Heterogeneous Heck Reaction Catalyzed by Recyclable Polymer-Supported *N*-Heterocyclic Carbene–Palladium Complex

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Abstract: The Heck reaction of aryliodides with *n*-butylacrylate proceeded in moderate to satisfactory yields when it was catalyzed by polymer-supported *N*-heterocyclic carbene–palladium complex. This catalyst was able to decrease the reaction time with high efficiency, because the catalytic sites were located only on the surface of the resin. It was also easily recovered quantitatively and reused many times with constant activity.

Key words: Heck cross-coupling reaction, *N*-heterocyclic carbene, palladium, heterogeneous catalyst

Palladium-catalyzed carbon–carbon bond forming reactions have contributed remarkably to synthetic organic chemistry.[1] Among these reactions, the Heck cross-coupling and related reactions have been extensively utilized in the preparation of olefinic compounds.[2]

When it comes to scaling up this process to an industrial level, the recovery of the expensive catalysts and their recycling are very much required.[3]

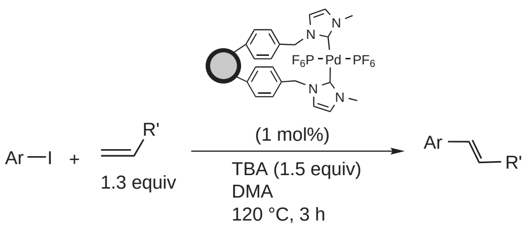
Heck reactions are mostly catalyzed by palladium complexes in homogeneous systems in the presence of phosphorus ligands, which are moisture and air sensitive and unrecoverable. In addition, various problems may be encountered with these catalysts due to their precipitation, instability at high reaction temperatures, difficulties of separation and recovery after use.[4] These problems can be overcome, however, by utilizing heterogeneous systems, made up of polymer-supported *N*-heterocyclic carbene (NHC) ligand and the palladium catalyst.[5]

However, cross-coupling reactions that are carried out using polymer-supported catalysts generally necessitate more drastic conditions than those using homogeneous catalysts. On the other hand, if the catalytic active sites are anchored on the surface of the polymer support and are thermally stable, such conditions are not usually required.[6]

We recently developed a polymer-supported *N*-heterocyclic carbene precursor and reported its application to the palladium-catalyzed Suzuki reaction. This polymer-supported NHC–Pd catalyst can increase the reaction rate and catalytic efficiency, due to the location of its active sites on the skin layer of the resin.[7]

In the course of our attempts to extend the scope of various heterogeneous cross-coupling reactions, we found that our polymer-supported NHC–Pd complex can also facilitate the formation of Csp^2–Csp^2 bonds with high efficiency, through a process known as the Heck reaction.[8] Furthermore, this stable catalyst can easily be recycled quantitatively by simple filtration.

In this communication, we report a heterogeneous Heck reaction, which is catalyzed by a recyclable polymer-supported NHC–Pd complex exhibiting excellent and constant activity (Scheme 1).



Scheme 1

We first investigated the use of various solvents in order to find the most appropriate conditions for the heterogeneous Heck reaction of 4-iodotoluene with *n*-butylacrylate using 1 mol% of the polymer-supported NHC–Pd catalyst.

Polar solvents such as dimethylformamide (DMF) and *N*,*N*-dimethylacetamide (DMA) gave better results than the other solvents that were tested (Table 1), with DMA being selected as the solvent of choice.

These results led us to conclude that the Heck reaction rate is solvent-dependent not only in homogeneous systems, but also in the present heterogeneous reaction.[9]

After choosing the most efficient solvent for the Heck reaction, we next examined the coupling of 4-iodotoluene with *n*-butylacrylate in the presence of various bases, in order to obtain more information about the effect of the base.

The reaction rate of this heterogeneous Heck reaction also proved to be significantly influenced by the bases that were used (Table 2). An outstanding increase in activity was observed with tributylamine (TBA) and *N*,*N*-dicyclohexylmethylamine (DCHMA). The use of other organic and inorganic bases resulted in moderate yields of the desired products.

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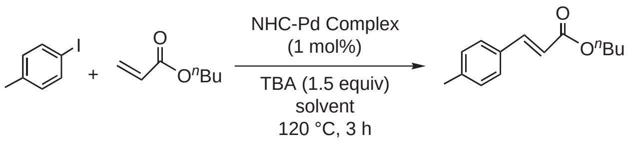
Table 1 Effect of the Solvent on the Polymer-Supported NHC–Pd-Catalyzed Heck Reaction of 4-Iodotoluene with *n*-Butylacrylate[a]



Entry	Solvent	Yield (%)[b]
1	DMA	95
2	DMF	91
3	Dioxane	88
4	DMSO	85
5	MeCN	77
6	THF	73

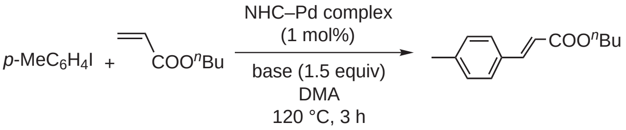
[a] Reaction conditions: 1.0 mmol 4-iodotoluene, 1.3 equiv *n*-butylacrylate, 10 mL solvent.
[b] Isolated yield.

In an attempt to extend the application of the polymer-supported NHC–palladium complex, under optimized conditions (1 mol% NHC–Pd complex, 1.5 equiv TBA, 3 h, 120 °C), the coupling of several representative aryliodides with *n*-butylacrylate was carried out.

