant

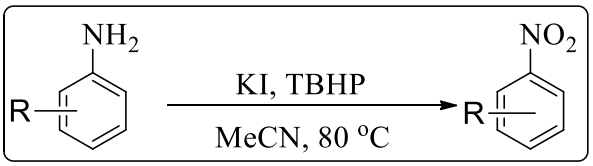
The reaction was chemoselective and included wide substrate diversity with excellent yield. In 2008, Tundo [70] and co-workers described heteropolyacids catalyzed, multiphase oxidation of aniline taking hydrogen peroxide as oxidant, Aliquat 336 as an ionic liquid (**Scheme 22**).



Scheme 22: Heteropolyacids catalyzed nitration of amines

The reaction facilitated selective conversion of anilines to corresponding nitro and nitroso derivatives in control reaction temperature. At 20 °C, the nitroso products were obtained exclusively with 85–99% yields having nitro products as minor product, while nitro products were found quantitative at 60 °C and the catalyst was also reusable in the multiphase system.

In 2009, Reddy and co-workers utilized potassium iodide [71] as catalyst and *tert*-butyl hydroperoxide as the external oxidant for a simple and convenient oxidation of aromatic primary amines to the corresponding nitro compounds (**Scheme 23**). Excellent selectivity was found with both electron deficient and electron-rich substrates.



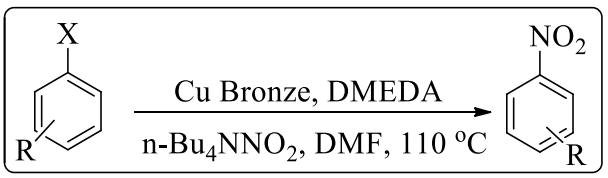
Scheme 23: KI/TBHP promoted oxidation of amines

In 2003, an alternative synthetic route to obtain nitro compounds from aromatic azides was developed using HOF·MeCN [72], a broad range of aliphatic azides was efficiently converted to the consequent nitro compounds with high yields within short reaction time (**Scheme 24**).

Scheme 24: Oxidation of aromatic azides

Recently, Sandford [73] and co-workers have reported oxidation of amines and azides in to nitro compounds with HOF·MeCN. The reaction protocol exhibited a wide range of substrates, such as aliphatic amines, aromatic amines as well as aliphatic azides. Electron-deficient aminopyridine substrates predominantly proceeded very efficiently and the corresponding nitro derivatives were found with high yields.

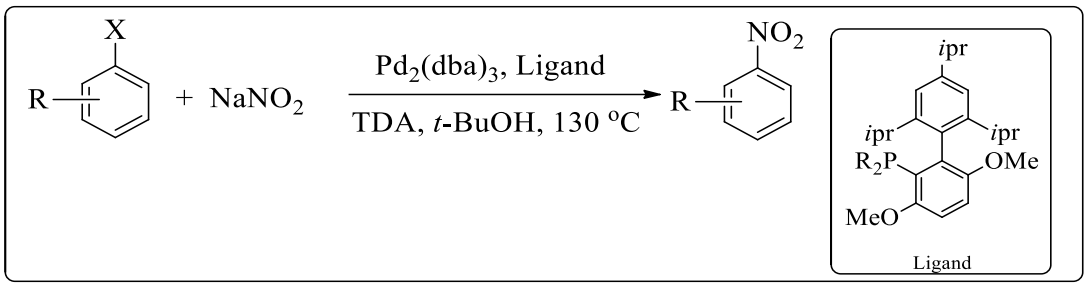
In 2005, Saito and co-workers [74] developed a novel nitrite salts aided *ipso*-nitration method for aryl halides using Cu powder/DMEDA as catalytic system (**Scheme 25**) and it was recognized as a useful move towards the drawbacks of conventional methods.



Scheme 25: Cu catalyzed nitration of aryl halide

However, it restricted its application towards heterocyclic moieties. They proposed an Ullmann-type plausible mechanistic pathway inserting Cu(I) species to the carbon–halogen bond of aryl halide followed by a halogen–nitrite exchange reaction. In the next, it progressed through reductive elimination pathway to give the nitro product and regenerated the catalytic Cu species.

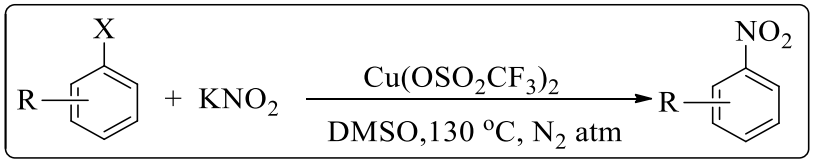
Later, Buchwald and co-workers [75] in 2009 illustrated a general and efficient procedure for the palladium-catalyzed *ipso* nitration of aryl chlorides, triflates and nonaflates to produce corresponding nitro products in high yields (**Scheme 26**).



Scheme 26: Buchwald's method for nitration of aryl halide

It was also exemplified that the use of biarylphosphine ligand and a phase transfer catalyst was essential to the outcome of the reaction. The phase transfer catalyst, tris(3,6-dioxaheptyl)amine (TDA, 5 mol%) increased the solubility of sodium nitrite in the solvent *t*-BuOH. This protocol demonstrated excellent regioselectivity, substrate compatibility and functional group tolerance including a various range of electron-releasing and electron withdrawing groups.

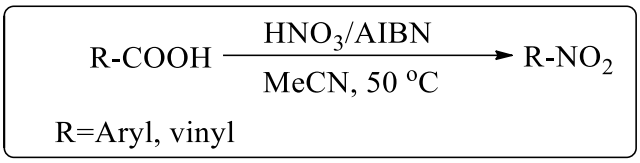
Recently, Kantam and co-workers [76] gave a description on a Cu-catalyzed *ipso*-nitration of aryl halides using nitrite salts under ligand-free conditions (**Scheme 27**). This method circumvented the use of expensive ligands and additionally was carried out in weakly basic condition. However, this reaction required high temperature and longer reaction time.



Scheme 27: Nitration of aryl halide using potassium nitrite

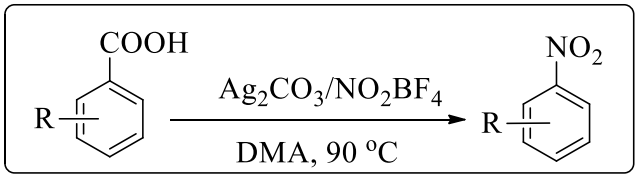
A few examples are found regarding *ipso*-nitration of carboxylic acids. Carboxylic acids are commercially available and convenient to synthesize by means of a huge number of conventional methods. Nowadays, carboxylic acids come out to be extremely promising raw materials for *ipso*-nitration because of their easy availability.

Roy and co-workers developed a mild nitro decarboxylation of ring activated benzoic acids, aromatic α, β-unsaturated carboxylic acids using nitric acid and catalytic AIBN [77]. It was believed that an acyloxy radical might be generated either by the reaction of acid with NO_3 radical or by the decomposition of acylnitrate. After that, the NO_2 radical was assumed to combine with the acyloxy radical in a bimolecular fashion to promote nitrodecarboxylation (**Scheme 28**).



Scheme 28: Nitration of carboxylic acid using AIBN/HNO_3

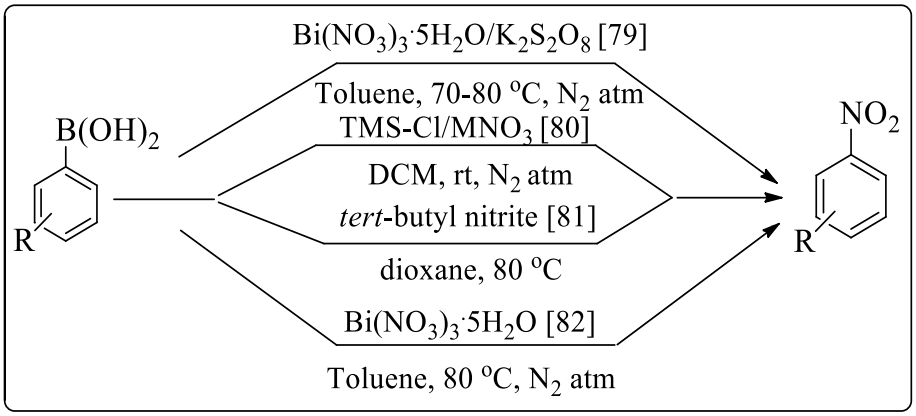
A silver (I)/nitronium tetrafluroborate proped up [78] *ipso*-nitration of carboxylic acid was developed recently by Venygopalon and his co-workers (**Scheme 29**).



Scheme 29: Silver (I)/nitronium tetrafluroborate proped up *ipso*-nitration of carboxylic acid

Although too many starting materials have been explored to improve the nitration of aromatics, *viz.* phenolic compounds, aryl halides, aryl amines, carboxylic acids etc, but still they are not free from the poor regioselectivity problem. Additionally, most of them are known as environment pollutants. In this context, nowadays, arylboronic acids come out to be an interesting and versatile alternative organic synthon for this type of transformations which can dominate poor regioselectivity problem to an extent and offer

some significant and preferable properties such as non-toxicity, heat and moisture resistance and easy availability with varying substitutions. Some reagents/catalysts have been reported for the transformation of arylboronic acids to nitroarenes, e.g. $Bi(NO_3)_3/K_2S_2O_8$ [79], TMS-Cl/MNO_3 (M=Ag, NH_4) [80]. Catalyst free conversions of arylboronic acids to nitro benzenes have also been observed utilizing *tertiary* butyl nitrile and bismuth nitrate as the nitrate source [81-82]. All of these transformations are shown in the following schematic diagram (**Scheme 30**).



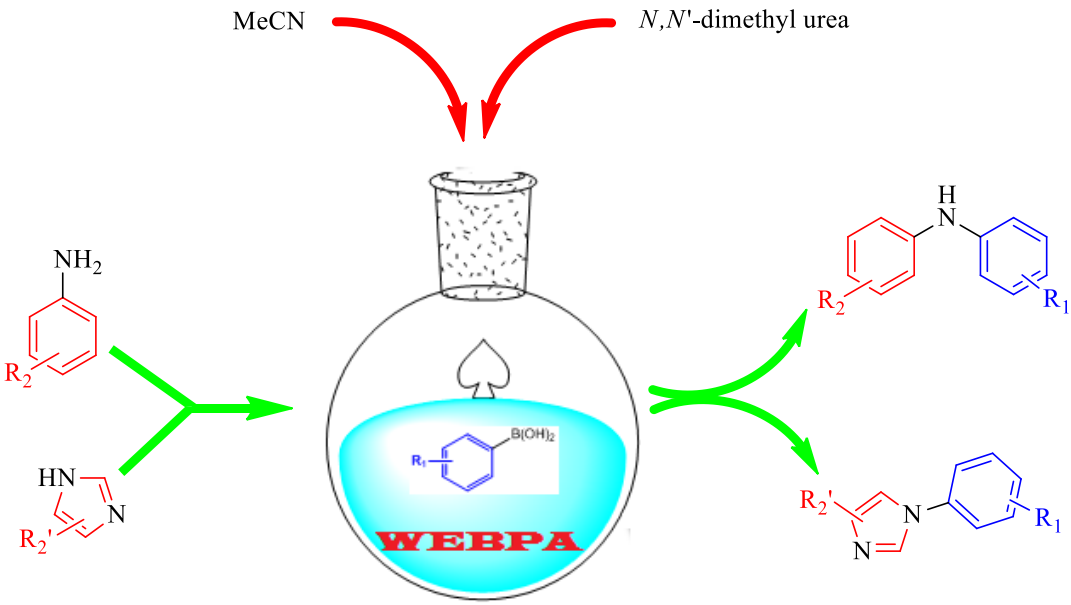
Scheme 30: Previous work on *ipso*-nitration

Although these reports assert successful *ipso*-nitration of arylboronic acids, but most of the reaction protocols use prolonged reaction time (30-72 h), high temperature to maximize catalytic performances. Moreover, many of them also suffer incompetency to heterocyclic moiety. Therefore, a highly active catalytic system is still desired for the said reaction protocol, which avoids the drawbacks like using high temperature, strong acid etc. because these drawbacks go against the "green and sustainable Chemistry" principles.

Chapter 3

Section 3.1

N,*N*'-dimethyl urea/ Cu(II) as an excellent promoter for room temperature *N*-arylation of aniline and imidazole in 'WEBPA': MeCN.



3.1. A. Introduction:

In recent years, the *N*-arylation of amines, anilines and imidazoles has attracted significant interest due to the frequent occurrence of these fragments in pharmaceutical and agriculture products [55]. Although couple of successful methods likes Buchwald-Hartwig amination, Ullmann coupling etc. were established for *N*-arylation of amines, yet, Cu mediated Chan-Lam *N*-arylation reaction is considered as most straightforward methodology for the said reaction. It is mainly due to the mild reaction condition, which uses air as oxidant and inexpensive Cu salt as catalyst. Apart from this, reactions are performed at room temperature using a less-toxic starting material arylboronic acid. But, the pioneering study was associated with some demerits like use of excess of Cu salt, halogenated solvents and long reaction time etc. Accordingly, some ligand based catalytic systems were also developed for easy progress and to minimize the reaction time. But, expensive nature of the ligands encourages the researchers to search for some easily available cost effective ligand systems. Again, today's world demands green and sustainable chemistry to be utilized everywhere in the synthetic procedures. In this context, application of naturally abundant agro waste as a reagent for the *N*-arylation reaction is highly appealing. To note, recently, a series of base catalyzed reactions have been modified by replacing commercial bases with natural feedstocks like "Water Extract of Banana Peel Ash" [82], "Water Extract of Rice Straw Ash" [83] and "Water Extract of Papaya Bark Ash" [84] etc. On the basis of these studies, we also intended to implicate a natural feedstock for the Chan-Lam cross-coupling reaction.

Here in, we describe a Cu acetate catalyzed Chan-Lam cross-coupling reaction for *N*-arylation of anilines and imidazoles using *N*,*N*'-dimethyl urea as a cheap and easily available ligand. Interestingly, we have utilized "Water Extract of Banana Peel Ash" (WEBPA) as a source of both solvent and base. A co-solvent acetonitrile is also used for better catalytic performance of the reaction.

3.1. B Experimental:

General information:

^{1}H and ^{13}C NMR spectra of the products were recorded in a JNM ECS 400 MHz NMR spectrophotometer (JEOL) using tetramethylsilane (TMS) as the internal standard. Chemical shift values are expressed in ppm. Coupling constants are expressed in Hertz. Reactions were monitored by thin-layer chromatography using aluminium sheets with silica gel $60F_{254}$ (Merck). UV light and Iodine vapour were used as visualizer. Chemicals are obtained from commercial source. EDX analysis of banana peel ash was carried out on a Scanning Electron Microscope (JEOL, JSM, Model 6390 LV). The ion analysis of "WEBPA" was carried out in an Ion Chromatograph (Metrohm, 882). Flame photometry experiment was conducted in a Flame Photometer (Systronics, 128).

Preparation of the natural base:

We first prepared the extract WEBPA from banana peels (scientific name: *Musa balbisianaColla*, family name Musaceae) by drying the peels and burning them to ash. 10 g of the ash was then suspended in 100 mL of water and stirred for 1 h at room temperature. Thereafter, the mixture was filtered in a suction filter and the extract was isolated. **(Fig. 1)**

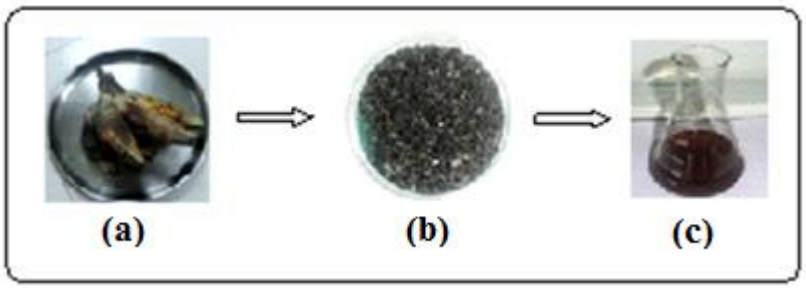


Fig. 1: (a) Musa balbisiana Colla fruits, (b) Burnt ash of peels of Musa balbisiana Colla fruits and (c) 'WEBPA'

Characterisation of the 'WEBPA':

The alkaline nature of the extract was confirmed by litmus test. By observing colour of the litmus paper we found the pH of the extract to be around 10. Energy Dispersive X-ray (EDX) analysis of the sample (known as kolakhar in local Assamese language) was carried out on a Scanning Electron Microscope to investigate the elemental composition in banana peel ash. The EDX analysis of the banana peel ash demonstrates that the

material contains higher amount of potassium and sodium followed by calcium and magnesium (**Fig. 2**). The atomic weight % of the elements is also calculated and is shown in the **Fig. 2**.

