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Developments in Suzuki-Miyaura cross coupling reaction (SMR) towards green synthesis

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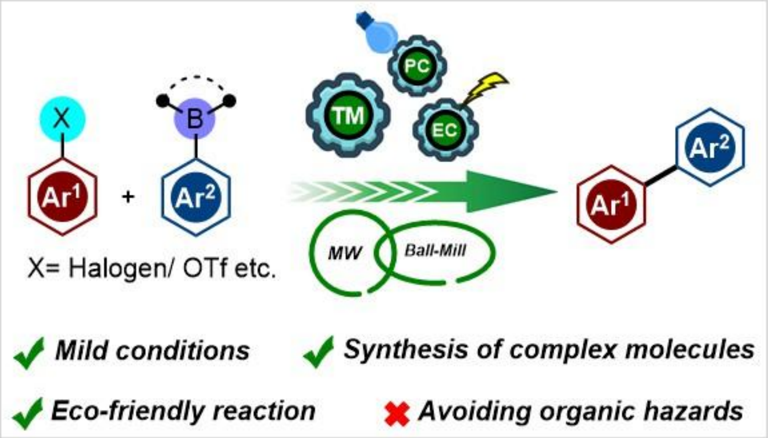
Abstract

This review presents a comprehensive overview of the Suzuki–Miyaura coupling reaction as advanced through greener techniques, focusing on literature from the past two full decades (2000–2020). It highlights the modifications made to the reaction using various devices and environmentally friendly approaches, paving the way toward a more sustainable future.



Keywords: Suzuki-Miyaura reaction; Green chemistry; Decarbonylative coupling; N-Heterocyclic carbene; Nanoparticles; Bio-polymers; Microwave; Ball mill

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1. Introduction

1.1. The Suzuki-Miyaura Cross Coupling Reaction (SMR)

A cross-coupling reaction is a transformation in which two different molecular fragments (either homo- or hetero-coupling partners) are joined together. Among these, transition-metal-catalyzed reactions, particularly those catalyzed by palladium, such as the Heck, Stille, Suzuki–Miyaura, Negishi, Hiyama, Kumada, Sonogashira, and Buchwald–Hartwig couplings, hold immense importance in organic synthesis.[1-7] These reactions provide powerful tools for C–C bond formation. The formation of C–C bonds (sp^2–sp^2 or sp^2–sp) is highly valuable in natural product synthesis, medicinal chemistry, materials science, supramolecular chemistry, catalysis, and polymer chemistry, among other fields. Although similar products can be obtained through other methodologies, the Suzuki–Miyaura reaction (SMR) is distinguished by its wide substrate scope, mild reaction conditions, easily separable by-products (boronic acids and their water-soluble derivatives), lower toxicity of boron-based reagents compared with metals such as Zn, Mg, Sn, or Cu, cost efficiency, and shorter reaction times. The SMR has found broad application in the synthesis of biologically and pharmaceutically important molecules, including CI-1034 and various CNS agents.[8–9] The incorporation of alkyl coupling partners has further increased the utility of this reaction.[10] In 2010, Heck, Suzuki, and Negishi received the Nobel Prize in chemistry for their pioneering contributions to cross-coupling reactions.[11] The first research paper introducing the Suzuki–Miyaura reaction was published in 1979 by Suzuki and Miyaura,[12–13] and the first review article on the reaction was also authored by the same researchers in 1995.[14]

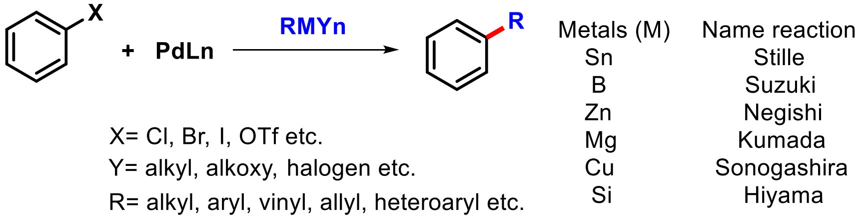


Figure 1. Transition metal catalyzed different cross-coupling reactions.

1.2 Green Chemistry

Green chemistry is defined as the application of a set of principles aimed at reducing or eliminating the use and generation of hazardous substances in the design, manufacture, and application of chemical products.[15] The concept emerged in response to the U.S. Pollution Prevention Act of 1990, which established a national policy focused on preventing pollution at its source through improved design—such as optimizing products, processes, raw material usage, and recycling—rather than relying on treatment or disposal. This shift in perspective has sparked growing interest among researchers in the field of green chemistry. The framework of green chemistry is guided by twelve key principles,[15] which include designing synthetic methods that maximize atom economy and prevent waste, selecting safer chemicals and solvents to minimize toxicity, and using non-hazardous reaction auxiliaries. Additionally, these principles advocate for the use of mild reaction conditions, renewable feedstocks, efficient catalytic systems, and the reduction of unnecessary reaction steps. They also emphasize the importance of ensuring that any unwanted by-products degrade safely, thereby reducing their potential environmental impact.

Preferred solvent	**Usable solvent**	**Undesired solvent**
Water	Cyclohexane	Pentane
Acetone	Toluene	Hexane(s)
Ethanol	Methyl	Di-isopropyl ether
2-Propanol	cyclohexane	Diethyl ether
1-propanol	TBME	Dichloromethane
Heptane	Isooctane	Dichloroethane
Ethyl Acetate	Acetonitrile	Chloroform
Isopropyl	2-Me THF	NMP
Acetate	THF	DMF
Methanol	Xylene	Pyridine
MEK	DMSO	DMAc
1-Butanol	Acetic Acid	Dioxane
^{t}BuOH	Ethylene	Dimethoxyethane
	Glycol	

Figure 2. Pfizer solvent selection guide.

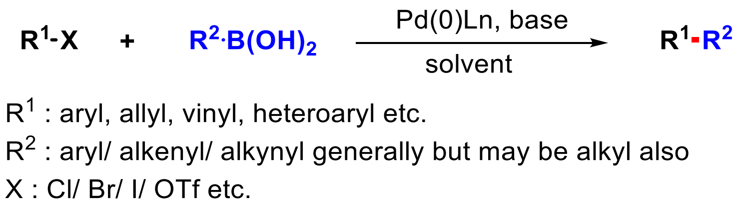
One of the major challenges in implementing green chemistry is the selection of cost-effective, environmentally friendly solvents, non-toxic reagents, and mild reaction media suitable for use in industrial, medical, and research settings. In recent years, international regulations have led to the blacklisting of several traditional solvents—such as carbon tetrachloride (CCl_4) and benzene—which, despite their historical use in both academia and industry, pose significant health and environmental risks.[16] From the perspective of synthetic organic chemistry, a key limitation remains the scarcity of green solvents that can effectively dissolve a wide range of organic compounds. However, it is noteworthy that many organic reactions have been found to proceed with high efficiency and yields in water,[17–19] despite the typically low solubility of organic substrates in aqueous media. A selection of eco-friendly solvents and alternatives to commonly used toxic or explosive solvents is presented below.[20]

Table 1. Nontoxic alternative solvents

Undesirable solvents	**Alternative**
Pentane, Hexane(s)	Heptane
Di-isopropyl ether, Diethyl ether, Dioxane, Dimethoxyethane	2-MeTHF or tert-butyl methyl ether
Chloroform, dichloroethane, carbon tetrachloride	Dichloromethane
Dimethylformamide, Dimethylacetamide, N-methylpyrrolidinone	Acetonitrile
Pyridine	Et_3N (if pyridine used as base)
Dichloromethane (extractions)	EtOAc, MTBE, toluene, 2-Me-THF
Dichloromethane (chromatography)	EtOAc/ heptanes
Benzene	Toluene

1.3 Mechanistic Aspects of SMR and Scope of Incorporation of Green Chemistry

Mechanistic studies on palladium-catalyzed cross-coupling reactions have been extensively conducted in recent years.[21–24] Among these, the Suzuki–Miyaura reaction stands out as one of the most thoroughly investigated, particularly during the latter part of the 20th century (Scheme 1). These mechanistic investigations have established that Pd(0) is the catalytically active species, which is typically generated in situ from a Pd(II) precursor. Notably, the in situ generated Pd(0) exhibits higher catalytic activity than commercially available Pd(0) complexes, which are often sensitive to moisture and less stable. Common Pd(II) sources include $PdCl_2$ and $Pd(OAc)_2$, with the latter being more effective due to its superior solubility in organic solvents. In the presence of a base—such as triethylamine (NEt_3) or *N,N*-diisopropylethylamine (DIPEA)—and phosphine-based ligands like tricyclohexylphosphine (PCy_3), triphenylphosphine (PPh_3), or 1,1'-bis(diphenylphosphino)ferrocene (dppf), Pd(II) is reduced to Pd(0), which then enters the catalytic cycle (Figure 3).[25] In this reaction, the ligand serves a dual purpose: it facilitates the reduction of Pd(II) to Pd(0) and stabilizes the resulting Pd(0) species.[26–29] Inorganic bases such as NaOH, KOH, K_2CO_3, and Cs_2CO_3 are commonly employed in the reaction medium. Beyond acting as a proton acceptor, the base also plays a crucial role in generating the transmetallation-active species from electron-deficient boranes or boronic acid derivatives (Figure 4).



$$R^1\text{-}X \quad + \quad R^2\text{-}B(OH)_2 \xrightarrow[\text{solvent}]{\text{Pd(0)Ln, base}} R^1\text{-}R^2$$

R^1 : aryl, allyl, vinyl, heteroaryl etc.
R^2 : aryl/ alkenyl/ alkynyl generally but may be alkyl also
X : Cl/ Br/ I/ OTf etc.

Scheme 1. General scheme of Suzuki-Miyaura cross coupling reaction.

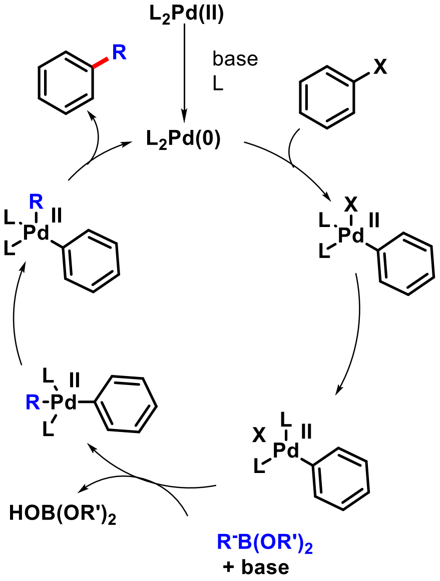


Figure 3. Catalytic cycle of classical SMR.

The choice of solvent plays a critical role in determining both the rate and yield of the Suzuki–Miyaura reaction (SMR). Traditionally, polar organic solvents such as tetrahydrofuran (THF), dimethylformamide (DMF), and acetonitrile (MeCN) have been widely used as effective media for this reaction. In some cases, nonpolar solvents like benzene and toluene have also been employed. Generally, the reaction proceeds under mild conditions. From a green chemistry perspective, the SMR holds particular significance compared to other cross-coupling reactions, as it aligns well with several of the Twelve Principles of Green Chemistry discussed in Section 1.2. Firstly, it is a catalytic process with high efficiency. Unlike many other cross-couplings, it utilizes non-toxic boron-based reagents, which are safer alternatives to tin-, copper-, or magnesium-based compounds. The reaction is typically carried out under mild conditions, leading to improved energy efficiency and reduced environmental hazards. Furthermore, the by-products are easily separable, the overall yields are high, and the process remains cost-effective—making SMR a preferred method in sustainable organic synthesis.

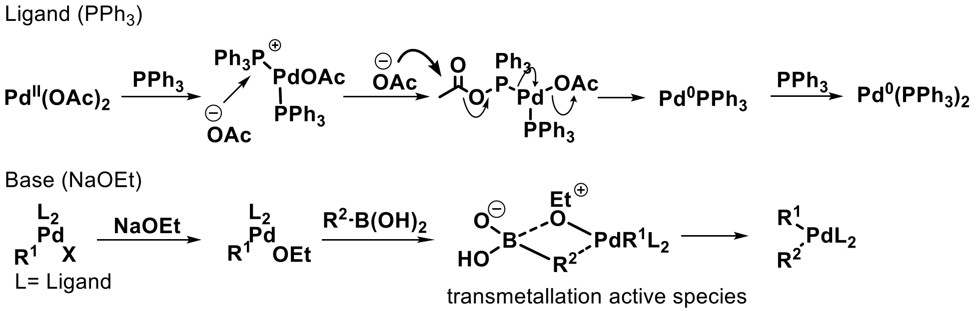


Figure 4. Role of ligand and base in SMR.

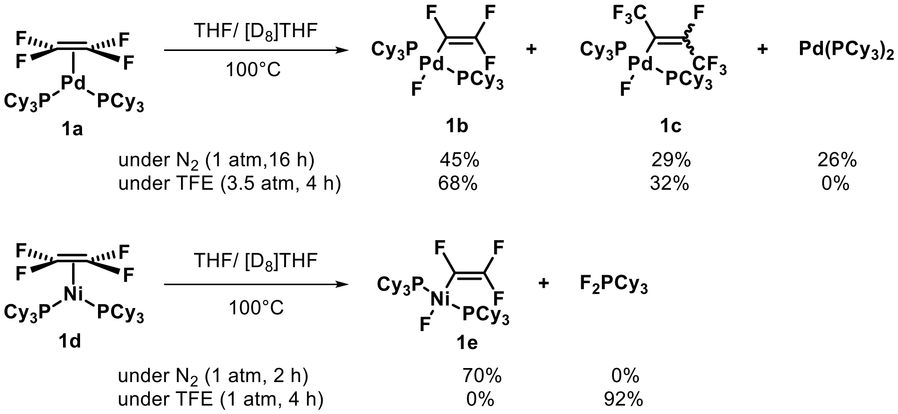
The Suzuki–Miyaura reaction aligns particularly well with the third, fourth, sixth, and ninth principles of green chemistry, offering significant advantages over other cross-coupling methods and making it highly attractive for industrial applications. However, it is not an entirely green process. The use of undesirable solvents such as THF, DMF, and benzene detracts from its environmental compatibility. Another major limitation is the reliance on phosphine-based ligands, which are associated with various health hazards, including respiratory issues, skin irritation, and gastrointestinal disturbances. Additionally, commonly used organic bases like DIPEA and pyridine also pose safety concerns. To move toward a truly eco-friendly version of this reaction, recent research has focused on developing solvent-free, base-free, and ligand-free protocols. These approaches aim to eliminate hazardous components while maintaining the reaction's efficiency and selectivity. In this review, we aim to highlight the latest advancements and modern green techniques that have been explored to improve the sustainability of the Suzuki–Miyaura reaction.

2. SMR under Base Free Conditions

In the Suzuki–Miyaura reaction, the base plays a crucial role by activating boronic acids (or their derivatives) for the transmetallation step, facilitating the reduction of the metal catalyst from M(II) to M(0), and helping to maintain the pH of the reaction medium. However, the use of base also presents a significant limitation: it can lead to the competitive decomposition of various organoboron substrates, thereby restricting the reaction's substrate scope.[30–32] As a result, there is considerable interest in developing base-free protocols or minimizing the amount of base required. Recent studies have demonstrated that the Suzuki–Miyaura reaction can proceed under base-free conditions in certain systems. In this section, we will explore these developments, along with the underlying mechanistic insights that support them.

2.1 Palladium-Fluoride Key Intermediate

In 2013, Sensuke Ogoshi and colleagues developed a novel strategy for C–C bond formation via C–F bond activation in fluorinated alkenes and arenes.[33] This approach is significant not only for enabling cross-coupling under base-free conditions but also for achieving the activation of the Csp^2–F bond, which possesses exceptionally high bond dissociation energy, without the need for external promoters.



Scheme 2. Generation of trifluorovinylpalladium(II) and trifluorovinylnickel(II) fluorides.

This reaction requires elevated temperature (100 °C) for Pd(0) to undergo oxidative addition into the C–F bond. The resulting [Pd–F] complexes, **1b** and **1e** (Scheme 2), serve as the active transmetallating species. These intermediates were isolated and characterized by ^{19}F-NMR and X-ray diffraction. Based on these findings, the proposed mechanism (Figure 5) involves formation of the η^2-TFE species **1f**, oxidative addition to form complex **1g**, base-free transmetallation, and reductive elimination to yield the product. Although this

SMR strategy reduces chemical usage, the requirement for THF as solvent and high temperature contradicts green chemistry principles.

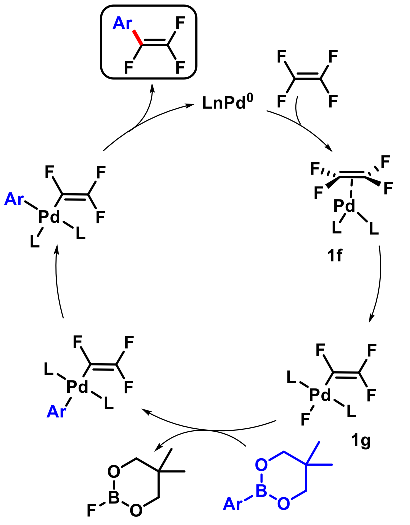
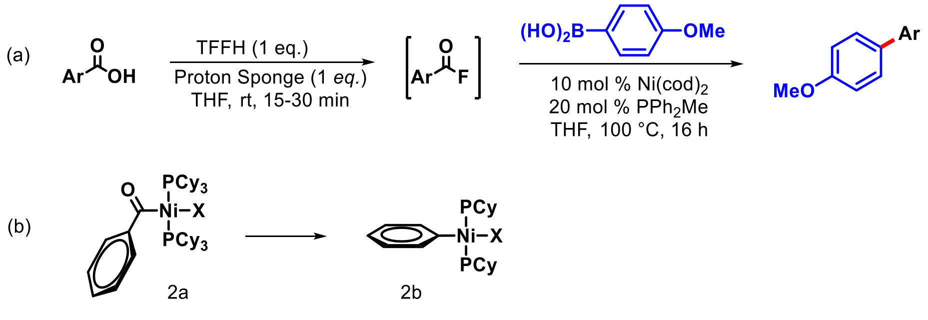


Figure 5. Proposed catalytic cycle.

2.2 Decarbonylative Coupling of Acid Fluorides

In 2018, M. S. Sanford and co-workers developed a novel Ni-catalyzed decarbonylative Suzuki–Miyaura reaction (SMR) that proceeds without any external base (Scheme 3).[34] This method is compatible with a broad range of base-sensitive boronic acids and biologically active carboxylic acid derivatives. Ni(0) is known to undergo oxidative addition with carboxylic acid derivatives[35–40] and Ni(II)-acyl intermediates can decarbonylate in the presence of suitable ligands.[36–40] Building on these findings, Sanford's group designed a two-step SMR starting from carboxylic acids, involving the formation of acid fluoride intermediates followed by cross-coupling.



Scheme 3. Ni catalyzed decarbonylative SMR.

They also found that in situ generated acid fluorides with the same reagents gave better yields. The initial oxidative addition forms the benzoyl nickel fluoride intermediate **2a**, followed by decarbonylation to produce the [Ni–F] complex (**2b**), which then undergoes transmetallation and reductive elimination to yield the product. Both intermediates **2a** and **2b** were characterized by X-ray diffraction. Notably, acid chlorides and bromides did not react under these conditions, likely because the small, highly charged fluoride ion coordinates with the boronate ester to facilitate transmetallation due to stronger B-F bond strength, unlike the bulkier chloride or bromide (Figure 6). Based on these findings and intermediate characterizations, a catalytic cycle similar to the previous case has been proposed.

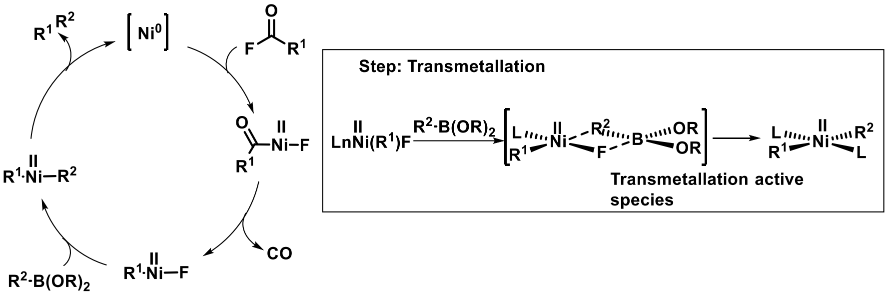
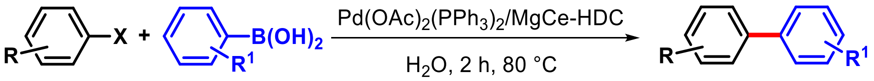


Figure 6. Catalytic cycle of decarbonylative SMR.

2.3 Using Catalytic Amount of Base

In 2019, Tomar *et al.* developed a fully green Suzuki–Miyaura reaction conducted in water using $Pd(OAc)_2(PPh_3)_2$ supported on a magnesium hydroxide–cerium carbonate hydroxide composite (MgCe-HDC).[41] The composite was prepared *via* a known method and characterized by XRD and SEM. This catalyst demonstrated excellent substrate scope with iodo substrates (Table 2) and could be used catalytically with easy recyclability.

Table 2. SMR using base supported catalyst



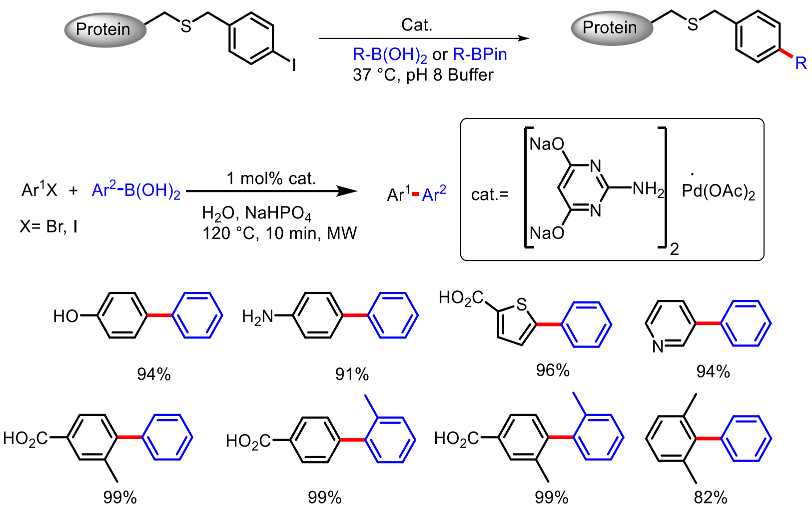
Leaving group	Yield
I	90.8 %
Br	55.5 %
OTs	24.6 %
Cl	19.5 %

3. SMR in Phosphine Free and Modified Phosphine Conditions

Phosphine-based ligands such as monodentate PPh_3, PCy_3, PEt_3, and bidentate ligands like dppf, dppe, and BINAP are commonly used in classical Suzuki–Miyaura reactions. However, these ligands are volatile, posing health risks and environmental concerns. They are also air- and moisture-sensitive, and expensive. Consequently, developing phosphine-free SMR has become an important focus in recent years. In this section, we discuss the use of phosphine-free ligands such as amines, porphyrins, and *β*-cyclodextrin.

3.1 Amine Based Ligands

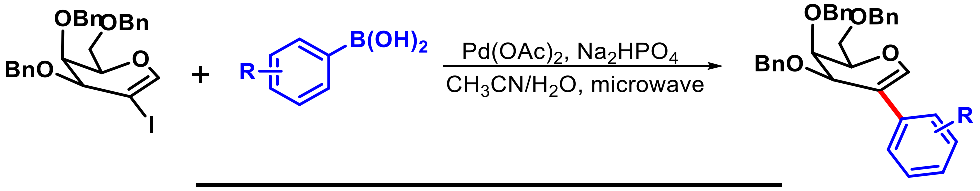
In 2009–2010, Davis *et al.* introduced an eco-friendly Suzuki–Miyaura reaction using a Pd-pyrimidine catalyst.[42–43] This method was applied to protein modification and other chemical reactions, delivering good yields under aerobic conditions (Scheme 4).



Scheme 4. SMR on a protein surface and in chemical field.

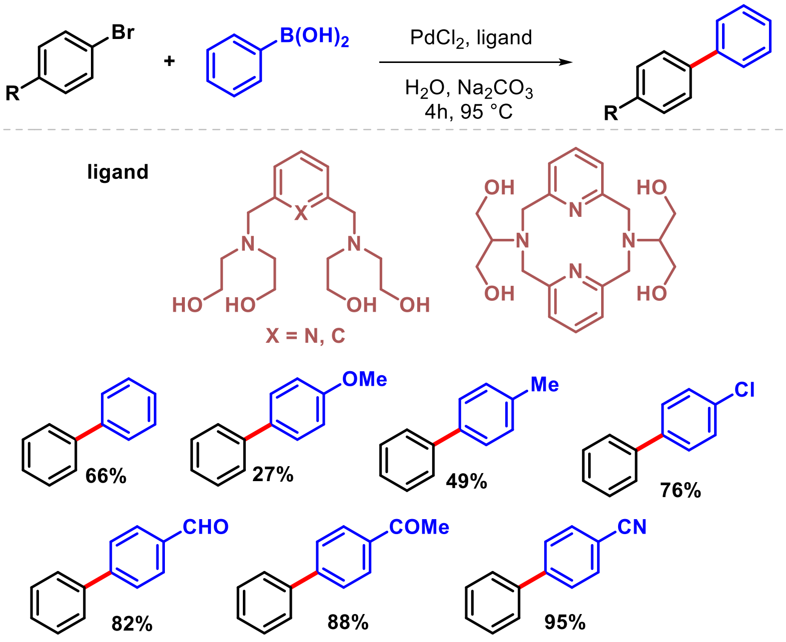
In 2012, the same group reported a regioselective Suzuki reaction using the Pd-pyrimidine catalyst to synthesize a carbohydrate mimic.[44] They optimized the reaction conditions, explored the substrate scope, and achieved excellent results (Table 3). The findings demonstrate that this modified catalyst is superior to palladium-phosphine catalysts due to its lower toxicity, greater stability in air, mild conditions, cost-effectiveness, shorter reaction times, as well as eco-friendliness in synthetic biochemistry.

