Université catholique de Louvain

Faculté d'Ingénierie Biologique, Agronomique et Environnementale

Pd-based heterogeneous catalysts for Suzuki coupling

Marc Jacquemin

Promoteur : Prof. E. Gaigneaux

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PART II

Abbreviations

Ar: aryl- groups
Ar-Br: aryl-bromide
Ar-X: aryl-halide
Ar-B(OH)$_2$ or **Ar'-B(OH)$_2$**: aryl boronic acid
BE: binding energy
C-HSS: activated carbon
C-LSS: carbon black
d (nm): particle size
D (%): dispersion
DMF: dimethylformamide
DP: deposition-precipitation
E$_c$: charging term (XPS)
FID: Flame ionisation detector
FTIR: Fourier transform infrared spectroscopy
ICDD-JCPDS: International Centre for Diffraction Data - Joint Committee on Powder Diffraction Standards
HT: hydrotalcite
K: Kelvin
LM: liquid medium
MAS NMR: magic angle spinning - nuclear magnetic resonance
MPa: megapascal
PZC: point of zero charge
Prod: productivity
Prod$_d$: productivity normalised by the metal dispersion
rpm: rotation per minute
R and R': aryl- or alkyl- groups
R$_{obs}$: reaction rate
SSA: specific surface area
TCD: thermal conductivity detector
TEM: transmission electron microscopy
TOF: turn-over-frequency
TOF$_d$: turn-over-frequency normalised by the metal dispersion
wt. %: mass percentage
WI: wet impregnation
X: halides
XPS: X-ray photoelectron spectroscopy
XRD: X-ray diffraction
Y: halides

CHAPTER I:
Introduction

Abstract

This section introduces the general context in which the thesis has been initiated and conducted. First, a detailed literature survey concerning the Suzuki coupling and the types of catalytic formulations employed is presented and then our own objectives are exposed in correlation with the limitations of the current knowledge. Finally, the strategy to address the questions raised throughout this section is developed.

1. General considerations about coupling reactions

Chemical reactions aiming at the coupling of carbon atoms are important methodologies for the preparation of several families of molecules. These reactions have recently emerged and are often a crucial step in the production of many compounds, especially in the synthesis of materials [1-3], natural products [4-6] and bioactive molecules [4, 7, 8].

Depending on the initial reactants, coupling reactions can be divided into two groups which are expressed as follows:

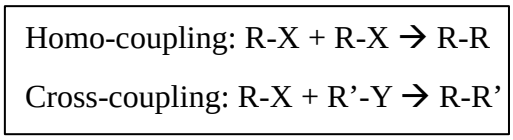

Figure I-1: Homo-coupling vs cross-coupling
(R, R' usually refer to aryl- or alkyl- groups) [9-11]

Homo-coupling refers to a reaction where two molecules of the same type react together to form a new symmetric compound (Figure I-1), such as in Wurtz [12] and Ullmann reactions [13] (Table I-1). At the opposite, cross-coupling is a reaction in which two different molecules react to produce a new non-symmetric compound as in e.g. Heck and Suzuki reactions [14] (Table I-1).

Many types of coupling reactions under various conditions have been developed over the last 170 years and named by scientists who first reported them. The first publication of a coupling reaction may be found in the middle of the nineteenth century. In 1855, Wurtz *et al.* [12] reported the homo-coupling of alkyl-halides using sodium metal as the catalyst. A few years later, some homo-coupling reactions using copper-based catalysts have been published such as in Glaser (1869) [15] and

Ullmann reactions (1901) [13]. In 1924, the first cross-coupling reaction was reported in the literature: the Gomberg-Bachmann reaction [16], where aromatic hydrocarbons were coupled with diazonium salts in the presence of a base. At that moment, the yields of the reactions for the desired products were very low, less than 40 %. In 1970's, the use of palladium-based catalysts had permitted to improve the yield of the coupling reactions. From that time, several cross-coupling reactions have been discovered, e.g. Heck (1972) [11, 14], Sonogashira (1973) [9, 17], Stille (1977) [18] and the Suzuki couplings (1979) [11, 14] (Table I-1).