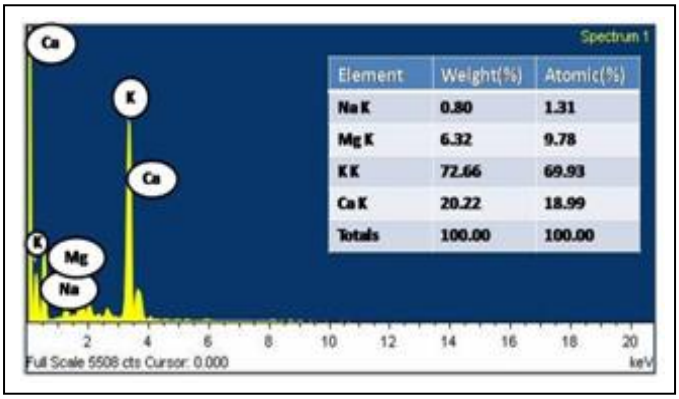


Fig. 2: EDX image of the banana peel ash

To acquire further information about the amount and nature of ions present in the aqueous extract, we performed ion chromatography (IC) analysis. The result obtained from the analysis is shown in **Fig. 3**. Further, to confirm the result obtained from IC analysis we have done flame photometry test in a Flame Photometer. The result from flame photometry test is compared with IC results in table 1, which show almost same quantity of ions (ppm) present in the banana peel.

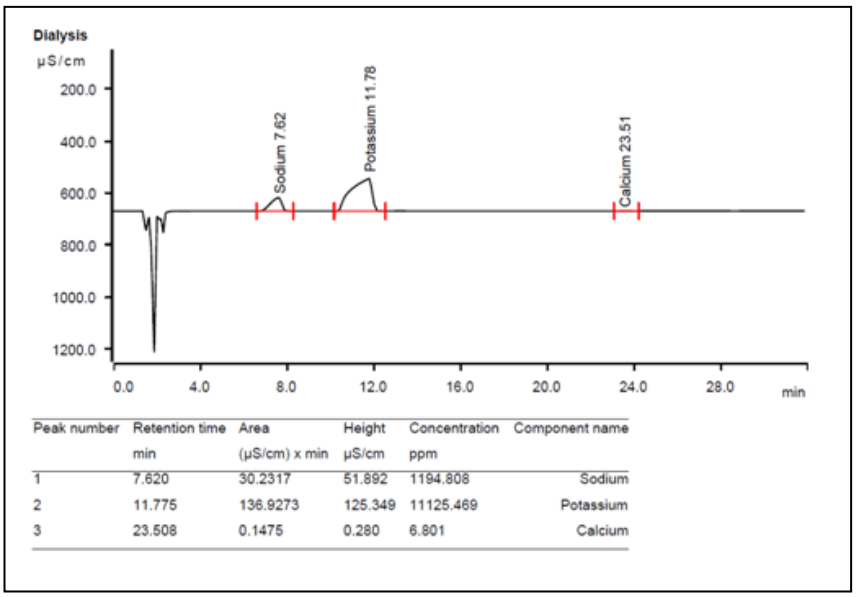


Fig. 3: IC curve of banana peel extract

Table 1. Comparison between flame photometry and ion-exchange chromatography result of banana peel extract

Entry	Metal	Metal Concentration [ppm] (By Flame photometry)	Metal Concentration [ppm] (By Ion chromatography)
1	K	11897.95	11125.46
2	Ca	9.812	6.801
3	Na	1161.98	1194
4	Li	Trace	Trace
5	Mg	Trace	Trace

General procedure for the *N*-arylation of anilines and imidazoles:

***N*-arylation of anilines:** In a 50 mL round-bottomed flask, a mixture of arylboronic acid (1.2 mmol), aniline (0.75 mmol), $Cu(OAc)_2.H_2O$ (10 mol%), *N*,*N*'-dimethyl urea (0.25 mmol) and WEBPA : MeCN (4 mL in 1:1) was added and stirred at room temperature in aerobic condition. The reaction was monitored by TLC. After completion of the reaction the reaction mixture was diluted with 20 mL of water and extracted with (3×20) mL of diethyl ether and the combined organic layer was washed with brine, dried over by Na_2SO_4 and evaporated in a rotary evaporator under reduced pressure. The crude was purified by column chromatography (hexane/ethylacetate, 9:1) on mesh silica (100–200) to get the desired product. The products were confirmed by ^{1}H NMR, ^{13}C NMR, FT-IR spectroscopy and mass spectrometry.

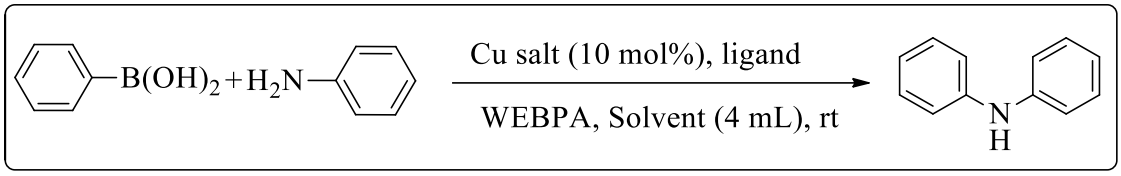
***N*-arylation of imidazoles:** In a 50 mL round-bottomed flask was charged with a mixture of arylboronic acid (1.2 mmol), aniline (1 mmol), $Cu(OAc)_2.H_2O$ (10 mol%), *N*,*N*'-dimethyl urea (0.25 mmol) and WEBPA:MeCN (4 mL in 1:1) and stirred at room temperature in aerobic condition. The reaction was monitored by TLC. After completion, the reaction mixture was diluted with 20 mL of water and extracted with (3×20) mL of diethyl ether and the combined organic layer was washed with brine and dried over by Na_2SO_4 and evaporated in a rotary evaporator under reduced pressure. The crude was purified by column chromatography (hexane/ethylacetate, 9:1) on mesh silica (100–200) to get the desired product. The products were confirmed by ^{1}H NMR, ^{13}C NMR, FT-IR spectroscopy and mass spectrometry.

3.1. C. Results and discussion:

At the very outset, we have examined the efficiency of 'WEBPA' as solvent and base in the cross-coupling reaction by taking 1.2 mmol of phenylboronic acid and 0.75 of mmol aniline as model substrates at room temperature using different Cu salts as catalysts. The initial reaction was done without using any external base and ligand, choosing $Cu(OAc)_2 \cdot H_2O$ (10 mol %) as the catalyst, but provided only 35% of the desired cross-coupled product at 12 h (Table 2, Entry 1). A series of experiments with different Cu salts was conducted in the same reaction condition but no improvement was observed than copper acetate catalyzed reaction (Table 2, Entries 2-4). The lower yield of the cross-coupled product guided us to check the effect of different easily available, cheap nitrogen based ligands like urea, thiourea and *N,N*'-dimethyl urea on the Cu catalyzed reaction (Table 2, Entries 5-7). The investigation resulted *N,N*'-dimethyl urea as the most suitable ligand for the efficient conversion with 74% isolated yield at 8 h (Table 2, Entry 7). In the next, the effect of *N,N*'-dimethyl urea on other Cu salts were also been checked, the best result was obtained with Cu acetate salt. Currently, it is noticed that in various reports regarding cross coupling reaction the addition of organic co-solvent in water dramatically increases the reaction yield. As a result, we examined the co-solvent effect on the reaction system taking *N,N*'- dimethyl urea/Cu acetate as the catalytic system and 'WEBPA' as the primary solvent (Table 2, Entry 11). We also investigated the reaction with various of co-solvents like MeOH, *i*-PrOH, THF, DMF, PEG 400, CH_3CN etc. along with 'WEBPA' in (1:1) ratio (Table 2, Entries 5-10). The experiments showed WEBPA: MeCN was the most effective solvent with a significant increase in yield of the reaction up to 87% from 74% (Table 2, Entry 9). Proceeding with this result, in next assessment, we optimized the amount of Cu acetate salt and ligand and found that 10 mol% of the Cu salt and 0.25 mmol of the ligand is enough for efficient conversion within 3 h.

Our next endeavor was to extend the scope of the protocol for *N*-arylation of imidazole. So, a model reaction was carried out between imidazoles (1 mmol) and phenylboronic acid (1.2 mmol) under the optimized condition for the *N*-arylation of anilines. To our delight, the first attempt was successful with 89% of isolated yield at 5h. So, the catalytic activities of these two protocols were evaluated under the same optimized reaction condition with electronically diverse arylboronic acids, anilines and imidazoles.

Table 2. Optimization of the reaction condition for catalyst, ligand and solvent[a]

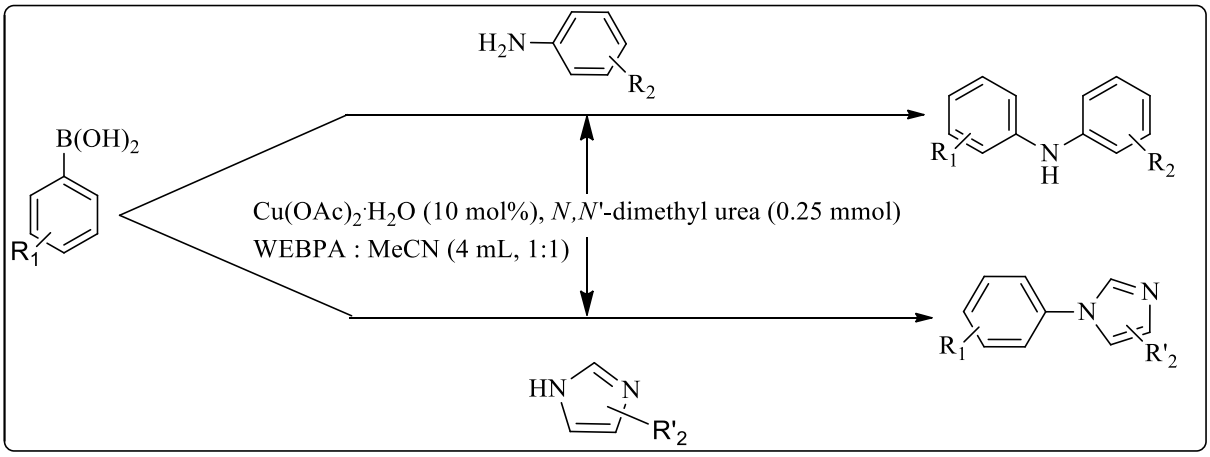


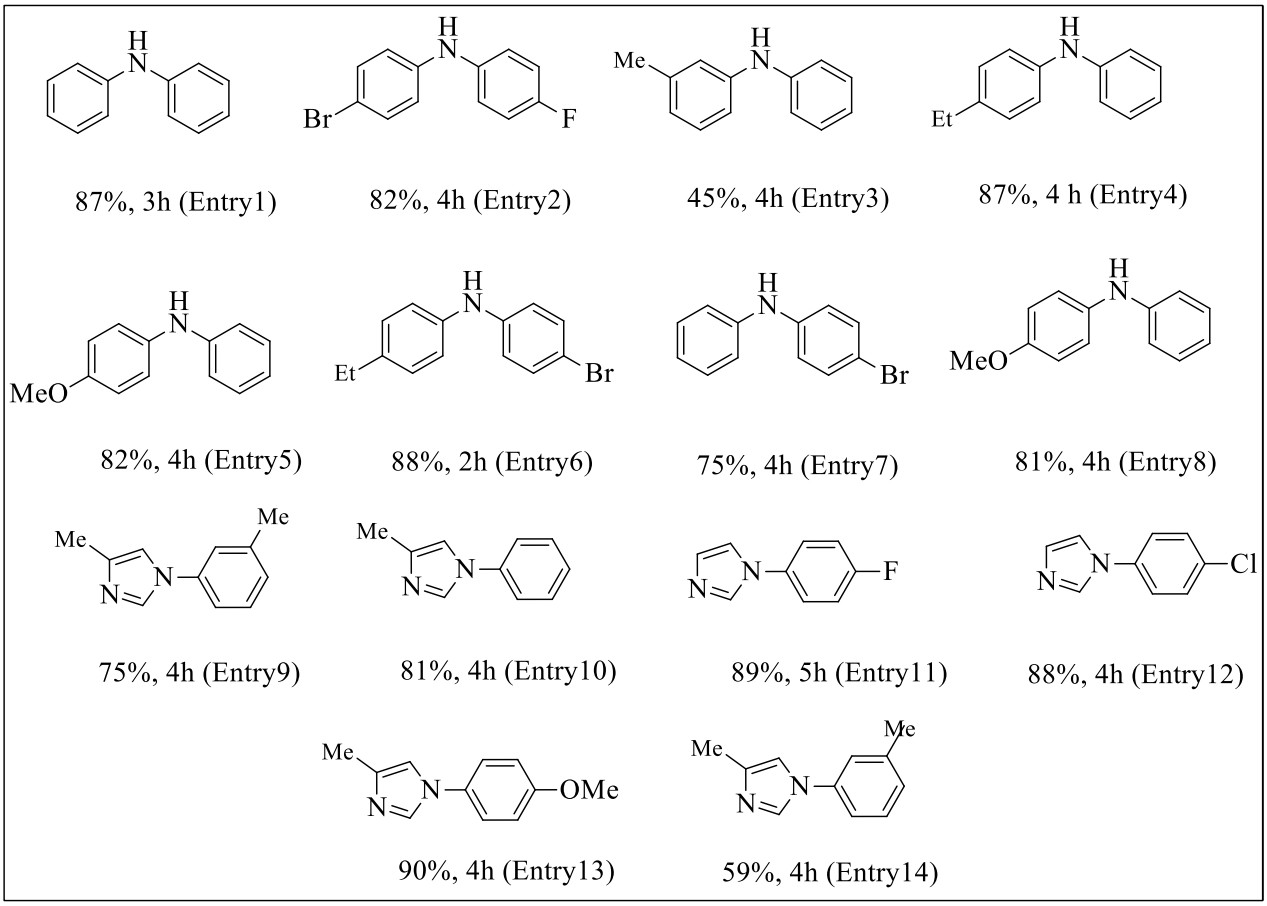
Entry	Cu salt (10 mol%)	Solvent	Time (h)	Additive	Yield (%)[b]
1	$Cu(OAc)_2{\cdot}H_2O$	WEBPA	12	Nil	35
2	CuI	WEBPA	12	Nil	20
3	$CuCl_2{\cdot}H_2O$	WEBPA	12	Nil	24
4	CuCl	WEBPA	12	Nil	10
5	$Cu(OAc)_2{\cdot}H_2O$	WEBPA	12	Urea	52
6	$Cu(OAc)_2{\cdot}H_2O$	WEBPA	12	Thiourea	55
7	$Cu(OAc)_2{\cdot}H_2O$	WEBPA	8	*N*,*N*'- dimethyl urea (1 mmol)	74
8	CuI	WEBPA	12	Do	42
9	$CuCl_2{\cdot}H_2O$	WEBPA	12	Do	45
10	CuCl	WEBPA	12	Do	47
11	$Cu(OAc)_2{\cdot}H_2O$	WEBPA: MeOH	5	Do	78
12	$Cu(OAc)_2{\cdot}H_2O$	WEBPA:PEG 400	6	Do	73
13	$Cu(OAc)_2{\cdot}H_2O$	WEBPA:MeCN	3	Do	87
14	$Cu(OAc)_2{\cdot}H_2O$	WEBPA:MeCN	3	*N*,*N*'- dimethyl urea (0.5 mmol)	87
15	$Cu(OAc)_2{\cdot}H_2O$	WEBPA:MeCN	3	*N*,*N*'- dimethyl urea (0.25 mmol)	87
16[c]	$Cu(OAc)_2{\cdot}H_2O$	WEBPA: MeOH	5	Do	78
17[c]	$Cu(OAc)_2{\cdot}H_2O$	WEBPA:MeCN	3	Do	72

[a]Reaction condition: Phenylboronic acid (1.2 mmol), aniline (0.75 mmol). [b]Isolated yield. [c]5 mol% of the catalyst was used.

The reaction protocols showed good to moderate yield in the optimized reaction condition bearing both electron donating and withdrawing group substituted arylboronic acids, anilines and imidazoles. The results are summarized in the table 3. Interestingly, we found that arylboronic acids containing electron donating groups provided good yield of coupling products than the boronic acids containing electron withdrawing moiety. Notably, 3-methyl phenylboronic acid showed reluctantancy towards coupling with both anilines and imidazoles. It may be due to the hindrance effect due to the methyl group at 3-position.

Table 3. Reaction scopes of the protocols using different arylboronic acids and *N*-nucleophiles[a]



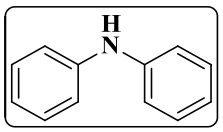


[a]Reaction condition: 1.2 mmol of arylboronic acid, 0.75 mmol of aniline, 1 mmol of imidazole, room temperature.

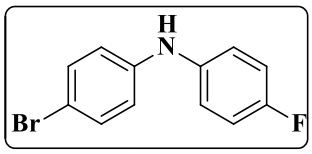
3.1. D. Conclusions:

In conclusion, we have established a competent natural base, 'WEBPA' mediated quick and Chan-Lam cross coupling reaction. The reactions are carried out by using a naturally occurring reagent which is utilized both as solvent and base. The ligand *N,N´*-dimethyl urea is cheap and easily available used to prompt up the reaction. The mentioned reagent is safe for handling and having renewable feedstock. The other advantage of the reaction protocol is that it avoids halogenated solvents and toxic chemicals.

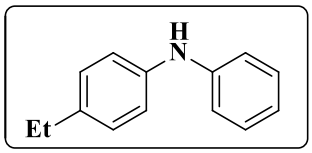
Chracterisation data for the products:



Diphenylamine (Entry 1, Table 3): White solid (Yield=87%), mp= 54-58 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.71(s, br, 1H), 6.99(t, *J*=8Hz, 2H), 7.11-7.11(m, 4H), 7.34-7.25(m, 4H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 143.2, 129.5, 121.1, 117.9 ppm.