Table 3. Synthesis of carbohydrate mimetics by SMR



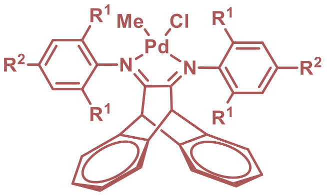
Entry	R	Time (min)	GC yield (%)
1	4-CN	5	95
2	4-OMe	5	95
3	4-F	5	90
4	2-Me	40	90
5	3-pyridyl	40	89
6	1-Naph	5	94
7	3,5 di $(CF_3)_2$	5	94

In 2013, David Morales and his team synthesized three water-soluble pincer ligands designed for Suzuki–Miyaura reactions in aqueous media (Scheme 5).[45] They optimized reaction conditions by varying parameters such as base and temperature, successfully synthesizing a wide range of compounds with satisfactory results.



Scheme 5. SMR using amine-based pincer ligands.

In 2017, Huo *et al.* reported amine-based (α-diimine)methylpalladium chloride catalysts for Suzuki–Miyaura reactions in green media like water-ethanol at room temperature.[46] While Pd(OAc)₂ gave only 26% yield, these catalysts boosted yields to 92–98% (Figure 7). They showed broad substrate scope and good turnover numbers (TON), with bulkier ligands leading to higher conversion and TON. The best catalyst was C3, where R¹ and R² were methyl groups.



C1: R^1= Me, R^2= H
C2: R^1= CMe$_3$, R^2= H
C3: R^1= R^2= Me
C4: R^1= Me, R^2= Br
C5: R^1= H, R^2= Cl
C6: R^1= H, R^2= CF$_3$

Figure 7. Some diimine based Pd-catalyst.

3.2 Porphyrin Based Ligands

In 2007, Ioannis D. Kostas and colleagues introduced a novel Suzuki–Miyaura reaction under homogeneous conditions using a water-soluble porphyrin-based Pd-catalyst. Previously, palladium porphyrin systems were used in applications like luminescent markers, oxygen sensors, and photo-induced protein cross-linking. This group was the first to perform SMR in pure water using such ligands (Figure 8).[47] They synthesized catalyst **3a**, characterized by UV spectroscopy and ^{1}H-NMR, achieving yields of 85–99% depending on the substrate

(Scheme 6). This catalyst was widely used in aqueous homogeneous cross-coupling as a cost-effective alternative to expensive palladium-phosphine catalysts.

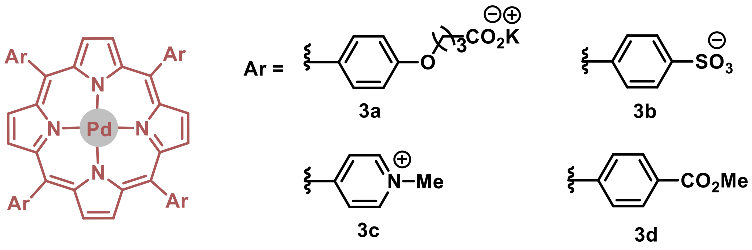
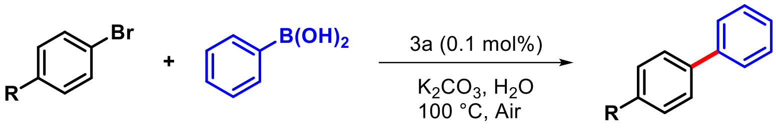


Figure 8. Porphyrin based Pd-catalyst



Entry	R	Time (h)	GC yield (%)
1	OMe	4	80
2	H	4	83
3	CN	4	Cycle-1: 100 Cycle-2: 76 Cycle-3: 53
4	CN	2	99
5	NO_2	1	93

Scheme 6. SMR in water using **3a**.

In 2010, Leu *et al.* applied a similar catalyst, **3c**, in homogeneous Heck coupling.[48] However, homogeneous reactions face challenges such as catalyst-product separation, catalyst recovery, product loss, and heavy metal contamination in the isolated products.

To address these issues, Liu *et al.* introduced a Pd-porphyrin functionalized ionic liquid anchored on modified SBA-15 (**3e**) and successfully performed Heck coupling in 2010.[49] In 2014, M. Moghadam group reported palladium-porphyrin catalysts supported on Dowex 50WX8 and Amberlite IR-120 resins (**3f** and **3g**) as recyclable, heterogeneous catalysts for Suzuki–Miyaura and Heck reactions.[50] These catalysts were easily recovered by filtration and reused multiple times with minimal loss of activity, characterized by UV-VIS, SEM, and TGA. Both reactions gave good yields (75–97%) in DMF-water (2:1). However, challenges remain, including Pd leaching, particle agglomeration, and low palladium utilization. Moreover, the use of toxic DMF and harsh conditions limits their green chemistry appeal, highlighting the need for simpler, more efficient heterogeneous catalysts.

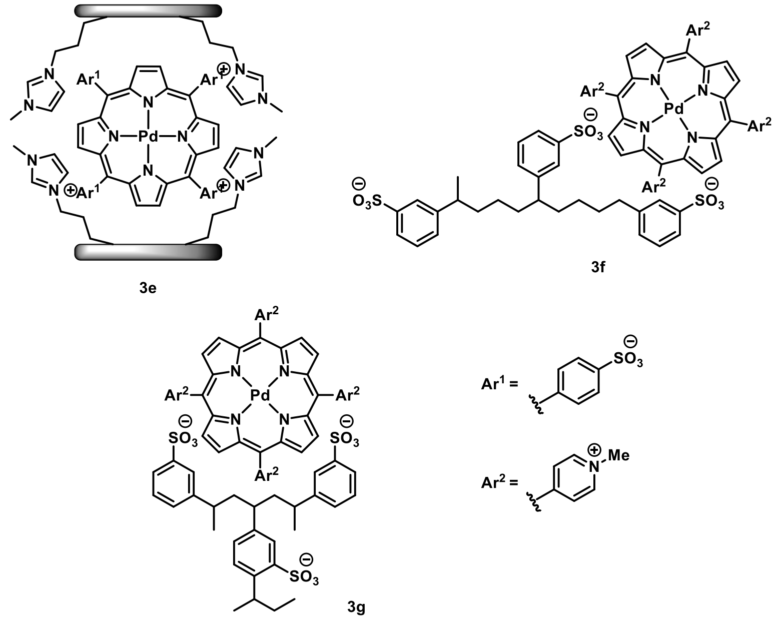
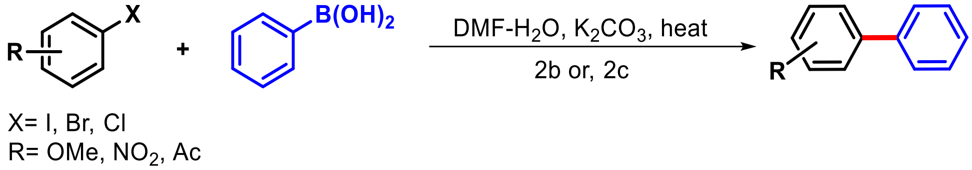


Figure 9. Some Pd-porphyrin catalyst for heterogeneous SMR.

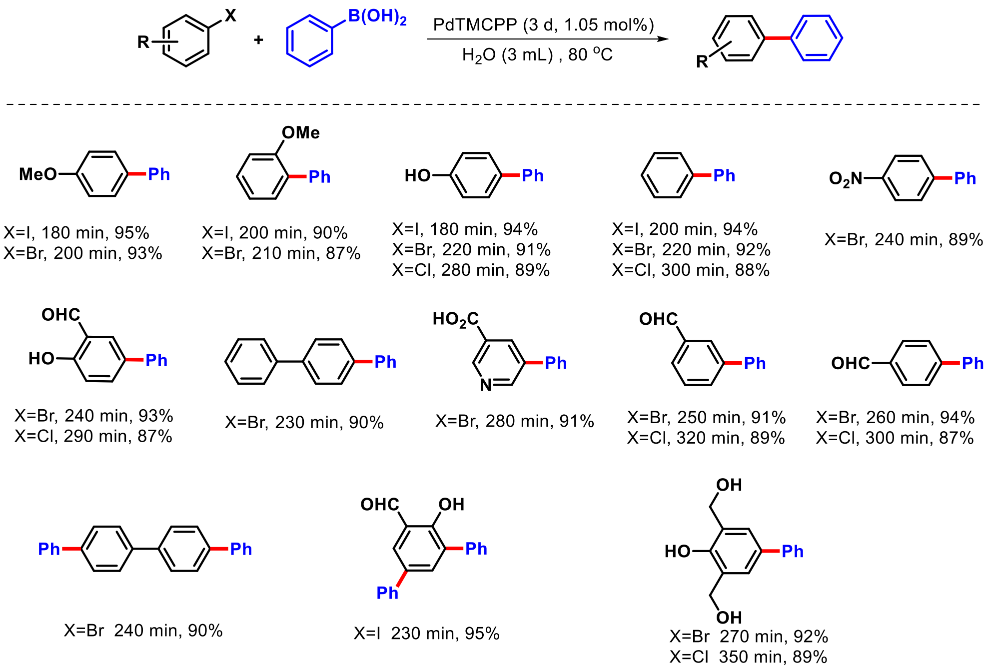


Scheme 7. SMR using resin bound catalyst.

Finally, in 2016, Mohsen Golestanzadeh and colleagues reported a new methodology using Pd-porphyrin catalyst 3d (Figure 8).[51] The catalyst was characterized by ^{1}H-NMR and FT-IR, with optimal yields achieved using 0.01 mmol of catalyst, 1.5 mmol of K_2CO_3, and water as the solvent at 80 °C.

Under these optimized conditions, excellent results were obtained (Table 4). The reactivity order of aryl halides followed the trend Cl < Br < I. Both electron-donating and electron-withdrawing substituted haloarenes, as well as heterocyclic halides, reacted smoothly under these conditions. In the same year, Luo *et al.* designed and synthesized novel picolinamide-modified *β*-cyclodextrins—water-soluble ligands for supramolecular catalysis—and proposed a possible reaction mechanism involving Pd(II)/Pd(IV) species, supported by experimental data and quantum chemical calculations.

Table 4. SMR using heterogeneous Pd-porphyrin catalyst



3.3 Cyclodextrin (CD) Based Ligands

Cyclodextrins are cyclic oligosaccharides classified as *α*-, *β*-, or *δ*-cyclodextrins, depending on whether they contain 5, 6, or 7 glycopyranose units, respectively. A key feature is their bucket-like structure with a hydrophilic exterior and a hydrophobic inner cavity. Their partial water solubility, homochirality, and ability to form inclusion complexes make them valuable in supramolecular chemistry—particularly in drug delivery[52–54] and as phase-transfer catalysts.[55–57] Their dual-affinity structure allows efficient interactions with organic molecules, often resulting in high reaction yields and easy product extraction.[58]

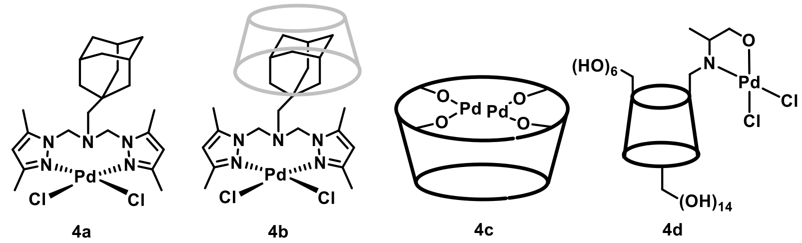
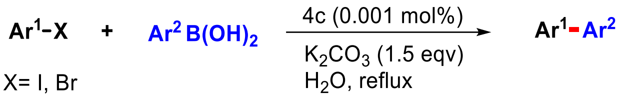


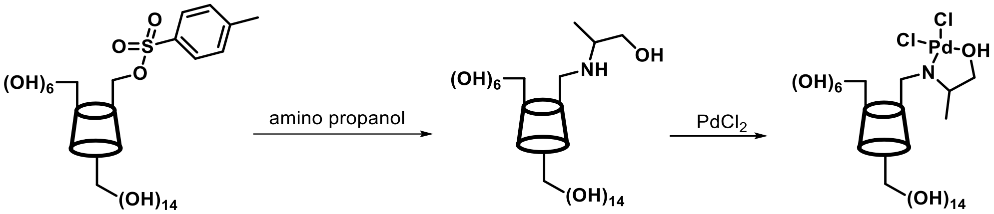
Figure 10. Different cyclodextrin based catalyst.

Based on the self-assembly behavior of adamantyl (Ad)-modified *β*-CD and pyrazole-based Pd(II) complexes, Young *et al.* designed a ligand that forms an insoluble complex, Ad-L-$PdCl_2$ (**4a**).[59] Through host–guest complexation with heptakis(2,6-di-O-methyl)-*β*-CD (dm*β*-CD), a water-soluble supramolecular catalyst (**4b**) was formed, which efficiently catalyzed the SMR (Figure 10). Reaction rate varied with solvent mixtures, following the order: H_2O–MeCN < H_2O–Acetone < H_2O–DMF < H_2O–MeOH, with the most eco-friendly mixture giving the best results due to improved catalyst solubility. This method involved a two-step catalyst preparation. In contrast, Kaboudin *et al.* (2016) developed a simpler approach by directly mixing alkaline *β*-CD and $Pd(OAc)_2$ at room temperature to form the active [Pd(II)–*β*-CD] catalyst, characterized by TGA, XRD, NMR, and FT-IR (Scheme 8).[60] Although yields were satisfactory, the need for reflux limited substrate scope.



Scheme 8. SMR using catalyst Pd(II)-*β*-CD.

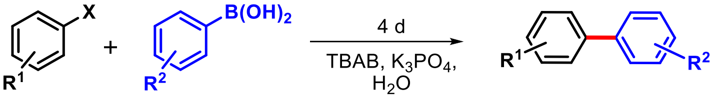
High catalyst loading and harsh reaction conditions remained challenges in earlier methods. These issues were partially resolved by F. Jian *et al.* in 2018, who used a fully water-soluble *β*-CD-based ligand in neat water.[61] The active catalyst, **4d** [$PdCl_2$(Ln@*β*-CD)], was synthesized as shown in Scheme 9 and characterized by ESI-MS.



Scheme 9. Preparation of the catalyst **4d**.

This catalyst was easily recyclable, retaining significant activity through six cycles. It also showed a broad substrate scope and an exceptionally high turnover number (TON: 1.2–3.1 × 10^6), indicating excellent catalytic efficiency (Table 5).

Table 5. $PdCl_2$(Ln@β-CD) catalyzed SMR



R^1	X	R^2	Yield (%)
H	Br	H	98
4-Me	Br	H	100
4-OMe	Br	H	94
2-Me	Br	H	83
3-OMe	Br	H	94
4-H	Br	4-Me	100
4-Me	Br	4-Me	92
4-OMe	Br	4-Me	90
3-OMe	Br	4-Me	96
4-H	Br	4-OMe	100
4-Me	Br	4-OMe	95
4-OMe	Br	4-OMe	100
2-Me	Br	4-OMe	88
3-OMe	Br	4-OMe	97

In the same year, Luo *et al.* reported another supramolecular catalyst— a picolinamide-based Pd based-cyclodextrin complex [Pd(II)@PCA-*β*-CD]—for Suzuki–Miyaura reactions in water, offering milder conditions, lower catalyst loading, and higher TON (Scheme 10).[62]

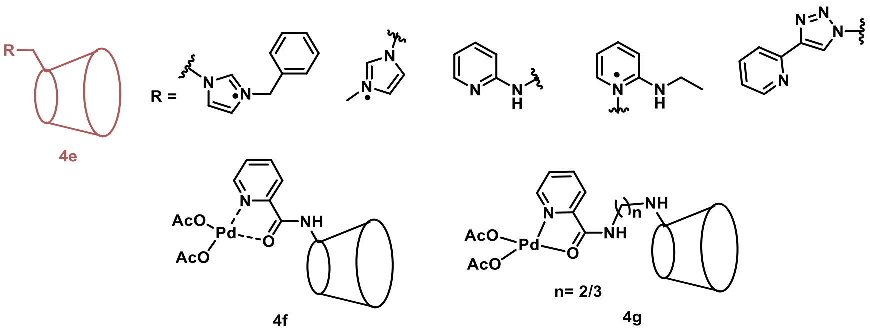
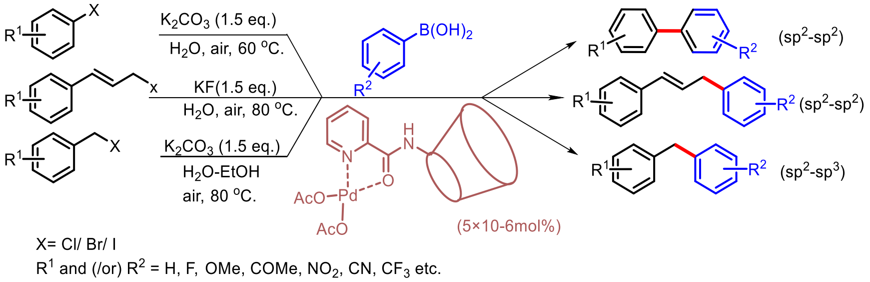


Figure 11. Some CD based ligands (**4e**) and Pd catalysts (**4f, 4g**).



Scheme 10. SMR using Pd(II)@PCA-*β*-CD catalyst.

They proposed a catalytic cycle involving Pd(II)/Pd(IV) centers, supported by experimental data and quantum chemical calculations (Figure 12). The highly water-soluble complexes **4f** and **4g** showed strong catalytic activity in SMR, with excellent recyclability and high TON, making them practically applicable. Under optimized conditions, good results were achieved across nearly 25 substrates. The key advantage of this method is its ability to achieve sp^2-sp^3 (C–C) coupling regardless of whether the groups are electron-donating or withdrawing (Scheme 10). Yields ranged from 73% to 98%, with TON values between 10^6 and 10^7, making it a highly efficient and practical green protocol for SMR in aqueous media.

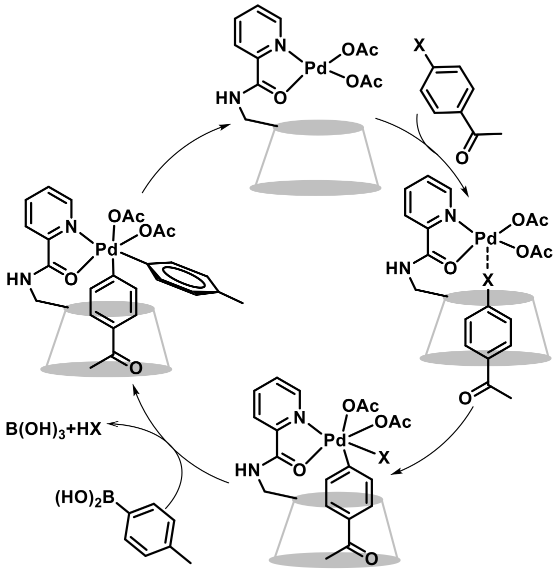
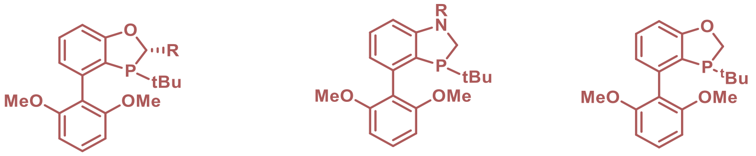


Figure 12. Catalytic cycle using Pd(II)@PCA-β-CD

3.4 Flow Technique Using Modified Phosphine Ligands

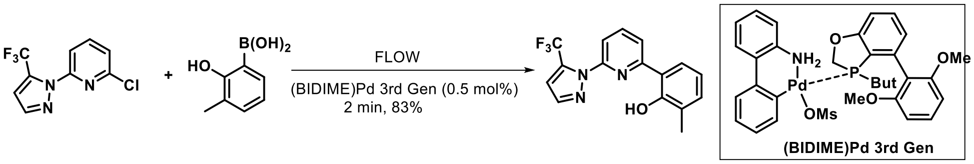
J. D. Sieber and colleagues developed a new Pd-based catalyst for SMR using flow chemistry (Scheme 11).[63] This approach is mainly applied in synthesizing biologically active compounds and active pharmaceutical ingredients (APIs).[64-68] They also prepared modified ligands for asymmetric SMR (**4h**) and regular SMR (**4i**, **4j**) (Figure 13).



4h.dihydrobenzooxaphosphole **4i.dihydrobenzoazaphosphole** **4j.BI-DIME**

Figure 13. Modified ligands for SMR.

The prepared Pd-loaded precatalyst was tested and compared with an in situ generated catalyst in batch mode using a green solvent mixture of water, isopropanol (IPA), and DME (5:3:1). In both cases, unreacted starting materials remained, indicating limitations under standard conditions. However, switching to a flow technique—allowing heating above the solvent's boiling point under pressure—dramatically improved performance. Using 2 equivalents of aryl halide at 120 °C, the yield reached 98% in just 2 minutes. The process used a catalytic amount of phosphine ligand and offers a sustainable, industry-relevant solution.



Scheme 11. SMR using flow chemistry.

3.5 Carbene & N-Heterocyclic Carbene (NHC) Based Ligands

Since the early 21st century, nucleophilic carbenes—particularly N-heterocyclic carbenes (NHCs)—have been widely used as ligands in various cross-coupling reactions, including the Suzuki–Miyaura reaction (SMR).[69–70] Initially, these reactions were conducted in toxic organic solvents such as DMF, THF, DCE, DMA, and toluene at elevated temperatures. In 2002, the Nolan group first introduced an NHC-based Pd–catalyst (**5a)** for Kumada coupling in DME under both aerobic and anaerobic conditions.[71] Later, in 2005, Organ *et al.* applied NHC ligands (**5a**–**5c**) in Suzuki coupling using dioxane.[72] This was followed by Herrmann *et al.* (2006) using ligands **5d**–**5f** in DMA,[73] Wass *et al.* (2007) with **5g** in DMA,[74] and Tsuji *et al.* (2008) with **5d** in THF and toluene.[75] These reactions showed broad substrate scope, good yields, and strong catalytic activity, with increased carbene bulkiness and nucleophilicity enhancing the process. The N-1-adamantyl ligand (**5b**) gave the best yields by accelerating reductive elimination. Effective Pd-catalysts were confirmed by single crystal XRD. However, challenges included long reaction times, use of carcinogenic solvents, high temperatures, and additives.

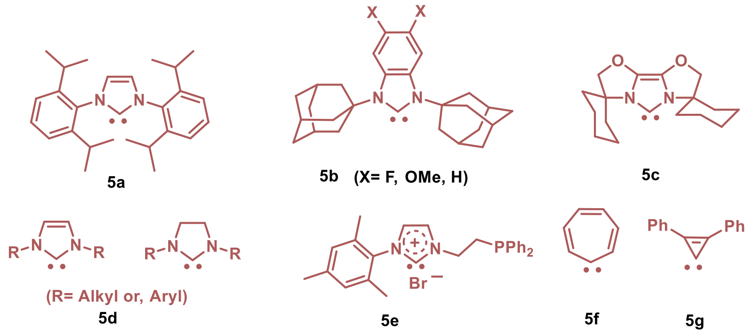
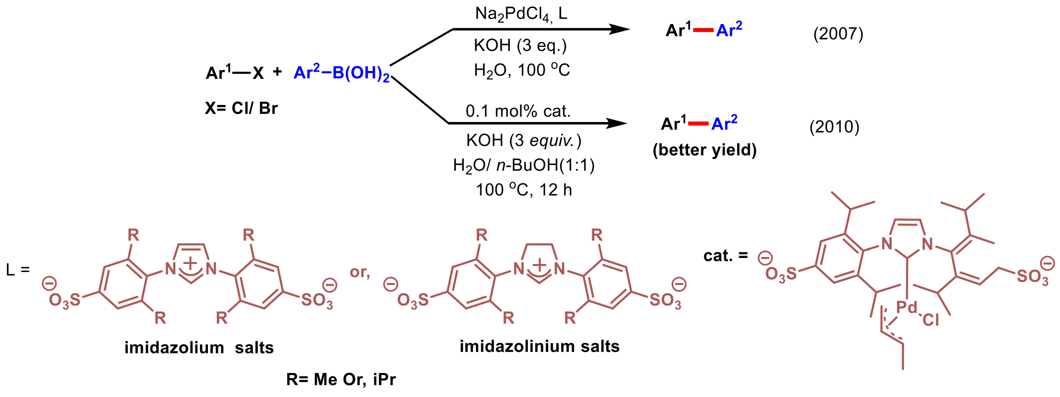


Figure 14. Some carbene ligands are used in SMR.

In 2006, Nolan *et al.* developed an eco-friendly method using (NHC)Pd(allyl)Cl in isopropanol, effective at room temperature with low catalyst loading for aryl chlorides and bromides.[76]

In 2007, Plenio's group introduced water-soluble N-heterocyclic imidazolium and imidazolinium ligands for SMR in green media, giving good yields even for aryl chlorides.[77] In 2010, they improved this with palladium catalysts based on *m*-sulfonated imidazolinium/imidazolium ligands, using a 1:1 water/*n*-butanol mixture to solve solubility issues, achieving excellent yields for aryl carbocyclic and heterocyclic substrates.[78]



Scheme 12. SMR using water soluble NHC ligand.