Prof. Richard F. Heck, Prof. Ei-ichi Negishi and Prof. Akira Suzuki were awarded the 2010 Nobel Prize in Chemistry for their works on “the development of palladium-catalyzed cross-coupling in organic synthesis” [19]. This award proves that the coupling reactions are significant and recognised tools for chemists to synthesise complex carbon molecules.

In particular the Suzuki coupling has become one of the most popular reactions. It is a useful method for the construction of conjugated dienes and higher polyene compounds of high stereoisomeric purity, as well as of biaryls and related molecules [6]. Furthermore, Suzuki coupling is one of the most widely-adopted reactions in the pharmaceutical industry.

Table I-1: Coupling reactions overview (R: alkyl; Ar: aryl and X: halides)

Reaction	Year	Reactant A	Reactant B	Homo/Cross coupling	Catalyst
Wurtz [12]	1855	R-X	R-X	Homo	Na
Glaser [15]	1863	RC≡CH	RC≡CH	Homo	Cu
Ullmann [13]	1901	Ar-X	Ar-X	Homo	Cu
Gomberg-Bachmann [16]	1924	Ar-H	Ar-N_2X	Cross	/
Kumada [20]	1972	Ar-X Vinyl-X	Ar-MgBr	Cross	Pd, Ni
Heck [11, 14]	1972	Ar-X Vinyl-X	Alkene	Cross	Pd
Sonogashira [17]	1973	Ar-X Vinyl-X	RC≡CH	Cross	Pd, Cu
Negishi [21]	1977	Ar-X Vinyl-X	R-Zn-X	Cross	Pd, Ni
Stille [18]	1977	Ar-X Vinyl-X	R-SnR_3	Cross	Pd
Suzuki [22]	1979	Ar-X Vinyl-X	Ar-$B(OR)_2$	Cross	Pd
Buchwald-Hartwig [23, 24]	1994	Ar-X Vinyl-X	R_2N-Sn-R_3	Cross	Pd

2. Suzuki coupling

The Suzuki coupling was firstly published in 1979 by Prof. Akira Suzuki [22, 25]. This reaction allows the combination of aryl-halides with aryl- or vinyl-boronic acids in the presence of a palladium-based

catalyst and a base (Figure I-2) [22, 25]. It is one of the most popular reactions for the production of biaryls for several reasons: (i) it uses mild conditions; (ii) it uses boron compounds which are stable, available and have a low toxicity and (iii) a wide range of substrates with various functional groups can be employed [11, 26, 27].

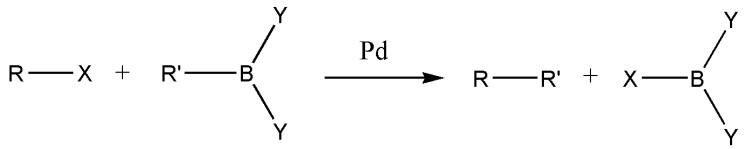

Figure I-2: Schematic representation of the Suzuki coupling (R and R': aryl, vinyl ; X : Br, Cl, I ; Y : OH, O-R) [6]

This reaction is widely performed to synthesise polyolefins [28] and substituted biaryls [11, 26, 27]. These biaryl structures are present in a large number of biologically active molecules [29] such as drugs (Valsartan, Telmisartan, etc.) or pesticides (Boscalid) [30, 31]. In addition, some of these structures are present in compounds with interesting physical properties such as liquid crystals, organic conductors or semiconductors, etc [11, 29, 32]. Examples are given in Figure I-3.

The reactivity of the aryl-halide (Ar-X) depends very strongly on the nature of the halides: I> Br>> Cl. Iodides and bromides are the most usually employed [11, 26]. Whereas chlorides are less reactive, more and more research is carried out about these chlorinated aryls due to their low cost and ready availability [26, 33, 34]. Triflate-aryls have also been studied but they are generally thermo-labile, hydrolysable and expensive [26, 35].