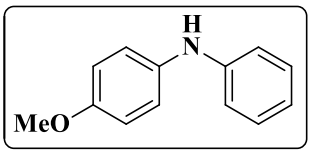


4-bromo-*N*-(4-fluorophenyl)benzenamine (Entry 2, Table 3): White solid (Yield=82%), mp= 82-85 C˚, ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.54(s, br, 1H), 7.32-7.25(m, 2H), 7.02-6.96(m, 4H), 6.82(d, *J*=8Hz, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 143.3, 132.2, 121.3, 121.2, 118.1, 116.2, 116.0, 112.2 ppm.

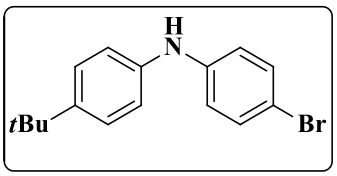


4-ethyl-*N*-phenylbenzenamine (Entry 4, Table 3): Brown solid (Yield=87%), mp= 80-85 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.61(s, br, 1H), 7.23-7.21(m, 2H), 7.12-7.10(m,

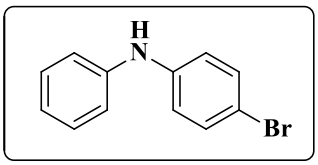
2H), 7.03-7.00(m, 4H), 6.87(t, *J*=8Hz, 1H), 2.59(q, *J*=8Hz, 3H), 1.24-1.21(m, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 143.9, 140.5, 137.5, 129.3, 128.7, 120.4, 118.8, 117.0, 28.2, 15.8 ppm.



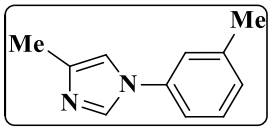
4-methoxy-*N*-phenylbenzenamine (Entry 5, Table 3): White solid (Yield=82%), mp= 105-110 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.49(s, br, 1H), 7.23-7.16(m, 3H), 7.08-7.06(m, 4H), 3.80(s, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 128.2, 128.0, 127.2, 121.1, 118.5, 114.6, 113.6, 54.5 ppm.



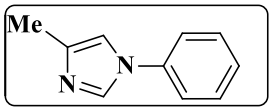
***N*-(4-*t*-butylphenyl)-4-bromobenzenamine (Entry 6, Table 3):** Brown solid (Yield=88%), mp=142-145 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.64(s, br, 1H), 7.32-7.29(m, 4H), 7.01(d, *J*=8Hz, 2H), 6.89(d, *J*=8Hz, 2H), 1.31(s, 9H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 139.7, 132.1, 126.2, 118.7, 118.4, 111.9, 34.2, 30.9 ppm.



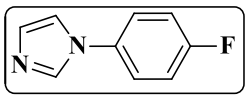
4-bromo-*N*-phenylbenzenamine (Entry 7, Table 3): Brown liquid (Yield=75%), ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.67(s, br, 1H), 7.35-7.32(m, 2H), 7.28(d, *J*=8Hz, 2H), 7.05(d, *J*=8Hz, 2H), 6.98-6.92(m, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 142.5, 132.2, 129.5, 121.7, 119.1, 118.3, 112.7 ppm.



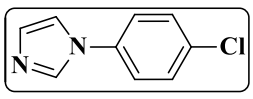
1-phenyl-1*H*-imidazole (Entry 9, Table 3): Brown liquid (Yield=89%), ^{1}H NMR (400 MHz, $CDCl_3$): 7.87(s, 1H), 7.50-7.47(m, 2H), 7.40-7.35(m, 3H), 2.28(m, 1H), 7.21(s, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.4, 135.6, 130.3, 129.9, 127.6, 121.6, 118.3 ppm.



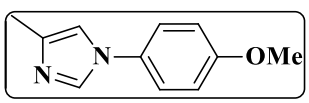
4-methyl-1-phenyl-1*H*-imidazole (Entry 10, Table 3): Brown liquid (Yield=88%), ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.75(s, 1H), 7.49-7.43(m, 3H), 7.35-7.33(m, 2H), 7.00(s, 1H), 2.30(s, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 139.4, 137.5, 134.6, 129.8, 127.2, 125, 6, 121.1, 114.6, 13.6 ppm.



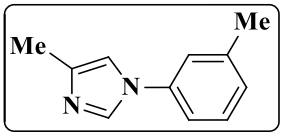
1-(4-fluorophenyl)-1*H*-imidazole (Entry 11, Table 3): Yellow gum (Yield=74%), ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.80(s, 1H), 7.38-7.35(m, 2H), 7.23-7.18(m, 4H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 162.9, 135.8, 133.6, 130.4, 123.5, 118.6, 116.9, 116.7 ppm.



1-(4-chlorophenyl)-1*H*-imidazole (Entry 12, Table 3): Brown liquid (Yield=78%), ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.89(s, 1H), 7.46(d, *J*=8Hz, 2H), 7.35-7.26(m, 4H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 136.1, 133.3, 120.0, 122.8 ppm.

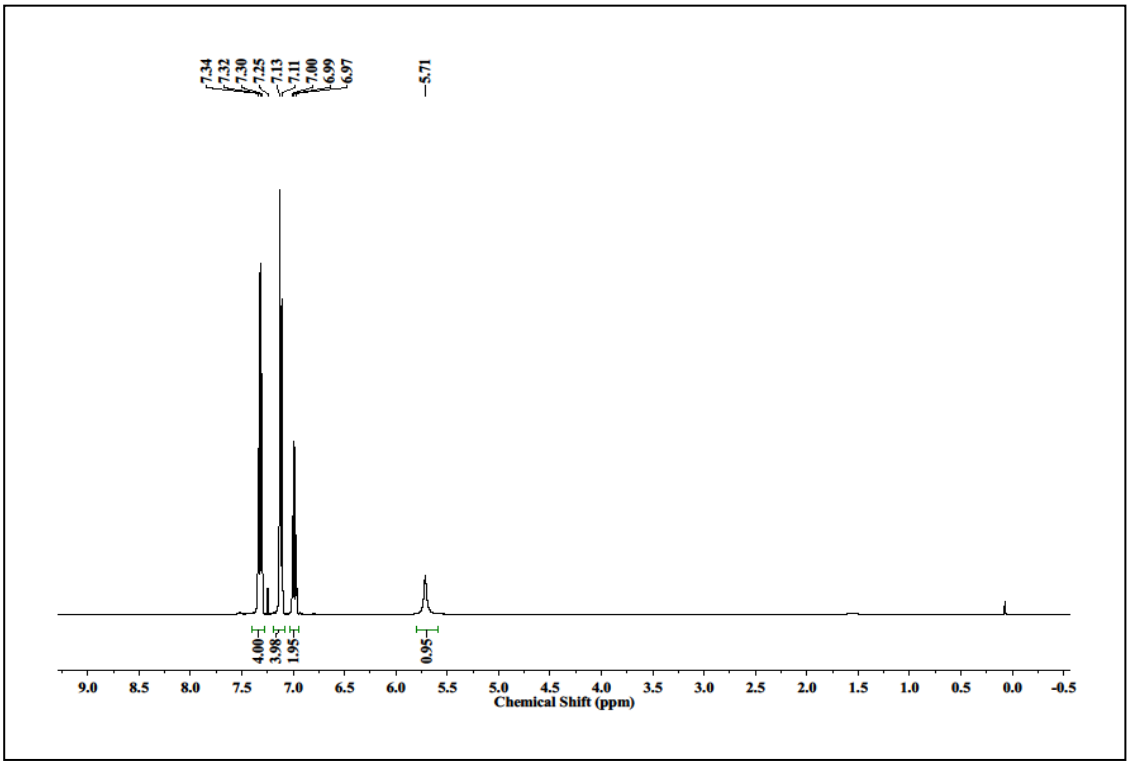


1-(4-methoxyphenyl)-4-methyl-1*H*-imidazole (Entry 13, Table 3): White solid (Yield=90%), mp= 150-152 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.65(s, 1H), 7.25(s, 1H), 7.21(d, *J*=8Hz, 1H), 6.99-6.92(m, 3H), 3.83(s, 3H), 2.28(s, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.7, 139.0, 134.8, 130.9, 127.0, 122.9, 114.9, 55.6, 13.6 ppm.

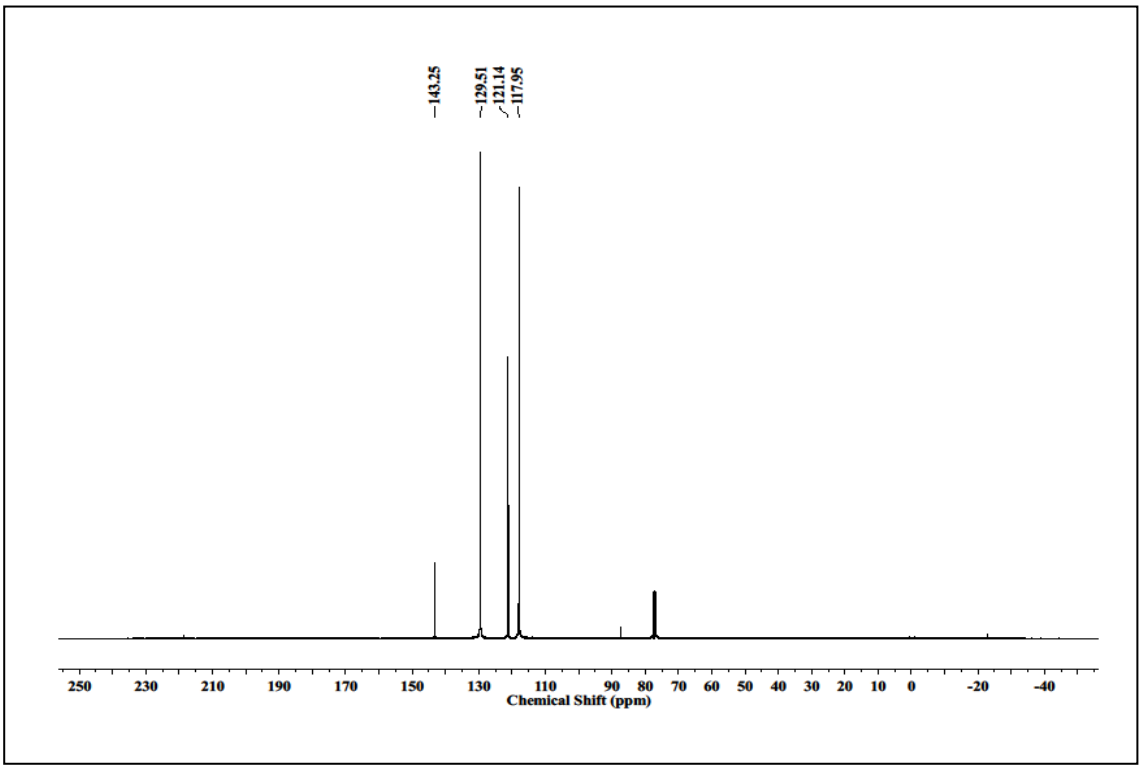


1-*m*-tolyl-1*H*-imidazole (Entry 14, Table 3): White solid (Yield=89%), mp= 140-142 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.80(s, 1H), 7.32-7.29(m, 1H), 7.22(s, 1H), 7.15-7.12(m, 4H), 2.38(s, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 140.1, 137.3, 135.6, 130.2, 129.7, 128.2, 122.1, 118.6, 118.3, 21.4 ppm.