In 2009, Çetinkaya *et al.* developed two water-soluble catalytic systems (**5h**, **5i**) by incorporating pyridinecarboxylic acid groups instead of water-soluble NHC ligands into the Pd-catalyst (Figure 15).[79] These catalysts demonstrated improved recyclability, successfully reused up to three times, but produced more homocoupling by-products compared to earlier catalysts. Aryl chlorides with electron-withdrawing groups gave better yields than those with electron-donating groups, though the overall substrate scope was limited.

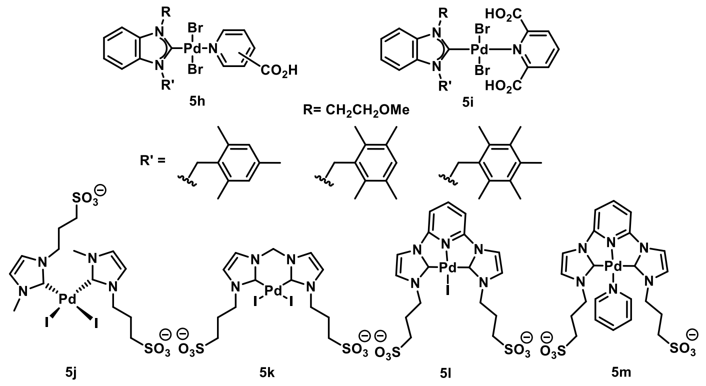


Figure 15. Some water soluble NHC-Pd-catalysts.

In 2011, Peris *et al.* developed new catalysts that outperformed earlier versions (Figure 16).[80] They synthesized four water-soluble catalysts: one with two monodentate NHC ligands in *cis*-configuration (**5j**), one with a *cis*-bidentate NHC (**5k**), and two tridentate NHCs of different types (**5l**, **5m**). Catalyst **5c** showed the best activity, achieving TONs of 10^4–10^5, converting aryl chlorides in 12 hours and bromides in just 2–3 hours with good yields (75–85% for chlorides and 80–99% for bromides). The use of a non-toxic water/isopropanol solvent further enhances the green chemistry appeal of this method.

In 2013, Szilvási and Veszprémi investigated the mechanistic aspects of SMR using NHC ligands.[81] Through kinetic studies and DFT calculations, they highlighted the importance of bulky substituents on the NHC-metal complex. The carbene's strong σ-donating ability influences electronic effects, while the bulky groups provide steric effects that enhance kinetic stability and promote reductive elimination. However, steric hindrance can impede oxidative addition, especially with *ortho*-substituted haloarenes, sometimes causing reaction failure. Their theoretical calculations helped to explain the catalytic activity by comparing energy requirements for various catalysts. In the same year, Kolychev *et al.* synthesized and characterized a series of 6-7 membered NHC-Pd complexes (**5o**) (Figure 17).[82] They characterized these catalysts (**$5o_1$–$5o_6$**) by single-crystal XRD and applied them in SMR. Notably, they exhibited higher activity toward heterocyclic substrates than homo-aryl ones under reflux conditions (Table 6). The process uses mild base, very low catalyst loading, short reaction times, and water as a solvent under aerobic conditions. Its broad substrate scope, cost efficiency, and absence of homo-coupling byproducts make it highly valuable both synthetically and environmentally, suggesting a strong potential for industrial applications in coupling heterocyclic compounds.

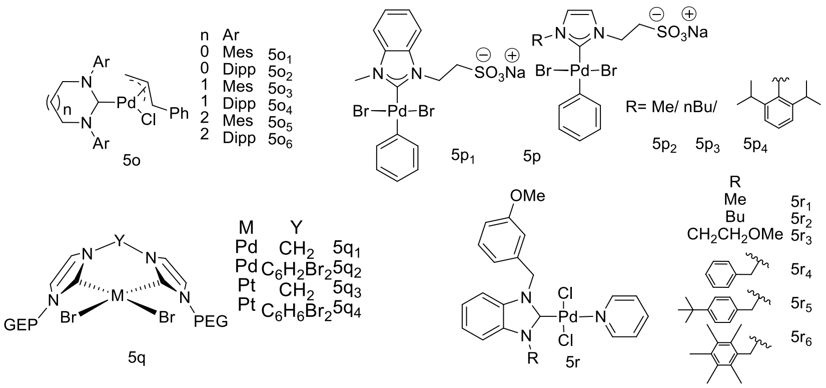
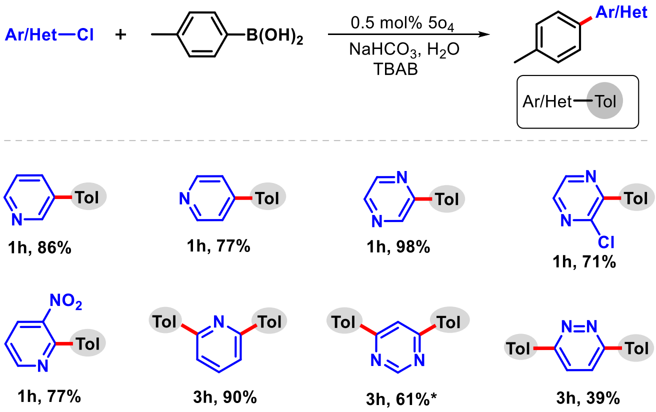


Figure 16. Some NHC based Pd-catalysts.

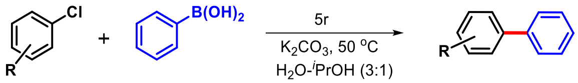
Table 6. Hetero-aryl coupling using NHC-Pd catalyst



In 2014, Zhong *et al.* developed SMR methodology using water-soluble PEPPSI-Pd-NHC catalysts (**5p**), with **5p$_4$** showing the best results. However, it required long reaction times (12–36 h) and gave lower yields with bulky substrates, while normal substrates reacted well at room temperature. The catalysts were reusable up to four times without significant activity loss.

In 2015, Strassner and coworkers introduced oligoether (PEG)-substituted bis-NHC Pd and Pt complexes (**5q**). Pd catalysts (**5q$_1$**, **5q$_2$**) showed moderate SMR yields (60–65%) at room temperature in water, improved to 80–90% at 60 °C in methanol-water (1:1), with TON ~800 and reusability for three cycles. Without methanol, yields dropped significantly, and phase transfer catalysts did not help even at 100 °C.

In 2019, Kaloğlu and Özdemir reported six new PEPPSI-type Pd–NHC complexes (**5r**) that efficiently catalyze SMR in aqueous phase. Synthesized as per Organ *et al.*, they were characterized by NMR, FT-IR, and elemental analysis. These catalysts perform well at only 50 °C in water-*i*PrOH (3:1), converting even less reactive aryl chlorides with various substituents. All six catalysts showed high efficiency, with **5r$_3$** being the best. This approach stands out for its green solvent use, mild conditions, short reaction times (0.5–2 h), and high yields (70–95%), making it the most effective PEPPSI-type NHC-Pd catalyzed SMR method reported to date.



Entry	R	Time	GC Yields (%)					
		(h)	$5r_1$	$5r_2$	$5r_3$	$5r_4$	$5r_5$	$5r_6$
1	H	2	87	86	90	83	81	88
2	4-Me	2	86	83	92	88	85	90
3	4-OMe	2	78	75	85	79	77	81
4	2-Me	3	69	65	78	71	73	75
5	2-OMe	3	59	55	65	57	58	60
6	4-COMe	2	89	86	95	92	90	94
7	4-NO_2	2	91	89	93	87	85	92

Scheme 13. SMRs catalyzed by **5j**.

3.6 SMR Using Other Nontoxic Ligands

Besides the protocols mentioned, several other ligands have emerged over the past decade for SMR, effective in eco-friendly media. In 2011, Zhou *et al.* developed an ammonium-functionalized, water-soluble bidentate nitrogen-containing ionic ligand (**6b**) and its non-ionic analogue (**6a**) for SMR in water (Figure 18).[86] They also synthesized the active catalyst **6c**, which showed lower reactivity compared to the in situ generated catalysts.

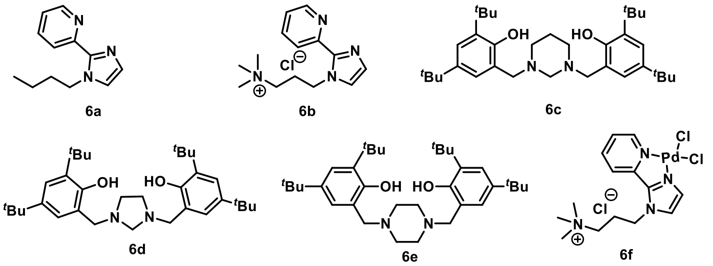
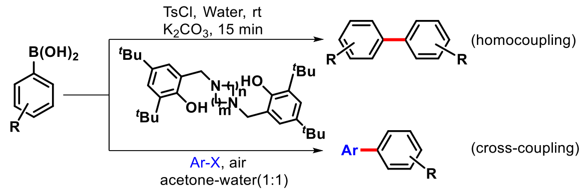


Figure 17. Some nontoxic ligands (**6a**-**6e**) and catalyst **6f** used in SMR.

The involvement of Pd(0) nanoparticles was confirmed by TEM analysis, mercury drop tests, and poisoning experiments. Aryl bromides with electron-withdrawing groups gave good yields, while those with electron-donating groups performed poorly. Adding TBAB, a phase transfer catalyst that forms $Bu_4NArB(OH)_3$, significantly improved reaction rates and yields, whereas surfactants like SDS and SDBS had no effect. Ligand **6a** showed lower catalytic activity compared to **6b** in this reaction.

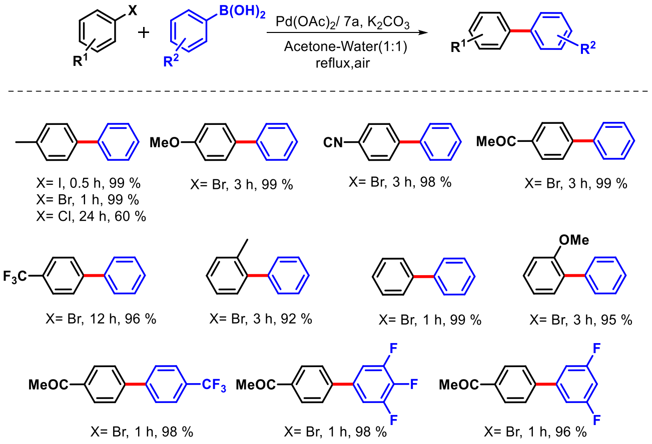
In 2013, Zhou *et al.* developed a new SMR method using amine-bridged bis(phenol) ligands **6d**, **6e**, and **6f** (Figure 18).[87] They synthesized these ligands following a known protocol and confirmed their structures by single crystal XRD. These ligands showed high efficiency in both homocoupling of aryl boronic acids and cross-coupling with aryl halides (Scheme 14). Acetone-water was used as the solvent for cross-coupling, while homocoupling was performed in water; both reactions proceeded well under aerobic and anaerobic conditions.



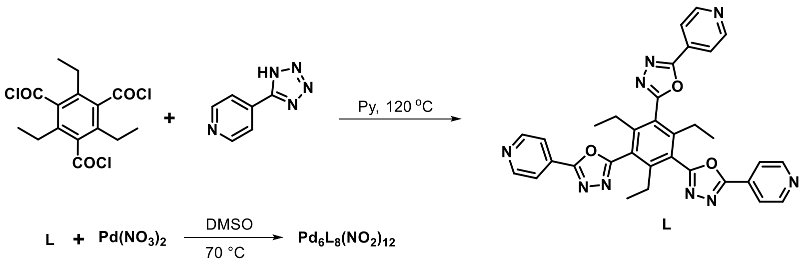
Scheme 14. Homo-coupling and cross-coupling using phenolic ligands.

Homocoupling reaction proceeded best with trace Ts-Cl, achieving over 95% yield at room temperature. In contrast, cross-coupling required no additives and gave excellent yields for both electron-rich and electron-deficient substrates at reflux temperature (Table 7).

Table 7. Phenolic ligand based SMR



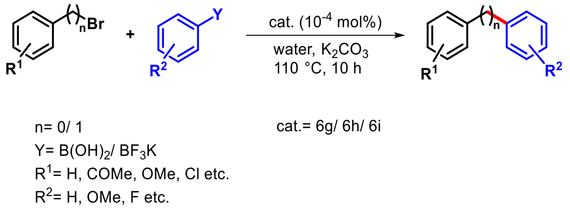
Around the same time, Zhao *et al.* developed a novel catalytic system based on a supramolecular assembly.[88] They synthesized a self-assembled Pd_6L_8 nanoball, a type of metal-organic framework (MOF), characterized by TEM and DLS (Scheme 15). This catalyst demonstrated excellent Suzuki–Miyaura reaction performance at very low loadings (10–100 ppm) under ambient conditions, working effectively in both homogeneous (water-ethanol 1:1) and heterogeneous (*o*-xylene) media. It catalyzed SMR of electron-rich, electron-deficient, and bulky aryl halides with high conversion rates (90–99% yield in 1–10 hours) and a TON of 9800 (at 100 ppm catalyst) at just 60 °C in aerobic conditions. The efficiency of this catalytic system was further demonstrated by its ability to activate even the least reactive aryl halide, fluorobenzene (PhF), achieving approximately 41% yield under the same conditions within 30 hours. The main drawback of this



Scheme 15. Synthesis of Pd_6L_8 nano balls.

method was the challenge of catalyst recovery in homogeneous conditions, which was addressed by switching to *o*-xylene as the solvent at 130 °C. However, the water–ethanol mixture remained the greener and more cost-effective medium, making it more attractive for practical applications.

In 2014, the Tsang group introduced a novel Suzuki–Miyaura reaction protocol using *closo*-carborane-based NBN pincer complexes in neat water (Scheme 16).[89] They synthesized two *ortho*-carborane complexes (**6g**, **6h**) and one *meta*-carborane complex (**6i**), characterized them *via* single crystal X-ray diffraction, and evaluated their catalytic activity in SMR. The complexes and their structures are presented in Figure 18.



Scheme 16. SMR using NBN-Pincer Complexes.

These *closo*-carborane-based complexes function as efficient homogeneous catalysts in aqueous media owing to their excellent water solubility. The optimal reaction conditions were found to be at 110 °C in water, without the need for any additives. Interestingly, the addition of phase transfer catalysts like TBAB, organic solvents, or stronger bases such as KOH significantly reduced the reaction yield. Among the three, complex **6g** demonstrated superior catalytic performance, offering a higher turnover number (TON) in the range of (7.7–9.9) × 10^5, along with excellent yield and selectivity. Notably, it enabled selective activation of the bromo (Br) functional group over the chloro (Cl) in substrates, achieving up to 97% selectivity, making it a highly valuable system for selective SMR in water. Besides boronic acids, aryl trifluoroborate salts were also good coupling partners of the aryl halides under this reaction conditions.

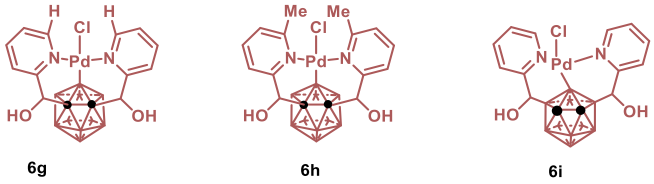


Figure 18. Some NBN pincer complexes.

In 2015, Liu *et al.* developed a green approach to the Suzuki–Miyaura reaction using an amide-based ligand **6j** (Figure 19).[90] The reaction was performed in a 1:1 water–ethanol mixture at 60–90 °C. Aryl bromides and iodides with electron-withdrawing groups gave excellent yields (up to >95%) within 4–5 hours. In contrast, electron-rich bromoarenes and aryl chlorides exhibited lower reactivity, providing moderate yields (50–80% for bromoarenes and 14–44% for chloroarenes) over a longer reaction time (10–20 hours).

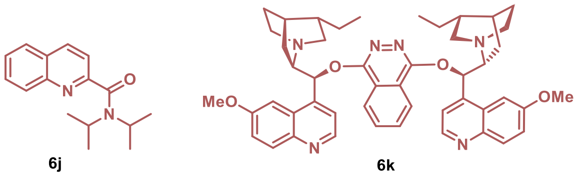


Figure 19. 6j- QADIA, **6k**- (DHQD)2PHAL.

Saikia *et al.* reported a significantly improved Suzuki–Miyaura reaction (SMR) protocol around the same time using the chiral ligand $(DHQD)_2PHAL$ (**6k**).[91] This method stands out as one of the most efficient phosphine-free and water-based SMR systems developed to date. The reaction demonstrated a broad substrate scope, excellent catalyst recyclability (up to five cycles), and required no external promoter. While electron-deficient aryl halides reacted efficiently, electron-rich boronic acids gave slightly lower yields. For heterocyclic substrates, a slightly higher catalyst loading (1 mol%) was necessary to prevent deactivation due to heteroatom–catalyst coordination. The green credentials of this protocol are particularly noteworthy: performed in neat water, room temperature conditions, no phase-transfer catalyst or additives, very low catalyst loading, minimal homocoupling by-products, efficient recyclability. This method is among the best examples of truly green SMR without toxic phosphine ligands. While other phosphine-free protocols exist, many lack either methodological efficiency or environmental appeal. Hence, only the most applicable and eco-friendly techniques have been highlighted in this section.

4. Ligand Free SMR Using Green Solvents

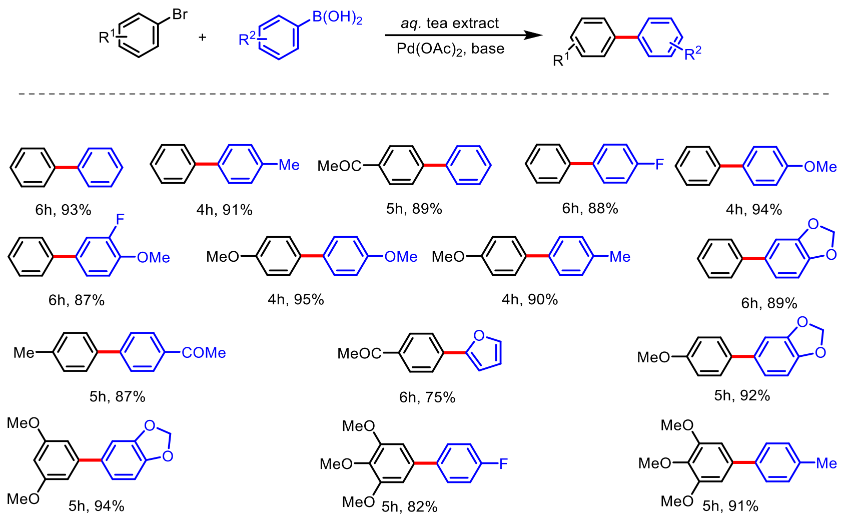
One of the most impactful advancements in Suzuki–Miyaura coupling (SMR) is the development of ligand-free protocols in green solvents such as water, ethanol, acetone, or their mixtures. Traditional SMR typically relied on toxic organic solvents like DMF, DMSO, THF, glycol, ether, or dioxane, which pose environmental and health hazards. The shift to greener solvents has significantly advanced sustainable synthetic chemistry. Historically, SMR also required expensive and toxic phosphine ligands, but over time, these have been replaced by greener alternatives like amines, N-heterocyclic carbenes (NHCs), and cyclodextrins (CDs). These ligand systems not only improved substrate scope but also aligned the reaction better with green chemistry principles, as previously discussed. However, completely eliminating ligands goes a step further—reducing chemical use, lowering costs, and simplifying the reaction process. This section focuses on such ligand-free SMR modifications, highlighting methods that are both environmentally and economically superior.

4.1 Use of Aqueous Extracts

Water is the most abundant, safe, cheap, and eco-friendly liquid, which has long attracted the interest of chemists as a green solvent. Although organic chemistry traditionally favored solvents that form homogeneous mixtures, it is now well recognized that water can play a key role in many reactions—even when most organic compounds have low solubility in it.[88-90] In such cases, water's hydrophobic effect helps to bring organic molecules closer together, increasing the chance of reaction. For water-soluble (hydrophilic) compounds, water also helps by lowering the reaction energy through solvation and hydrogen bonding.

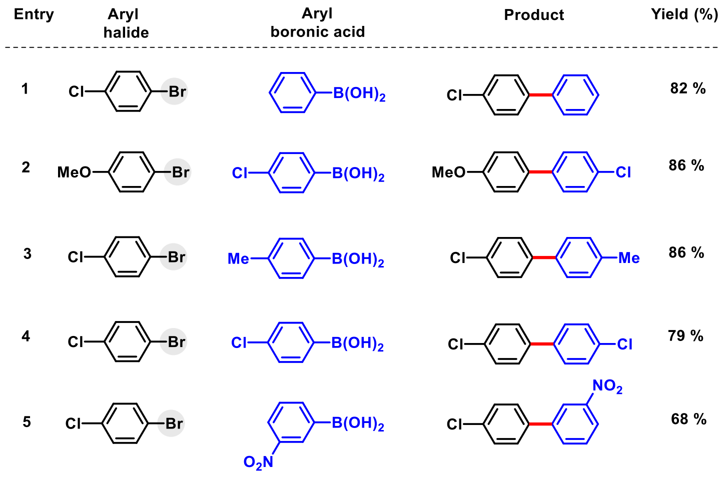
4.1.1 Water Extract of Tea (WET). A mild and fully green ligand-free Suzuki coupling protocol was developed by R.C. Boruah and co-workers in 2014, using aqueous tea extract at room temperature.[91] The reaction exhibited excellent chemoselectivity towards bromo over chloro groups, even at elevated temperatures, and tolerated base-sensitive functional groups well. After optimizing the conditions, a broad substrate scope and high selectivity were achieved (Tables 8 and 9). The active species—Pd nanoparticles (Pd NPs)—were formed in situ by the reduction of Pd(II) using polyphenols present in the tea extract. Their formation was confirmed via powder XRD and HR-TEM. This method is notable for being highly selective, eco-friendly, and cost-effective.

Table 8. SMR using aqueous tea extract



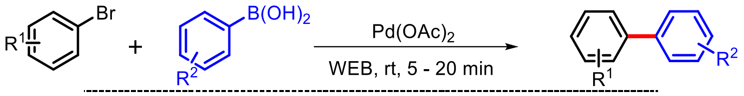
In 2016, H. Veisi and his team explored the detailed mechanism of the Suzuki–Miyaura reaction (SMR) using water extract of tea (WET) and expanded their study to other reactions as well.[92] According to their findings, flavanols and gallic acid derivatives such as (+)-catechin, epicatechin, gallocatechin, epicatechin gallate, (−)-epigallocatechin, and (−)-epigallocatechin gallate—naturally present in green tea extract—effectively reduced Pd(II) to Pd(0) nanoparticles without the need for any hazardous reducing agents. The resulting active Pd catalyst was thoroughly characterized using UV-VIS spectroscopy, XRD, FTIR, FE-SEM, TEM, and EDX analysis.

Table 9. Selectivity of reaction using WET



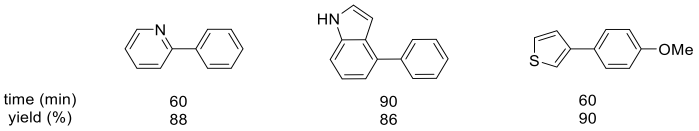
4.1.2 Water Extract of Banana (WEB). In 2015, Saikia *et al.* reported a Suzuki–Miyaura reaction (SMR) protocol using water extract of banana without the need for any added base, ligand, or activator.[93] They prepared the extract by drying banana peels, burning them to ash, then mixing with water and filtering. This eco-friendly extract proved highly effective for a wide range of substrates, including heterocyclic compounds (Table 10). The water extract of banana (WEB) containing various bases like phosphates and carbonates likely boosted the reaction significantly. Notably, the extract could be recovered and reused multiple times. Since bananas are widely available, and the extract can also be made from the trunk and rhizome of the banana plant, this method is a highly efficient, low-cost, and fully green approach for forming C–C bonds.

Table 10. SMR with WEB



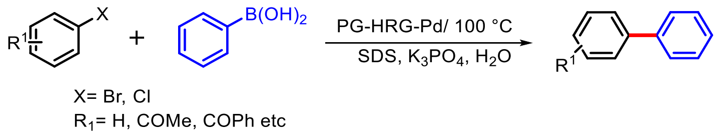
Entry	R^1	R^2	Time (min)	Yield (%)
1	4-OMe	H	5	99
2	3-OMe	H	10	98
3	4-Me	H	10	99
4	4-Me	4-OMe	10	99
5	4-Me	4-CF_3	15	97
6	4-NO_2	H	10	99
7	4-CN	H	10	98
8	H	4-OMe	10	99
9	4-CHO	H	15	96
10	3-CHO	H	15	95
11	2-CHO	H	20	92

Heterocyclic Substrates:



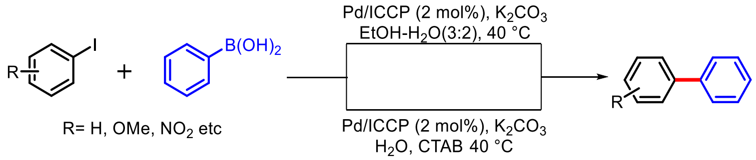
4.1.3 Water Extract of Rice Straw Ash (WERSA). Saikia *et al.* developed another SMR protocol using an aqueous extract of rice straw ash (WERSA) at room temperature, which proceeded smoothly without any external base, ligand, or additives.[94] They optimized the reaction conditions and tested a range of substrates. Although both electron-rich and electron-deficient substrates participated, the yields were moderate, ranging from 45% to 85%, with an average of about 65%, which is lower compared to other methods. Chemical analysis of rice straw showed it contains metal oxides such as Fe_2O_3, TiO_2, CaO, SiO_2, MgO, K_2O, Al_2O_3, and Na_2O. In water, these convert to metal hydroxides that act as internal bases, facilitating the reaction. The catalyst could be recycled and reused up to 6-7 times.