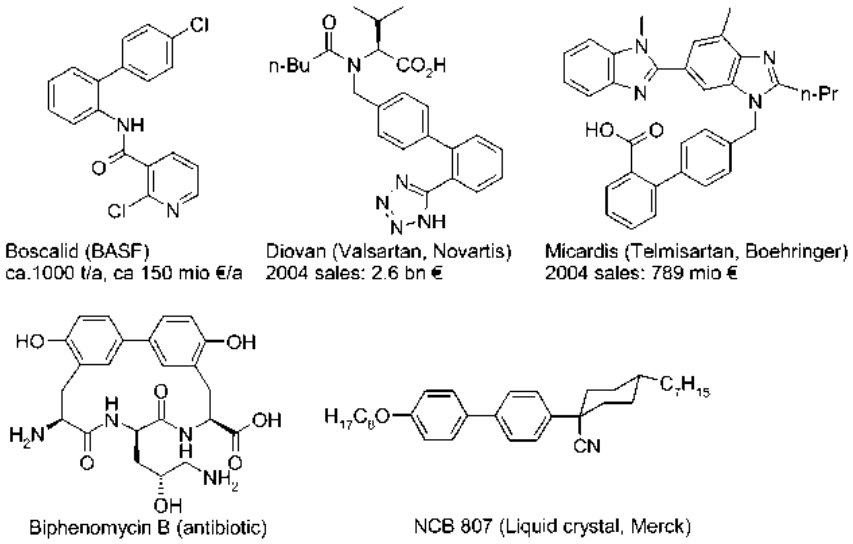

Figure I-3: Examples of molecules produced via the Suzuki coupling [32]

The solvent is a significant component of the reaction because it must be able to solubilise the reactants, the products and the base. Polar aprotic solvents such as dimethylformamide (DMF) [36-38] or tetrahydrofuran (THF) [37, 39] (Figure I-4) are generally employed to perform the reaction. Other types of solvents can be found in the literature such as toluene, water, ethanol, methanol, glycerol, etc. [40-46].

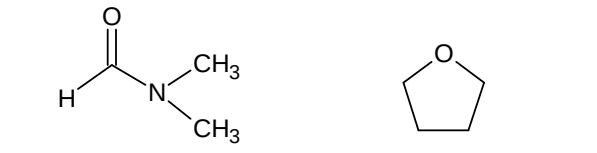

Figure I-4: Dimethylformamide (DMF) and tetrahydrofuran (THF) structures

In addition, the bases used in these reactions largely vary. The most common and effective bases are potassium carbonate (K_2CO_3) and sodium carbonate (Na_2CO_3) [26, 33, 39, 47]. However, other bases such as sodium phosphate (Na_3PO_4) [26, 39], cesium carbonate (Cs_2CO_3) [26] or organic bases such as tert-butylamine (TBA) [36] and N,N-diisopropylethylamine (DIPEA) were sometimes considered, leading to good biaryl yields [48, 49].

Other parameters such as the duration (between 1 and 48 hours) of the catalytic tests, the reaction temperature (between 293 and 393 K) or even the quantities of reactants differ considerably from one reaction to another, showing the wide variety of ways that have been implemented to achieve and study the Suzuki reaction [11, 26, 31, 49].

3. Catalysts

The Suzuki cross-coupling reaction needs the presence of a palladium-based catalyst. A tremendous variety of catalysts have been used to perform this coupling whatever they were homogeneous or heterogeneous.

3.1. Homogeneous catalysts

The Suzuki reaction is traditionally carried out with homogeneous catalysts. These are often soluble palladium complexes generally associated with ligands of monoarylphosphine type such as the tetrakis(triphenylphosphine) palladium ($Pd(PPh_3)_4$) (Figure I-5) [39, 50]. However, a large number of alternative homogeneous catalysts are reported in the literature like $PdCl_2$ [11, 26] and $Pd(OAc)_2$ [45, 51]. Some groups of researchers have tried to develop more efficient types of

ligands: for example the catalysts of Buchwald [52, 53], Beller [54], Nolan [55] and Herrmann [56]. Examples are given in Figure I-6.