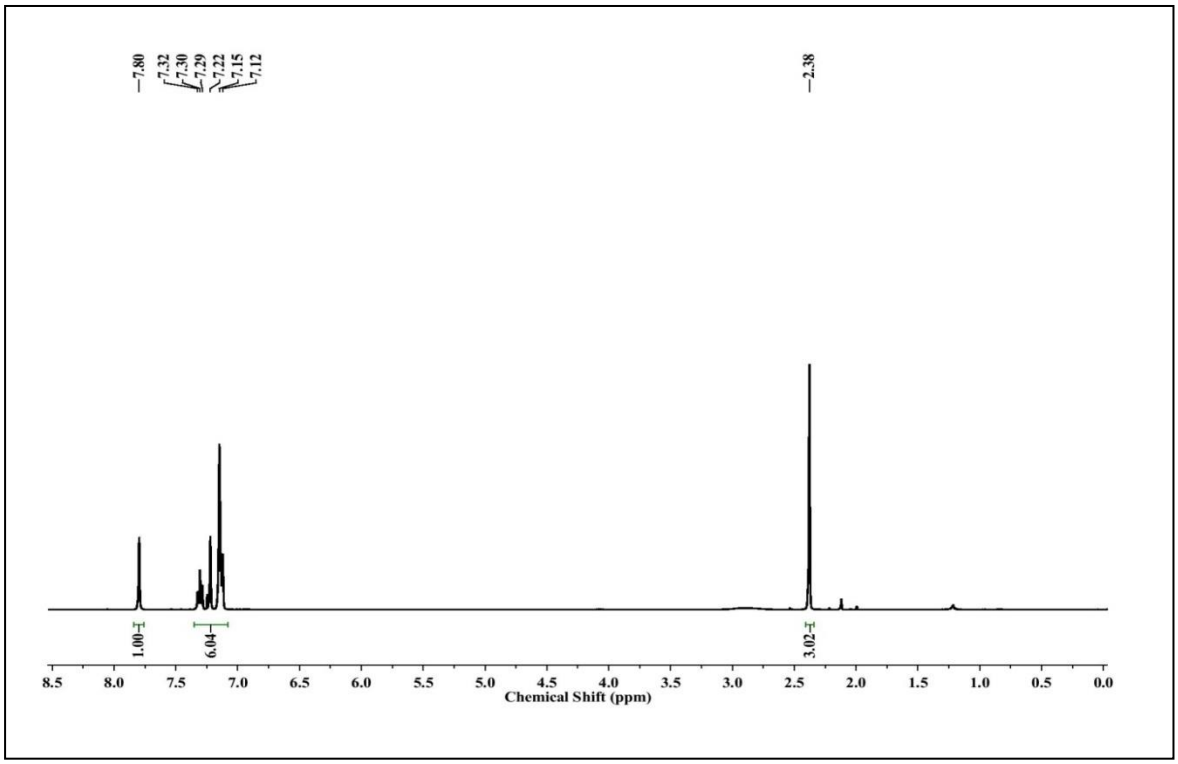
^{1}H NMR spectrum of diphenylamine



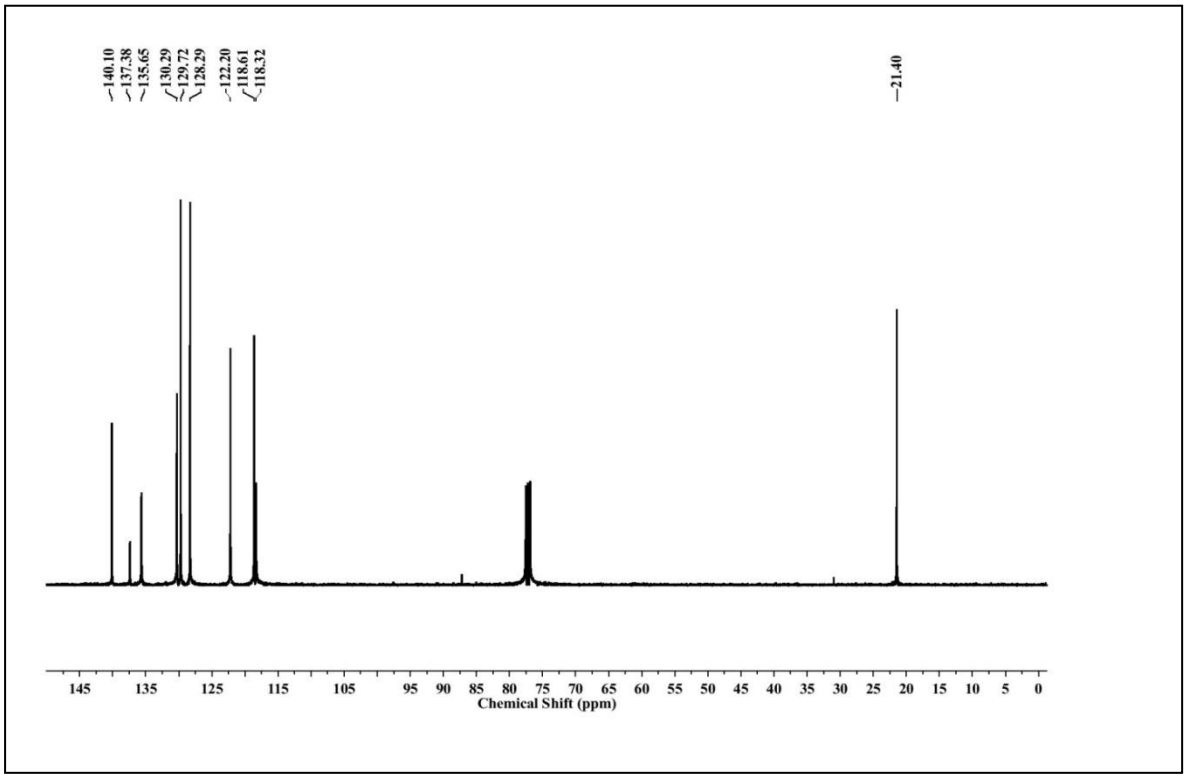
^{13}C NMR spectrum of diphenylamine



^{1}H NMR spectrum of 1-*m*-tolyl-1*H*-imidazole



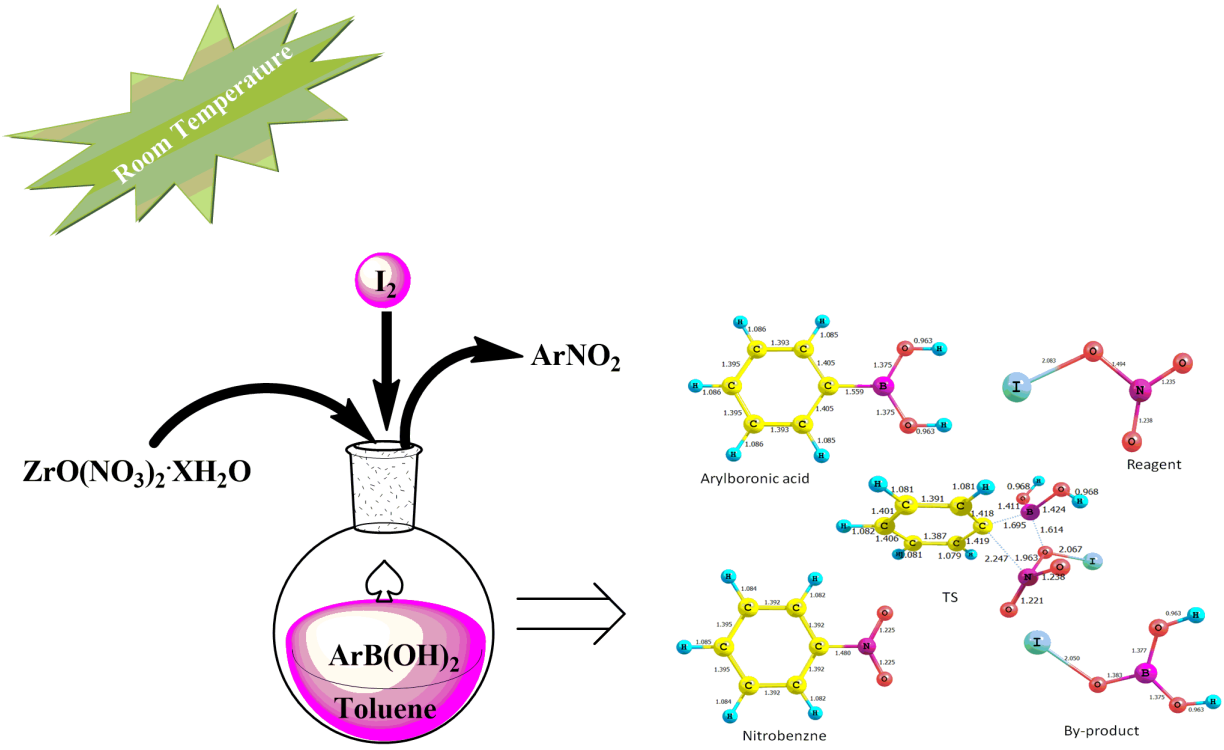
^{13}C NMR spectrum of 1-*m*-tolyl-1*H*-imidazole



Chapter 3

Section 3.2

Molecular iodine catalyzed *ipso*-nitration of arylboronic acid at room temperature with zirconium oxynitrate: A theoretical and experimental investigation.



Strong acid/oxidant free condition.
Avoids high temperature, ligand etc.
Mild oxidant and nitrating agent are used.

3.2. A. Introduction:

In the challenging domain of synthetic organic chemistry, nitration of arenes has emerged as one of the most fundamental and important organic transformation reactions, both for academic interest and industrial applications. The aromatic nitro compounds find lots of interest in the field of pharmaceutical science, plastic technology, dye chemistry and in the synthesis of explosive compounds. We have already discussed about the demerits associated with the classical aromatic nitration process in the introduction section of chapter 3. To overcome these problems varieties of protocols were established employing nitrate salts/oxidants system on different substrates like aryl halide, phenolic compounds, aryl azide etc. Transition metal catalysis is also observed to be used for the synthesis of nitroarenes. Though these methods are able to eliminate some drawbacks like use of strong acids, carcinogenic starting material etc. but they cannot find a permanent solution for poor regioselectivity and functional group tolerance. So, nowadays arylboronic acids have emerged out to be prominent candidate to remove such regioselectivity and functional group tolerance problem. A few reports are found on *ipso*-nitration of arylboronic acid using nitrate salt and oxidant furnishing moderate to good conversion and most of them are applicable towards both aryl and hetero aryl moieties. But, still researchers are paying increasing attention for development of methodology towards *ipso*-nitration of arylboronic acid because the reported protocols are performed high temperature or take long reaction time. Moreover, many of them also involves strong oxidizing agent.

Continuing our project to develop mild and efficient protocol for C-N bond formation reaction, herein, in this section, we report an *ipso*-nitration of arylboronic acid using zirconium oxynitrate as a nitrating species and molecular iodine as an oxidizing agent. In recent times, there is an increasing interest on molecular iodine catalyzed organic transformations owing to its numerous advantages such as it is powerful, inexpensive and readily available catalyst [85]. This has also relevance with regard to green chemistry. On the other hand, easily available, $ZrO(NO_3)_2{\cdot}XH_2O$ is safe and easy to hand nitrating source [86]. In order to provide strong support to the experimental work for the titled reaction, theoretical calculation was performed using DFT. Here, based in these findings, we present feasibility of the reaction and exploration of the reaction pathway on potential energy surface (PES) along with transition state (TS). Intrinsic

reaction coordinate (IRC) calculation has also been performed to confirm the smooth transition from the reactant to product through the respective TS.

3.2. B. Experimental:

General information:

^{1}H and ^{13}C NMR spectra of the products were recorded in a JNM ECS 400 MHz NMR spectrophotometer (JEOL) using tetramethylsilane (TMS) as the internal standard. Chemical shift values are expressed in ppm. Coupling constants are expressed in Hertz. Reactions were monitored by thin-layer chromatography using aluminium sheets with silica gel $60F_{254}$ (Merck). UV light and Iodine vapour were used as visualizer. Chemicals are obtained from commercial sources.

General experimental procedure for *ipso*-nitration of arylboronic acid:

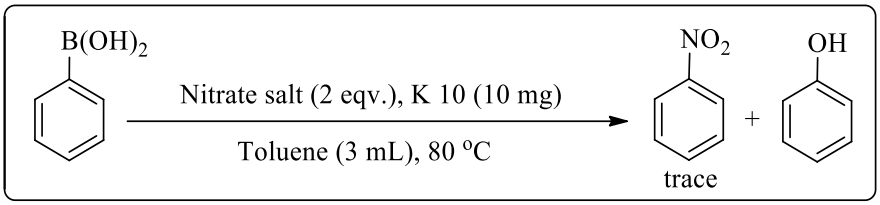
A 50 mL two necked round bottomed flask was charged with arylboronic acid (1 mmol), $ZrO(NO_3)_2{\cdot}XH_2O$ (1.5 mmol), Iodine (10 mol%) and the reaction mixture was stirred at room temperature in toluene (4 mL) under nitrogen atmosphere. After completion of the reaction (TLC), the reaction mixture was filtered with whatman filter paper 40 and the residue was washed with ethyl acetate followed by DCM (3×15 mL) and diluted with water (10 mL). The DCM extract was washed with sodium thiosulphate solution (10 mL). The separated organic layer was dried over anhydrous sodium sulphate, filtered and concentrated under reduced pressure. The crude material so obtained was purified by column chromatography on silica gel (eluting ethyl acetate: hexane). All the compounds were characterized by ^{1}H and ^{13}C NMR spectroscopy and finally compared with authentic compounds.

3.2. C. Results and discussion:

To optimize our *ipso*-nitration protocol, we planned to investigate our reaction with different nitrate sources such as cupric nitrate, ammonium nitrate, cobalt nitrate, silver nitrate, zirconium oxynitrate etc. To begin with, a round bottomed flask was charged

with 1 mmol of phenylboronic acid as the model substrate and cupric nitrate (2 mmol) as the nitrating agent under stirring followed by heating up to 80 ˚C. Initially, we decided to perform the reaction with 10 mg of montmorillonite K 10 clay as an acidic additive and it showed very little conversion to nitroarenes along with formation of phenol as the side product. Interestingly, the reaction without K 10 showed no conversion to nitroarene at all. This particular result signified the importance of acidic additive for targeted nitrobenzene product. For the next assessment, we carried out the reaction with diverse nitrate salts. When we replaced the cupric nitrate salt by ammonium nitrate, cobalt nitrate, silver nitrate and sodium nitrate formation of phenol discontinued but the yield of the nitroarene was found to be moderate (Table 1, Entries 2-5). However, we observed slightly better results with zirconium oxynitrate salt as nitrating source (Table 1, Entry 6).

Table 1. Optimization of reaction condition for different nitrate salt[a]



Entry	Nitrate salt	Yield (%)[b]
1	Cupric nitrate	20
2	Ammonium nitrate	25
3	Cobalt nitrate	40
4	Silver nitrate	8
5	Sodium nitrate	13
6	Zirconium oxynitrate	55

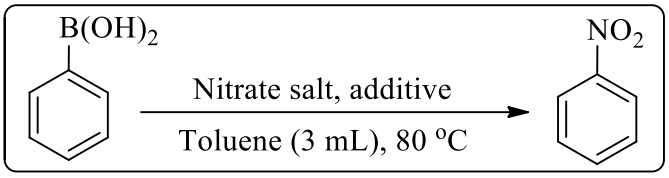
[a]Reaction condition: Phenylboronic acid (1 mmol), temperature: 80 °C. [b]Isolated yield

Further, fixing $ZrO(NO_3)_2{\cdot}XH_2O$ (2 mmol), oxidants were altered with the aim to achieve better conversion. Progress of the reaction was checked with solid acids such as *p*-TSA, silica, alumina etc. However, no noticeable improvement in result was observed (Table 2, Entries 1-3). Interestingly, use of *o*-phosphoric acid as an oxidant gave better conversion with $ZrO(NO_3)_2{\cdot}XH_2O$ as the nitrate source (Table 2, Entry 4). However, acetic acid as additive failed to afford a good conversion of the desired product nitrobenzene.Interestingly, the reaction catalyzed by molecular iodine showed best

conversion with trace amount of nitrosobenzene (Table 2, Entry 6) in 12 h at 80 ˚C. Moreover, use of other additives such as silica, montmorillonite K 10 along with molecular iodine, the reaction completed quickly although formation of nitrosobenzene was also observed. Then, we move forward to check the reaction with iodine (20 mol%) as oxidant and tried with other nitrate sources (Table 2, Entries 7-11). Again, we found zirconium nitrate as the most suitable nitrating agent for *ipso*-nitration protocol. Several test reactions were carried out by using different amounts of I_2 to optimize the amount of catalyst for maximum yield of the product. It has been observed that with 20 mol% of the catalyst (molecular iodine), the reaction was completed in 12 h (Table 2, Entry 6). Then, the reaction was carried out with 15 mol%, 10 mol%, and 5 mol% (Table 2, Entries 12-15) of catalyst respectively under the same reaction conditions. Comparable yield was obtained with 15 mol% and 10 mol% of the catalyst in 12 h. However, the reaction with 5 mmol% of the catalyst did not show completion even after 24 h. Interestingly, when the reaction was carried out at room temperature using 10 mol% of the catalyst, to our delight, the reaction was complete with the same yield of conversion in 18 h. Later, by varying the amount of the nitrate salt, we found best result with 1.5 mmol of the nitrate salt (Table 2, Entry 16), and further lowering of the amount nitrate salt to 1 mmol afforded lower yield of the product (Table 2, Entry 17). At last to know the effect of air in the reaction, we performed a reaction under N_2 atmosphere keeping all other reaction parameter same as in Entry 16, Table 2. Interestingly, we observed a better result with exclusive formation of nitrobenzene. Formation of byproduct nitrosobenzene was completely ceased under nitrogen atmosphere. Additionally, the reaction was completed within short time interval in comparison to air atmosphere.

To study the effect of solvents in our system, the reaction was investigated with different polar, non-polar, protic and aprotic solvents. Among the aprotic solvents such as toluene, xylene, DCM and chloroform, except toluene and xylene, others failed to show efficiency as good solvent. The reaction did not proceed smoothly in DMSO, iso-propanol, methanol, and water and showed poor conversion. Among toluene and xylene, we consider toluene as the best solvent. The effect of different solvents on the reaction is shown in Table 3.

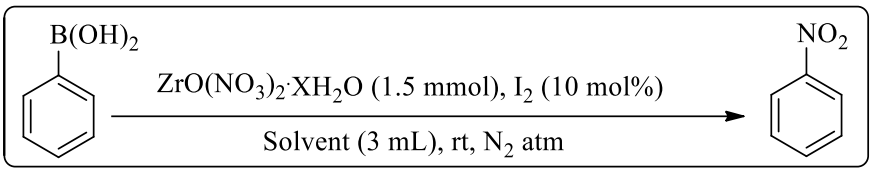
Table 2. Optimization of reaction condition[a] for different additives, nitrate salt and amount of the catalyst



Entry	Nitrate salt	Additive	Time (h)	Yield (%)[b,c]
1	Zirconium oxynitrate (2 mmol)	*p*-TSA (15 mg)	22	42
2	Zirconium oxynitrate (2 mmol)	Silica (15 mg)	24	34
3	Zirconium oxynitrate (2 mmol)	Alumina (15 mg)	24	45
4	Zirconium oxynitrate (2 mmol)	H_3PO_4 (2 mL)	24	84
5	Zirconium oxynitrate (2 mmol)	CH_3COOH (2 mL)	24	23
6	Zirconium oxynitrate (2 mmol)	I_2 (20 mol%)	12	89
7	Cupric nitrate (2 mmol)	I_2 (20 mol%)	12	45
8	Cobalt nitrate (2 mmol)	I_2 (20 mol%)	12	25
9	Ammonium nitrate (2 mmol)	I_2 (20 mol%)	12	20
10	Silver nitrate (2 mmol)	I_2 (20 mol%)	12	28
11	Sodium nitrite (2 mmol)	I_2 (20 mol%)	12	30
12	Zirconium oxynitrate (2 mmol)	I_2 (15 mol%)	12	89
13	Zirconium oxynitrate (2 mmol)	I_2 (10 mol%)	12	89
14	Zirconium oxynitrate (2 mmol)	I_2 (5 mol%)	24	67
15[c]	Zirconium oxynitrate (2 mmol)	I_2 (10 mol%)	18	89
16[c]	Zirconium oxynitrate (1.5 mmol)	I_2 (10 mol%)	18	89
17[c]	Zirconium oxynitrate (1 mmol)	I_2 (10 mol%)	18	65
18[c,d]	Zirconium oxynitrate (1.5 mmol)	I_2 (10 mol%)	12	92

[a]Reaction condition: Phenylboronic acid (1 mmol), Nitrate salt (2 mmol), Toluene (3 mL). [b]Isolated yield. unless otherwise noted. [c]Room temperature. [d]Under nitrogen atmosphere.

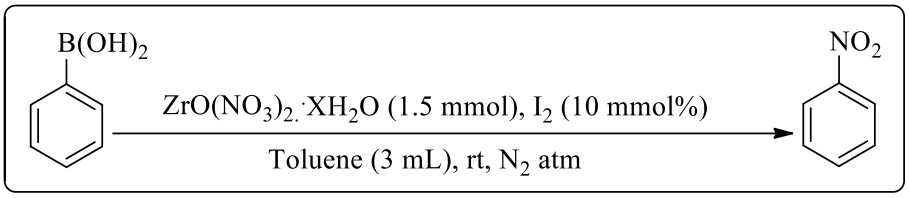
Table 3. Effect of different solvents on the reaction



Entry	Solvent	Yield (%)
1	Toluene	89
2	Xylene	83
3	DCM	62

4	Chloroform	62
5	DMSO	38
6	Iso-propanol	16
7	Methanol	20
8	Water	8

So, based on our observations, we fixed the optimized reaction conditions as outlined in **Scheme 1**.

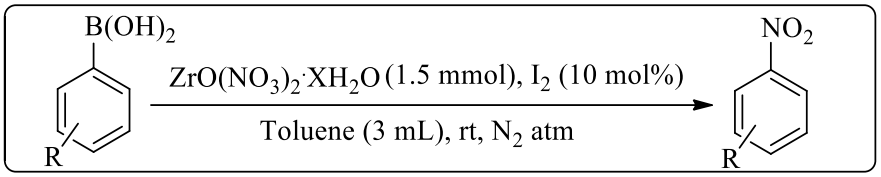


Scheme 1: Optimized reaction condition for the reaction

With the optimized reaction conditions, further study on the generality of the *ipso*-nitration protocol was extended to variety of substituted arylboronic acids (Table 4, Entries 1-17). Phenylboronic acids having electron withdrawing as well as donating groups also found to give corresponding nitrobenzene in excellent yields. Heteroarylboronic acids provided moderate results (Table 4, Entries 12 and 13). Interestingly, no significant effects were observed for sterically demanded arylboronic acid moiety (Table 4; Entries 5, 10, 12, 13, 15 and 16) as well as electron donating and withdrawing substrates.