4.1.4 Water Extract of Plant (Pulicaria glutinosa Extract = PGE). In 2017, M. Khan and colleagues reported a green Suzuki–Miyaura reaction (SMR) method using an aqueous extract of the flowering plant *Pulicaria glutinosa*.[95] The active catalyst, Pd@graphene nanocatalyst (PG-HRG-Pd), was prepared by simultaneous reduction of graphene oxide (GO) and $PdCl_2$ under mild conditions with the help of the plant extract (PGE). The antioxidants in PGE, such as terpenoids and flavonoids, facilitated the reduction process and stabilized the nanocatalyst by adhering to its surface, significantly improving its dispersibility in water. The catalyst was characterized using HRTEM, XRD, UV-visible spectroscopy, FTIR, and Raman spectroscopy. The reaction was carried out at 100 °C in pure water, with SDS as a surfactant phase transfer catalyst and K_3PO_4 as the base. The method worked well for normal aryl substrates, but substrates like 4-chlorobenzophenone showed low yields, around 38%.



Scheme 17. SMR using PGE extract in water.

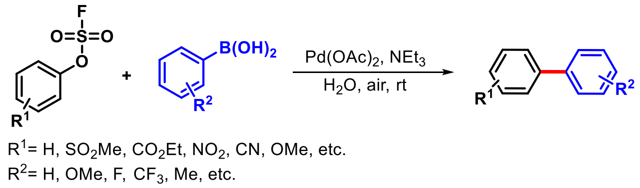
4.1.5 Extract of Mussel Shell Particle. In 2018, S. Wacharasindhu and his team developed a palladium nanoparticle catalyst supported on $CaCO_3$ plates (Pd/ICCP) derived from mussel shells for use as a heterogeneous catalyst in the Suzuki–Miyaura reaction.[96] The catalyst was prepared from the shells of the Asian green mussel (*Perna viridis*) and characterized using SEM, TEM, and EDX techniques. Notably, this catalyst can operate in both homogeneous and heterogeneous phases by using an ethanol-water mixture or water as the solvent, respectively. Their optimized conditions, tested with 4-iodoanisole and phenyl boronic acid, showed that the ethanol-water (3:2) solvent mixture with organic base DIPA or inorganic bases like Cs_2CO_3, Na_2CO_3, and K_2CO_3 gave nearly 100% yields. Similarly, in the heterogeneous system using water with CTAB and K_2CO_3, comparable high yields were also achieved. Another advantage of this method is the mild reaction temperature (40 °C) which allowed huge substrate scope; having both electron donating, withdrawing groups. In all the cases yields were very good (>90%).



Scheme 18. SMR using Pd/ICCP.

4.2 'On Water SMR' Using Aryl Fluorosulfate Substrate

In 2015, Liang *et al.* developed a novel Suzuki–Miyaura reaction protocol carried out in pure water without any co-solvents such as methanol, THF, or DMF, and without additives like phase transfer catalysts (Scheme 19).[97] The reaction proceeded under heterogeneous conditions at room temperature in the presence of air. They prepared aryl fluorosulfate substrates from commercially available phenols. Aryl fluorosulfates, bromides, iodides, and triflates bearing electron-withdrawing groups (such as CN) gave good yields, with fluorosulfates providing the best results. Interestingly, organic bases like triethylamine and 4-methylmorpholine outperformed inorganic bases in this reaction. The reaction was very fast, and the catalyst is reusable. So it was both time and cost effective and highly applicable as a sustainable protocol.

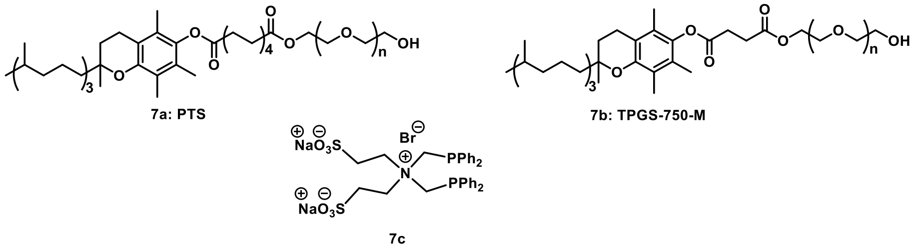


Scheme 19. SMR using fluorosulfates.

4.3 SMR in Green Solvents Using Surfactant

Performing organic reactions in water without water-soluble ligands or co-solvents creates heterogeneous conditions, which makes catalyst recycling easier but often results in lower yields and can cause metal catalysts to aggregate. A better approach is to run the reaction under homogeneous conditions in water, where the organic product can be more easily separated. This can be achieved by using surfactants that form micelles, allowing reactions to occur inside the lipophilic core of these micelles. Here, water acts as the bulk medium, promoting surfactant and particle organization through entropic effects. This method offers an excellent way to carry out Suzuki–Miyaura reactions in water under homogeneous conditions, without relying on any organic co-solvents.

In 2011, Lipshutz *et al.* introduced several important reactions—including Heck, Suzuki, Negishi, Sonogashira, Buchwald coupling, olefin metathesis with the 2nd generation Grubbs catalyst, and C-H activation—carried out in water under homogeneous conditions using surfactants.[98] Here, we will focus on the Suzuki–Miyaura reaction (SMR) specifically. They tested two different surfactants, PTS (**7a**) and TPGS-750-M (**7b**), for the SMR and made key observations. At room temperature, surfactant **7b** outperformed **7a**, delivering higher yields, faster reaction rates, and better catalyst recyclability—successfully reused up to seven times.



7a: PTS

7b: TPGS-750-M

7c

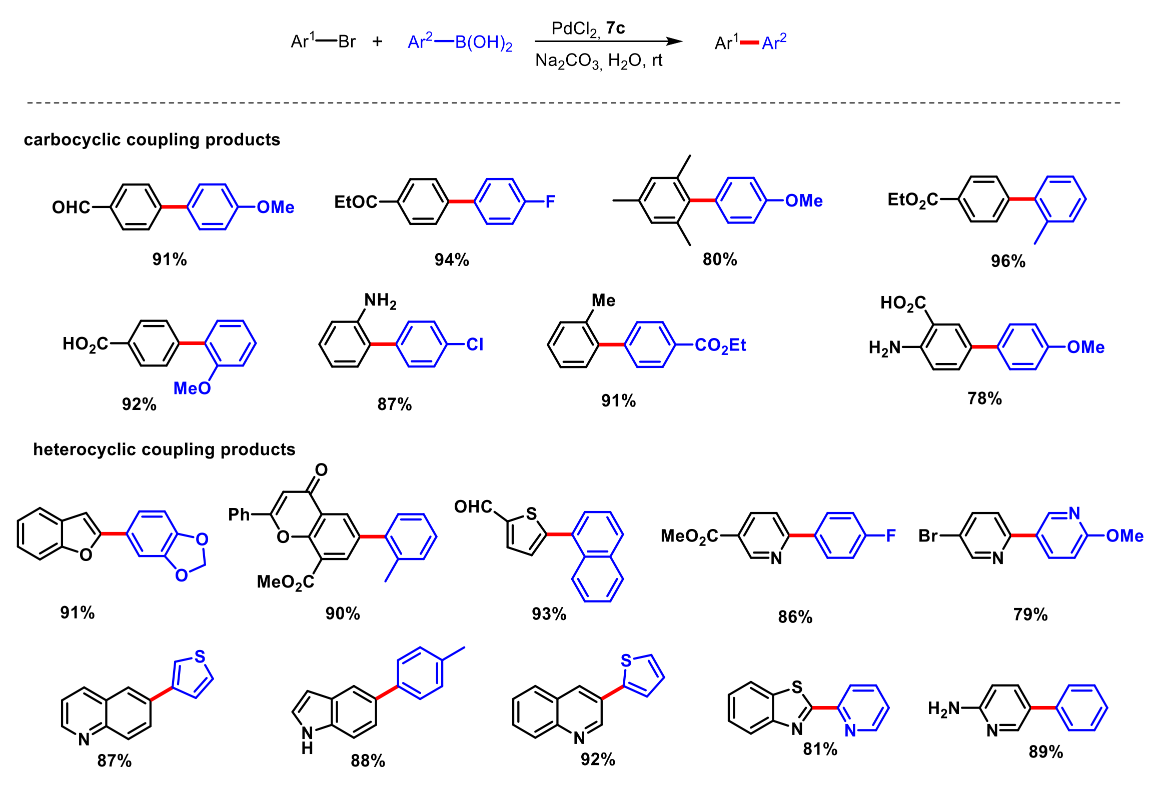
Figure 20. Surfactants for SMR in water.

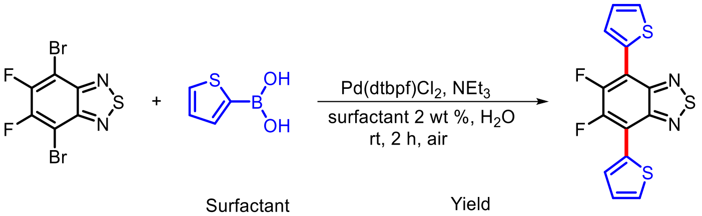
Micellization plays a crucial role in organic reactions carried out in water with surfactants, as the reaction occurs within the lipophilic core of the micelle. Therefore, a surfactant with a lower critical micelle concentration (CMC) is more efficient. Building on this principle, Qiu *et al.* developed a reaction system in aqueous medium using a bidentate phosphine-type zwitterionic surfactant (**7c**), which functions both as a ligand and a surfactant, featuring a low CMC and reduced surface energy.[99] As expected, it demonstrated superior catalytic activity compared to ionic surfactants such as CTAB and SDS. The substrate scope (Table 11) was notably broad, including bulky heterocyclic and electron-rich, water-insoluble compounds. Moreover, this method was successfully applied in a one-pot gram-scale synthesis with excellent regioselectivity.

In 2017, K. Ebitani and colleagues reported the synthesis of biphenyl from the less-reactive chlorobenzene using a hydrotalcite-supported palladium chloride ($PdCl_2$/HT) catalyst in ethanol with surfactants.[100] Without surfactants, the reaction showed poor reactivity, even at 100 °C and with high concentrations of base, substrate, and catalyst. However, the addition of surfactants significantly improved the yields, with Triton-X-100 and ICO-520 giving the best results at 96% and 87%, respectively.

In 2018, Sanzone *et al.* reported the synthesis of symmetrical and unsymmetrical 4,7-diaryl-5,6-difluoro-2,1,3-benzothiadiazole (DTBT) using surfactants in water.[101] They optimized the reaction conditions with various surfactants and found that a Kolliphor EL/Span-80 mixture (7:3) gave the best results at room temperature under aerobic conditions (Scheme 20).

Table 11. SMR using a Zwitterionic surfactant





Surfactant	Yield
Kolliphor EL	68 %
Kolliphor EL/Tween 80 (7:3)	75 %
Kolliphor EL/Span 80 (7:3)	97 %

Scheme 20. Synthesis of DTBT by SMR.

This reaction was also adapted to synthesize unsymmetrical compounds by adjusting the reaction conditions, demonstrating its selectivity. Additionally, the catalyst could be reused up to four times without significant loss in yield, maintaining an excellent 95% yield.

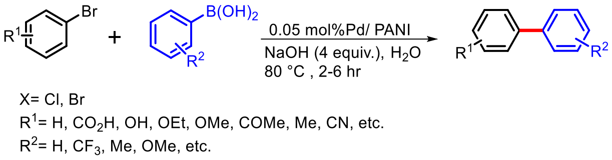
4.4 SMR in Green Solvents Using Metal Nanoparticles (NPs)

Nanocatalysts are far more efficient than traditional catalysts because of their tiny particle size and large surface area. These nanoparticles disperse well in solvents, often forming colloidal mixtures known as semi-heterogeneous systems, which significantly boost catalytic activity. Nanoparticles combine the best features of both homogeneous catalysts (such as low catalyst loading, high turnover numbers, and fast reaction rates) and heterogeneous catalysts (like good recyclability). Because of these advantages, nanocatalysts have attracted great interest from researchers over the past two decades. Many efforts have been made to replace conventional metal complexes with metal nanoparticles in cross-coupling reactions and C–H activation.

Recently, various effective nanocatalysts—both supported and unsupported—have been developed and successfully applied in cross-coupling. In this section, we will focus on metal nanoparticle-catalyzed Suzuki–Miyaura reactions carried out in eco-friendly media.

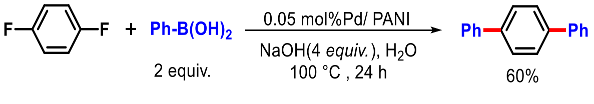
4.4.1 Palladium Nanoparticles (Pd-NPs). Palladium has been the most widely used metal in cross-coupling reactions since their discovery, making Pd nanoparticles (Pd NPs) a natural focus for researchers. In 1996, Reetz *et al.* were the first to use Pd nanoparticles in DMA solvent, demonstrating high efficiency for both Suzuki and Heck couplings, though this method was not environmentally friendly.[102] Later, in 2000, Li *et al.* introduced a greener approach by using Pd nanoparticles stabilized with poly(N-vinyl-2-pyrrolidone) (PVP) in aqueous ethanol.[103] They prepared a colloidal catalytic system, characterized it by TEM, and carried out SMR under reflux for extended periods (12-48 hours) with a limited substrate scope. Although this process was not ideal methodologically, it marked an important milestone in the development of green chemistry approaches involving metal nanoparticles.

In 2007, B. J. Gallon and his co-workers reported an improved method using Pd nanoparticles supported on polyaniline (PANI) nanofibers.[104] This catalytic system proved highly efficient, enabling the Suzuki-Miyaura reaction of less reactive aryl chlorides bearing electron-donating groups as well as heterocyclic substrates (Scheme 21).



Scheme 21. SMR using PANI supported Pd NPs.

Typically, even unreactive aryl fluorides could undergo the SMR using this catalyst, although the reaction required a longer time (24 hours at 100°C) (Scheme 22). The catalyst loading was very low, and it could be recycled up to 10 times without any significant loss in activity. Another major advantage of this method is the suppression of unwanted homocoupling by-products, likely due to the mild reaction conditions and the strong reducing nature of PANI, which stabilizes the Pd nanoparticles without involving the boronic acid. Overall, this strategy represents a fully green technique with high yields, minimal by-products, excellent catalyst recyclability, and mild, eco-friendly reaction conditions.



Scheme 22. SMR of aryl fluoride.

In 2008, Wei *et al.* reported a Suzuki–Miyaura reaction carried out in water using a nanoreactor composed of poly(N-isopropylacrylamide)-grafted Pd nanoparticles (Pd@PNIPAM).[105] Here, the Pd nanoparticle core was surrounded by a corona of poly(N-isopropylacrylamide) brushes, creating a nano-environment that could accommodate guest molecules. This setup allowed aryl halides and boronic acids to penetrate into the core, where the Pd nanoparticles catalyzed the reaction. This effective supramolecular catalytic system delivered good yields in water at room temperature. Additionally, the catalyst could be easily recycled thanks to the formation of a stable colloidal solution in water. Kinetic studies revealed that both hydrophilic and hydrophobic substrates reacted efficiently under nearly identical conditions.

In 2012, Cacchi and his team developed a Pd nanoparticle-based catalytic system stabilized by natural polysaccharides—alginate (**8a**) or gellan (**8b**) (Figure 21).[106] Unlike traditional Suzuki–Miyaura reactions using aryl halides and aryl boronic acids, this method employed aryl diazonium salts and potassium aryl trifluoroborates as coupling partners. The reaction took place under mild conditions (40 °C in water) with extremely low catalyst loadings (0.01–0.002 mol%) in aerobic atmosphere, achieving high yields and a broad substrate scope. The main limitation was the relatively long reaction time (12–48 hours). The best results were obtained using either **8a** or **8b** in a water-ethanol mixture or a 1:1 mixture of both in neat water. Overall, this represented a valuable advancement in SMR by introducing alternative coupling partners and eco-friendly reaction conditions.

In 2013, Deraedt *et al.* reported a modified Suzuki–Miyaura reaction using Pd nanoparticles stabilized by dendritic nanoreactors **8c** and **8d**, which feature 1,2,3-triazole ligands with hydrophilic triethylene glycol (TEG) end groups.[107] This catalytic system enabled the reaction to proceed efficiently at 28 °C, delivering high turnover numbers (TON) and satisfactory yields in an ethanol-water solvent mixture.

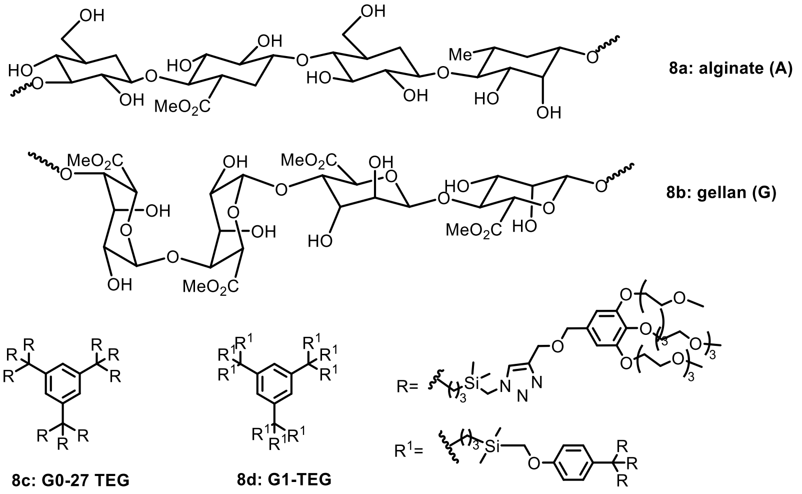
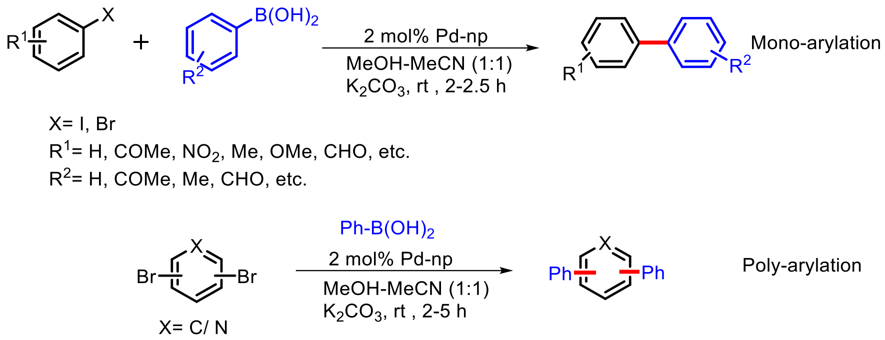


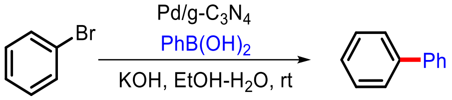
Figure 21. Polysaccharides (**8a**, **8b**) and dendrimers (**8c**, **8d**) for the stabilization of Pd NPs.

Interestingly, lower catalyst loadings (around 10^{-4} mol%) resulted in higher turnover numbers (TONs on the order of 10^5) but slower reaction rates. In contrast, higher catalyst loadings (0.01 mol%) produced better yields (over 90% in most cases) within shorter reaction times, although the TONs were lower (around 10^4). This approach was effective across a wide range of substrates and is significant from a green chemistry perspective. In the same year, P. K. Mandal and D. K. Chand introduced another novel method using unsupported Pd nanoparticles—without any stabilizing agents like polysaccharides, dendrimers, or biopolymers. They conducted the reaction in a methanol-acetonitrile solvent mixture at room temperature (Scheme 23).[108] Both electron-rich and electron-deficient aryl halides(including chlorides), as well as bulky heterocyclic substrates, underwent coupling in 2–3 hours with high yields. Polyarylation also proceeded efficiently with excellent selectivity. For heterocyclic substrates, the reaction was slower and yields were somewhat lower (70%–85%), but still satisfactory.



Scheme 23. SMR using unsupported Pd NPs.

In 2015, Sun *et al.* reported a Suzuki–Miyaura coupling reaction catalyzed by a novel system: Pd nanoparticles supported on graphitic carbon nitride (Pd/g-C_3N_4).[109] This nanocomposite showed excellent catalytic activity at room temperature in a water-ethanol solvent mixture under aerobic conditions. Using a model reaction, they achieved complete conversion (Scheme 24).

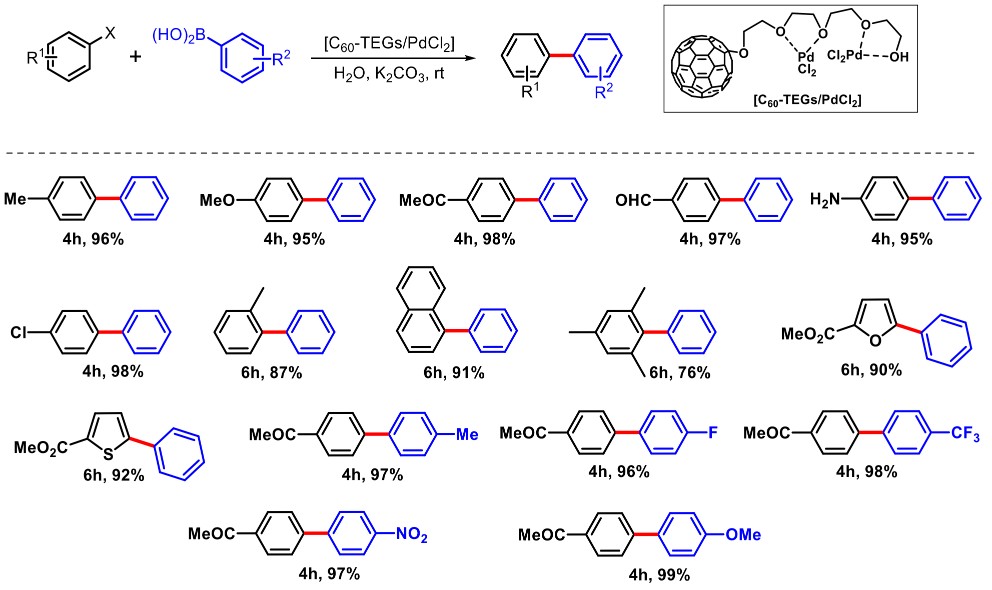


Scheme 24. SMR using Pd NPs supported on graphitic carbon nitride (Pd/g-C_3N_4).

They attributed the excellent results to the abundant nitrogen-containing anchor sites in the graphitic carbon nitride composite, which promoted the dispersion and stabilization of the Pd nanoparticles. Additionally, the π–π stacking interactions between the aryl halide molecules and g-C_3N_4 facilitated easier access of the halides to the Pd nanoparticles, making the reaction more efficient.

In 2018, Mäsing *et al.* reported a Light-Emitting Diode (LED)-assisted method for preparing Pd nanoparticles and their application in the Suzuki–Miyaura reaction.[110] They synthesized the nanoparticles by irradiating $Pd(OAc)_2$ with visible LED light, stabilizing them with commercially available polyvinylpyrrolidone (PVP). This catalytic system was highly efficient, requiring very short reaction times—just 1.5 hours for four consecutive cycles in the coupling of phenyl boronic acid and iodobenzene—with consistently good yields for both electron-rich and electron-deficient substrates. Around the same time, Li *et al.* introduced a water-soluble fullerene-supported $PdCl_2$ nanocatalyst [C_{60}-TEGS/$PdCl_2$].[111] This catalyst was prepared by coordinating water-soluble fullerene nanoparticles with palladium chloride, and its distribution in water was analyzed using dynamic light scattering (DLS). After optimizing reaction conditions and screening various substrates, they achieved excellent yields under very mild conditions (see Table 12). An added advantage of this system was its excellent recyclability.

Table 12. SMR using a fullerene supported $PdCl_2$ nanocatalyst

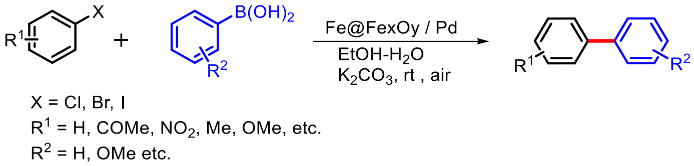


They demonstrated that the reaction could be successfully carried out for five consecutive catalytic cycles, with the catalyst easily recovered by simple extraction and without any significant loss in activity. Overall, the high yields, excellent selectivity, and fully green reaction conditions make this approach highly efficient and one of the most notable recent advances in Suzuki–Miyaura reactions.

Most recently, Campisciano and his team introduced a catalytic system using Pd nanoparticles supported on multi-walled carbon nanoforms (CNFs), including carbon nanotubes (MWCNTs) and carbon nanohorns (CNHs).[112] The Pd nanoparticles were stabilized by CNFs-polyimidazolium, and the system was thoroughly characterized using TGA, XPS, HRTEM, and NMR techniques. This catalyst proved highly efficient for both Suzuki–Miyaura and Heck coupling reactions; here, we focus on its performance in SMR. The reaction worked best in water with the organic base DIPA, or in a water-ethanol mixture using the inorganic base K_2CO_3. However, a drawback of this method is the relatively high reaction temperature (100°C), which somewhat limits the substrate scope. Despite this, the catalyst is easily recyclable, and yields are satisfactory across a range of substrates, regardless of whether they bear electron-donating or electron-withdrawing groups.