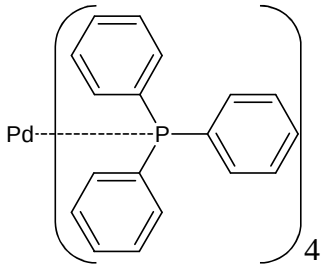

Figure I-5: Tetrakis(triphenylphosphine) palladium ($Pd(PPh_3)_4$) catalyst [57]

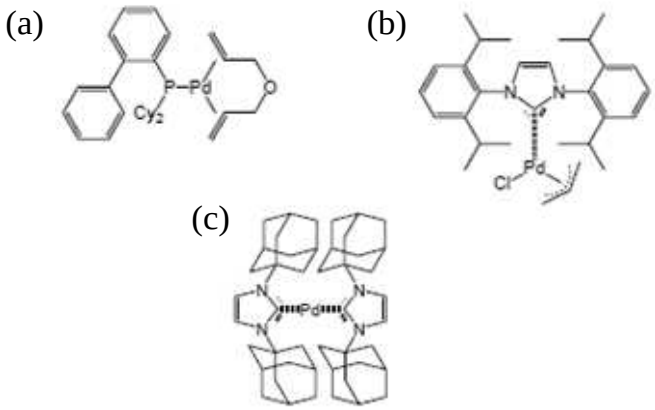

Figure I-6: Examples of homogeneous catalysts with various ligands: (a) Beller catalyst, (b) Nolan catalyst and (c) Herrmann catalyst

Whatever the homogeneous palladium-based catalysts, it is generally accepted in the literature that the mechanism of the Suzuki reaction is a catalytic cycle comprising three main steps (Figure I-7): (i) the oxidative addition, (ii) the transmetallation and finally, (iii) the reductive elimination [11, 26, 29, 31].

The first step of the mechanism is the reaction between the catalysts containing a zero valent-palladium species (Pd^0) and the aryl-halide to form the palladium complex (1) (Figure I-7). This step is called "oxidative addition" because Pd^0 is oxidized into Pd^{2+} by the addition of the aryl-halide. It has been established that when using a catalyst such as $Pd(PPh_3)_4$, the reactive species in the oxidative addition is a low-liganded complex $Pd^0(PPh_3)_2$ obtained after the decomplexation of two (PPh_3) ligands. The halogen of the complex (1) is easily displaced by hydroxide ions to form a R_1-Pd^{2+}-OH complex (2).

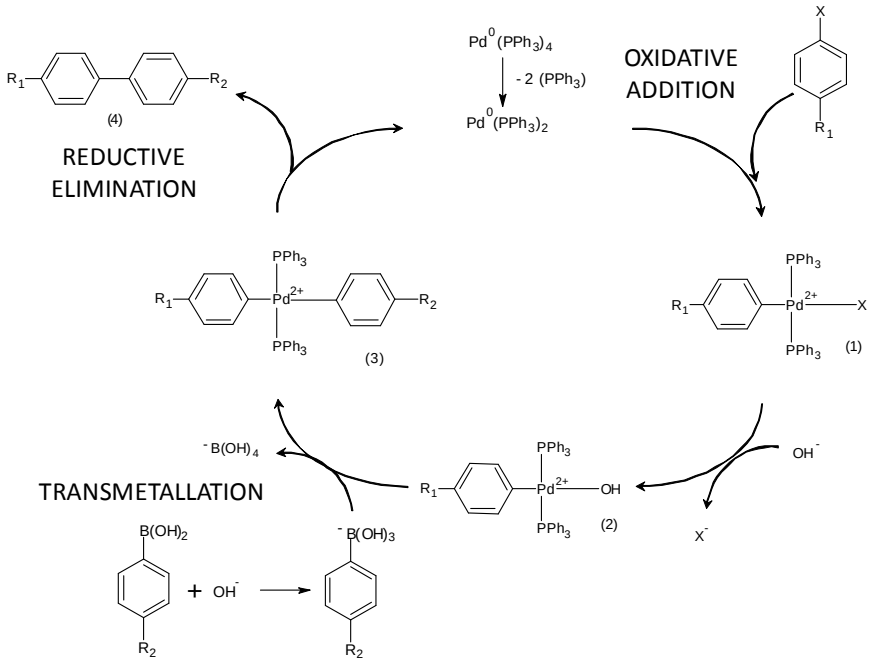

Figure I-7: Catalytic cycle of the Suzuki coupling with homogeneous catalysts: example of $Pd(PPh_3)_4$ catalyst

The transmetallation step first needs the presence of a base to activate the boronic acid (Figure I-8). The latter behaves as a Lewis acid in the presence of an anionic base to produce a much more reactive

boronate complex. The transmetallation leads to the formation of biaryl-Pd^{2+} species (3).