It has been reported that the *ipso*-nitration of arylboronic acids usually progressed through free radical pathway [93]. So, to investigate the reaction mechanism, at first we have performed the radical trapping experiment by using stoichiometric amount of radical scavenger 2,2,6,6-tetramethyl piperidine-*N*-oxide (TEMPO). We added TEMPO to the reaction mixture under the same condition but the reaction was found to progress even after addition of the same; this result ruled out the possibility of radical mechanism for the current reaction protocol.

Table 4. Molecular iodine catalyzed synthesis of nitrobenzene from arylboronic acids[a]



Entry	R	Time (h)	Yield (%)[b,c]
1	H	12	89
2	4-bromo	18	84
3	4-formyl	12	85
4	3-formyl	20	79
5	2,4-dichloro	18	85
6	3-chloro	18	87
7	4-hydroxy	16	85
8	4-amino	12	89
9	4-methoxy	12	86
10	2-methyl	20	78
11	4-methyl	16	81
12	2-thiophenyl	8	83
13	2-methoxy-6-pyridyl	11	80
14	4-flouro	14	86
15	2,4-diflouro	17	86
16	2-chloro	16	84
17	4-chloro	14	88

[a]Reaction condition: Phenylboronic acid (1 mmol), Nitrate salt (1.5 mmol), Toluene (3 mL), room temperature. [b]Isolated yield. [c]Under N_2 atm.

Therefore, we have suggested a plausible mechanistic pathway based on the reported procedure of non radical pathway [80] (**Fig. 1**). It is believed that initially, iodine reacts with nitrate salt to form a nitro substituted iodine monoxide species, consequently the oxygen of this species reacts at electron deficient boron via the lone pair of electron and forms an intermediate (A) which rearranges to form the desired nitrobenzene.

Mechanism of the reaction:

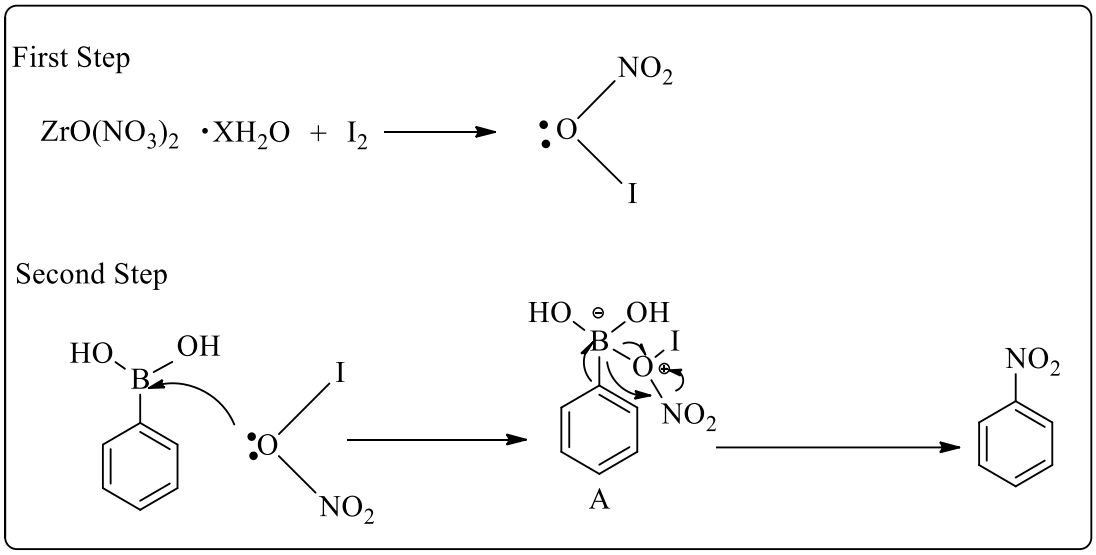
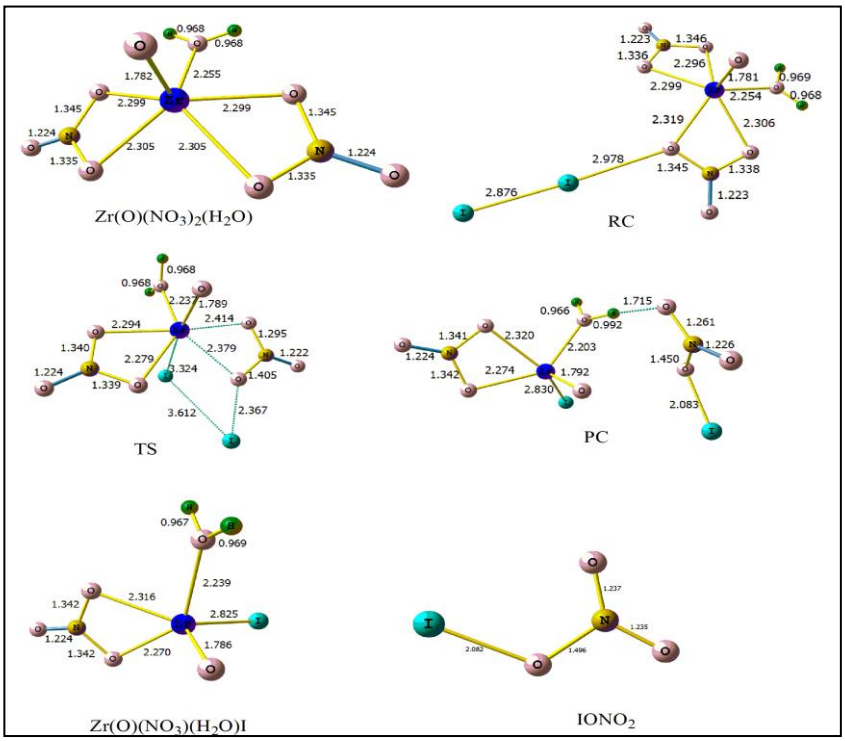


Fig. 1: Plausible reaction mechanism

To visualize more insight into the reaction, theoretical investigation was carried out. The optimized structures of different species involved in the title reaction along with the first step obtained by DFT are shown in **Fig. 2.**

The vibrational frequencies of all of the optimized structures involved in both the steps are found to be positive, thereby, confirming them to be at energy minima except TSs (step 1 & step 2) which have negative frequencies at -77 *i* cm^{-1} and 256 *i* cm^{-1} respectively. Visualization of the imaginary frequency revealed a qualitative confirmation of the existence of TSs connecting reactants and products. IRC performed for each TS at the same level of theory and IRC plots is shown in **Fig. 3**. Results show that each transition state smoothly connects the reactant and the product sides. To understand the feasibility of the reaction path, standard reaction enthalpy ($\Delta_r H^0$) and Gibbs free energy ($\Delta_r G^0$) for the titled reaction were calculated (using the data provided in Table 6).



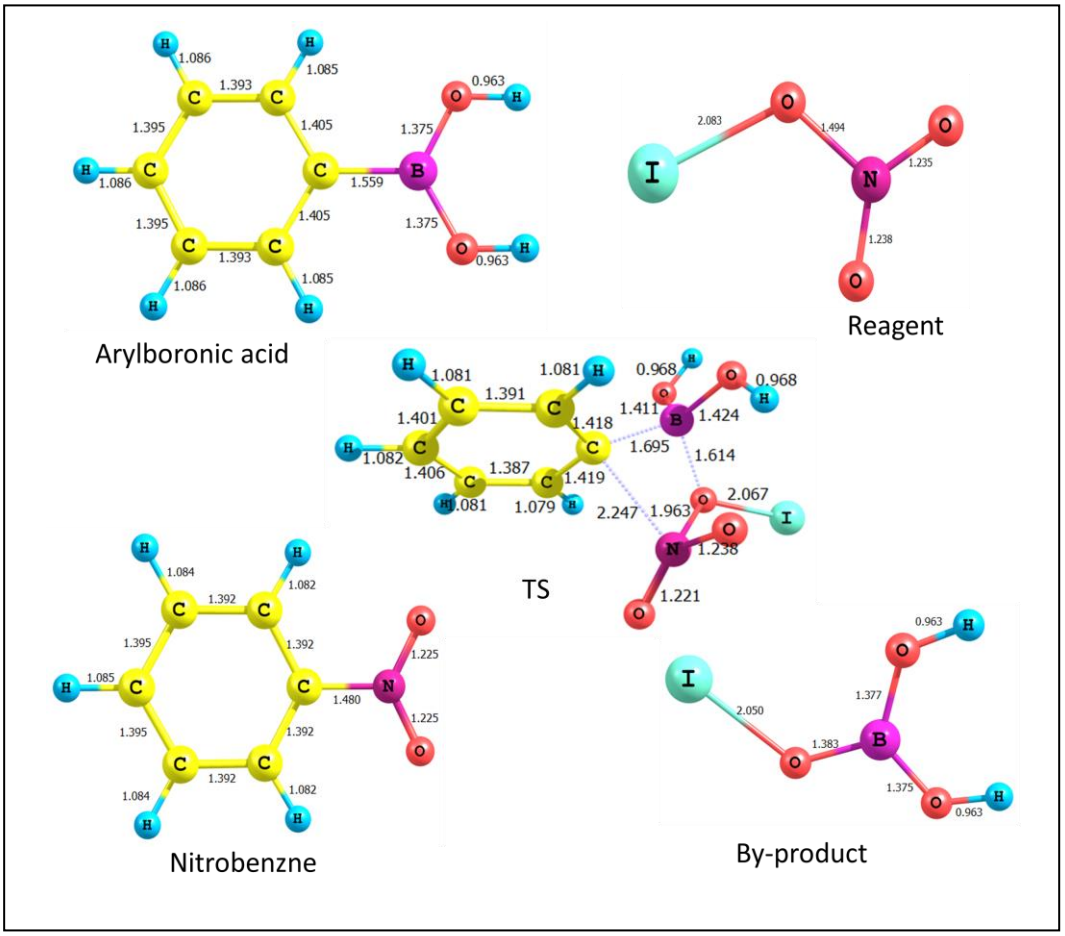


Fig. 2: Optimized structures of different species involved in both the steps.

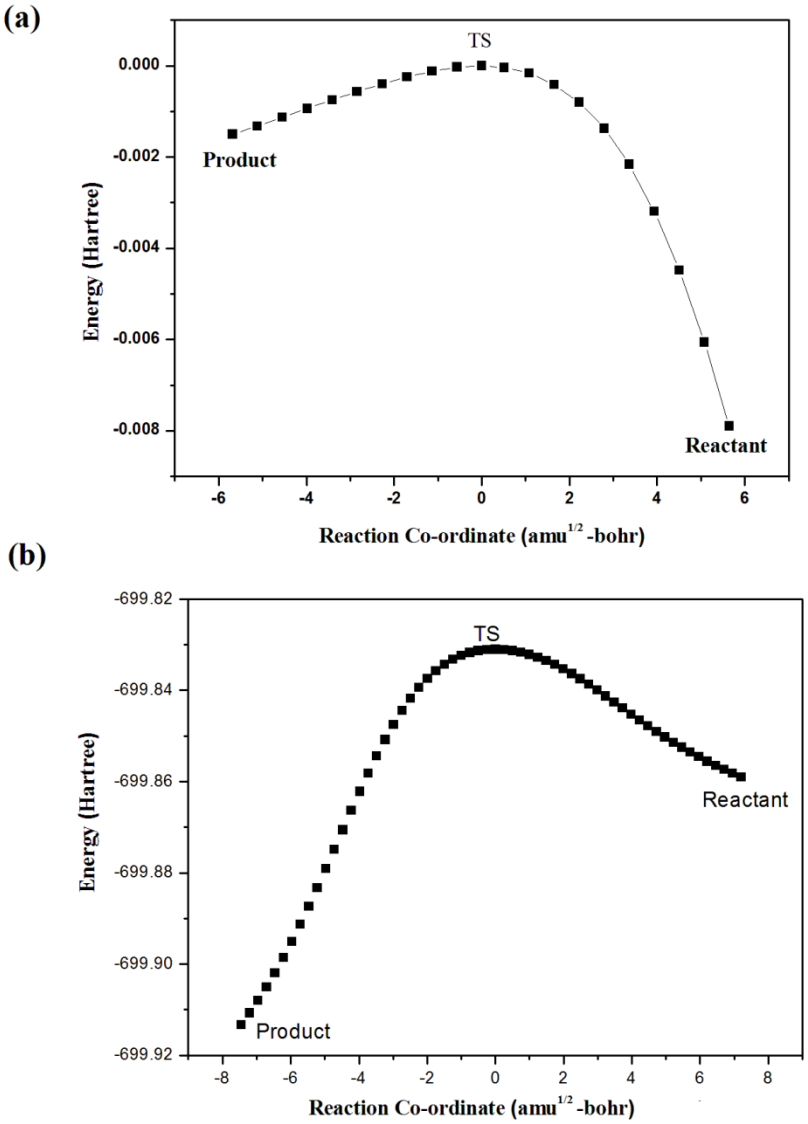


Fig. 3: IRC plots of transition states of (a) 1st step and (b) 2nd step

The $\Delta_r H^0$ and $\Delta_r G^0$ for the 1st step are found to be 38.70 kcal mol^{-1} and 35.75 kcal mol^{-1} respectively, indicating that this step is endothermic at 298 K. For the 2nd step, these values are obtained at -67.86 kcal mol^{-1} and -67.84 kcal mol^{-1} respectively which indicate the feasibility of the reaction. Relative energies (including ZPE) for each of the species are determined (Using data of Table 6) with respect to the reactants, setting it arbitrarily at zero and the results are recorded in Table 5.

A potential energy diagram (**Fig. 4**) of both steps are constructed with the results obtained at the DFT (B3LYP) level. The results show that the barrier height of 1st step is

34.32 kcal mol^{-1} and in the 2nd step they possesses a barrier height of 90.16 kcal mol^{-1} at B3LYP/6-31+G (d,p) level of theory.

Table 5. Relative energies (kcal mol^{-1}) of species involved in the reaction calculated at DFT (B3LYP) and levels of theory.

Reaction steps	Species	Relative Energies(Kcal mol^{-1})
1st step	$Zr(O)(H_2O)(NO_3)_2 + I_2$	0.00
	RC	-1.95
	TS	34.32
	PC	-6.04
	$Zr(O)(NO_3)I(H_2O) + IONO_2$	12.20
	$C_6H_5B(OH)_2+IONO_2$	0.00
2nd step	TS	90.16
	$C_6H_5NO_2+IOB(OH)_2$	-67.79

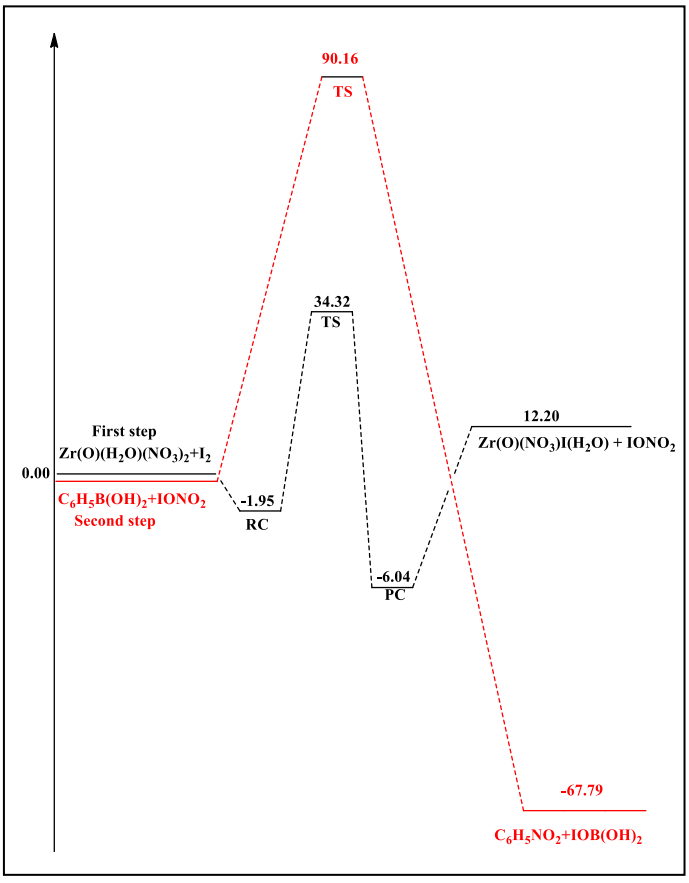


Fig. 4: Potential energy diagram of 1st step (black line) and 2nd step (red line).

From the above results we have also deduced the schematic diagram of the mechanism of both the steps. The involvement of each species in the mechanism is shown in Fig. 5.