4.4.2 Hybrid Palladium Nanoparticles (Pd-Cu, Pd-Ag, Pd-Fe etc.). Besides Pd nanoparticles, nanocatalysts made from mixed metals—such as Pd combined with Au, Ag, Ni, Fe—or Pd nanoparticles supported on metal oxides like Fe_2O_3 have also become common in coupling reactions. In these systems, the additional metals or metal compounds often play an active role in the reaction. Sometimes, these composites form magnetically active nanocatalysts that can be easily separated from the reaction mixture using magnetic separation. This makes the isolation process more efficient, reduces the need for extra chemicals, and improves overall yields. As a result, these mixed-metal or supported nanocatalysts are generally more powerful than simple Pd nanoparticles alone.

In 2010, Zhou *et al.* introduced a novel catalyst for Suzuki–Miyaura reactions: iron/iron oxide core–shell nanoparticles (Fe@FexOy) supporting palladium.[113] This catalyst system helped generate the active Pd(0) species by reducing Pd(II). The composite catalyst was synthesized and characterized using XPS, TEM, and EDX (Scheme 25). It efficiently catalyzed SMR at room temperature under aerobic conditions in a water-ethanol solvent system, using only 0.5 mol% catalyst. The yields were excellent (>90%) for both electron-rich and electron-deficient substrates, though slightly lower (>80%) for sterically bulky substrates. The catalyst could be easily separated by simple centrifugation and reused without the need for extra solvents to extract the product, making it a fully green and sustainable method for C–C cross-coupling.



X = Cl, Br, I
R^1 = H, COMe, NO_2, Me, OMe, etc.
R^2 = H, OMe etc.

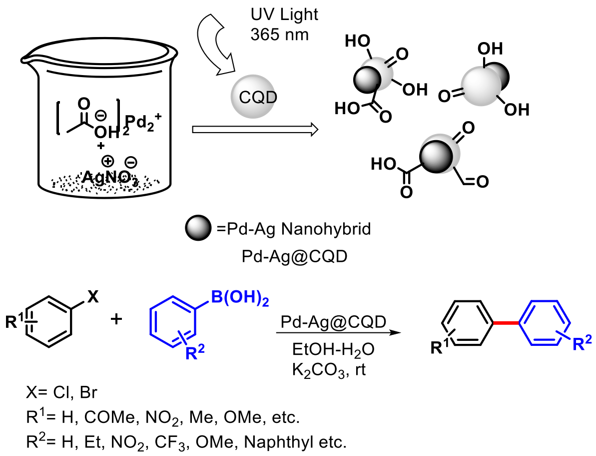
Scheme 25. SMR by Fe@Fe$_x$O$_y$NPs supported Pd.

In 2013, Smith *et al.* introduced Cu-Pd bimetallic nanoparticles as a novel catalyst for the Suzuki–Miyaura reaction.[114] Copper, being a redox-active metal, facilitates the reduction of Pd(II) to Pd(0) under ligand-free conditions. This bimetallic catalyst had previously been used in oxidation reactions of formic acid and menthol, but this was its first application in cross-coupling reactions such as Heck, Suzuki, and Sonogashira couplings. The Suzuki reaction was performed under microwave-assisted conditions at 120 °C in a water-ethanol mixture and completed in just 10 minutes. The catalyst showed good yields across a wide range of substrates, including both electron-rich and electron-deficient, as well as bulky compounds.

In 2014, Xiao *et al.* reported a photocatalytic Suzuki coupling reaction using Au–Pd nanoparticles supported on ZrO_2.[115] The ZrO_2 support provided stability to the system, while the Au–Pd nanoalloy absorbed light to catalyze the reaction. The best results, with excellent yield and selectivity, were achieved in a DMF-water (3:1) mixture at 30°C within 2–6 hours. Using an LED light source proved more effective than halogen lamps. They also attempted to eliminate DMF by employing a phase transfer agent (CTAB), but the yields were lower. Overall, while not the most efficient or green method, this photocatalytic approach is notable for its innovative use of light-driven catalysis.

In 2016, Gholinejad and his team developed a magnetically active catalyst: Pd nanoparticles supported on Fe_3O_4 functionalized with carbon dots (Pd@C-dots@Fe_3O_4).[116] This was a modification of Zhou *et al.*'s catalyst.[113] The catalyst, containing carboxylic acid and hydroxyl groups, was water-soluble, eliminating the need for a phase transfer catalyst. It was thoroughly characterized by SEM, TEM, EDS, solid-state UV spectroscopy, vibrating sample magnetometry, XRD, and XPS. This catalyst efficiently promoted the Suzuki–Miyaura reaction in water under mild conditions. Bulky substrates gave good yields after 18–24 hours, while simpler substrates converted almost completely within 5–12 hours. The catalyst was magnetically recoverable and reusable up to eight cycles. In the same year, Handa *et al.* reported another SMR method using $Pd(OAc)_2$ at ppm levels combined with an excess of a cheaper $Cu(OTf)_2$ (10 mol%).[117] While Cu(II) salts alone could catalyze the reaction, the times were long (40–72 hours). Adding Pd(II) salt in trace amounts significantly sped up the process. This mixed catalyst system enabled bulky substrates to undergo SMR, which wasn't possible with only Cu(II). Here, Pd served as the active catalyst, and Cu(II) helped regenerate Pd(0) after each cycle, reducing the amount of expensive Pd needed.

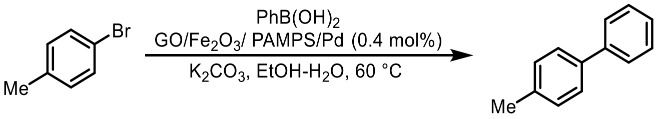
In 2017, R. Bayan and N. Karak developed a novel methodology employing bimetallic Pd-Ag hybrid nanoparticles supported on carbon quantum dots (Pd–Ag@CQD).[118] They synthesized this bimetallic nanohybrid *via* an in situ UV-assisted reduction of Pd(II) and Ag(I) ions using carbon quantum dots (CQDs) as both the reducing and stabilizing agent. The structural and physicochemical properties of the resulting nanocatalyst were thoroughly characterized using UV–VIS spectroscopy, XRD, FTIR, TEM, and energy-dispersive X-ray spectroscopy (EDX) (Scheme 26).



Scheme 26. UV-irradiated synthesis of bimetallic nanocomposite and SMR catalyzed by it.

This catalytic system proved to be highly effective, facilitating the reaction at room temperature in a water-ethanol solvent under mild basic conditions. It serves as a prime example of Suzuki–Miyaura reactions carried out under heterogeneous conditions. The synergistic interaction between the Pd and Ag components in the nanohybrid significantly enhanced catalytic performance, reducing reaction times to 1–3 hours and boosting yields to 75%–95%. Moreover, thanks to the heterogeneous nature of the system, the catalyst could be easily recovered and reused effectively for up to five consecutive cycles.

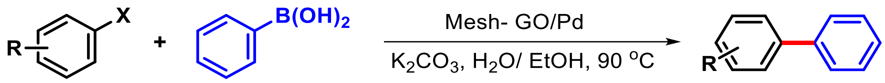
Around the same time, Asadi *et al.* reported a novel method for SMR using Pd nanoparticles immobilized on graphene oxide (GO) that was modified with poly(2-acrylamido-2-methyl-1-propansulfonic acid) (PAMPS) and decorated with magnetic Fe_3O_4 (Scheme 27).[119] The incorporation of PAMPS into GO significantly improved the water solubility and overall homogeneity of the catalytic system, which in turn enhanced its catalytic activity. Additionally, PAMPS acted as an intrinsic ligand, eliminating the need for any external ligands to stabilize the Pd(0) species.



Scheme 27. PAMP modified GO-Fe_2O_3 supported Pd NPs catalyzed SMR.

The Fe_3O_4 supporting system helps the catalyst to be magnetically active that favored the separation of the catalyst. Both the yield and TON are very high with a lower reaction time in case of both electron rich and deficient aryl bromides and iodides but to some extent higher in case of chlorides. The catalyst can be resolved magnetically and recycled up to 7 times without significant loss of catalytic activity (Scheme 27). The Fe_3O_4 support imparts magnetic properties to the catalyst, facilitating its easy separation from the reaction mixture. This system demonstrates high yields and turnover numbers (TON) with relatively short reaction times for both electron-rich and electron-deficient aryl bromides and iodides, though the efficiency is somewhat lower with aryl chlorides. The catalyst can be magnetically recovered and reused up to seven cycles without significant loss of activity (Scheme 27). More recently, in 2019, Mohazzab *et al.* reported the use of stainless-steel mesh-supported GO/Pd nanoparticles as catalysts for both Stille and Suzuki reactions in eco-friendly media (Table 13).[120] They have developed a stainless-steel mesh-supported graphene oxide/palladium nanoparticles (mesh-GO/Pd-NPs) catalyst through a three-step process: deposition of GO onto the stainless-steel mesh via electrophoresis, synthesis of Pd nanoparticles by laser ablation in liquids, and immobilization of these Pd nanoparticles onto the mesh-GO support. The catalyst was characterized using UV-Vis spectroscopy, SEM, EDS, and FTIR techniques. Focusing on the Suzuki–Miyaura reaction (SMR), the catalytic system demonstrated efficient performance at 90 °C in a water-ethanol solvent mixture, achieving satisfactory yields within 1.5–2.5 hours (see Table 13). Additionally, the catalyst exhibited high recyclability, maintaining activity over multiple cycles (Figure 22). This methodology is significant from a green chemistry perspective because it uses inexpensive, non-toxic ligands, eliminates the need for homogeneous catalysts and harmful organic solvents, and provides high yields, short reaction times, and excellent catalyst stability and reusability.

Table 13.SMR catalyzed by Stainless steel mesh-GO/Pd NPs



Entry	R	X	Time (min)	Yields (%)
1	H	I	90	97
2	4-OMe	I	90	93
3	2-OMe	I	90	91
4	4-Me	I	90	91
5	3-NO_2	I	90	85
6	4-COMe	I	90	94
7	H	Br	150	95
8	4-OMe	Br	150	90
9	4-Me	Br	150	90
10	3-NO_2	Br	150	81
11	4-OMe	Br	150	89
12	4-CN	Br	150	84

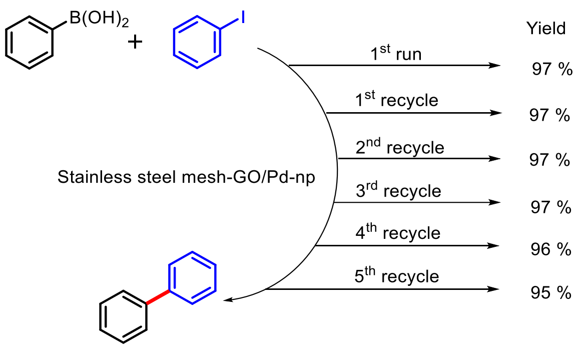
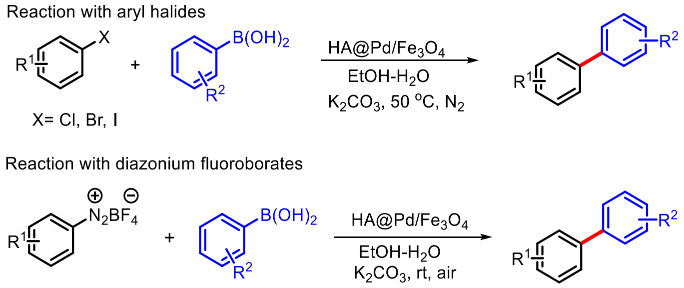


Figure 22. Recyclability of stainless-steel mesh-GO/Pd NPs.

A similar approach was recently reported by A.N. Chinchole and coworkers, who developed a slightly different catalyst system: Pd nanoparticles supported on humic acid-coated nano ferrites (HA@Pd/Fe_3O_4) as a magnetically recoverable catalyst for Suzuki and Heck coupling reactions.[121] This catalyst was prepared from inexpensive, naturally abundant soil-derived precursors such as humic acid, fulvic acid, and humin. It was thoroughly characterized by XPS, EDX, FT-IR, XRD, SEM, TEM, and ICP-AES. This system represents one of the best-modified catalysts discussed in this section, showing high efficiency under very mild reaction conditions (30–50 °C) in a water-ethanol solvent mixture. Both electron-rich and electron-deficient substrates, including bulky and heterocyclic compounds, underwent Suzuki–Miyaura reactions smoothly. Notably, not only aryl halides but also aryl diazonium fluoroborate salts served as effective coupling partners with aryl boronic acids under these conditions (Scheme 28). The catalyst demonstrated excellent conversion rates, high yields, and remarkable recyclability. Additionally, this method is cost-effective due to the use of readily available soil-derived materials and mild reaction conditions, making it an environmentally friendly and practical option for cross-coupling reactions.



Scheme 28. HA@Pd/Fe_3O_4 catalyzed SMR.

4.4.3 Nickel Nanoparticles (Ni-NPs). In the periodic table, nickel (Ni) belongs to the same group as palladium (Pd) and exhibits similar reactivity. However, due to its smaller d-orbitals, Ni possesses some unique properties. For instance, Ni complexes undergo oxidative addition more readily than Pd, but their higher reactivity often leads to lower selectivity. Nevertheless, Ni complexes are significantly cheaper than Pd and are frequently used as alternative catalysts, especially in cross-coupling reactions.[122–123] Although Ni catalysts have been employed in Suzuki–Miyaura reactions (SMR) since the early 2000s, earlier methods lacked green chemistry relevance due to harsh conditions—such as high temperatures, long reaction times, toxic reducing agents, and difficulties in storage and handling.[124–125] Recent advancements, however, involving nickel nanoparticles in water or alcohol-based solvents—particularly under heterogeneous conditions—have opened up new avenues in green synthetic chemistry.

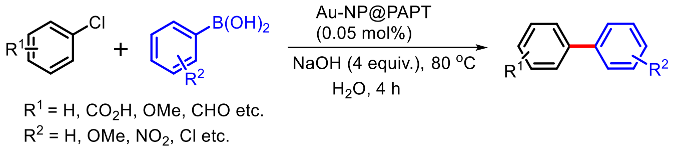
In 2011, Kalbasi and Mosaddegh developed a new nickel-based catalyst for the Suzuki–Miyaura reaction (SMR), using nickel nanoparticles supported on a poly(N-vinyl-2-pyrrolidone)/TiO_2-ZrO_2 composite (Ni–PVP/TiO_2-ZrO_2).[126] The reaction was carried out in a methanol–water solvent mixture at 60 °C. The catalyst was prepared by reducing $NiCl_2$ with hydrazine hydrate ($N_2H_4{\cdot}H_2O$) in the presence of the PVP/TiO_2-ZrO_2 support. Interestingly, a higher concentration of $NiCl_2$ during catalyst preparation led to better yields, while changes in the amount of PVP/TiO_2-ZrO_2 had little effect. Without the TiO_2-ZrO_2 support, the catalyst still worked, but both the reaction rate and yield dropped significantly. Overall, this solid Ni-based catalyst offers several advantages over traditional Pd catalysts: a) high catalytic activity under mild conditions; b) easy separation after the reaction; c) good reusability over multiple cycles. It represents a promising, cost-effective, and greener alternative to Pd-based systems for SMR.

In 2014, Zhong *et al.* reported a nickel nanoparticle (Ni NPs)–catalyzed carbonylative Suzuki reaction for the synthesis of biaryl ketones.[127] The reaction was carried out under a carbon monoxide (CO) atmosphere at a relatively low temperature of 80 °C, using polyethylene glycol (PEG) as a green, non-toxic, and inexpensive solvent. The Ni catalyst was generated in situ from commercially available $NiCl_2$, making the procedure both simple and cost-effective. The reaction conditions were mild and showed a broad substrate scope, tolerating both electron-rich and electron-deficient aryl halides, as well as bulky and heterocyclic substrates. This method provides a novel and efficient approach for synthesizing biaryl ketones, which are valuable intermediates in pharmaceuticals and advanced organic materials.

In 2015, Handa *et al.* developed a green Suzuki–Miyaura reaction (SMR) method using a nickel nanocatalyst in water.[128] The reaction was carried out at a mild temperature (40–45 °C) using the surfactant TPGS-750-M, which enabled micellar catalysis, and only a small amount (3 mol%) of MeMgBr (Grignard reagent) as a reducing agent. Among various Ni-based catalysts tested, $Ni(dppf)Cl_2$ was found to be the most effective. Under these conditions, it generated Ni(0) nanoparticles, which acted as the active catalyst. Cryo-TEM and SEM images showed that the nanoparticles were located either inside the micelles or on the surface of aggregated nanomicelles, likely enhancing the transport of organic substrates from the micelle's lipophilic core to the catalyst surface. This method showed excellent efficiency with a broad substrate scope, including both homo- and heteroaryl systems, offering high yields and good catalyst recyclability. It stands out as a highly sustainable and effective approach for cross-coupling reactions in water.

4.4.4 Gold Nanoparticles (Au-NPs). Gold(I) shares the same electronic configuration as Pd(0) and Ni(0), which explains its similar reactivity in various catalytic transformations. Since the early 21st century, gold complexes have been explored as catalysts in reactions involving redox processes and cross-coupling.[129–131] However, their application has remained limited, primarily due to gold's high cost. In recent years, gold nanoparticles (AuNPs) have emerged as promising heterogeneous catalysts for cross-coupling reactions in environmentally friendly media. Unlike traditional gold complexes, AuNPs do not require toxic ligands or harmful organic solvents, aligning well with green chemistry principles. Moreover, gold is less toxic compared to palladium, copper, and other transition metals commonly used in such reactions. Thus, despite its expense, gold nanoparticles offer a valuable and sustainable alternative—particularly for the Suzuki–Miyaura reaction (SMR)—due to their low toxicity, ligand-free operation, and eco-friendly nature.

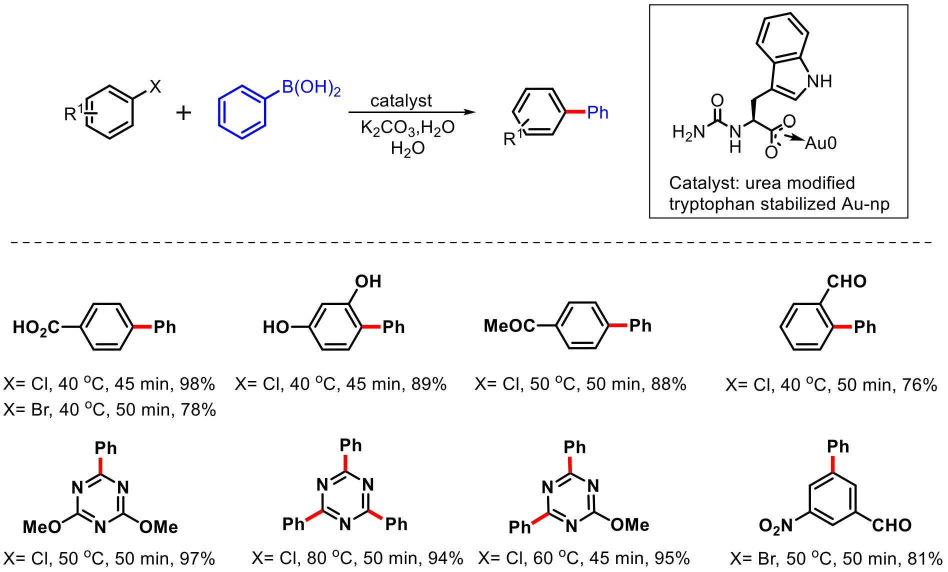
In 2009, Han *et al.* first reported the Suzuki–Miyaura reaction (SMR) catalyzed by polymer-stabilized gold nanoparticles (Au NPs).[132] They employed poly(2-aminothiophenol) (PATP) as a stabilizing agent, leveraging its unique structure—π-electrons from the benzene ring and thiol groups—to effectively cap and stabilize the Au nanoparticles. The catalyst was thoroughly characterized using TEM, XRD, XPS, UV-Vis, and FTIR spectroscopy. This catalytic system demonstrated remarkable activity under mild conditions, even for less reactive chloroarenes, which are typically challenging for palladium- and nickel-based catalysts. Yields exceeded 90% for substrates bearing electron-withdrawing groups and were above 80% for others. Notably, the catalyst exhibited excellent recyclability, retaining full activity over six consecutive runs, making it an efficient and sustainable alternative for cross-coupling reactions (Scheme 29).



Scheme 29. SMR using gold-NPs.

In 2014, Fakhri *et al.* developed a ligand-free SMR method using gold nanoparticles supported on graphene oxide (GO).[133] GO, already known as an effective support for metallic NPs, enhanced the catalyst's performance. Characterized by XRD, BET, FTIR, Raman, SEM, and EDS, the catalyst showed excellent yield (>90%) in short time and was recyclable up to five runs. Later, in 2019, Haldar and coworkers reported a urea-modified tryptophan-based reducing and stabilizing system for synthesizing Au NPs in water.[134] Using $HAuCl_4$ as the gold source, tryptophan's side chain NH reduced Au^{3+} to Au^0, while the carboxylic group stabilized the nanoparticles. The catalyst, characterized by UV-Vis, FTIR, FE-SEM, and TEM, enabled efficient SMR in water at 40 °C within 40–60 minutes under aerobic conditions. It was highly stable and reusable up to five times, easily separable by centrifugation, and stands out as one of the most eco-friendly and efficient Au-based SMR catalysts to date (Table 14).

Table 14. SMR using urea modified tryptophan-stabilized gold nanoparticles in water



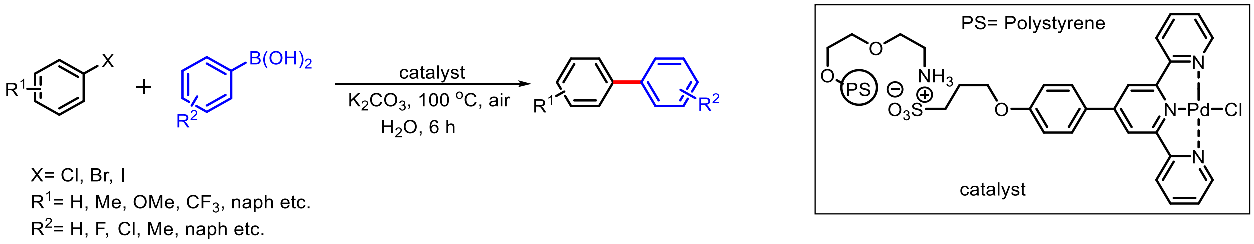
4.5 SMR Using Solid/Polymer Supported Catalysts

Besides aqueous extractions and surfactant-assisted systems, solid-supported or polymer-bound metal catalysts—both ligand-free and ligand-bound—are now widely used. Their key advantage lies in easy separation via filtration or centrifugation, as they exist in a quasi-heterogeneous phase in aqueous solvents. Another notable advancement is the use of ionic liquid-bound catalysts, which form a separate phase from both aqueous and organic layers, allowing for simple recovery and improved product purity. While polymer-supported catalysis has been known for decades, its application in non-organic (green) solvents is a breakthrough of this century.[135] In this section, we focus on these advanced catalytic systems.

4.5.1 Solid Bound Catalyst. In 2012, Guan *et al.* reported a novel solid-bound catalyst, $PdCl_2(py)_2$@SHS, for Suzuki–Miyaura reactions (SMR) in eco-friendly media.[136] They encapsulated $PdCl_2(py)_2$ within non-toxic silicalite-1 hollow spheres (SHS) and characterized it *via* SEM, TEM, XRD, N_2-sorption, FTIR, and XPS. The hydrophilic microporous silica facilitated reactions in water, while alcohol adsorption improved reactant solubility—making water-ethanol the ideal solvent. The reaction proceeded efficiently at 60 °C, with high conversion rates (TOF ~10^3 h^{-1}, yield 83–99%). The catalyst was reusable up to 10 cycles with an average TON of 25,800, attributed to the anti-leaching effect of the zeolite shell. Overall, this is a highly efficient and stable catalytic system for SMR in green media.

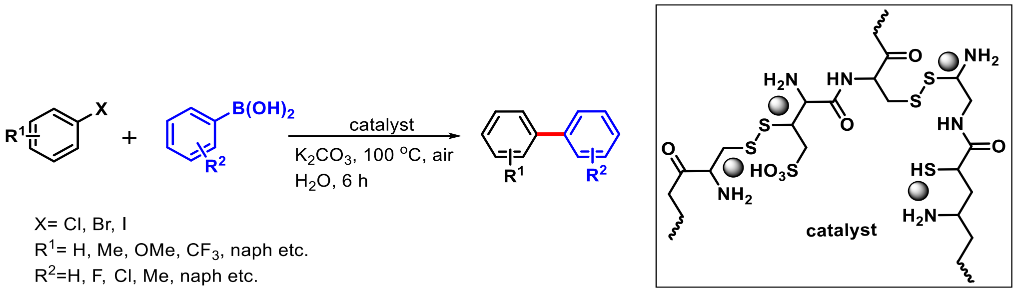
In 2019, Chowdhury and his team developed a solid-bound catalyst: palladium-impregnated amine co-condensed hexagonal mesoporous silica for SMR and Heck coupling in water.[137] The system delivered >90% yield and >99% selectivity at just 80 °C, regardless of substrate electronics. The catalyst is easily reusable *via* filtration. However, the main drawback is the use of DMF as a co-solvent, which limits its alignment with green chemistry principles.

4.5.2 Polymer and Bio-polymer Supported Catalyst. Recently, biopolymers like cellulose, pectin, and peptides have gained popularity as eco-friendly supports for metal catalysts, including in SMR. Section 4.4 covered some nanoparticle-supported polymers; here, we discuss other highly active polymer-supported catalysts. In 2001, Buchwald and Parrish introduced a polymer-bound phosphine palladium catalyst for SMR.[138] This ligand is nonvolatile, non-toxic, air-stable, and eco-friendly due to its polymer support. It works well at mild conditions (65 °C) in THF with Cs_2CO_3, offers a broad substrate scope, good yields, and can be reused up to four times by simple filtration. Following their work, many polymer-bound catalysts were developed but often required harsh conditions or toxic solvents like dioxane or DMF, limiting their green credentials. In 2011, Suzuka *et al.* reported a novel PS-PEG-supported terpyridine-Pd(II) catalyst effective for SMR in water (Scheme 30).[139] This heterogeneous catalyst performs well at 100 °C under aerobic conditions, tolerates bulky boronic acids, and is easily recovered and reused without reactivation.