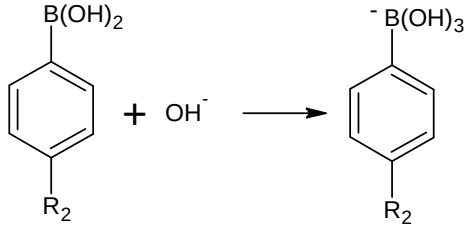

Figure I-8: Activation of the phenylboronic acid in the presence of a base

The final step of the mechanism is a reductive elimination to produce the final biaryl molecules. In this last step, Pd^{2+} is reduced into its metallic form (Pd^0) and thus starts again the catalytic cycle.

As it appears from this catalytic cycle, the base has a dual purpose: (i) the halide of the Ar-Pd-X complex (1) is displaced by hydroxide ions to produce the more reactive Ar-Pd-OH species (2) and (ii) in the presence of a base, the phenylboronic acid (pKa ~8.8) [58] is activated into a hydroxylboronate complex $Ar\text{-}B(OH)_3^-$ (Figure I-8). The activation of the phenylboronic acid increases the nucleophilicity of the aryl group and thus promotes the transmetallation.

The formation of carbon-carbon bonds with homogeneous catalysts has a high potential. Indeed, this type of catalysts has some advantages: (i) the catalyst is in the same phase as the substrate, which leads to a very efficient catalysis that is not hampered by diffusion problems, (ii) every single metal atom is catalytically active and (iii) the rate and selectivity of the catalyst are easily modified by changing the metal, the counterion and the ligand [58]. Unfortunately, these soluble complexes of palladium

suffer from important downsides: (i) difficulties to recover the homogeneous catalysts and therefore to re-use them, (ii) high costs and (iii) contamination of the product with Pd. This last point is particularly important in the synthesis of pharmaceutical molecules for which the tolerated concentration of residual metal is very low (less than 5 ppm) [59]. So, for these reasons, organic chemistry is gradually turning to re-usable and cheaper heterogeneous catalysts.

3.2. Heterogeneous catalysts

The use of heterogeneous catalysts would overcome the drawbacks of the homogeneous ones. Indeed, to carry out the Suzuki reaction, the active metal, namely palladium, can be immobilised on various supports such as activated carbon, oxides or polymers [11, 26, 59, 60]. This last category will not be detailed in this thesis but for example, polystyrene [61] and polyethylene [62] are used as supports for palladium to perform the Suzuki coupling. An interesting example is the use of a micelle comprising Pd nanoparticle and a star-shaped block copolymer as a catalyst to perform this reaction [63].

Palladium-based catalysts supported on activated carbon (Pd/C)

Palladium on activated carbon is widely employed in industrial processes and particularly as a hydrogenation catalyst [64, 65]. More recently, Pd/C catalyzed cross-coupling reactions have received considerable attention such as the Heck [66-68], Stille [69], Sonogashira [70, 71] and Suzuki couplings [68, 72].

The first Suzuki coupling catalyzed by Pd/C appeared in 1994 for the synthesis of liquid crystals [72]. Since then, palladium on activated

carbon has become the most popular heterogeneous catalyst to achieve the Suzuki coupling for several reasons. This solid can work with a wide variety of substrates (bromide, iodide, chloride) and reaction conditions (temperature, ultra-sound, and microwave). Indeed, these catalysts are very stable in acidic or basic conditions and are highly resistant to heating [73]. Furthermore, palladium can be easily recovered by burning the activated carbon under an oxygen flow.

However, specific activities of Pd/C-catalysts are low compared to those obtained in homogeneous catalysis [11, 26, 33, 43, 44, 74].