As shown in Table 3, the reaction of electron-deficient aryliodides with *n*-butylacrylate gave almost quantitative yields. The electron-rich 4-iodoanisole and sterically hindered 2-iodotoluene were also converted to the coupled products in three hours with high yields (Table 3, entries 3 and 4).

One of the most attractive features exhibited by this polymer-supported NHC–Pd catalyst is that a low catalyst loading (1 mol%) provided sufficient activity for successful Heck cross-coupling reactions in a shorter reaction time (3 h) than that required by the previously reported heterogeneous catalysts (16–24 h), without any palladium leaching.[10]

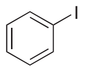
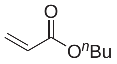
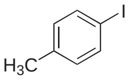
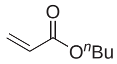
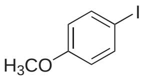
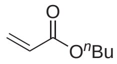
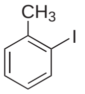
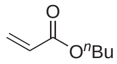
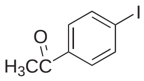
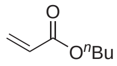
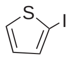
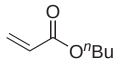
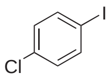
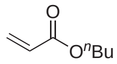
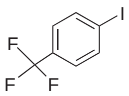
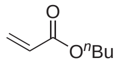
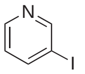
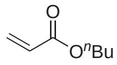
Table 2 Effect of the Base on the Polymer-Supported NHC–Pd-Catalyzed Heck Reaction of 4-Iodotoluene with *n*-Butylacrylate[a]



Entry	Base	Yield (%)[b]
1	TBA	95
2	DCHMA	92
3	Cs_2CO_3	70
4	TEA	55
5	NaOAc	43

[a] Reaction conditions: 1.0 mmol 4-iodotoluene, 1.3 equiv *n*-butyl acrylate, 10 mL DMA.
[b] Isolated yield.

Table 3 Heck Reaction of Aryliodides with *n*-Butylacrylate Using Polymer-Supported NHC–Pd[a]

Entry	Aryl iodide	Alkene	Yield (%)[b]
1			95
2			95
3			95
4			93
5			94
6			70
7			94
8			94
9			84

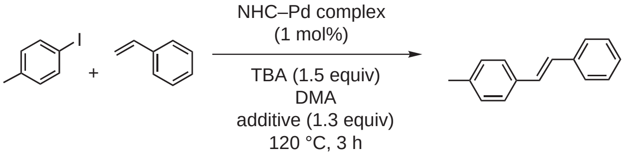
[a] Reaction conditions: 1 mol% NHC–Pd complex, 1.0 mmol aryliodides, 1.3 equiv *n*-butylacrylate, 10 mL DMA, 1.5 equiv TBA, 3 h, 120 °C.
[b] Isolated yield.

Tetraalkylammonium salts have been used for increasing the yield and selectivity of Heck-type reactions.[11] Accordingly, the effect of these additives was also investigated in the case of the coupling of 4-iodotoluene and styrene.

In the absence of any additive, the desired product, 1-methyl-4-styrylbenzene was obtained in 70% yield under optimal conditions. However, even better results were achieved when 1.3 equivalents of a tetrabutylammonium salt was added. In this case, tetrabutylammonium acetate raised the yield of the product from 70% to 85%, while tetrabutylammonium iodide proved to be the least effective salt (Table 4).

To evaluate the reusability of the catalyst, the coupling of iodobenzene with *n*-butylacrylate was chosen as a model reaction. The product was extracted conveniently with diethyl ether. The residual NHC–Pd complex was filtered and reused as the catalyst for the next run without

Table 4 Effect of Tetrabutylammonium Salts on the Polymer-Supported NHC–Pd-Catalyzed Heck Reaction[a]



Entry	Additives	Yield (%)[b]
1	–	70
2	n-Bu_4NAc	85
3	n-Bu_4NBr	80
4	n-Bu_4NI	77

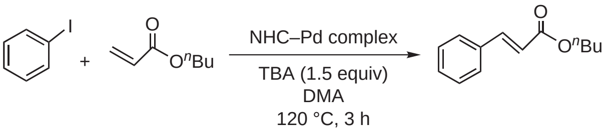
[a] Reaction conditions: 1.0 mmol 4-iodotoluene, 1.3 equiv styrene, 10 mL DMA.
[b] Isolated yield.

regeneration or further addition of the catalyst. The NHC–Pd catalyst remained highly active after six consecutive cycles of the Heck reaction, and the product butylcinnamate was obtainted in high yield in each recycled reaction (Table 5).

Meanwhile, the last two filtrates (entries 5 and 6) were analyzed by ICP-AES, which proved there was no palladium leaching during these processes.[12]

In summary, we demonstrated the use of a stable and reusable polymer supported *N*-heterocyclic carbene–palladium complex for the Heck reaction. The major advantages of our system are that the catalyst can be recycled and the product obtained with high yield in a shortened reaction time, due to the high efficiency of the NHC–Pd complex located solely on the surface of the polymer-supported resin.

Table 5 Recycling of Catalyst System[a]



Entry	Recycle	Yield (%)[b]
1	1	95
2	2	95
3	3	95
4	4	94
5	5	95
6	6	94

[a] Reaction conditions: 1.0 mmol 4-iodobenzene, 1.3 equiv *n*-butylacrylate, 10 mL DMA.
[b] Isolated yield.

Acknowledgment

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(12) The filtrate was treated with a mixture (2 mL) of concd HCl and HNO_3 (3:1, v/v) at 50 °C for 1 h. Following this, the resulting solution was filtered, and diluted with H_2O to 20 mL, then analyzed by ICP-AES.