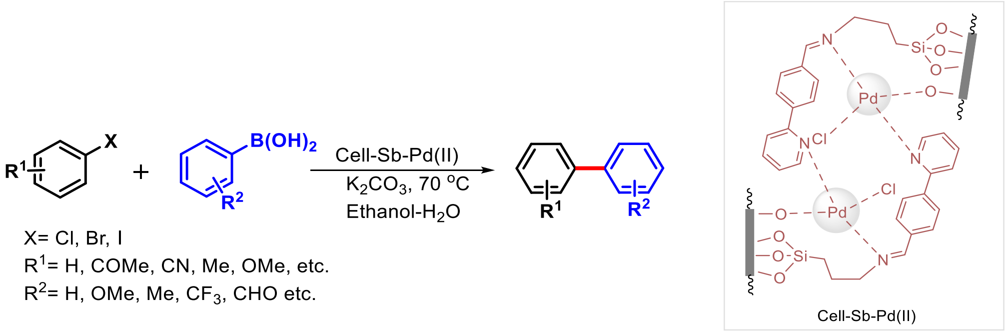


Scheme 30. PS-PEG polymer supported catalyst in SMR.

In the following years, polymer-supported catalysts, especially those using biopolymers, advanced significantly, enabling SMR in fully eco-friendly media. In 2012, the Ma group reported SMR in pure water using a metal–biopolymer complex (Scheme 31).[140] They employed animal fibers (wool) as the catalyst support. The ordered amino acid chains in wool acted both as solid-phase ligands and helped evenly distribute palladium on the fiber surface. This resulted in an effective, fully heterogeneous catalyst system requiring no phase transfer agents or activators. Remarkably, even water-insoluble aryl halides reacted successfully when added as solids. Yields were excellent (>90% for electron-deficient substrates and 75–80% for others) with easy catalyst recycling by simple filtration, making the process highly attractive.



Scheme 31. SMR using animal-fiber supported catalyst.



Scheme 32. SMR using cellulose-supported Pd-catalyst.

In 2014, Ebitani and co-workers developed a palladium catalyst grafted on amino-functionalized organozinc coordination polymer (Pd/AZC) for SMR in eco-friendly media.[141] Prepared from readily available materials like zinc nitrate, benzyl alcohol, and aniline, the catalyst was characterized by SEM, TEM, XPS, and XRD. It showed strong activity in ethanol at 80 °C under aerobic conditions, achieving 80–99% conversion within 0.3–3 hours and a high TON (2.1×10^6) without additives.

More recently, in June 2019, Dong *et al.* reported a cellulose-supported Pd(II)-Schiff base catalyst [Cell-Sb-Pd(II)] (Scheme 32).[142] Characterized by FTIR, TGA, XRD, SEM, TEM, XPS, and NMR techniques, this catalyst efficiently promoted SMR in a water-ethanol system under mild conditions within 1–3 hours. It showed excellent yields, high TON, and could be recycled five times by simple centrifugation.

4.5.3. Microwave (MW) Assisted SMR. Microwaves are electromagnetic waves with lower frequency and longer wavelength than visible light, initially used for household purposes. In 1986, Gedye *et al.* first demonstrated their utility in organic synthesis[143] and reported microwave-assisted reactions the same year.[144] Since then, microwaves have become valuable tools in synthetic chemistry. The first microwave-mediated Suzuki reactions appeared in 1996, using $Pd(PPh_3)_4$ as catalyst for both homogeneous[145] and solid-phase[146] biaryl synthesis. The main advantage of microwaves is their strong radiation, which efficiently activates substrates. This technique aligns well with green chemistry principles, as it shortens reaction time, reduces cost, and often allows reactions in eco-friendly solvents like water or even solvent-free conditions. In this section, we discuss SMR facilitated by microwave irradiation in the presence of solvents.

In 1999, Blettner and co-workers first reported microwave-assisted SMR using a water-PEG solvent mixture.[147] However, their method required substrates with carboxylic acid groups esterified to PEG, adding extra steps and limiting substrate scope, which reduced its attractiveness. In 2002, Leadbeater and Marco developed a microwave-assisted SMR in neat water using $Pd(OAc)_2$ without any ligand, though TBAB additive was needed in some cases.[148] Reactions completed in just 5 minutes with a broad substrate scope including electron-rich, electron-deficient, and heteroaryl halides. Yields were good for aryl substrates but moderate for heteroaryl ones. This was the first report of microwave-assisted SMR in fully eco-friendly conditions, making it historically significant.

In 2010, Martins *et al.* reported a microwave-assisted Suzuki reaction catalyzed by Pd(0) nanoparticles supported on PVP polymer (Pd-PVP).[149] The polymer acted as a stabilizer, eliminating the need for ligands. Prepared by a known method,[150] the catalyst showed high efficiency under microwave heating, delivering excellent yields (75%-95%) in just 12 minutes using ethanol as solvent, with TON values in the range of 10^4–10^5.

In 2011, a new microwave-assisted SMR method[151] using ionic liquid N-butylpyridinium salts was reported. Although its exact role is unclear, the reaction didn't proceed well without it. Using 3 mol% Pd(OAc)$_2$ and NEt$_3$, the reaction completed in just 5 minutes with high yield. The ionic liquid enabled a clean reaction and easy product separation, making it an efficient C–C cross-coupling method.

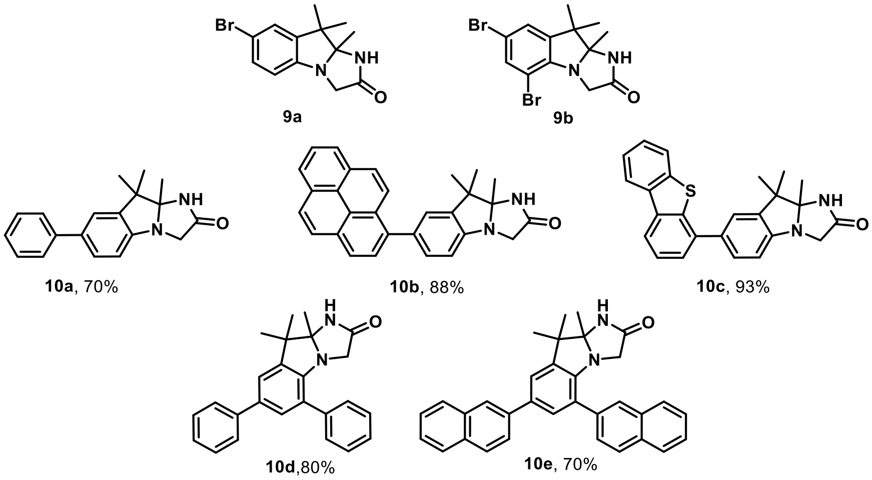


Figure 23. 9a, 9b: Aryl halides synthesized by Zukauskaitė *et al.* **10a-10e**: Microwave assisted SMR product in ligand-free conditions.

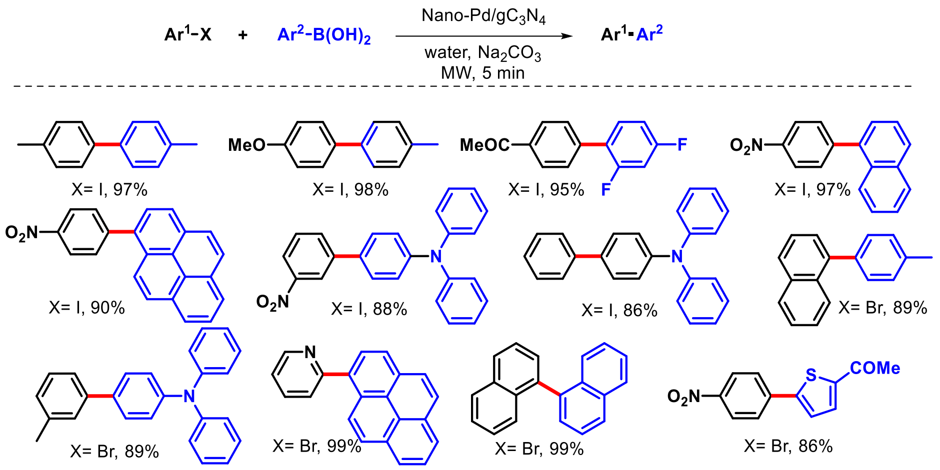
In 2013, Shen *et al.* reported a pyridine-pyrazole/Pd(II) complex as a catalyst for MW-assisted SMR in an eco-friendly water-ethanol mixture.[152] The catalyst was characterized by NMR, IR, HRMS, and single-crystal XRD. Under optimized conditions, the reaction completed in just 2 minutes using only 0.1 mol% catalyst, which remained recyclable up to four runs. In 2016, Zukauskaitė and colleagues synthesized fluorescent arylindoline derivatives *via* MW-assisted SMR of bulky aryl halides and boronic acids in ligand-free ethanol-water, achieving satisfactory yields between 70% and 93%.[153]

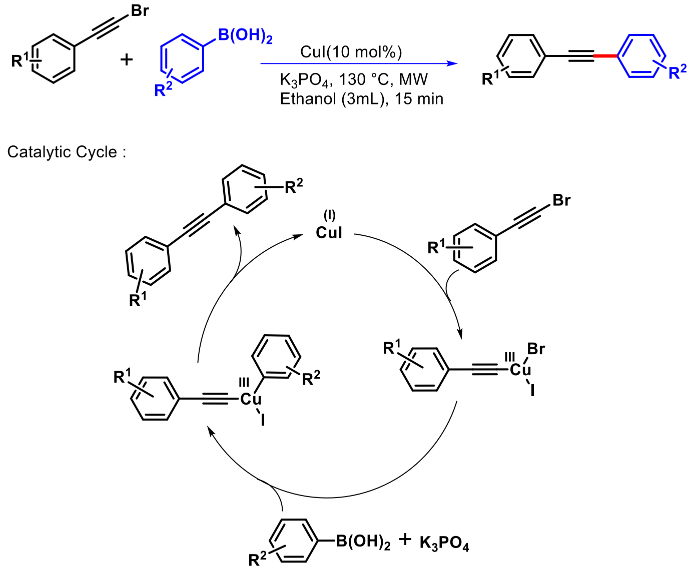
In 2017, Sharma and co-workers reported a microwave-assisted SMR using a nano-Pd/gC$_3$N$_4$ composite catalyst in neat water.[154] Prepared as per Fageria et al. (2015)[155] and characterized by powder XRD, this catalyst delivered 85%-99% yields in just 15 minutes with only 0.009 mol% catalyst under MW irradiation. Notably, even bulky substrates gave excellent yields (Table 15).

In 2018, Elazab *et al.* employed Pd nanoparticles supported on copper oxide for Suzuki coupling under microwave irradiation in a water-ethanol solvent.[156] This nanocatalyst efficiently produced 82%-90% yields in just 10 minutes without needing additional activation or phase transfer catalysts. Both electron-rich and deficient, bulky, and heterocyclic halides gave satisfactory results, and the catalyst was reusable up to four cycles.

In 2019, Kumar and team reported a novel MW-assisted Csp–Csp^2 coupling via Csp–Br activation using a cost-effective CuI catalyst (cheaper than Pd) (Scheme 33).[157] The reaction completes within 15 minutes in ethanol solvent.

Table 15. MW assisted SMR catalyzed by Pd/gC_3N_4 nanocomposite





Scheme 33. CuI catalyzed activation of alkynyl bromide.

A series of compounds were synthesized with excellent yields (>85%). Based on the substrate scope and products, a catalytic cycle was proposed. This protocol presents a novel strategy for activating alkynyl halides and is highly valuable both methodologically and from a green chemistry perspective. It uses an eco-friendly solvent (ethanol), offers good yields, fast reaction rates, mild conditions, and replaces expensive Pd with affordable Cu.

5. SMR under Solvent Free Conditions

Solid-state organic reactions are highly valuable in synthetic chemistry due to their green credentials—eliminating harmful solvents and toxic ligands—while offering shorter reaction times and cost efficiency.

Although solvent-free reactions have gained recent popularity, the concept dates back to the 1950s–60s with R. B. Merrifield's peptide synthesis work, which earned him the Nobel Prize in 1984.[158] Two popular modern approaches include microwave (MW)-assisted solvent-free reactions and ball-mill solid-phase reactions. Solid-state Suzuki–Miyaura reactions (SMR) emerged in the late 20th century by simply heating catalyst-reactant mixtures, despite some drawbacks. This section will explore these methods in detail.

5.1 SMR in Thermal Mediate Solvent Free Conditions

In 1999, Kabalka *et al.* reported a solvent-free SMR using potassium fluoride/γ-alumina (KF/Al_2O_3) with a ligand-free Pd(0) catalyst.[159] The KF-impregnated alumina performed better than bases. The reaction was done at 100 °C for 4 hours. However, the substrate scope was limited—only aryl iodides reacted well (>90% yield), while aryl bromides and chlorides were mostly unreactive. Thus, the method had limited synthetic utility.

After extensive research, in 2011 Khruscheva and colleagues developed an improved solvent-free SMR method using ferrocene palladium cycle catalysts at 20–100 °C, depending on the substrate and catalyst.[160] Although the substrate scope was broader, yields were generally low. Around the same time, Monguchi *et al.* reported a solid-state SMR using Pd-C catalyst with aryl bromides and Cs_2CO_3 as a strong base.[161] This method gave good yields and a wide substrate scope but required a high temperature (100 °C) and long reaction time (24 hours), limiting its practicality.

In 2019, Pentsak and Ananikov reported a solid-phase SMR using palladium nanoparticles supported on multi-walled carbon nanotubes (Pd-NPs/MWCNT) with K_2CO_3 as base.[162] This method, operated simply by heating, showed excellent substrate scope and high conversion rates (>90%). Notably, aryl bromides were more reactive than iodides, likely due to bond energies and lack of solvation effects. The catalyst was recyclable up to seven times without loss of activity, making it a highly efficient solid-state SMR protocol.

Solid-phase SMR under heating has notable drawbacks: the high temperatures needed can reduce substrate scope due to catalyst instability and long reaction times. Additionally, many haloarenes are gummy liquids, causing the reaction to proceed in a semi-liquid rather than solid phase, which lowers yields and complicates product separation.

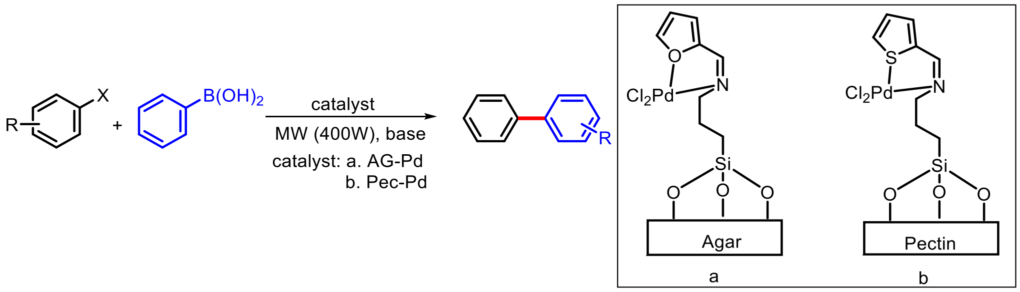
5.2 Microwave (MW) Assisted SMR under Solvent-Free Conditions

In 2000, Kabalka *et al.* developed a microwave-assisted solid-phase SMR using Pd-doped KF-impregnated alumina ($Pd\text{-}KF/Al_2O_3$).[163] Previously, their catalyst showed poor results under conventional heating, but with microwave assistance, the reaction completed in just 2 minutes with yields over 80% and an improved substrate scope—marking a significant improvement in solvent-free SMR.

In 2012, Chang *et al.* reported a novel solvent-free SMR method using Pd/MCM-41 and Pd/SBA-15 catalysts under microwave irradiation with mild base K_2CO_3.[164] Pd/MCM-41 proved more effective, delivering excellent results within 10 minutes and a broad substrate scope, though aryl chlorides gave low yields. This represents a promising green technique with potential for commercial use.

In 2018, Baran's group introduced an agar-supported palladium catalyst (AG-Pd) for solid-phase SMR.[165] The reaction proceeded solvent-free at 50 °C, offering excellent yields across a wide range of substrates in only 6 minutes. Usually, even the less reactive aryl chlorides gave satisfactory results with this method. Additionally, the catalyst was recyclable up to 10 runs, which is significantly higher than most other techniques. Most recently, in 2019, the same group developed another immobilized catalyst: a Schiff base-functionalized pectin-supported Pd catalyst (Pct-Pd).[166] A comparison of the yields from these two catalytic systems is presented in Table 16.

Table 16. SMR in solid phase using AG-Pd and Pct-Pd catalyst



Entry	X	R	Yield (a)	Yield (b)
1	I	4-OMe	99	99
2	I	3-NO_2	95	95
3	I	4-NH_2	91	85
4	I	2-Me	76	71
5	I	3-Me	81	77
6	I	4-Me	85	83
7	Br	2-OMe	89	83
8	Br	3-OMe	94	90
9	Br	4-OMe	97	95
10	Br	4-CN	97	92
11	Br	3-NO_2	94	88
12	Br	4-NO_2	98	96
13	Br	3-NH_2	80	73
14	Br	4-NH_2	85	82
15	Br	3-Me	62	69
16	Br	4-Me	70	76
17	Cl	2-OMe	68	58
18	Cl	3-OMe	74	70
19	Cl	4-OMe	79	75
20	Cl	3-NO_2	81	74
21	Cl	4-CN	79	80

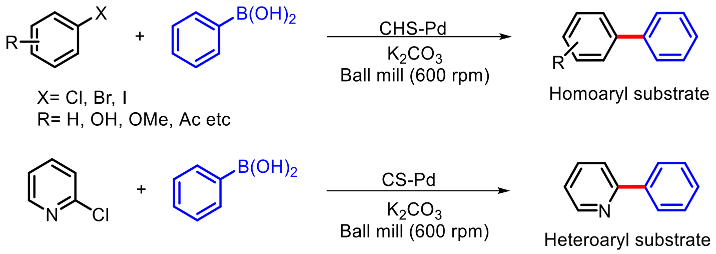
5.3 Mechanochemical Induced SMR under Solvent Free Conditions

A ball mill is a grinder that uses mechanical energy from rapidly revolving metal balls (600-700 rpm) to grind solids and drive reactions. Originally developed in the 1870s for pottery, it has become a popular method in the 21st century for solvent-free organic and inorganic synthesis.[167-169] Advantages include avoiding toxic ligands and solvents, lower temperatures, shorter reaction times, and minimal by-products, making product isolation easier and yields higher. This makes ball milling a highly efficient green chemistry technique.

In 2008, Schneider and Ondruschka first reported solid-phase SMR using a ball mill.[170] They employed KF-impregnated alumina (KF@Al_2O_3) as both reactant support and base, with six balls at 800 rpm, without added heat or radiation. This method produced a series of compounds within 10 minutes with excellent yields. Aryl chlorides were unreactive, but bromides and iodides reacted with an unusual order of reactivity: Br > I.

Although the reason is unclear, it is likely due to bond energy and the lack of solvent cage effects in the solid state. Both simple and bulky substrates gave very satisfactory yields.

In 2012, Cravotto *et al.* used a chitosan-based Pd catalyst (CS-Pd) for solid-phase SMR (Scheme 34).[171] The previous year (2011), they had applied the same catalyst in a water-dioxane (8:1) mixture, but the substrate scope and yields were quite limited.[172] However, using the ball mill significantly improved yields (74%-99%) and reduced reaction times, with minimal formation of homo-coupling byproducts. This method works well for haloarenes with both electron-donating and withdrawing groups, as well as heteroaryl substrates, making it a notable advancement over their earlier solvent-based study.

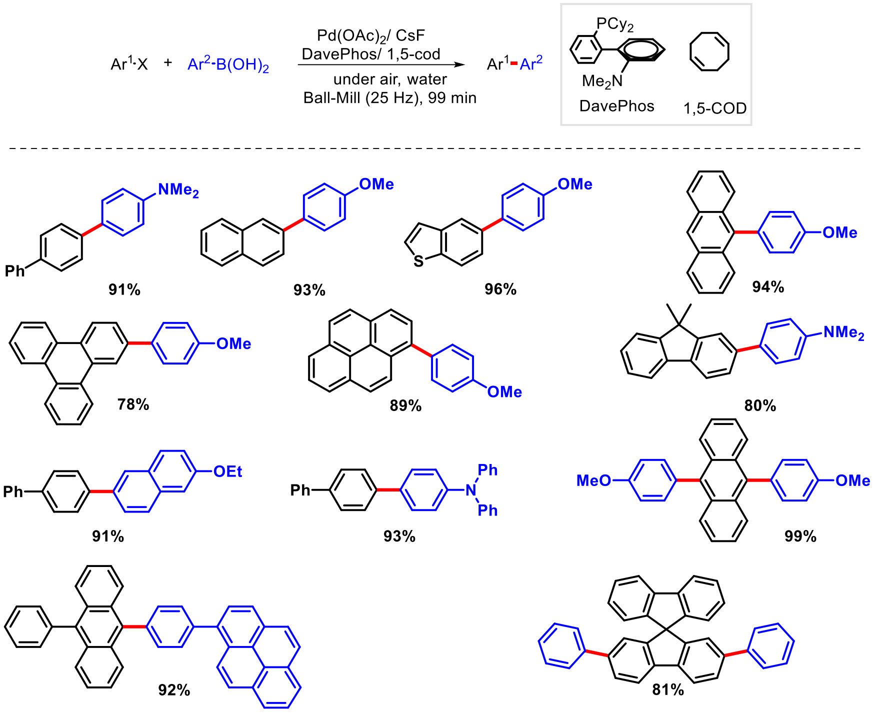


Scheme 34. SMR using mechanochemistry.

In 2019, Seo *et al.* reported a new solid-state SMR method using mechanochemistry.[173] They employed palladium acetate with bulky ligands such as DavePhos, RuPhos, and BrettPhos, alongside olefin additives like 1,5-COD, cyclohexene, and cyclopentene. The best results were achieved using DavePhos with 1,5-COD. SEM analysis confirmed the formation of Pd nanoparticles, which drive the reaction, while the olefin additives likely act as dispersants to prevent nanoparticle aggregation. The key success of this method is its effective coupling of chloride substrates—something not achieved before with ball-milling. Beyond simple substrates, it excels in large-scale synthesis of bulky cross-coupled products with high yields (Table 17). This promising approach has strong potential for future commercialization as a fully green industrial process.

Ball milling offers an excellent eco-friendly reaction method, though it is still an emerging technique rather than a conventional one. In the future, it has great potential to become a key approach for completely pollution-free, green synthesis.

Table 17.SMR using mechanochemical process[a,b]

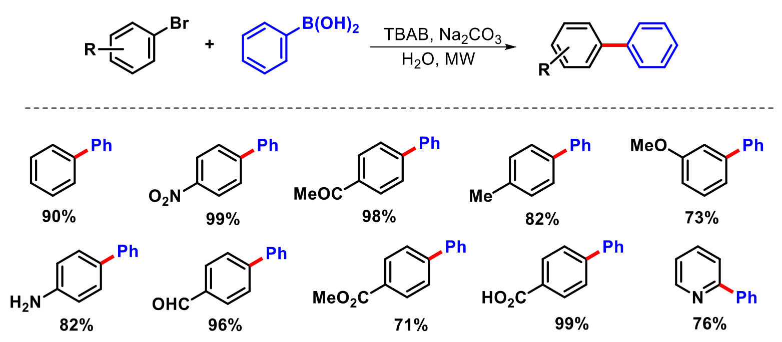


6. Suzuki-Type Coupling under Metal-Free Conditions

The Suzuki–Miyaura reaction (SMR) is a prime example of metal-catalyzed C–C coupling, typically using metals like Pd, Cu, or Ni. However, these inorganic metals can be toxic at certain levels, posing safety concerns for pharmaceutical applications where drug molecules must be free of metal impurities. Complete removal of these metals from the reaction mixture is practically difficult, limiting the reaction's use in drug synthesis. Beyond eliminating toxic ligands and solvents, a major challenge is reducing or replacing metal catalysts in SMR. This has led to the rise of organocatalysis, which employs non-toxic organic molecules as catalysts instead of metals. The earliest example dates back to Justus von Liebig's synthesis of oxamide from dicyan and water, catalyzed by acetaldehyde. Yet, organocatalysis in Suzuki-type couplings remains rare, with only a few reports available. This section will explore those examples and their mechanisms.

In 2003, Leadbeater and Marco reported a transition metal-free Suzuki-type coupling in water using the phase transfer catalyst TBAB under microwave irradiation.[174] They also tested conventional heating at 150 °C with the same conditions, but the yields for non-activated aryl halides were poor even after 16 hours, whereas the microwave method completed the reaction in just 4–5 minutes with much better results.

Table 18. MW assisted metal free Suzuki type coupling



Among the haloarenes, the reaction rate followed the order Br > I >> Cl. The substrate scope was broad, although no mechanism was proposed by the authors (Table 18). In the same year, Chao-Jun Li suggested a probable mechanism for this metal-free coupling (Figure 24),[175] proposing that the reaction may proceed *via* two possible pathways: a radical pathway and a metathesis pathway.