Palladium-based catalysts supported on oxide supports

An alternative to carbon-supported catalysts is the use of metallic oxide supports. The use of Pd supported on materials other than carbon for the Suzuki coupling is found in the literature: Pd can be deposited on SiO_2 [75], SiO_2-TiO_2 [37], Al_2O_3 [76], Al_2O_3–ZrO_2 [76], Al_2O_3–ZrO_2–Eu_2O_3 [76], MCM-41 [77], zeolites [75], sepiolites [78], MgLa mixed oxides [79], layered double hydroxide (LDH) [4], metal organic framework (MOF) [80], KF/Al_2O_3 [81] and MgO [76]. The activity of these catalysts is very low compared to the one obtained with homogeneous and Pd/C catalysts and the conditions under which they are used, are therefore quite hard (temperature, pH), which may lead to dissolve them.

More generally, several recurrent problems have been encountered in the articles concerning the use of supported catalysts whether on activated carbon or metallic oxides. As shown previously (Figure I-7), the active species in homogeneous catalysis for the Suzuki coupling is the zero-valent palladium (Pd^0). During the catalytic cycle, Pd^0 is

oxidized into Pd^{2+} and again reduced to repeat the cycle. For the heterogeneous catalysts, the nature of the active phase has not yet been well elucidated and investigations on this subject often lead to contradictory conclusions, particularly in terms of the oxidation state of the active species (Pd^0 and/or Pd^{2+}) [11, 26, 59, 66, 77, 82-84].

Furthermore, some authors argue that Pd species must be leached from the support into the solution in order to achieve the Suzuki coupling. According to these authors, the leached palladium is re-deposited on the support after the reductive elimination step of the catalytic cycle [38, 74, 85, 86].

Whatever the heterogeneous palladium-based catalysts, the knowledge of the Suzuki coupling mechanism is limited and research leads to contradictory results which bring to a blurred situation.

4. Batch vs continuous processes

Interest in liquid-phase synthetic processes performed in continuous-type reactor is growing for industry and particularly for the pharmaceutical sector. Indeed, these reactors have several advantages in terms of economic, environment and safety compared to batch-type processes, traditionally used for the synthesis of pharmaceutical molecules [31, 32].

Batch reactors using homogeneous catalysts have several drawbacks: (i) the recovery and the re-use of this type of catalysts are difficult because of their dissolution in the reaction medium, (ii) trace of catalysts, remaining dissolved even after separation and purification, may persist in the interest product, (iii) high operational costs due to long periods of inactivity between successive batches for emptying, cleaning,

filling the reactor and restarting a run and finally (iv) problems with the selectivity of the products. In fact, it is likely that a too long residence time in the reactor leads to consecutive reactions and thus to a loss of selectivity for the desired product. The use of continuous processes makes it possible to reduce or eliminate the problems encountered when using batch reactors. However, the synthetic processes in continuous reactor require heterogeneous catalysts immobilised in a fixed-bed that must be crossed by the reaction mixture.

Currently, the vast majority of pharmaceutical molecules are synthesised by the coupling of aromatic sp^2 carbons (among others the Suzuki reaction) in batch processes in which the problems described above occur. Generally, this reaction is performed in the presence of homogeneous palladium catalysts. Heterogeneous catalysts such as Pd on activated carbon are also sometimes used. However, those are not transferable to a continuous process because they cause overpressure problems upstream of the catalytic bed and diffusional limitations related, on the one hand, to the diffusion of reactants inside of the activated carbon pores, and on the other hand, to the diffusion of products from the pores to the outside of the materials.

The further understanding of the intervention of the heterogeneous catalysts in the Suzuki cross-coupling may allow us to adapt them (tune them) to allow their use in continuous reactor (with its benefits) with performances equal to, or even better than, those obtained with homogeneous catalysts in batch reactors.

5. Towards the objectives of the thesis

As exposed in the previous sections, the knowledge in the literature about the Suzuki coupling with heterogeneous catalysts is relatively limited and current research leads to contradictory results which bring to a blurred situation. The understanding of the Suzuki reaction mechanism with heterogeneous catalysts is particularly limited. Is it a real heterogeneous catalysis or has the active metal (Pd) indeed to be leached from the supports in order to perform the Suzuki cross-coupling ? Furthermore, the nature of the active Pd oxidation state is not yet well-defined and investigations on this subject lead to conflicting conclusions.