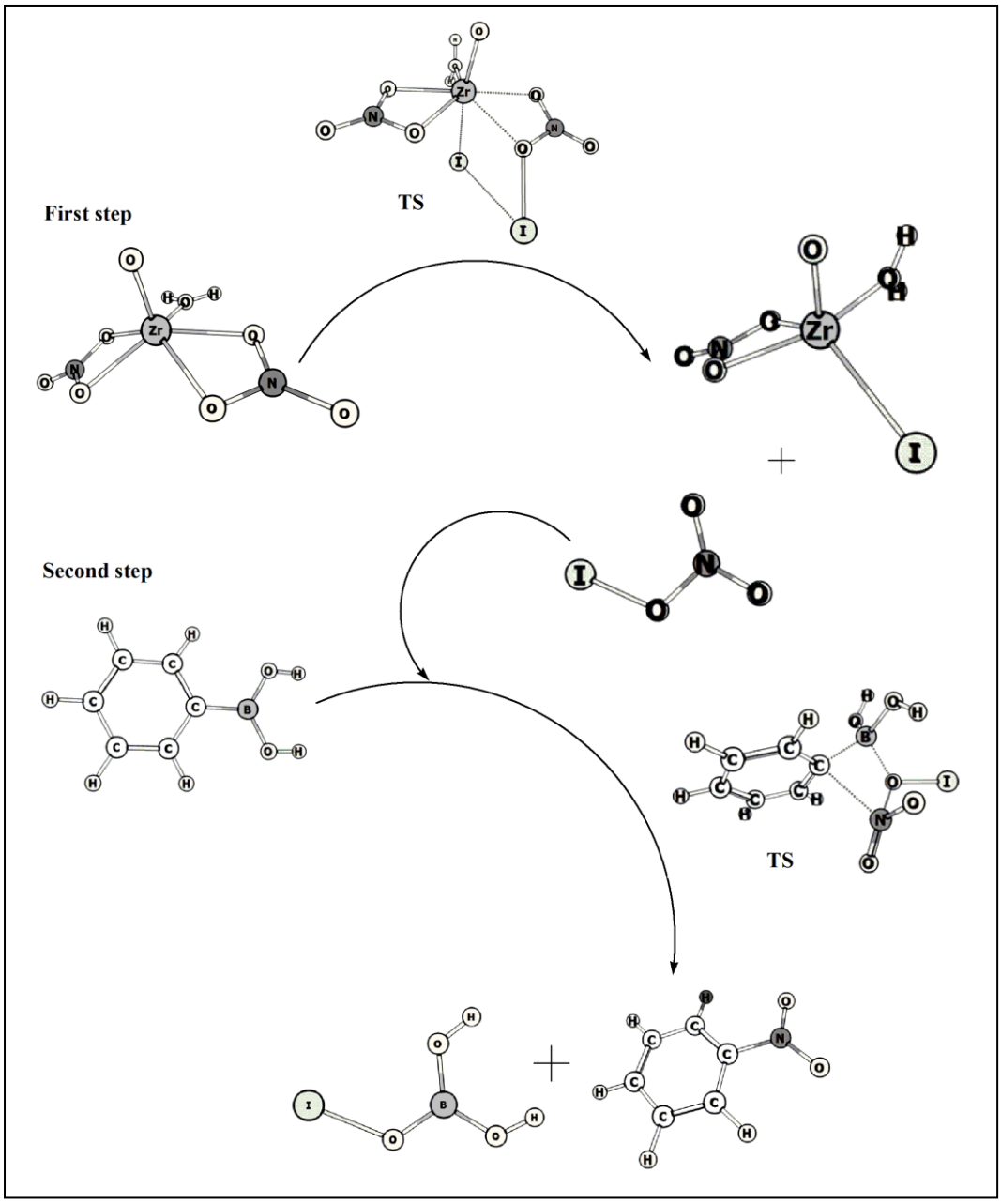


Fig. 5: Schematic diagram of the reaction mechanism.

Computational details:

The geometries of all the species involved in both the steps of the overall reaction channel are optimized at density functional B3LYP [87, 88] level of theory. During

geometry optimization, 6-311G+(d) basis set [89] was used for all elements except heavy atoms (I and Zr). Considering the strong relativistic effect of I and Zr atom, we have employed Los Alamos national laboratory 2 double zeta (LanL2DZ) basis set with effective core potential [90] for both heavy atoms present. In order to determine the nature of stationary points on the potential energy surface, vibrational frequency calculation was made using the same level of theory at which the optimization was made. All the electronic calculations were performed using GAUSSIAN 09 program package. The stationary points were identified to correspond to stable minima on the respective PES by ascertaining that all the harmonic vibrational frequencies were real and positive. The TSs in the reaction were obtained using synchronous transition-guided quasi-Newton (STQN) method [91, 92] and the first order saddle point was characterized by the presence of only one imaginary frequency (NIMAG=1). Intrinsic reaction coordinate (IRC) calculations were also performed in order to ascertain that the transition of reactant to product via corresponding TS was smooth. The minimum energy path (MEP) was obtained by IRC calculation performed [93].

3.2. D. Conclusions:

In conclusion, we have developed a mild, facile and efficient methodology for *ipso*-nitration of arylboronic acids catalyzed by molecular iodine (10 mol%) at room temperature with moderate to excellent yield. The methodology is applicable to both aryl- and heteroarylboronic acids within shorter reaction time. The new protocol is superior to the existing methodologies as it uses mild and safe nitrating source avoiding stronger acids. The most important factor is that the reaction occurs at room temperature which is an energy saving process. The reaction has added advantages such as non-requirement of any base and ligand. We have also analyzed the reaction mechanism theoretically using modern DFT. DFT calculation results show that the reaction is thermodynamically favorable and we have also proposed a reaction pathway along with TS on PES.

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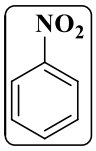
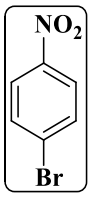
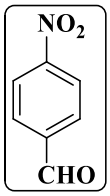
Characterisation data of the products:



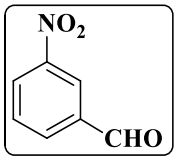
Nitrobenzene (**Entry 1, Table 4**): Yellow liquid (Yield=89%), ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.21(d, *J*=8.4Hz, 2H), 7.70-7.68(m, 1H), 7.54(d, *J*=8Hz, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 148.2, 134.7, 129.4, 123.3 ppm.



4-bromonitrobenzene (**Entry 2, Table 4**): White solid (Yield=84%), mp= 120-126 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.08(d, *J*=7.6Hz, 2H), 7.67(d, *J*=7.6Hz, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 147.0, 132.7, 132.5, 130.0, 125.0 ppm.

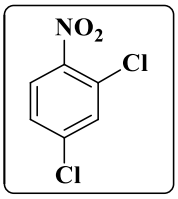


4-formylnitrobenzene (**Entry 3, Table 4**): White solid (Yield=85%), mp= 102-106 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 10.18(s, 1H), 8.40(d, *J*=6.8Hz, 2H), 8.10(d, *J*=8.4Hz, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 190.5, 151.1, 140.1, 130.6, 124.3 ppm.

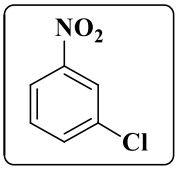


3-formylbiphenyl (**Entry 4, Table 4**): Brown solid (Yield=79%), mp= 55-60 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 10.14(s, 1H), 8.73-8.72(m, 1H), 8.53-8.50(m, 1H), 8.25(d,

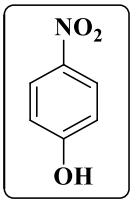
J=8Hz, 1H), 7.81-7.77(m, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 189.9, 148.8, 137.4, 134.8, 130.5, 128.7, 124.5 ppm.



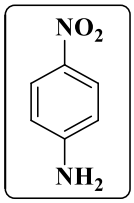
2,4-dichloronitrobenzene (**Entry 5, Table 4**): Yellow liquid (Yield=85%), ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.83(s, 1H), 7.48-7.47(m, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 156.6, 138.7, 131.1, 130.9, 129.7, 128.8, 128.2, 127.5, 126.9, 121.0, 111.4, 55.7 ppm.



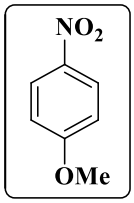
3-chloronitrobenzene (**Entry 6, Table 4**): White solid (Yield=87%), mp= 45-50 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.22-8.21(m, 1H), 8.15-8.10(m, 1H), 6.663-6.661(m, 1H), 7.51-7.47(m, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 148.8, 135.5, 134.8, 128.3, 130.4, 123.9, 121.7 ppm.



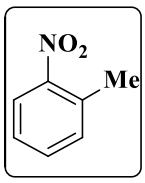
4-hydroxynitrobenzene (**Entry 7, Table 4**): White solid (Yield=85%), mp= 270-275 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.18(d, *J*=9.2Hz, 2H), 6.94(d, *J*=8Hz, 2H), 6.66(s, br, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 161.7, 141.5, 126.4, 115.8 ppm.



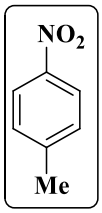
4-aminonitrobenzene (**Entry 8, Table 4**): Yellow solid (Yield=89%), mp= 330-335 ˚C, ^{1}H NMR (400 MHz, acetone-d_6): δ 7.95(d, *J*=6.8Hz, 2H), 6.70(d, *J*=7.2Hz, 2H), 6.03(s, br, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 155.2, 137.3, 126.1, 112.7 ppm.



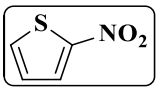
4-methoxynitrobenzene (**Entry 9, Table 4**): White solid (Yield=86%), mp= 50-53 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.22-8.19(d, *J*=9.2Hz, 2H), 6.96(d, *J*=7.2Hz, 2H), 3.91 (s, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 164.6, 141.5, 126.0, 114.0, 56.0 ppm.



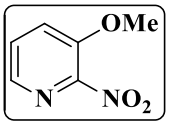
2-methylnitrobenzene (**Entry 10, Table 4**): Yellow liquid (Yield=78%), ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.13-7.09(m, 1H), 6.75-6.73(m, 1H), 6.65-6.62(m, 2H), 2.29(s, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 155.5, 139.9, 129.5, 121.6, 116.1, 112.3, 21.4 ppm.



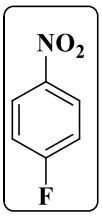
4-methylnitrobenzene (**Entry 11, Table 4**): White solid (Yield=81%), mp= 50-55 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.11(d, *J*=8.8Hz, 2H), 7.33-7.27(m, 2H), 2.46(s, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 146.1, 129.9, 123.5, 21.7 ppm.



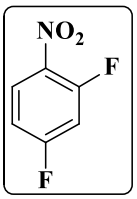
2-thiophenyl nitrobenzene (**Entry 12, Table 4**): White gum (Yield=83%), ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.93-7.92(m, 1H), 7.56-7.55(m, 1H), 7.40-7.39(m, 1H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 132.6, 128.6, 127.5, 127.0, 126.9 ppm.



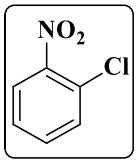
3-methoxy-2-nitropyridine (**Entry 13, Table 4**): White solid (Yield=80%), mp= 75-80 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.41-8.40(m, 1H), 8.29-8.28(m, 1H), 7.07-7.04(m, 1H), 4.12(s, 3H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 156.6, 151.8, 135.1, 134.0, 116.5, 54.8 ppm.



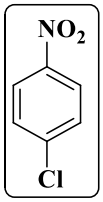
4-Fluoronitrobenzene (**Entry 14, Table 4**): Yellow liquid (Yield=86%), ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.28(d, *J*=8Hz, 2H), 7.24(d, *J*=8Hz, 2H), 7.39-7.36(m, 2H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.6, 165.0, 144.4, 126.4, 126.3, 116.5, 116.3 ppm.



2,4-diflouronitrobenzene (**Entry 15, Table 4**): Yellow solid (Yield=86%), mp= 12-15 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.19-8.17(m, 1H), 7.09-7.05(m, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.1, 164.4, 134.1, 128.3, 128.27, 112.2, 106.6 ppm.

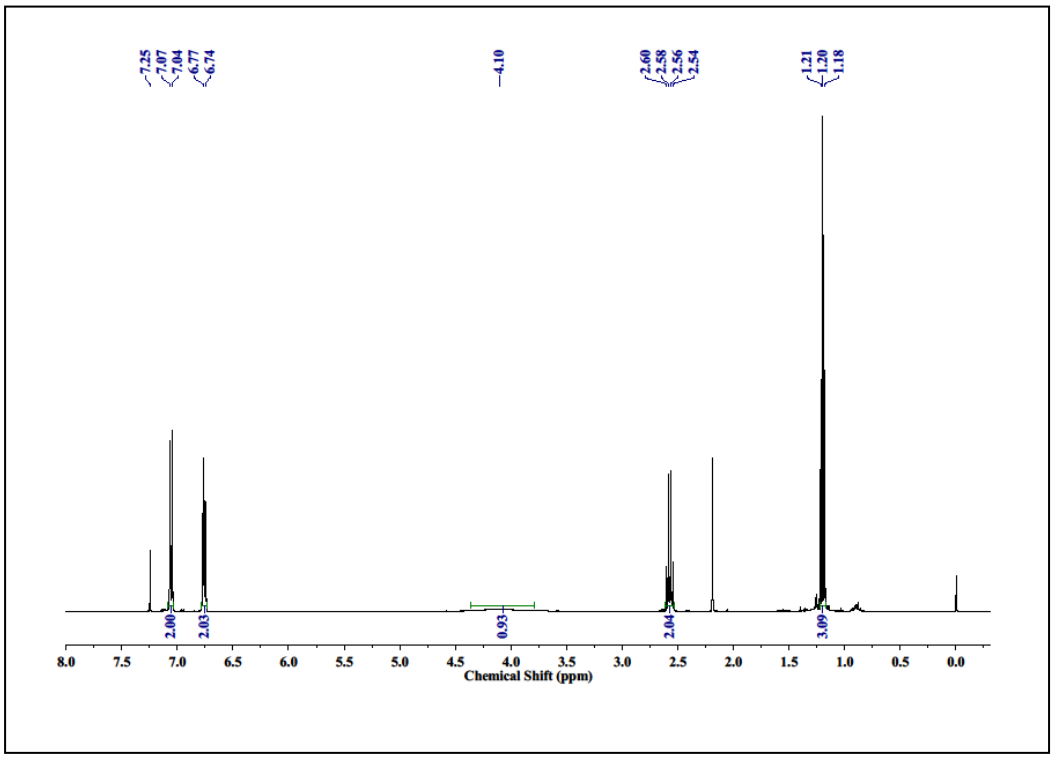


2-chloronitrobenzene (**Entry 16, Table 4**): Yellow solid (Yield=84%), mp= 30-33˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.87-7.85(m, 1H), 7.56-7.53(m, 2H), 7.45-7.40(m, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 148.1, 133.2, 131.9, 127.4, 125.6 ppm.



4-chloronitrobenzene (**Entry 17, Table 4**): Yellow solid (Yield=88%), mp= 80-85 ˚C, ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.79(d, *J*=8.4Hz, 2H), 7.52(d, *J*=9.2 Hz, 2H) ppm; ^{13}C NMR (100 MHz, $CDCl_3$): δ 146.5, 141.4, 129.6, 125.0 ppm.

^{1}H NMR spectrum of 4-amino-nitrobenzene



^{13}C NMR spectrum of 4-amino-nitrobenzene

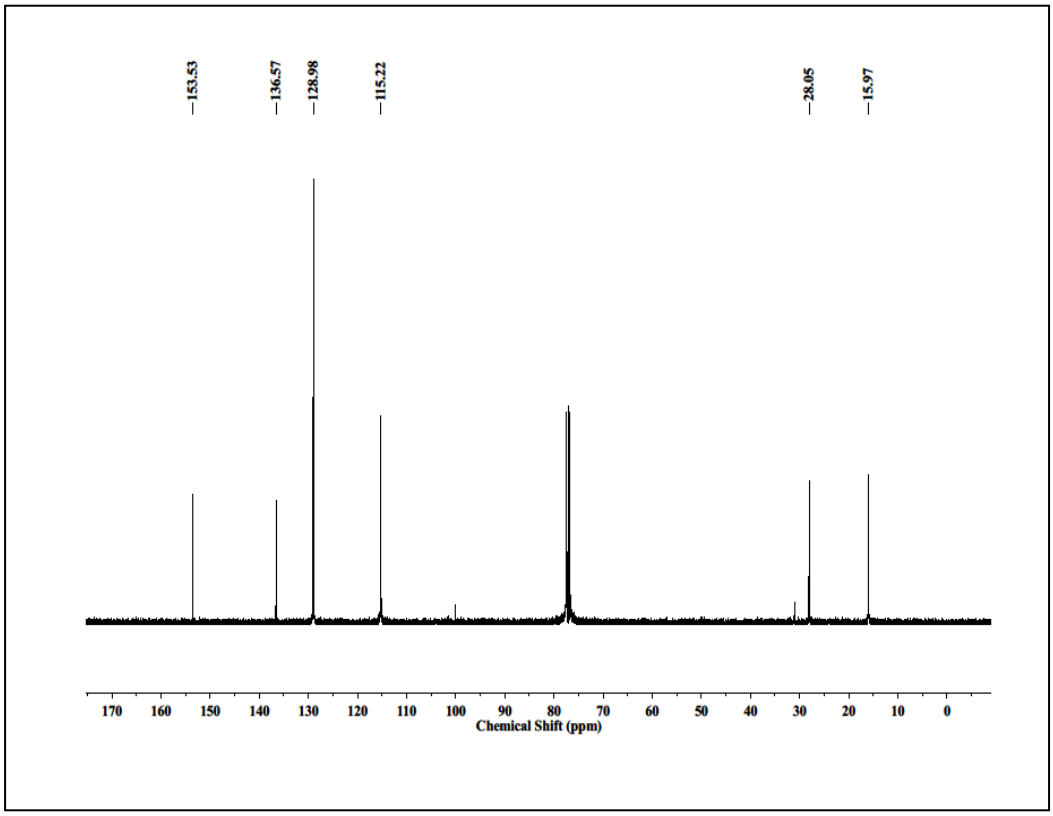


Table 6. Coordinates (in Ås) of each atom of optimized $Zr(O)(H_2O)(NO_3)_2$

Atom	Z (At. No.)	X	Y	Z
Zr	40	0.000014513	-0.000004167	0.000015292
O	8	0.000001194	0.000014612	-0.000010102
O	8	0.000005008	-0.000016823	-0.00001247
O	8	0.000012326	0.000006479	-0.000027584
O	8	0.000003218	-0.00002635	0.00002484
O	8	0.000000213	-0.000000003	0.000005771
O	8	-0.000005614	0.000009817	-0.000001544
H	1	0.000002442	0.000017604	0.000021422
H	1	0.000002884	0.000018472	0.00002084
N	7	-0.000033599	0.000000255	-0.00002812
N	7	0.00000124	0.000005228	-0.000018491
O	8	0.000014666	-0.000008883	0.000003232
O	8	-0.000018492	-0.000016241	0.000006914