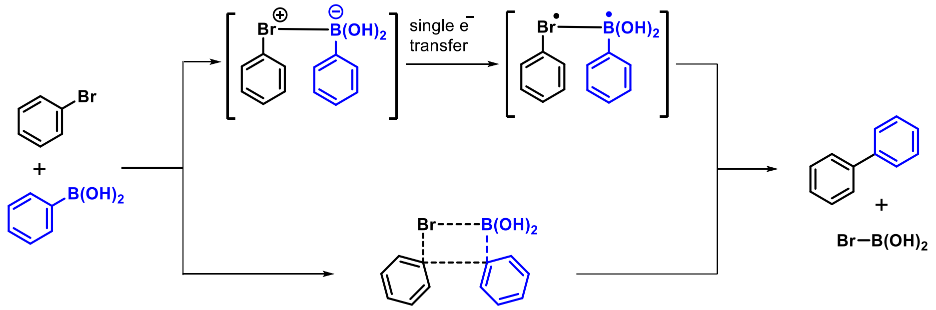


Figure 24. Mechanism of metal-free Suzuki-type coupling.

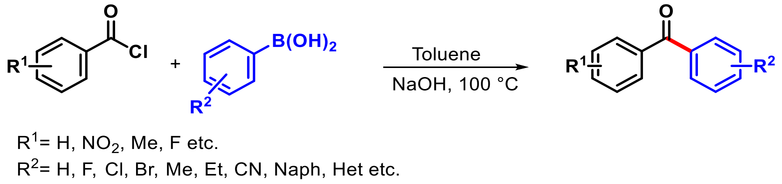
According to the radical concept, either an internal electron transfer generates a diradical species, or an external diradical forms within the substrate "cage," both leading to product formation. Another possibility involves σ-bond metathesis of a borate complex, which also results in the product.

At the same time, Leadbeater and his group extended their previous work by focusing on substrate scope and the impact of various reaction parameters.[176] They found that the highest yield was achieved at 150 °C under microwave irradiation, while both lower and higher temperatures reduced yields—especially at higher temperatures due to proto-deboronation of the boronic acid, which produced substituted benzene. A base was essential, with Na$_2$CO$_3$ proving most effective in aqueous media. The phase transfer catalyst played a key role by activating the boronic acid through formation of the [ArB(OH)$_3$]$^-$[R$_4$N]$^+$ complex. They thus provided a comprehensive explanation of the reaction's scope and limitations. Later in 2005 the author critically reevaluate a previously reported transition-metal-free Suzuki-type coupling of aryl halides and boronic acids, showing that trace palladium contaminants (as low as ~50 ppb from sodium carbonate) — not a truly metal-free mechanism — are responsible for the observed biaryl formation.[177] They provide evidence that ultralow levels of palladium catalysis account for the coupling, and present a revised protocol using controlled, ultralow palladium concentrations. The study also explores how the purity of boronic acids affects reaction outcomes, challenging claims of alternative "metal-free" pathways .

In the same year, Kabalka *et al.* developed a Suzuki-type alkenylation of allylic alcohols using alkenylboron dihalides as coupling partners instead of the usual aryl halides and boronic acids.[178] The reaction was carried out in DCM at room temperature with the strong base n-BuLi. While the substrate scope and yields were satisfactory, the method wasn't fully eco-friendly due to the use of DCM and n-BuLi. Nevertheless, this work was significant for introducing new types of coupling partners in cross-coupling chemistry.

In 2013, Ueda *et al.* reported a Suzuki-type coupling between propargylic carbon and sp^2-hybridized aryl carbon in a biphasic (water-$CHBr_3$) solvent system.[179] However, the yields were moderate, substrate scope limited, and the reaction time was long—about 18 hours.

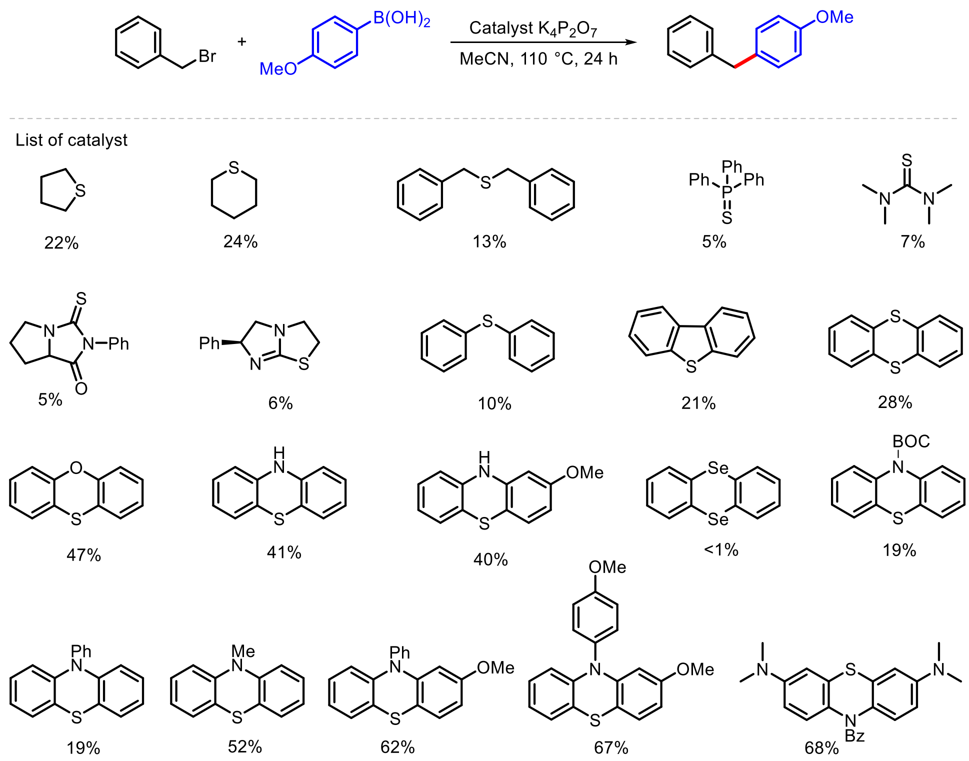
Later, in 2017, Jadhav *et al.* developed a metal-free Suzuki-type coupling of acid chlorides and boronic acids to synthesize dissymmetric ketones (Scheme 35).[180] Previously, this transformation was carried out using Pd catalysts or Lewis acid-mediated Friedel-Crafts acylation, both requiring sensitive conditions and often giving lower yields. This new metal-free method is a significant improvement, as it avoids air- and moisture-sensitive reagents and catalysts. The reaction offers broad functional group tolerance, excellent regioselectivity, shorter reaction times, and high yields (85%-95%). Thus, it represents not just a cross-coupling reaction but a truly green and efficient approach to ketone synthesis.



Scheme 35. Metal-free Suzuki-type coupling of acyl chlorides with boronic acids.

In 2018, Huang *et al.* reported a Suzuki-type coupling in acetonitrile using a sulfur-containing organocatalyst.[181] This efficient metal-free method enables Csp^3–Csp^2 coupling in eco-friendly conditions without any transition metals. They designed and synthesized 20 different sulfur-containing catalysts (Table 19), showing good reactivity even with chloride substrates. $K_4P_2O_7$ was the best base for simple substrates, while K_2CO_3 worked better for electron-rich ones. Mechanistic studies and intermediate isolation revealed that the organocatalyst first undergoes an S_N2 reaction with the halides, followed by base-promoted sulfur ylide formation and boron-centered "ate" complexation. A 1,2-methyl shift then occurs, ending with protodeboronation to give the final product (Figure 25).

Table 19. Optimization of reaction conditions with various organocatalysts.



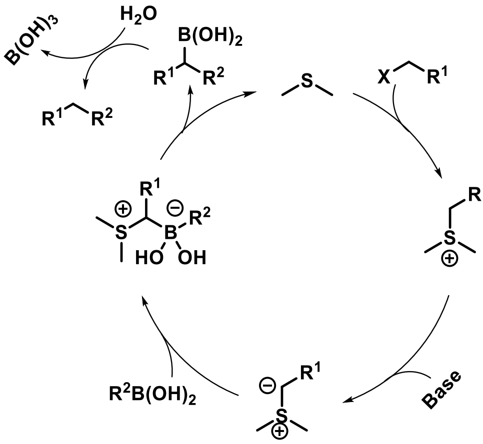
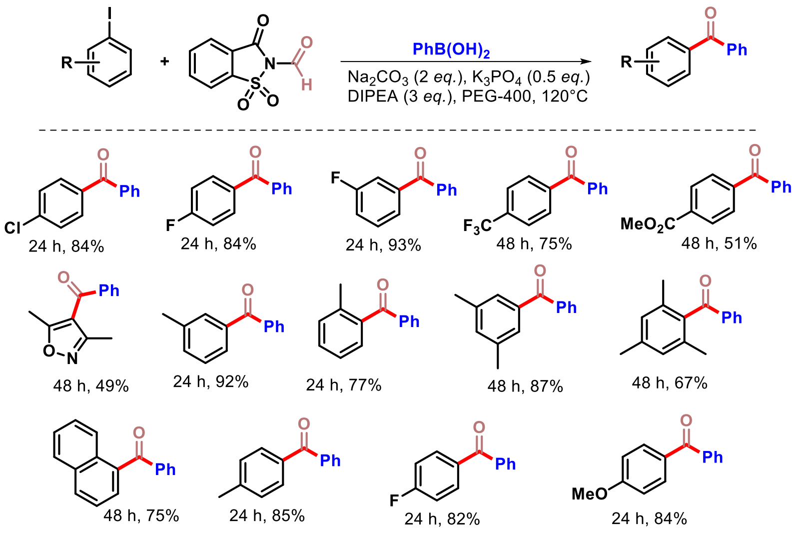


Figure 25. Catalytic cycle using an organocatalyst.

Recently, Yu et al. developed a metal-free carbonylative Suzuki-type cross-coupling.[182] Traditionally, such reactions required Pd catalysts under CO atmosphere or used acid chlorides as substrates. Following this, several CO surrogates like molybdenum hexacarbonyl, acetic formic anhydride, and 9-methylfluorene-9-carbonyl chloride were introduced to replace gaseous CO.[183-186] In 2013, Ueda *et al.* first reported N-formylsaccharin as a CO surrogate,[187] which was later used by the Bhanage group for SMR in 2017 using a Pd

Table 20. Carbonylative Suzuki type coupling without any metal-catalyst



catalyst.[188] Finally, in 2019, Yu and co-workers modified the reaction to metal-free conditions.[189] They optimized the reaction parameters and explored a broad substrate scope, achieving very good yields with electron-rich, electron-deficient, and sterically bulky substrates (Table 20). They also proposed a radical mechanism based on experimental evidence, illustrated in Figure 26. Besides its eco-friendly nature, this reaction is highly valuable for synthesizing pharmaceutically important molecules such as fenofibrate and naphthylphenstatin. Thus, it represents a significant method for producing both symmetrical and unsymmetrical ketones.

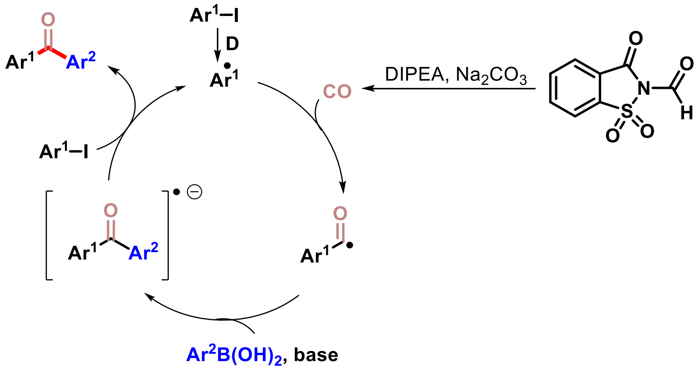


Figure 26. Radical cycle of carbonylative Suzuki type coupling in metal-free conditions.

7. Conclusions

In conclusion, it is clear that SMR has become increasingly important and appealing in green chemistry over the past two decades. Various improved catalytic systems have been developed to boost reaction yields, increase TON, enhance catalyst recyclability, and reduce chemical usage and costs—marking significant progress in sustainable chemistry. Notably, performing reactions in fully aqueous media, solid-phase synthesis via ball milling and microwave technology, and the shift towards organocatalysis over traditional metal catalysts are key advancements. These new catalytic approaches have also expanded the substrate scope and diversity. Moving forward, research will likely focus on designing more cost-effective, high-performance catalysts for large-scale, sustainable, and pollution-free industrial applications.

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References

1. Heck, R. F. *Org. React.,* **2004**, *27*, 345. https://doi.org/10.1002/0471264180.or027.02
2. Milstein, D.; Stille, J. *J. Am. Chem. Soc.,* **1979**, *101,* 4992. https://doi.org/10.1021/ja00511a032
3. Suzuki, A. *Pure Appl. Chem*., **1985**, *57* 1749. https://doi.org/10.1351/pac198557121749.
4. Negishi, E. *Acc. Chem. Res*. **1982**, *15* 340. https://doi.org/10.1021/ar00083a001.
5. Haas, D.; Hammann, J. M.; Greiner, R.; Knochel, P. *ACS Catal.,* **2016**, *6*, 1540. https://doi.org/10.1021/acscatal.5b02718.
6. Nakao, Y.; Hiyama, T. *Chem. Soc. Rev.,* **2011**, *40*, 4893. https://doi.org/10.1039/C1CS15122.
7. Chinchilla, R.; Nájera, C. *Chem. Soc. Rev.,* **2011**, *40*, 5084. https://doi.org/10.1039/C1CS15071E.
8. Jacks, T. E.; Belmont, D. T.; Briggs, C. A.; Horne, N. M.; Kanter, G. D.; Karrick, G. L.; Krikke, J. J.; McCabe, R. J.; Mustakis, J. G.; Nanniga, T. N.; Risedorph, G. S.; Seamans, R. E.; Skeean, R.; Winkle, D. D.; Zennie, T. M. *Org. Proc. Res. Dev*., **2004**, *8*, 201. https://doi.org/10.1021/op034104g
9. Lipton, M. F.; Mauragis, M. A.; Maloney, M. T.; Veley, M. F.; Bor, D. W. V.; Newby, J. J.; Appell, R. B.; Daugs, E. D. *Org. Proc. Res. Dev*. **2003**, *7*, 385. https://doi.org/10.1021/op025620u.
10. Matos, K.; Soderquist, J. A. *J. Org. Chem.* **1998**, *63*, 461. https://doi.org/10.1021/jo971681s
11. Seechurn, C. C. J.; Kitching, M. O.; Colacot, T. J.; Snieckus, V. *Angew. Chem. Int. Ed.,* **2012***, 51***,** 5062. https://doi.org/10.1002/anie.201107017.
12. Miyaura, N.; Yamada, K.; Suzuki, A. *Tetrahedron Lett.,* **1979**, *20***,** 3437. https://doi.org/10.1016/S0040-4039(01)95429-2.
13. Miyaura, N.; Suzuki, A. *J. Chem. Soc., Chem. Commun.* **1979**, 866. https://doi.org/10.1039/C39790000866.
14. Miyaura, N.; Suzuki, A. *Chem. Rev.,* **1995**, *95*, 2457.

https://doi.org/10.1021/cr00039a007.

15. Anastas, P. T.; Warner, J. C. **1998** (Oxford [England]; New York: Oxford university press)
16. Prat, D.; Wells, A.; Hayler, J.; Sneddon, H.; McElroy, C. R.; Shehadad, S. A.; Dunn, P. J. *Green Chem.,* **2016**, *18,* 288. https://doi.org/10.1039/C5GC01008.
17. Blackmond, D. G.; Armstrong, A.; Coombe, V.; Wells, A. *Angew. Chem. Int., Ed.,* **2007**, *46*, 3798. https://doi.org/10.1002/anie.200604952.
18. Narayan, S.; Muldoon, J.; Finn, M. G.; Fokin, V. V.; Kolb, H. C.; Sharpless, K. B. *Angew. Chem. Int. Ed.,* **2005**, *44*, 3275. https://doi.org/10.1002/anie.200462883.
19. Cruz, D. G.; Tejedor, D.; Armas, P.; Morales, E. Q.; Tellado, F. G. *Chem. Commun.,* **2006**, 2798. https://doi.org/10.1039/B606096J.
20. Afonsi, K.; Colberg, J.; Dunn, P. J.; Fevig, T.; Jennings, S.; Johnson, T. A.; Kleine, H. P.; Knight, C.; Nagy, M. A.; Perry, D. A.; Stefaniakc, M. *Green Chem.*, **2008**, *10*, 31. https://doi.org/10.1039/B711717E.
21. MacQuarrie, S.; Horton, J. H.; Barnes, J.; McEleney, K.; Loock, H. P.; Crudden, C. M. *Angew. Chem. Int. Ed.,* **2008**, *47*, 3279. https://doi.org/10.1002/anie.200800153.
22. Centomo, P.; Zecca, M.; Zoleo, A.; Maniero, A. L.; Canton, P.; Jeřábek, K.; Corain, B. *Phys. Chem. Chem. Phys.,* **2009**, *11*, 4068. https://doi.org/10.1039/B819776H.
23. Centomo, P.; Zecca, M.; Kralik, M.; Gasparovicova, D.; Jerabek, K.; Canton, P.; Corain, B. *J. Mol. Catal. A: Chem.,* **2009**, *300*, 48. https://doi.org/10.1016/j.molcata.2008.10.039.
24. Shao, L.; Zhang, B.; Zhang, W.; Hong, S. Y.; Schlögl, R.; Su, D. S. *Angew. Chem. Int. Ed.,* **2013**, *52*, 2114. https://doi.org/10.1002/anie.201207362.
25. Espinet, P.; Echavarren, A. *Angew. Chem. Int. Ed.,* **2004**, *43*, 4704. https://doi.org/10.1002/anie.200300638.
26. Amatore, C.; Jutand, A. *Acc. Chem. Res.,* **2000**, *33*, 314. https://doi.org/10.1021/ar980063a.
27. Amatore, C.; Jutand, A.; Thuilliez, A. *Organometallics,* **2001**, *20*, 3241. https://doi.org/10.1021/om0101137.
28. Abelman, M. M.; Oh, T.; Overman, L. E. *J. Org. Chem.,* **1987**, *52*, 4130. https://doi.org/10.1021/jo00227a038.
29. Amatore, C.; Carre, E.; Jutand, A.; M'Bark, M. A.; *Organometallics,* **1995**, *14*, 1818. https://doi.org/10.1021/om00004a039.
30. Lennox, A. J. J.; Jones, G. C. L. *Angew. Chem. Int. Ed.*, **2013**, *52*, 7362. https://doi.org/10.1002/anie.201301737.
31. Cox, P. A.; Reid, M.; Leach, A. G.; Campbell, A. D.; King, E. J.; Jones, G. C. L.; *J. Am. Chem. Soc*., **2017**, *139*, 13156. https://doi.org/10.1021/jacs.7b07444.
32. Cox, P. A.; Leach, A. G.; Campbell, A. D.; Jones, G. C. L. *J. Am. Chem. Soc*., **2016**, *138*, 9145. https://doi.org/10.1021/jacs.6b03283.
33. Ohashi, M.; Saijo, H.; Shibata, M.; Ogoshi, S. *Eur. J. Org. Chem.,* **2012**, *2013*, 443. https://doi.org/10.1002/ejoc.201201405.

34. Malapit, C. A.; Bour, J. R.; Brigham, C. E.; Sanford, M. S. *Nature,* **2018**, *563*, 100. https://doi.org/10.1038/s41586-018-0628-7.
35. Zhang, Y.; Rovis, T. *J. Am. Chem. Soc*., **2004**, *126*, 15964. https://doi.org/10.1021/ja044113k
36. Muto, K.; Yamaguchi, J.; Musaev, D. G.; Itami, K. *Nat. Commun*., **2015**, *6*, 7508. https://doi.org/10.1038/ncomms8508.
37. Shi, S.; Meng, G.; Szostak, M. *Angew. Chem. Int. Ed*., **2016**, *55*, 6959. https://doi.org/10.1002/anie.201601914.
38. Guo, L.; Rueping, M. *Acc. Chem. Res*., **2018**, *51*, 1185. https://doi.org/10.1021/acs.accounts.8b00023
39. Makdissi, J. M.; Vandavasi, J. K.; Newman, S. G. *Org. Lett*., **2018**, *20*, 4094. https://doi.org/10.1021/acs.orglett.8b01646.
40. Ichiishi, N.; Malapit, C. A.; Wozniak, L.; Sanford, M. S. *Org. Lett*., **2018**, *20*, 44. https://doi.org/10.1021/acs.orglett.7b03305.
41. Tomar, R.; Singh, N.; Kumar, N.; Tomar, V.; Chandra, R. *Catal. Lett*., **2019**, *149*, 1589. https://doi.org/10.1007/s10562-019-02723-9.
42. Spicer, C. D.; Davis, B. G. *Chem. Commun.,* **2011**, *47*, 1698. https://doi.org/10.1039/C0CC04970K.
43. Chalker, J. M.; Wood, C. S. C.; Davis, B. G. *J. Am. Chem. Soc.,* **2009**, *131*, 16346. https://doi.org/10.1021/ja907150m.
44. Cobo, I.; Matheu, M. I.; Castillon, S.; Boutureira, O.; Davis, B. G. *Org. Lett*., **2012**, *14*, 1728. https://doi.org/10.1021/ol3003139.
45. Lucas, C. C.; Toscano, R. A.; Morales, D. M. *Tetrahedron Lett.,* **2013**, *54*, 3116. https://doi.org/10.1016/j.tetlet.2013.04.007.
46. Huo, P.; Li, J.; Liu, W.; Mei, G. *Chin. J. Chem.,* **2017**, *35*, 363. https://doi.org/10.1002/cjoc.201600616.
47. Kostas, I. D.; Coutsolelos, A. G.; Charalambidis, G.; Skondra, A. *Tetrahedron Lett.,* **2007**, *48*, 6688. https://doi.org/10.1016/j.tetlet.2007.07.141
48. Wan, Q. X.; Liu, Y. *Catal. Lett.,* **2009**, *128*, 487. https://doi.org/10.1007/s10562-008-9780-2.
49. Zhang, J.; Feng, Z. G.; Popović, Z.; Lu, Y.; Liu, Y. *Materials Research Bulletin,* **2010**, *45*, 1648.
50. Bagheri, O.; Sadegh, F.; Moghadam, M.; Tangestaninejad, S.; Mirkhani, V.; Baltork, I. M.; Safiri, M. *Appl. Organometal. Chem.,* **2014**, *28*, 337. https://doi.org/10.1002/aoc.3131.
51. Alamdari, R. F.; Golestanzadeh, M.; Bagheri, O. *Appl. Organometal. Chem.,* **2017**, *31*, e3698. https://doi.org/10.1002/aoc.3698.
52. Li, J.; Loh, X. J. *Advanced Drug Delivery Reviews,* **2008**, *60*, 1000. https://doi.org/10.1016/j.addr.2008.02.011.
53. Davis, M. E.; Brewster, M. E. *Nat. Rev. Drug Discov.,* **2004**, *3*, 1023. https://doi.org/10.1038/nrd1576.
54. Uekama, K.; Hirayama, F.; Irie, T. *Chem. Rev.,* **1998**, *98*, 2045. https://doi.org/10.1021/cr970025p.
55. Zhang, B. L.; Breslow, R. *J. Am. Chem. Soc.,* **1997**, *119*, 1676. https://doi.org/10.1021/ja963769d.