Based on the accepted mechanism in homogeneous catalysis [11, 29, 31], the Suzuki reaction requires the action of a base. This is also true for the heterogeneous processes in which a base (typically K_2CO_3) must systematically be added to the system [26, 87]. Furthermore, one of the reactants is an acid (boronic acid). In the heterogeneous reaction, all reactants (acids and bases) will have to interact with the catalyst surface or even adsorb on it. Understanding the acido-basic phenomena that govern the heterogeneous reaction turns out to be of the utmost importance in the search for optimised formulations.

In this context the central objective of the thesis is thus to understand - and consequently take advantage of - the intervention of heterogeneous catalysts in the reaction mechanism of the Suzuki coupling.

Four intermediate objectives have been identified to reach the main one described above:

(i) determining if the Suzuki coupling with heterogeneous catalysts is really heterogeneous and not homogeneous;

(ii) identifying the properties that a catalyst has to possess (or not) to be active in the Suzuki coupling, e.g. the specific surface area, the porosity, the palladium oxidation state, the palladium crystalline phase, etc;

(iii) enlightening the influence of the acido-basic properties of the supports and catalysts on Suzuki cross-coupling reaction;

(iv) identifying the mechanistic steps of the Suzuki coupling with heterogeneous catalysts via a kinetic study of the reaction.

6. Strategy

The strategy employed in thesis is divided into four sections that are developed below.

The Suzuki coupling

To meet our objectives, it is firstly necessary to choose a probing reaction for the synthesis of biaryls. Precisely, our choice was directed towards two Suzuki reactions but the expected product, namely the 4-methylbiphenyl, is the same for both reactions. In the first one, the reactants are 4-bromotoluene and phenylboronic acid. The second one also implies the 4-bromotoluene but the phenylboronic acid is replaced by a phenylboronic acid pinacol ester. This last one is detectable by gas chromatography contrarily to the phenylboronic acid, so making it possible to follow the conversion of this reactant as a function of time.

These probe reactions employ identical reactants to those implemented in the pharmaceutical industry in batch processes with homogeneous catalysts. Therefore, these reactions are used to evaluate the activity of the catalysts developed in this thesis in a realistic context.

Concerning the nature of the halide of the aryl-halide (Ar-X), we have decided to use bromides because they have an intermediate reactivity between the iodides (very reactive) and the chlorides (slightly reactive). In general, chlorides are cheaper than bromides and iodides. However, we were not able to perform the Suzuki coupling in the beginning of this thesis with an aryl-chloride. An optimization of reaction conditions was necessary with this reactant, but without the guarantee that the reaction would work. On the contrary, the reaction with bromides was quickly developed and gave good activities. Thus, it was possible to optimize directly the reaction conditions and test our catalysts with the aryl-bromide. That is for these reasons that the bromide was chosen.

Pd-based catalysts supported on carbons

The first part of this thesis investigates the use of Pd-based catalysts supported on activated carbon and carbon black to perform the coupling reaction. Indeed, they are sometimes used more or less efficiently in batch type reactors for Suzuki reactions. The study of these catalysts will allow to identify the essential characteristics (palladium oxidation state, palladium dispersion, acido-basicity and texture of the supports) that a catalyst has to possess (or not) to perform the Suzuki coupling. Furthermore, these catalysts will serve as a reference for the catalytic performances of the oxide-supported catalysts developed later on in this research.

Carbon black possesses pores of a larger size (mesoporous) and a lower specific surface area than activated carbon (microporous). The comparison between them will allow us to understand the influence of the texture among others on the diffusion of reactants and products inside the pores.

Different chemical treatments will additionally be applied to the two carbon supports in order to modify the groups present on their surface and therefore modify their acido-basic properties. The treatments may affect the dispersion of Pd on the supports but also the catalytic activity. Indeed, the hypothesis that we want to assess is that the acido-basic properties of the supports should influence the catalytic activity. In other words the balance of the acidic, and basic, characteristics of the catalysts, could play a role on the adsorption of the reactants and of the base, and consequently affect the activity of the Suzuki reaction.

Significant attention will be paid to the leaching of the active metal (palladium) in the liquid medium.