Table 7. Coordinates (in Ås) of each atom of optimized RC

Atom	Z (At. No.)	X	Y	Z
Zr	40	0.000005921	0.000001095	0.000005459
O	8	0.000004645	-0.000001417	0.000000145
O	8	0.000005815	-0.000009168	0.00001331
O	8	-0.000004347	0.000001512	0.000002504
O	8	-0.000001185	-0.000000512	0.000002252
O	8	0.000002325	-0.000003142	0.000006666
O	8	-0.000000974	0.000003192	-0.000006538
H	1	-0.000001314	0.000004342	0.000008176
H	1	-0.000000506	0.000003182	0.000008026
N	7	-0.000003248	0.000000290	0.000001230
N	7	0.000003652	0.000003829	0.000003902
O	8	-0.000003757	0.000002326	0.000001428
O	8	0.000000871	-0.000002673	0.000003622
I	53	-0.000002939	0.000005014	-0.000003988
I	53	-0.000004959	-0.000007870	0.000023036

Table 8. Coordinates (in Ås) of each atom of optimized TS

Atom	Z (At. No.)	X	Y	Z
Zr	40	-0.000014374	0.000012567	-0.000003413
O	8	0.000006839	0.000020483	0.000005919
O	8	-0.000005022	0.000007145	0.000019045
O	8	0.000010272	-0.000004551	-0.000003791
O	8	0.000029684	-0.000000014	-0.000022356

O	8	-0.000022462	0.000006645	0.000004369
O	8	0.000004212	0.000040465	-0.000005833
H	1	0.000019387	0.000018185	-0.000004452
H	1	0.000010644	0.000000607	-0.000002931
N	7	0.000014444	-0.000003678	-0.000020632
N	7	-0.000013614	-0.00003142	0.000028506
O	8	0.000024256	-0.000010411	-0.00002583
O	8	-0.000032375	-0.000005871	0.000027634
I	53	-0.000032789	-0.0000286	0.000008253
I	53	0.000000901	-0.000021551	-0.000004489

Table 9. Coordinates (in Ås) of each atom of optimized PC

Atom	Z (At. No.)	X	Y	Z
Zr	40	-0.000000934	-0.000002521	-0.000007955
O	8	0.000006168	-0.000010444	-0.000003169
I	53	-0.000009141	0.000007428	-0.000032811
O	8	-0.0000156	0.000001301	-0.000003006
H	1	0.000000215	0.000025788	0.00001038
H	1	-0.000008185	0.000020622	0.000013652
O	8	-0.000000598	0.000003627	0.000010346
O	8	0.000004629	-0.000009129	-0.000007237
N	7	0.000003309	-0.000003287	0.000003662
O	8	0.000004415	-0.000005318	0.000008705
N	7	0.000013757	-0.000010523	0.000014559
12	8	-0.00000516	0.000001922	-0.000009963
I	53	0.000001081	-0.000008777	-0.000018926
O	8	-0.000001465	0.000001687	0.000011515
O	8	0.00000751	-0.000012376	0.000010249

Table 10. Coordinates (in Ås) of each atom of optimized $Zr(O)(NO_3)I(H_2O)$

Atom	Z (At. No.)	X	Y	Z
Zr	40	0.000011387	0.000003578	-0.000014526
O	8	0.000005884	0.000012345	-0.000011832
I	53	-0.000007498	-0.000011436	0.000005741
O	8	0.000004665	-0.000016915	-0.000021502
H	1	0.000014032	0.000001247	-0.000014716
H	1	0.000000403	-0.000029446	-0.000007046
O	8	-0.000003571	-0.000001748	0.000012606
O	8	-0.000007128	0.00001682	0.000014839
N	7	-0.000011692	0.000010277	0.000015853
O	8	-0.000006485	0.000015277	0.000020583

Table 11. Coordinates (in Ås) of each atom of optimized arylboronic Acid ($BC_6H_7O_2$)

Atom	Z (At. No.)	X	Y	Z
C	6	1.943429000	1.207370000	0.000019000
C	6	0.550652000	1.204513000	0.000039000
C	6	-0.171777000	-0.000014000	0.000012000
C	6	0.550668000	-1.204532000	-0.000019000
C	6	1.943446000	-1.207371000	-0.000022000
C	6	2.642112000	0.000004000	-0.000005000
H	1	2.485255000	2.148278000	0.000022000
H	1	0.010685000	2.145741000	0.000060000
H	1	0.010715000	-2.145770000	-0.000059000
H	1	2.485284000	-2.148273000	-0.000043000
H	1	3.727998000	0.000011000	-0.000016000
B	5	-1.731042000	-0.000028000	0.000001000
O	8	-2.382900000	-1.210612000	0.000031000
O	8	-2.382812000	1.210645000	-0.000055000
H	1	-3.345152000	-1.188091000	0.000159000
H	1	-3.345067000	1.188168000	-0.000076000

Table 12. Coordinates (in Ås) of each atom of optimized Reagent (NO_3I)

Atom	Z (At. No.)	X	Y	Z
N	7	1.968763000	0.081477000	-0.000207000
O	8	0.798139000	-0.846620000	0.000436000
I	53	-1.102000000	0.006025000	-0.000038000
O	8	3.021111000	-0.565733000	-0.000208000
O	8	1.758833000	1.301143000	0.000205000

Table 13. Coordinates (in Ås) of each atom of optimized nitrobenzene ($C_6NH_5O_2$)

Atom	Z (At. No.)	X	Y	Z
C	6	-1.821319000	-1.210157000	-0.000061000
C	6	-0.429833000	-1.218586000	-0.000034000
C	6	0.242309000	0.000008000	-0.000002000
C	6	-0.429843000	1.218595000	0.000063000
C	6	-1.821330000	1.210151000	0.000058000
C	6	-2.515856000	-0.000006000	-0.000010000
H	1	-2.362730000	-2.149748000	-0.000118000
H	1	0.133323000	-2.142239000	-0.000061000
H	1	0.133304000	2.142254000	0.000101000
H	1	-2.362748000	2.149737000	0.000109000
H	1	-3.600782000	-0.000010000	-0.000021000
N	7	1.722374000	0.000001000	-0.000003000
O	8	2.291147000	1.084500000	-0.000143000
O	8	2.29113400	-1.084505000	0.000134000

Table 14. Coordinates (in Ås) of each atom of optimized byproduct (BH_2O_3I)

Atom	Z (At. No.)	X	Y	Z
O	8	0.745804000	-0.795163000	0.000270000
I	53	-1.143879000	-0.001499000	-0.000027000
B	5	1.890622000	-0.019327000	0.000041000
O	8	1.780482000	1.353665000	0.000096000
O	8	3.061601000	-0.739394000	-0.000201000
H	1	2.537580000	1.949206000	-0.000239000
H	1	3.931797000	-0.325988000	0.000135000

Table 15. Energies, enthalpies and Gibb's free energies (including ZPE) of all the species involved in the reaction (all values are in Hartree) calculated at DFT (B3LYP) level

Species	Energy (E)	Enthalpy (H)	Gibbs Energy (G)
Step1			
$Zr(O)(H_2O)(NO_3)_2$	-758.966735	-758.952819	-759.007744
I_2	-22.76898	-22.765085	-22.794938
RC	-781.738826	-781.719939	-781.794168
TS	-781.684135	-781.66612	-781.734158
PC	-781.693756	-781.675277	-781.747528
$Zr(O)(NO_3)I(H_2O)$	-490.082151	-490.070126	-490.122698
Step2			
$PhB(OH)_2$	-408.245009	-408.236142	-408.277782
$IONO_2$	-291.592151	-291.586106	-291.623013
$PhNO_2$	-436.763306	-436.755509	-436.795351
$IOB(OH)_2$	-263.181889	-263.174881	-263.213566
TS	-699.693481	-699.678743	-699.735345

References:

[1] [a] Ramachandiran, K., Muralidharan, D., and Perumal, P. T. Palladium catalyzed alkylation of indole via aliphatic C–H bond activation of tertiary amine. *Tetrahedron Letters*, *52*(28): 3579-3583, 2011. [b] Breitler, S., Oldenhuis, N. J., Fors, B. P., and Buchwald, S. L. Synthesis of unsymmetrical diarylureas via Pd-catalyzed C–N cross-coupling reactions. *Organic Letters*, 13(12):3262-3265, 2011.

[2] Kosugi, M., Kameyama, M., and Migita, T. Palladium-catalyzed aromatic amination of aryl bromides with *N*,*N*'-di-ethylamino-tributyltin. *Chemistry Letters*, 12(6):927-928, 1983.

[3] Guram, A. S., Rennels, R. A., and Buchwald, S. L. A simple catalytic method for the conversion of aryl bromides to arylamines. *Angewandte Chemie International Edition*, 34(12):1348-1350, 1995.

[4] Breitler, S., Oldenhuis, N. J., Fors, B. P., and Buchwald, S. L. Synthesis of unsymmetrical diarylureas via Pd-catalyzed C–N cross-coupling reactions. *Organic Letters*, 13(12):3262-3265, 2011.

[5] Perez, F. and Minatti, A. Palladium-catalyzed C, N-cross-coupling reactions of 3-halo-2-aminopyridines. *Organic Letters*, 13(8):1984-1987, 2011.

[6] Ueda, S., Su, M., and Buchwald, S. L. Highly N_2-selective palladium-catalyzed arylation of 1,2,3-Triazoles. *Angewandte Chemie International Edition*, 50(38):8944-8947, 2011.

[7] Wolfe, J. P. and Buchwald, S. L. Scope and limitations of the Pd/BINAP-catalyzed amination of aryl bromides. *The Journal of Organic Chemistry*, 65(4):1144-1157, 2000.

[8] Ali, M. H. and Buchwald, S. L. An improved method for the palladium-catalyzed amination of aryl iodides. *The Journal of Organic Chemistry*, 66(8):2560-2565, 2001.

[9] Gajare, A. S., Toyota, K., Yoshifuji, M., and Ozawa, F. Solvent free amination reactions of aryl bromides at room temperature catalyzed by a (π-Allyl) palladium complex bearing a diphosphinidenecyclobutene ligand. *The Journal of Organic Chemistry*, 69(19):6504-6506, 2004.

[10] Tewari, A., Hein, M., Zapf, A., and Beller, M. Efficient palladium catalysts for the amination of aryl chlorides: A comparative study on the use of phosphium salts as precursors to bulky, electron-rich phosphines. *Tetrahedron*, 61(41):9705-9709, 2005.

[11] Hill, L. L., Crowell, J. L., Tutwiler, S. L., Massie, N. L., Hines, C. C., Griffin, S. T., and Li, H. Synthesis and X-ray structure determination of highly active Pd(II), Pd(I), and Pd (0) complexes of di(*tert*-butyl) neopentylphosphine (DTBNpP) in the arylation of amines and ketones. *The Journal of Organic Chemistry*, 75(19):6477-6488, 2010.

[12] Reddy, C. V., Kingston, J. V., and Verkade, J. G. (t-Bu)$_2$PN P (i-BuNCH$_2$CH$_2$)$_3$N: New efficient ligand for palladium-catalyzed C−N couplings of aryl and heteroaryl bromides and chlorides and for vinyl bromides at room temperature. *The Journal of Organic Chemistry*, 73(8):3047-3062, 2008.

[13] Hartwig, J. F. Evolution of a fourth generation catalyst for the amination and thioetherification of aryl halides. *Accounts of Chemical Research*, 41(11):1534-1544, 2008.

[14] Broggi, J., Clavier, H., and Nolan, S. P. *N*-Heterocyclic carbenes (NHCs) containing *N*-*C*-palladacycle complexes: synthesis and reactivity in aryl amination reactions. *Organometallics*, 27(21):5525-5531, 2008.

[15] Maiti, D., Fors, B. P., Henderson, J. L., Nakamura, Y., and Buchwald, S. L. Palladium-catalyzed coupling of functionalized primary and secondary amines with aryl and heteroaryl halides: Two ligands suffice in most cases. *Chemical Science*, 2(1):57-68, 2011.

[16] Ueda, S., Ali, S., Fors, B. P., and Buchwald, S. L. Me_3(OMe)*t*BuXPhos: a surrogate ligand for Me_4*t*BuXPhos in palladium-catalyzed C–N and C–O bond-forming reactions. *The Journal of Organic Chemistry*, 77(5):2543-2547, 2012.

[17] Klapars, A., Antilla, J. C., Huang, X., and Buchwald, S. L. A general and efficient copper catalyst for the amidation of aryl halides and the *N*-arylation of nitrogen heterocycles. *Journal of the American Chemical Society*, 123(31):7727-7729, 2001.

[18] Goodbrand, H. B. and Hu, N. X. Ligand-accelerated catalysis of the Ullmann condensation: Application to hole conducting triarylamines. *The Journal of Organic Chemistry*, 64(2):670-674, 1999.

[19] Altman, R. A. and Buchwald, S. L. 4,7-dimethoxy-1,10-phenanthroline: An excellent ligand for the Cu-catalyzed *N*-arylation of imidazoles. *Organic Letters*, 8(13):2779-2782, 2006.

[20] Kuil, M., Bekedam, E. K., Visser, G. M., van den Hoogenband, A., Terpstra, J. W., Kamer, P. C., and van Strijdonck, G. P. Mild copper-catalyzed *N*-arylation of azaheterocycles with aryl halides. *Tetrahedron Letters*, 46(14):2405-2409, 2005.

[21] Xie, Y. X., Pi, S. F., Wang, J., Yin, D. L., and Li, J. H. 2-aminopyrimidine-4,6-diol as an efficient ligand for solvent-free copper-catalyzed *N*-arylations of imidazoles with aryl and heteroaryl halides. *The Journal of Organic Chemistry*, 71(21):8324-8327, 2006.

[22] Wong, K. T., Ku, S. Y., and Yen, F. W. Facile synthesis of 9-azajulolidine and its application to post-Ullmann reactions. *Tetrahedron Letters*, 48(29):5051-5054, 2007.

[23] Han, C., Shen, R., Su, S., and Porco, J. A. Copper-mediated synthesis of *N*-acyl vinylogous carbamic acids and derivatives: Synthesis of the antibiotic CJ-15,801. *Organic Letters*, 6(1):27-30, 2004.

[24] Liu, Y. H., Chen, C., and Yang, L. M. Diazabutadiene: a simple and efficient ligand for copper-catalyzed *N*-arylation of aromatic amines. *Tetrahedron Letters*, 47(52):9275-9278, 2006.

[25] Cristau, H. J., Cellier, P. P., Spindler, J. F., and Taillefer, M. Highly efficient and mild Copper-catalyzed *N*-and *C*-arylations with aryl bromides and iodides. *Chemistry-A European Journal*, 10(22):5607-5622, 2004.

[26] Xie, Y. X., Pi, S. F., Wang, J., Yin, D. L., and Li, J. H. 2-Aminopyrimidine-4,6-diol as an efficient ligand for solvent-free copper-catalyzed *N*-arylations of imidazoles with aryl and heteroaryl halides. *The Journal of Organic Chemistry*, 71(21):8324-8327, 2006.

[27] Cristau, H. J., Cellier, P. P., Spindler, J. F., and Taillefer, M. Highly efficient and mild copper-catalyzed *N*- and *C*- arylations with aryl bromides and iodides. *Chemistry-A European Journal*, 10(22):5607-5622, 2004.

[28] Kwong, F. Y., Klapars, A., and Buchwald, S. L. Copper-catalyzed coupling of alkylamines and aryl iodides: An efficient system even in an air atmosphere. *Organic Letters*, 4(4):581-584, 2002.

[29] Shafir, A. and Buchwald, S. L. Highly selective room-temperature copper-catalyzed C−N coupling reactions. *Journal of the American Chemical Society*, 128(27):8742-8743, 2006.

[30] Kwong, F. Y. and Buchwald, S. L. Mild and efficient copper-catalyzed amination of aryl bromides with primary alkylamines. *Organic Letters*, 5(6):793-796, 2003.

[31] Zhu, D., Wang, R., Mao, J., Xu, L., Wu, F., and Wan, B. Efficient copper-catalyzed amination of aryl halides with amines and NH heterocycles using rac-BINOL as ligand. *Journal of Molecular Catalysis A: Chemical*, 256(1):256-260, 2006.