56. Reetz, M. T.; Waldvogel, S. R. *Angew. Chem. Int. Ed.,* **1997**, *36*, 865. https://doi.org/10.1002/anie.199708651
57. Monflier, E.; Blouet, E.; Barbaux, Y.; Mortreux, A. *Angew. Chem. Int. Ed.,* **1994**, *33*, 2100. https://doi.org/10.1002/anie.199421001.
58. Takahashi, K. *Chem. Rev.,* **1998**, *98*, 2013. https://doi.org/10.1021/cr9700235.
59. Qi, M.; Tan, P. Z.; Xue, F.; Malhi, H. S.; Zhang, Z.; Young, D. J.; Hor, T. S. A. *RSC Adv.,* **2015**, *5*, 3590. https://doi.org/10.1039/C4RA13953D.
60. Kaboudin, B.; Salemi, H.; Mostafalu, R.; Kazemi, F.; Yokomatsu, T. *J. Organomet. Chem.,* **2016**, *818*, 195. https://doi.org/10.1016/j.jorganchem.2016.06.007.
61. Zhou, X.; Guo, X.; Jian, F.; Wei, G. *ACS. Omega.,* **2018**, *3*, 4418. https://doi.org/10.1021/acsomega.8b00469.
62. Luoa, K.; Zhanga, L.; Yang, R.; Jin, Y.; Lin, J. *Carbohydr. Polym.,* **2018**, *200*, 200. https://doi.org/10.1016/j.carbpol.2018.07.089.
63. Sieber, J. D.; Buono, F.; Brusoe, A.; Desrosiers, J.; Haddad, N.; Lorenz, J. C.; Xu, Y.; Wu, H.; Zhang, L.; Han, Z. S.; Roschangar, F.; Song, J. J.; Yee, N. K.; Senanayake, C. H. *J. Org. Chem.,* **2019**, *84*, 4926. https://doi.org/10.1021/acs.joc.8b03040.
64. Noel, T.; Kuhn, S.; Musacchio, A. J.; Jensen, K. F.; Buchwald, S. L. *Angew. Chem. Int. Ed.,* **2011**, *50*, 5943. https://doi.org/10.1002/anie.201101480.
65. Noel, T.; Musacchio, A. J. *Org. Lett*., **2011**, *13*, 5180. https://doi.org/10.1021/ol202052q.
66. Mateos, C.; Rincon, J. A.; Hidalgo, B. M.; Villanueva, J. *Tetrahedron Lett.,* **2014**, *55*, 3701. https://doi.org/10.1016/j.tetlet.2014.05.010.
67. Cole, K. P.; Campbell, B. M.; Forst, M. B.; Groh, J. M.; Hess, M.; Johnson, M. D.; Miller, R. D.; Mitchell, D.; Polster, C. S.; Reizman, B. J.; Rosemeyer, M. *Org. Process Res. Dev.,* **2016**, *20*, 820. https://doi.org/10.1021/acs.oprd.6b00030
68. Konda, V.; Rydfjord, J.; Savmarker, J.; Larhed, M. *Org. Process Res. Dev.,* **2014**, *18*, 1413. https://doi.org/10.1021/op5001989
69. Hillier, A. C.; Grasa, G. A.; Viciu, M. S.; Lee, H. M.; Yang, C.; Nolan, S. P. *J. Organomet. Chem.,* **2002**, *653*, 69. https://doi.org/10.1016/S0022-328X(02)01154-3
70. Fortman, G. C.; Nolan, S. P. *Chem. Soc. Rev.,* **2011**, *40*, 5151. https://doi.org/10.1039/C1CS15088J
71. Viciu, M. S.; Kissling, R. M.; Stevens, E. D.; Nolan, S. P. *Org. Lett.,* **2002**, *4*, 2229. https://doi.org/10.1021/ol0260831
72. Hadei, N.; Kantchev, E. A. B.; O'Brien, C. J.; Organ, M. G. *Org. Lett.,* **2005**, *7***,** 1991. https://doi.org/10.1021/ol050471w
73. Herrmann, W. A.; Öfele, K.; Schneider, S. K.; Herdtweck, E.; Hoffmann, S. D. *Angew. Chem. Int. Ed.,* **2006**, *45*, 3859. https://doi.org/10.1002/anie.200503589
74. Wass, D. F.; Haddow, M. F.; Hey, T. W.; Orpen, A. G.; Russell, C. A.; Wingad, R. L.; Green, M. *Chem. Commun.,* **2007**, 2704. https://doi.org/10.1039/B702827J
75. Ohta, H.; Fujihara, T.; Tsuji, Y. *Dalton Trans.,* **2008**, 379.

https://doi.org/10.1039/B715412G

76. Marion, N.; Navarro, O.; Mei, J.; Stevens, E. D.; Scott, N. M.; Nolan, S. P. *J. Am. Chem. Soc.,* **2006**, *128*, 4101. https://doi.org/10.1021/ja057704z
77. Fleckenstein, C.; Roy, S.; Leuthaüßer, S.; Plenio, H. *Chem. Commun.,* **2007**, 2870. https://doi.org/10.1039/B703658B
78. Roy, S.; Plenio, H. *Adv. Synth. Catal.,* **2010**, *352*, 1014. https://doi.org/10.1002/adsc.200900886
79. Türkmen, H.; Can, R.; Çetinkaya, B. *Dalton Trans.,* **2009**, 7039. https://doi.org/10.1039/B907032J
80. Godoy, F.; Segarra, C.; Poyatos, M.; Peris, E. *Organometallics,* **2011**, *30*, 684. https://doi.org/10.1021/om100960t
81. Szilvási, T.; Veszprémi, T. *ACS Catal.,* **2013**, *3*, 1984.
82. Kolychev, E. L.; Asachenko, A. F.; Dzhevakov, P. B.; Bush, A. A.; Shuntikov, V. V.; Khrustalevc, V. N.; Nechaev, M. S. *Dalton Trans.,* **2013**, *42*, 6859. https://doi.org/10.1039/C3DT32860K
83. Zhong, R.; Pöthig, A.; Feng, Y.; Riener, K.; Herrmann, W. A.; Kühn, F. E. *Green Chem.,* **2014**, *16*, 4955. https://doi.org/10.1039/C4GC00986J
84. Munz, D.; Allolio, C.; Meyer, D.; Micksch, M.; Roessner, L.; Strassner, T. *J. Organomet. Chem.,* **2015**, *794*, 330. https://doi.org/10.1016/j.jorganchem.2015.03.027
85. Kaloğlu, N.; Ozdemir, I. *Tetrahedron,* **2019**, *75*, 2306. https://doi.org/10.1016/j.tet.2019.02.062
86. Zhou, C.; Wang, J.; Li, L.; Wang, R.; Hong, M. *Green Chem.,* **2011**, *13*, 2100. https://doi.org/10.1039/C1GC15060J
87. Zhou, Z.; Liu, M.; Wu, X.; Yu, H.; Xu, G.; Xie, Y. *Appl. Organometal. Chem.,* **2013**, *27*, 562. https://doi.org/10.1002/aoc.3033
88. Zhao, C.; Ma, J.; Liu, Q.; Yu, Y.; Wang, P.; Li, Y.; Wang, K.; Dong, Y. *Green Chem.,* **2013**, *15*, 3150. https://doi.org/10.1039/C3GC41154K
89. Tsang, M. Y.; Vinas, C.; Teixidor, F.; Planas, J. G.; Conde, N.; SanMartin, R.; Herrero, M. T.; Domínguez, E.; Lledós, A.; Vidossich, P.; Lazarte, D. C. *Inorg. Chem.,* **2014**, *53*, 9284. https://doi.org/10.1021/ic5013999
90. Liu, H.; Li, X.; Liu, F.; Tan, Y.; Jiang, Y. *J. Organomet. Chem.,* **2015**, *794*, 27. https://doi.org/10.1016/j.jorganchem.2015.06.009.
91. Saikia, B.; Ali, A. A.; Boruah, P. R.; Sarma, D.; Baruaew, N. C. *New J. Chem.,* **2015**, *39*, 2440. https://doi.org/10.1039/C5NJ00288E
92. Veisi, H.; Rostami, A.; Shirinbayan, M. *Appl. Organometal. Chem.*, **2016**, e3609. https://doi.org/10.1002/aoc.3609
93. Boruah, P. R.; Ali, A. A.; Saikia, B.; Sarma, D. *Green Chem.,* **2015**, *17*, 1442. https://doi.org/10.1039/C4GC02522A
94. Boruah, P. R.; Ali, A. A.; Chetia, M.; Saikia, B.; Sarma, D. *Chem. Commun.,* **2015**, *51*, 11489. https://doi.org/10.1039/C5CC04561D
95. Khan, M.; Kuniyil, M.; Shaik, M. R.; Khan, M.; Adil, S. F.; Warthan, A. A.; Alkhathlan, H. Z.; Tremel, W.; Tahir, M. N.; Siddiqui, M. R. H. *Catalysts,* **2017**, *7*, 20.

https://doi.org/10.3390/catal7010020

96. Chotnitikornkun, S.; Sukwattanasinitt, M.; Wacharasindhu, S. *Materials Today: Proceedings,* **2018**, *5*, 10910. https://doi.org/10.1016/j.matpr.2018.01.003
97. Liang, Q.; Xing, P.; Huang, Z.; Dong, J.; Sharpless, K. B.; Li, X.; Jiang, B. *Org. Lett.,* **2015**, *17*, 1942. https://doi.org/10.1021/acs.orglett.5b00654
98. Lipshutz, B. H.; Ghorai, S.; Abela, A. R.; Moser, R.; Nishikata, T.; Duplais, C.; Krasovskiy, A. *J. Org. Chem*., **2011**, *76*, 4379. https://doi.org/10.1021/jo101974u
99. Qiu, P.; Zhao, J. Y.; Shia, X.; Duan, X. H. *New J. Chem.,* **2016**, *40*, 6568. https://doi.org/10.1039/C6NJ00377J
100. Choudhary, H.; Jia, J.; Nishimura, S.; Ebitani, K. *Asian J. Org. Chem.,* **2017**, *6*, 274. https://doi.org/10.1002/ajoc.201600606
101. Sanzone, A.; Calascibetta, A.; Ghiglietti, E.; Ceriani, C.; Mattioli, G.; Mattiello, S.; Sassi, M.; Beverina, L. *J. Org. Chem.,* **2018**, *83*, 15029. https://doi.org/10.1021/acs.joc.8b02204
102. Reetz, M. T.; Breinbauer, R.; Wanninger, K. *Tetrahedron Lett.*, **1996**, 37, 4499. https://doi.org/10.1016/0040-4039(96)00924-0
103. Li, Y.; Hong, X. M.; Collard, D. M.; Sayed, M. A. E. *Org. Lett.,* **2000**, *2*, 2385. https://doi.org/10.1021/ol0061687
104. Gallon, B. J.; Kojima, R. W.; Kaner, R. B.; Diaconescu, P. L. *Angew. Chem. Int. Ed.,* **2007**, *46*, 7251. https://doi.org/10.1002/anie.200701389
105. Wei, G.; Zhang, W.; Wen, F.; Wang, Y.; Zhang, M. *J. Phys. Chem.,* **2008**, *112*, 10827. https://doi.org/10.1021/jp800741t
106. Cacchi, S.; Caponetti, E.; Casadei, M. A.; Giulio, A. D.; Fabrizi, G.; Forte, G.; Goggiamani, A.; Moreno, S.; Paolicelli, P.; Petrucci, F.; Prastaro, A.; Saladino, M. L. *Green Chem.,* **2012**, *14*, 317. https://doi.org/10.1039/C2GC15679B
107. Deraedt, C.; Salmon, L.; Etienne, L.; Ruiz, J.; Astruc, D. *Chem. Commun.,* **2013**, *49*, 8169. https://doi.org/10.1039/C3CC45132A
108. Mandali, P. K.; Chand, D. K. *Catal. Commun.*, **2013**, *31*, 16. https://doi.org/10.1016/j.catcom.2012.10.020.
109. Sun, J.; Fu, Y.; He, G.; Sun, X.; Wang, X. *Applied Catalysis B: Environmental,* **2015**, *165*, 661. https://doi.org/10.1016/j.apcatb.2014.10.072.
110. Mäsing, F.; Nüsse, H.; Klingauf, J.; Studer, A. *Org. Lett.,* **2018**, *20*, 752. https://doi.org/10.1021/acs.orglett.7b03892.
111. Li, J.; Huo, P.; Zheng, J.; Zhou, X.; Liu, W. *RSC Adv.,* **2018**, *8*, 24231. https://doi.org/10.1039/C8RA03754J.
112. Campisciano, V.; Calabrese, C.; Liotta, L. F.; Parola, V. L.; Spinella, A.; Aprile, C.; Gruttadauria, M.; Giacalone, F. *Appl Organometal Chem.,* **2019**, e4848. https://doi.org/10.1002/aoc.4848.
113. Zhou, S.; Johnson, M.; Veinot, J. G. C. *Chem. Commun.,* **2010**, *46*, 2411. https://doi.org/10.1039/B922462A.
114. Smith, S. E.; Siamaki, A. R.; Gupton, B. F.; Carpenter, E. E. *RSC Adv.,* **2016**, *6*, 91541. https://doi.org/10.1039/C6RA17369A.

115. Xiao, Q.; Sarina, S.; Jaatinen, E.; Jia, J.; Arnold, D. P.; Liu, H.; Zhu, H. *Green Chem.,* **2014**, *16*, 4272. https://doi.org/10.1039/C4GC00588K.
116. Gholinejad, M.; Seyedhamzeh, M.; Razeghi, M.; Najera, C.; Zareh, M. K. *ChemCatChem.,* **2016**, *8*, 441. https://doi.org/10.1002/cctc.201600994.
117. Handa, S.; Smith, J. D.; Hageman, M. S.; Gonzalez, M.; Lipshutz, B. H. *ACS Catal.,* **2016**, *6*, 8179. https://doi.org/10.1021/acscatal.6b02809.
118. Bayan, R.; Karak, N. *ACS Omega,* **2017**, *2*, 8868. https://doi.org/10.1021/acsomega.7b01504.
119. Asadi, S.; Sedghi, R.; Heravi, M. M. *Catal. Lett.,* **2017**, *147*, 2045. https://link.springer.com/article/10.1007/s10562-017-2089-2
120. Mohazzab, B. F.; Jaleh, B.; Issaabadi, Z.; Nasrollahzadeh, M.; Varma, R. S. *Green Chem.,* **2019**, *21*, 3319. https://doi.org/10.1039/C9GC00889F.
121. Chinchole, A. N.; Dubey, A. V.; Kumar, A, V. *Catal. Lett.,* **2019**, *149*, 1224. https://doi.org/10.1007/s10562-019-02703-z.
122. Cao, Z.; Xie, S.; Fang, H.; Shi, Z. *J. Am. Chem. Soc.,* **2018**, *140*, 13575. https://doi.org/10.1021/jacs.8b08779.
123. Giovannini, R.; Stüdemann, T.; Devasagayaraj, A.; Dussin, G.; Knochel, P. *J. Org. Chem.,* **1999**, *64*, 3544. https://doi.org/10.1021/jo982317b.
124. Lipshutz, B. H.; Sclafani, J. A.; Blomgren, P. A. *Tetrahedron,* **2000**, *56*, 2139. https://doi.org/10.1016/S0040-4020(99)01096-0.
125. Lipshutz, B. H.; Butler, T.; Swift, E. *Org. Lett.,* **2008**, *10*, 697. https://doi.org/10.1021/ol702453q
126. Kalbasi, R. J.; Mosaddegh, N. *Bull. Korean Chem. Soc.,* **2011**, *32*, 2584. https://doi.org/10.5012/bkcs.2011.32.8.2584.
127. Zhong, Y.; Gong, X.; Zhu, X.; Ni, Z.; Wang, H.; Fu, J.; Han, W. *RSC Adv.,* **2014**, *4*, 63216. https://doi.org/10.1039/C4RA10739J.
128. Handa, S.; Slack, E. D.; Lipshutz, B. H. *Angew. Chem. Int. Ed.,* **2015**, *54*, 11994. https://doi.org/10.1002/anie.201505136.
129. Arellano, C. G.; Corma, A.; Iglesias, M.; Sánchez, F. *J. Catal.,* **2006**, *238*, 497. https://doi.org/10.1016/j.jcat.2005.12.015.
130. Haruta, M. *Gold Bulletin,* **2004**, *37*, 27. https://doi.org/10.1007/BF03215514.
131. Abad, A.; Concepción, P.; Corma, A.; Garcîa, H. A. *Angew. Chem. Int. Ed.,* **2005**, *44*, 4066. https://doi.org/10.1002/anie.200500382.
132. Han, J.; Liu, Y.; Guo, R. *J. Am. Chem. Soc.,* **2009**, *131*, 2060. https://doi.org/10.1021/ja808935n
133. Fakhri, P.; Nasrollahzadeh, M.; Jaleh, B. *RSC Adv.,* **2014**, *4*, 48691. https://doi.org/10.1039/C4RA06562J.
134. Sasmal, S.; Debnath, M.; Nandi, S. K.; Haldar, D. *Nanoscale Adv.,* **2019**, *1*, 1380. https://doi.org/10.1039/C8NA00273H.
135. Benaglia, M.; Puglisi, A.; Cozzi, F. *Chem. Rev.,* **2003**, *103*, 3401. https://doi.org/10.1021/cr010440o
136. Guan, Z.; Hu, J.; Gu, Y.; Zhang, H.; Li, G.; Li, T. *Green Chem.,* **2012**, *14*, 1964. https://doi.org/10.1039/C2GC35302D.

137. Das, P. P.; Prabhakaran, V. C.; Nanda, S.; Sen, D.; Chowdhury, B. *ChemistrySelect,* **2019,** *4*, 3823. https://doi.org/10.1002/slct.201803485.
138. Parrish, C. A.; Buchwald, S. L. *J. Org. Chem.,* **2001**, *66*, 3820. https://doi.org/10.1021/jo010025w
139. Suzuka, T.; Kimura, K.; Nagamine, T. *Polymers,* **2011**, *3*, 621. https://doi.org/10.3390/polym3010621
140. Ma, H.; Cao, W.; Bao, Z.; Lei, Z. *Catal. Sci. Technol.,* **2012**, *2*, 2291. https://doi.org/10.1039/C2CY20126G.
141. Choudhary, H.; Nishimura, S.; Ebitani, K. *J. Mater. Chem. A,* **2014**, *2*, 18687. https://doi.org/10.1039/C4TA03889D.
142. Dong, Y.; Bi, J.; Zhu, D.; Meng, D.; Ming, S.; Guo, W.; Chen, Z.; Liu, Q.; Guo, L.; Li, T. *Cellulose,* **2019**, *26*, 7355. https://doi.org/10.1007/s10570-019-02568-w.
143. Gedye, R.; Smith, F.; Westaway, K.; Ali, H.; Baldisera, L.; Laberge, L.; Rousell, J. *Tetrahedron Lett.,* **1986**, *27*, 279. https://doi.org/10.1016/S0040-4039(00)83996-9.
144. Giguere, R. J.; Bray, T. L.; Duncan, S. M.; Majetich, G. *Tetrahedron Lett.,* **1986**, *27*, 4945. https://doi.org/10.1016/S0040-4039(00)85103-5.
145. Hallberg, A.; Larhed, M. *J. Org. Chem.,* **1996**, *61*, 9582. https://doi.org/10.1021/jo9612990
146. Hallberg, A.; Lindeberg, G.; Larhed, M. *Tetrahedron Lett.,* **1996**, *37*, 8219. https://doi.org/10.1016/0040-4039(96)01872-2.
147. Blettner, C. G.; Konig, W. A.; Stenzel, W.; Schotten, T. *J. Org. Chem.,* **1999**, *64*, 3885. https://doi.org/10.1021/jo982135h
148. Leadbeater, N. E.; Marco, M. *Org. Lett.,* **2002**, *4*, 2973. https://doi.org/10.1021/ol0263907
149. Martins, D. L.; Alvarez, H. M.; Aguiar, L. C. S. *Tetrahedron Lett.,* **2010**, *51*, 6814. https://doi.org/10.1016/j.tetlet.2010.09.145.
150. Teranishi, T.; Miyake, M. *Chem. Mater*., **1998**, *10*, 594. https://doi.org/10.1021/cm9705808
151. Castro, K. L. S.; Lima, P. G.; Miranda, L. S. M.; Souza, R. O. M. A. *Tetrahedron Lett*., **2011**, *52*, 4168. https://doi.org/10.1016/j.tetlet.2011.06.009.
152. Shen, L.; Huang, S.; Nie, Y.; Lei, F. *Molecules,* **2013**, *18*, 1602. https://doi.org/10.3390/molecules18021602.
153. Zukauskaitė, Z.; Buinauskaitė, V.; Solovjova, J.; Malinauskaitė, L.; Kveselytė, A.; Bieliauskas, A.; Ragaitė, G.; Šačkus, A. *Tetrahedron,* **2016**, *72*, 2955. https://doi.org/10.1016/j.tet.2016.04.010.
154. Sharma, S.; Nazir, R.; Pande, S.; Sarkar, B. R. *ChemistrySelect,* **2017**, *2*, 8745. https://doi.org/10.1002/slct.201701527.
155. Fageria, P.; Nazir, R.; Gangopadhyay, S.; Barshilia, H. C.; Pande, S. *RSC Adv*., **2015**, *15*, 80397. https://doi.org/10.1039/C5RA12463H.
156. Elazab, H. A.; Sadek, M. A.; Idreesy, T. T. E. *Adsorption Science & Technology,* **2018**, *36*, 1352. https://doi.org/10.35940/ijitee.L2899.119119

157. Babu, S. A.; Saranya, S.; Rohit, K. R.; Anilkumar, G. *ChemistrySelect,* **2019**, *4*, 1019. https://doi.org/10.1002/slct.201803144.
158. Merrifield, B. A. *J. Am. Chem. Soc*., **1963**, *85*, 2149. https://doi.org/10.1021/ja00897a025
159. Kabalka, G. W.; Pagni, R. M.; Hair, C. M. *Org. Lett.,* **1999**, *1*, 1423. https://doi.org/10.1021/ol990972f
160. Khruscheva, N. S.; Bulygina, L. A.; Sokolov, V. I. *Russ. Chem. Bull. Int. Ed*., **2011**, *60*, 503.
161. Monguchi, Y.; Fujita, Y.; Hashimoto, S.; Ina, M.; Takahashi, T.; Ito, R.; Nozaki, K.; Maegawa, T.; Sajiki, H. *Tetrahedron,* **2011**, *67*, 8628. https://doi.org/10.1016/j.tet.2011.09.043.
162. Pentsak, E. O.; Ananikov, V. P. *Eur. J. Org. Chem.,* **2019**, 4239. https://doi.org/10.1002/ejoc.201900410.
163. Kabalka, G. W.; Pagni, R. M.; Wang, L.; Namboodiri, V.; Hair, C. M. *Green Chemistry,* **2000**, *2*, 120. https://doi.org/10.1039/B001191F.
164. Chang, W.; Chae, G.; Jang, S. R.; Shin, J.; Ahn, B. J. *Ind. Eng. Chem. Res.,* **2012**, *18*, 581.
165. Baran, T.; Baran, N. Y.; Menteş, A. *Int. J. Biol. Macromol*., **2018**, *115*, 249. https://doi.org/10.1016/j.ijbiomac.2018.04.057.
166. Baran, T. *Int. J. Biol. Macromol*., **2019**, *127*, 232. https://doi.org/10.1016/j.ijbiomac.2019.01.046.
167. Takacs, L. *Prog. Mater. Sci.,* **2002**, *47*, 355. https://doi.org/10.1016/S0079-6425(01)00002-0.
168. Rodrıǵuez, B.; Bruckmann, A.; Rantanen, T.; Bolm, C. *Adv. Synth. Catal.,* **2007**, *349*, 2213. https://doi.org/10.1002/adsc.200700252.
169. Stolle, A.; Szuppa, T.; Leonhardt, S. E.; Ondruschka, B. *Chem. Soc. Rev.,* **2011**, *40*, 2317. https://doi.org/10.1039/C0CS00195C.
170. Schneider, F.; Ondruschka, B. *ChemSusChem,* **2008**, *1*, 622. https://doi.org/10.1002/cssc.200800086.
171. Cravotto, G.; Garella, D.; Tagliapietra, S.; Stolle, A.; Schüßler, S.; Leonhardtb, S. E. S.; Ondruschka, B. *New J. Chem.,* **2012**, *36*, 1304. https://doi.org/10.1039/C2NJ40064B.
172. Martina, K.; Leonhardt, S. E. S.; Ondruschka, B.; Curini, M.; Binello, A.; Cravotto, G. *J. Mol. Catal. A: Chem.,* **2011**, *334*, 60. https://doi.org/10.1016/j.molcata.2010.10.024.
173. Seo, T.; Ishiyama, T.; Kubota, K.; Ito, H. *Chem. Sci*., **2019**, *10*, 8202. https://doi.org/10.1039/C9SC02185J.
174. Leadbeater, N. E.; Marco, M. *Angew. Chem. Int. Ed.,* **2003**, *42*, 1407. https://doi.org/10.1002/anie.200390362.
175. Li, C. *Angew. Chem. Int. Ed*., **2003**, *42*, 4856. https://doi.org/10.1002/anie.200301672.
176. Leadbeater, N. E.; Marco, M. *J. Org. Chem.,* **2003**, *68*, 5660. https://doi.org/10.1021/jo034230i
177. Arvela, R. K.; Leadbeater, N. E.; Sangi, M. S.; Williams, V. A.; Granados, P.; Singer, R. D. *J. Org. Chem.* **2005**, *70*, 161. https://pubs.acs.org/doi/10.1021/jo048531j

178. Kabalka, G. W.; Yao, M.; Borella, S.; Wu, Z. *Chem. Commun.,* **2005**, 2492. https://doi.org/10.1039/B502026C.
179. Ueda, M.; Nishimura, K.; Ryu, I. *Synlett,* **2013**, *24,* 1683. DOI: 10.1055/s-0033-1339199.
180. Jadhav, S.; Rashinkar, G.; Salunkhe, R.; Kumbhar, A. *Tetrahedron Lett.,* **2017,** *58,* 3201. https://doi.org/10.1016/j.tetlet.2017.06.048.
181. He, Z.; Song, F.; Sun, H.; Huang, Y. *J. Am. Chem. Soc.,* **2018,** *140,* 2693. https://doi.org/10.1021/jacs.8b00380
182. Yu, D.; Xu, F.; Li, D.; Han, W. *Adv. Synth. Catal.,* **2019**, *361,* 3102. https://doi.org/10.1002/adsc.201900306.
183. Jafarpour, F.; Ranjbar, P. R.; Kashani, A. O. *Eur. J. Org. Chem.,* **2011**, 2128. https://doi.org/10.1002/ejoc.201001733.
184. Bjerglund, K. M.; Skrydstrup, T.; Molander, G. A. *Org. Lett.,* **2014**, *16,* 1888. https://doi.org/10.1021/ol5003362.
185. Zhao, H.; Du, H.; Yuan, X.; Wang, T.; Han, W. *Green Chem.,* **2016**, *18,* 5782. https://doi.org/10.1039/C6GC02158A.
186. Qi, X.; Zhou, C.; Peng, J.; Ying, J.; Wu, X. *Tetrahedron Lett.,* **2017**, *58,* 4153. https://doi.org/10.1016/j.tetlet.2017.09.063.
187. Ueda, T.; Konishi, H.; Manabe, K. *Angew. Chem. Int. Ed.,* **2013**, *52,* 8611. https://doi.org/10.1002/anie.201303926.
188. Gautam, P.; Gupta, R.; Bhanage, B. M. *Eur. J. Org. Chem.,* **2017**, 3431. https://doi.org/10.1002/ejoc.201700543.
189. Yu, D.; Xu, F.; Li, D.; Han, W. *Adv. Synth. Catal.,* **2019**, *361,* 3102. https://doi.org/10.1002/adsc.201900306.

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