Pd-based catalysts supported on oxide supports

The second part of the thesis concerns a systematic screening aiming at investigating the activity of palladium-based catalysts supported on different oxide supports. Our choice was directed towards on solids commonly used in catalysis, namely TiO_2, SiO_2, Al_2O_3, MgO, ZrO_2 and CeO_2. They were chosen for two main reasons. (i) These materials have porosities (meso- or macropores) that are, in principle, more easily modifiable and controllable than carbon supports [88]. (ii) They have quite different physico-chemical properties compared to each other, particularly in terms of their acido-basic character, reducibility, hydrophobicity/hydrophilicity and ability to disperse palladium particles.

Two techniques for catalyst syntheses will be used for each oxide support previously mentioned: the wet impregnation and the deposition-precipitation. We hope to get larger Pd dispersions for the deposition-precipitation than for wet impregnation thus allowing the study of the effect of Pd dispersion and particle size on the catalytic performance. A significant attention has also been paid again to the leaching of the active metal (palladium) in the liquid medium.

Two mixed oxides catalytic systems have additionally been chosen to further highlight the possible influence of acid-base properties of supports and catalysts on the catalytic activity. These systems have been selected thanks to the catalytic data obtained from the screening but also in terms of ease of modulating the acido-basic properties of the materials. These mixed oxide systems selected are:

- Si-Al mixed oxides whose acid properties strongly depend on the Si/Al ratio [89] ;
- Mg-Al mixed oxides which are materials whose basic properties vary in function of the Mg/Al ratio [90-92].

Kinetic studies

An experimental reaction rate expression will be finally determined by varying the concentration of the reactants (4-bromotoluene, phenylboronic acid and the base (K_2CO_3)) and the reaction temperature. This experimental reaction rate will be deduced for our best catalysts supported on carbon materials and oxide supports. Based on the accepted mechanism of the Suzuki coupling in homogeneous catalysis and on the results obtained on the previous chapters, theoretical rate expressions will be also determined by making assumptions about the reaction pathway with a heterogeneous catalyst. By comparing the experimental

and theoretical expressions, the idea is to identify the rate limiting step of the Suzuki coupling. Having a better understanding of the Suzuki coupling mechanism and particularly identifying the rate limiting step, might indeed eventually allow to determine which parameter(s) influence(s) the catalytic performances of the Suzuki reaction, and ultimately improve them.

7. Content of the thesis

This current chapter (**Chapter I**) consists in a brief review of literature on the Suzuki coupling, the catalysts used to perform this reaction, the objectives, the strategy and the content of this thesis. The necessary information concerning the experimental set-ups for the physico-chemical characterisations of the different materials and for the evaluation of the catalytic performances in the Suzuki coupling will be given in **Chapter II**.

P**art I** concerns Pd-based catalysts supported on carbons and is divided into two sections. The first section (**Chapter III**) compares the results obtained by the catalysts supported on activated carbon and carbon black. Both supports possessing quite different textural properties, the comparison will allow us to elucidate the influence of them on the Suzuki coupling. The influences of Pd loading and Pd oxidation state have been also studied in this chapter. The reproducibility of the catalytic tests performed with our materials and the occurrence of Pd leaching are checked. The second section of the part I (**Chapter IV**) highlights the influence of the acido-basic properties of the supports on the Suzuki coupling.

Part II focuses on the catalysts supported on oxide supports. The first chapter of this part (**Chapter V**) reports a systematic screening aiming at investigating the activity of palladium-based catalysts supported on different oxide supports. The influence of the acidity is studied on Pd supported on a series of silica-alumina with different Si/Al ratios in **Chapter VI** and the influence of the basicity is evaluated on Mg-Al mixed oxides with various compositions in **Chapter VII**.

In **Part III**, a kinetic study has been carried out on the best catalysts supported on carbon materials and on oxide supports (**Chapter VIII**). The comparison of the experimental reaction rate with the theoretical ones allows identifying the rate-limiting step of the Suzuki reaction. The Chapter VIII also presents a tentative mechanism of the Suzuki coupling with heterogeneous catalysts.

An overall discussion about the obtained results in this thesis is made in **Chapter IX**.

Finally, a last chapter (**Chapter X**) presents the main conclusions of this thesis.