[32] Chen, Y. J. and Chen, H. H. 1,1,1-Tris (hydroxymethyl) ethane as a new, efficient, and versatile tripod ligand for copper-catalyzed cross-coupling reactions of aryl iodides with amides, thiols, and phenols. *Organic Letters*, 8(24):5609-5612, 2006.

[33] [a] Zhang, H., Cai, Q., and Ma, D. Amino acid promoted CuI-catalyzed C−N bond formation between aryl halides and amines or *N*-containing heterocycles. *The Journal of Organic Chemistry*, 70(13):5164-5173, 2005. [b] Ma, D. and Cai, Q. L-Proline promoted

Ullmann-type coupling reactions of aryl iodides with indoles, pyrroles, imidazoles or pyrazoles. *Synlett*, 2004(1):128-130, 2004. [c] Alcalde, E., Dinarès, I., Rodríguez, S., and Garcia de Miguel, C. Synthetic approaches to sterically hindered *N*-arylimidazoles through copper-catalyzed coupling reactions. *European Journal of Organic Chemistry*, 2005(8):1637-1643, 2005. [d] Lv, X., Wang, Z., and Bao, W. CuI catalyzed C–N bond forming reactions between aryl/heteroaryl bromides and imidazoles in [Bmim]BF_4. *Tetrahedron*, 62(20):4756-4761, 2004. [e] Sreedhar, B., Kumar, K. S., Srinivas, P., Balasubrahmanyam, V., and Venkanna, G. T. CuI/L-histidine catalyzed *N*-arylation of heterocycles. *Journal of Molecular Catalysis A: Chemical*, 265(1):183-185, 2007. [f] Huang, Y. Z., Gao, J., Ma, H., Miao, H., and Xu, J. Ninhydrin: an efficient ligand for the Cu-catalyzed *N*-arylation of nitrogen-containing heterocycles with aryl halides. *Tetrahedron Letters*, 49(6):948-951, 2008.

[34] Guo, X., Rao, H., Fu, H., Jiang, Y., and Zhao, Y. An inexpensive and efficient copper catalyst for *N*-Arylation of amines, amides and nitrogen containing heterocycles. *Advanced Synthesis & Catalysis*, 348(15):2197-2202, 2006.

[35] [a] Cristau, H. J., Cellier, P. P., Spindler, J. F., and Taillefer, M. Mild conditions for copper-catalysed *N*- arylation of Pyrazoles. *European Journal of Organic Chemistry*, 4: 695-709, 2004. [b] Cristau, H. J., Cellier, P. P., Spindler, J. F., and Taillefer, M. Highly efficient and mild copper-catalyzed *N*-and *C*-arylations with aryl bromides and iodides. *Chemistry-A European Journal*, 10(22):5607-5622, 2004.

[36] Xu, L., Zhu, D., Wu, F., Wang, R., and Wan, B. Mild and efficient copper-catalyzed *N*-arylation of alkylamines and N–H heterocycles using an oxime-phosphine oxide ligand. *Tetrahedron*, 61(27):6553-6560, 2005.

[37] Lu, Z., Twieg, R. J., and Huang, S. D. Copper-catalyzed amination of aromatic halides with 2-*N*,*N'*-dimethylaminoethanol as solvent. *Tetrahedron Letters*, 44(33):6289-6292, 2003.

[38] Liu, L., Frohn, M., Xi, N., Dominguez, C., Hungate, R., and Reider, P. J. A soluble base for the copper-catalyzed imidazole *N*-arylations with aryl halides. *The Journal of Organic Chemistry*, 70(24):10135-10138, 2005.

[39] Kang, S. K., Lee, S. H., and Lee, D. Copper-catalyzed *N*-arylation of amines with hypervalent iodonium salts. *Synlett*, 2000(07):1022-1024, 2000.

[40] Arnauld, T., Barton, D. H., and Doris, E. The chemistry of pentavalent organobismuth reagents. Part 14. Recent advances in the copper-catalyzed phenylation of amines. *Tetrahedron*, 53(12):4137-4144, 1997.

[41] López-Alvarado, P., Avendan, C., and Menéndez, J. C. *N*-arylation of azoles and their benzo derivatives by *p*-tolyllead triacetate. *Tetrahedron Letters*, 33(5):659-662, 1992.

[42] Lam, P. Y., Deudon, S., Averill, K. M., Li, R., He, M. Y., DeShong, P., and Clark, C. G. Copper-Promoted C−N bond cross-coupling with hypervalent aryl siloxanes and room-temperature *N*-arylation with aryl iodide. *Journal of the American Chemical Society*, 122(31):7600-7601, 2000.

[43] Lam, P. Y., Clark, C. G., Saubern, S., Adams, J., Averill, K. M., Chan, D. M., and Combs, A. Copper promoted aryl/saturated heterocyclic CN bond cross-coupling with arylboronic acid and arylstannane. *Synlett*, 2000(5):674- 676, 2000.

[44] Chan, D. M., Monaco, K. L., Wang, R. P., and Winters, M. P. New *N*- and *O*-arylations with phenylboronic acids and cupric acetate. *Tetrahedron Letters*, 39(19):2933-2936, 1998.

[45] Collman, J. P. and Zhong, M. An efficient diamine copper complex-catalyzed coupling of arylboronic acids with imidazoles. *Organic Letters*, 2(9):1233-1236, 2000.

[46] Collman, J. P., Zhong, M., Zeng, L., and Costanzo, S. The $[Cu(OH):TMEDA]_2Cl_2$-catalyzed coupling of arylboronic acids with imidazoles in water. *The Journal of Organic Chemistry*, 66(4):1528-1531, 2001.

[47] Collman, J. P., Zhong, M., Zhang, C., and Costanzo, S. Catalytic activities of Cu (II) complexes with nitrogen-chelating bidentate ligands in the coupling of imidazoles with arylboronic acids. *The Journal of Organic Chemistry*, 66(23):7892-7897, 2001.

[48] Lam, P. Y., Vincent, G., Clark, C. G., Deudon, S., and Jadhav, P. K. Copper-catalyzed general C-N and C-O bond cross-coupling with arylboronic acid. *Tetrahedron Letters*, 42(20): 415-3418, 2001.

[49] Antilla, J. C. and Buchwald, S. L. Copper-catalyzed coupling of arylboronic acids and amines. *Organic Letters*, 3(13):2077-2079, 2001.

[50] Quach, T. D. and Batey, R. A. Ligand and base-free copper(II)-catalyzed C–N bond formation: Cross-coupling reactions of organoboron compounds with aliphatic amines and anilines. *Organic Letters*, 5(23):4397-4400, 2003.

[51] Kaboudin, B., Abedi, Y., and Yokomatsu, T. Cu II–β Cyclodextrin complex as a nano catalyst for the homo and cross-coupling of arylboronic acids under ligand and base-free conditions in air: Chemoselective cross-coupling of arylboronic acids in water. *European Journal of Organic Chemistry*, 2011(33):6656-6662, 2011.

[52] Kantam, M. L., Venkanna, G. T., Sridhar, C., Sreedhar, B., and Choudary, B. M. An efficient base-free *N*-arylation of imidazoles and amines with arylboronic acids using copper-exchanged fluorapatite. *The Journal of Organic Chemistry*, 71(25):9522-9524, 2006.

[53] Islam, S. M., Mondal, S., Mondal, P., Roy, A. S., Tuhina, K., Salam, N., and Mobarak, M. A reusable polymer supported copper catalyst for the C–N and C–O bond cross-coupling reaction of aryl halides as well as arylboronic acids. *Journal of Organometallic Chemistry*, 696(26):4264-4274, 2012.

[54] Singh, B. K., Stevens, C. V., Acke, D. R., Parmar, V. S., and Van der Eycken, E. V. Copper-mediated *N*- and *O*- arylations with arylboronic acids in a continuous flow microreactor: A new avenue for efficient scalability. *Tetrahedron Letters*, 50(1):15-18, 2009.

[55] Gogoi, A., Sarmah, G., Dewan, A., and Bora, U. Unique copper–salen complex: An efficient catalyst for *N*-arylations of anilines and imidazoles at room temperature. *Tetrahedron Letters*, 55(1):31-35, 2014.

[56] Roy, S., Sarma, M. J., Kashyap, B., and Phukan, P. A quick Chan–Lam C–N and C–S cross-coupling at room temperature in the presence of square pyramidal [Cu $(DMAP)_4I]I$ as a catalyst. *Chemical Communications*, 52(6):1170-1173, 2016.

[57] Guy, C. S., and Jones, T. C. Copper-mediated *N*-arylation of quinazolinediones. *Synlett*, 2009(14):2253-2256, 2009.

[58] Chan, D. M., Monaco, K. L., Li, R., Bonne, D., Clark, C. G., and Lam, P. Y. Copper promoted C-N and C-O bond cross-coupling with phenyl and pyridylboronates. *Tetrahedron Letters*, 44(19):3863-3865, 2003.

[59] Yamamoto, Y., Takizawa, M., Yu, X. Q., and Miyaura, N. Cyclic Triolborates: Air and water stable ate complexes of organoboronic acids. *Angewandte Chemie International Edition*, 47(5):928-931, 2008.

[60][a] Ono, N. The nitro aldol (Henry) reaction. *The Nitro Group in Organic Synthesis*, 30-69, 2001. [b] Belciug, M. P. and Ananthanarayanan, V. S. Interaction of calcium channel antagonists with calcium: Structural studies on nicardipine and its Ca^{2+} complex. *Journal of Medicinal Chemistry*, 37(25):4392-4399, 1994.

[61] Samajdar, S., Becker, F. F., and Banik, B. K. Surface-mediated highly efficient regioselective nitration of aromatic compounds by bismuth nitrate. *Tetrahedron Letters*, 41(42):8017-8020, 2000.

[62] Bose, A. K., Ganguly, S. N., Manhas, M. S., Rao, S., Speck, J., Pekelny, U., and Pombo-Villars, E. Microwave promoted rapid nitration of phenolic compounds with calcium nitrate. *Tetrahedron Letters*, 47(12):1885-1888, 2006.

[63] Anuradha, V., Srinivas, P. V., Aparna, P., and Rao, J. M. *p*-Toluenesulfonic acid catalyzed regiospecific nitration of phenols with metal nitrates. *Tetrahedron Letters*, 47(28):4933-4935, 2006.

[64] Koley, D., Colón, O. C., and Savinov, S. N. Chemoselective nitration of phenols with *tert*-butyl nitrite in solution and on solid support. *Organic Letters*, 11(18):4172-4175, 2009.

[65] Kilpatrick, B., Heller, M., and Arns, S. Chemoselective nitration of aromatic sulfonamides with tert-butyl nitrite. *Chemical Communications*, 49(5):514-516, 2013.

[66] Liu, Y. K., Lou, S. J., Xu, D. Q., and Xu, Z. Y. Regiospecific synthesis of nitroarenes by palladium-catalyzed nitrogen-donor, directed aromatic C-H nitration. *Chemistry-A European Journal*, 16(46):13590-13593, 2010.

[67] Zhang, L., Liu, Z., Li, H., Fang, G., Barry, B. D., Belay, T. A., and Liu, Q. Copper-mediated chelation-assisted ortho nitration of (hetero) arenes. *Organic Letters*, 13(24):6536-6539, 2011.

[68] Dirk, S. M., Mickelson, E. T., Henderson, J. C., and Tour, J. M. Oxidation of electron-deficient anilines by HOF. A route to nitro-containing compounds for molecular electronic devices. *Organic Letters*, 2(21):3405-3406, 2010.

[69] Firouzabadi, H. and Amani, N. I. K. Tungstophosphoric acid catalyzed oxidation of aromatic amines to nitro compounds with sodium perborate in micellar media. *Green Chemistry*, 3(3):31-132, 2001.

[70] Tundo, P., Romanelli, G. P., Vázquez, P. G., Loris, A., and Aricó, F. Multiphase oxidation of aniline to nitrosobenzene with hydrogen peroxide catalyzed by heteropolyacids. *Synlett*, 2008(7):967-970, 2008.

[71] Reddy, K. R., Maheswari, C. U., Venkateshwar, M., and Kantam, M. L. Selective oxidation of aromatic amines to nitro derivatives using potassium iodide *tert*-butyl hydroperoxide catalytic system. *Advanced Synthesis & Catalysis*, 351(2):93-96, 2009.

[72] Rozen, S. and Carmeli, M. From azides to nitro compounds in a few seconds using HOF: CH_3CN. *Journal of the American Chemical Society*, 125(27):8118-8119, 2003.

[73] McPake, C. B., Murray, C. B., and Sandford, G. Sequential continuous flow processes for the oxidation of amines and azides by using HOF□□MeCN. *ChemSusChem*, 5(2):312-319, 2012.

[74] Saito, S. and Koizumi, Y. Copper-catalyzed coupling of aryl halides and nitrite salts: A mild Ullmann-type synthesis of aromatic nitro compounds. *Tetrahedron Letters*, 46(28):4715-4717, 2005.

[75] Fors, B. P. and Buchwald, S. L. Pd-catalyzed conversion of aryl chlorides, triflates, and nonaflates to nitroaromatics. *Journal of the American Chemical Society*, 131(36):12898-12899, 2009.

[76] Joseph, P. A., Priyadarshini, S., Kantam, M. L., and Maheswaran, H. Copper catalyzed *ipso*-nitration of iodoarenes, bromoarenes and heterocyclic haloarenes under ligand-free conditions. *Tetrahedron Letters*, 53(12):1511-1513, 2012.

[77] Das, J. P., Sinha, P., and Roy, S. A nitro-Hunsdiecker reaction: From unsaturated carboxylic acids to nitrostyrenes and nitroarenes. *Organic Letters*, 4(18):3055-3058, 2002.

[78] Natarajan, P., Chaudhary, R., and Venugopalan, P. Silver (I)-promoted *ipso*-nitration of carboxylic acids by nitronium tetrafluoroborate. *The Journal of Organic Chemistry*, 80(21):10498-10504, 2015.

[79] Manna, S., Maity, S., Rana, S., Agasti, S., and Maiti, D. *Ipso*-nitration of arylboronic acids with bismuth nitrate and perdisulfate. *Organic Letters*, 14(7):1736-1739, 2012.

[80] Prakash, G. S., Panja, C., Mathew, T., Surampudi, V., Petasis, N. A., and Olah, G. A. *Ipso*-nitration of arylboronic acids with chlorotrimethylsilane−nitrate salts. *Organic Letters*, 6(13):2205-2207, 2004.

[81] Wu, X. F., Schranck, J., Neumann, H., and Beller, M. Convenient and mild synthesis of nitroarenes by metal-free nitration of arylboronic acids. *Chemical Communications*, 47(46):12462-12463, 2011.

[82] Boruah, P. R., Ali, A. A., Saikia, B., and Sarma, D. A novel green protocol for ligand free Suzuki–Miyaura cross-coupling reactions in WEB at room temperature. *Green Chemistry*, 17(3):1442-1445, 2015.

[83] Boruah, P. R. and Ali, A. A, Chetia, M., Saikia, B., and Sarma, D. Pd $(OAc)_2$ in WERSA: A novel green catalytic system for Suzuki–Miyaura cross-coupling reactions at room temperature. *Chemical Communications*, 51(57):11489-11492, 2015.

[84] Sarmah, M., Dewan, A., Mondal, M., Thakur, A. J., and Bora, U. Analysis of the water extract of waste papaya bark ash and its implications as an in situ base in the ligand-free recyclable Suzuki–Miyaura coupling reaction. *RSC Advances*, 6(34):28981-28985, 2016.

[85] Das, S., Borah, R., Devi, R. R., and Thakur, A. J. Molecular iodine in protection and deprotection chemistry. *Synlett*, 2008(18):2741-2762, 2008.

[86] Shinde, S. S., Said, M. S., Surwase, T. B., and Kumar, P. Mild regiospecific alcoholysis and aminolysis of epoxides catalyzed by zirconium (IV) oxynitrate. *Tetrahedron Letters*, 56(43):5916-5919, 2015.

[87] Kim, K. and Jordan, K. D. Comparison of density functional and MP2 calculations on the water monomer and dimer. *The Journal of Physical Chemistry*, 98(40):10089-10094, 1994.

[88] Stephens, P. J., Devlin, F. J., Chabalowski, C., and Frisch, M. J. Ab initio calculation of vibrational absorption and circular dichroism spectra using density functional force fields. *The Journal of Physical Chemistry*, 98(45):11623-11627, 1994.

[89] Raghavachari, K. and Trucks, G. W. Excitation energies of first row transition metals Sc–Cu. *The Journal of Chemical Physics*, 91(2):1062-1065, 1989.

[90] Hay, P. J. and Wadt, W. R. Ab initio effective core potentials for molecular calculations. Potentials for the transition metal atoms Sc to Hg. *The Journal of Chemical Physics*, 82(1):270-283, 1985.

[91] Peng, C. and Bernhard, S. H. Combining synchronous transit and quasi□Newton methods to find transition states. *Israel Journal of Chemistry*, 33(4):449-454, 1993.

[92] Peng, C., Ayala, P. Y., Schlegel, H. B., and Frisch, M. J. Using redundant internal coordinates to optimize equilibrium geometries and transition states. *Journal of Computational Chemistry*, 17(1):49-56, 1996.

[93] Gonzalez, C. and Schlegel, H. B. Reaction path following in mass-weighted internal coordinates. *Journal of Physical Chemistry*, 94(14):5523-5527, 1990.