INTERNATIONAL DOCTORAL SCHOOL OF THE USC

Víctor
Fariña Torres

PhD Thesis

DEVELOPMENT OF CARBON-CARBON BOND FORMING REACTIONS USING A HETEROBIMETALLIC Pd-Fe METAL-ORGANIC FRAMEWORK AS HETEROGENOUS CATALYST

Santiago de Compostela, 2025

Doctoral Programme in Chemical Science and Technology

INTERNATIONAL DOCTORAL
SCHOOL OF THE USC

DOCTORAL THESIS

DEVELOPMENT OF CARBON-CARBON BOND FORMING REACTIONS USING A HETEROBIMETALLIC Pd-Fe METAL-ORGANIC FRAMEWORK AS HETEROGENOUS CATALYST

Author

Víctor Fariña Torres

Supervisor/s: Martín Fañanás Mastral

Tutor: Martín Fañanás Mastral

PHD PROGRAMME IN CHEMICAL SCIENCE AND TECHNOLOGY

SANTIAGO DE COMPOSTELA

The data organization in the corresponding sections of the present thesis dissertation was conducted in accordance with the DOG 167/2024, article 34.2, which states that *the doctoral thesis should include, as a minimum, an abstract, an introduction, the objectives and hypotheses, the general methodology, the analysis of the results and their discussion, the general conclusions and the bibliography. These parts should be clearly indicated in the thesis to facilitate its identification and reading.*

The format of the manuscript was adapted to the criteria *of homogeneity, typographic readability and functional ease* included in the recommended guidelines provided by the International PhD School of the University of Santiago de Compostela (EDIUS), as carried out by the Publications and Scientific Exchange Service.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

AGRADECIMIENTOS

Para empezar, me gustaría agradecer a mi tutor y director de tesis Martín Fañanás por haber confiado en mi para realizar la tesis en su grupo de investigación, enseñarme y ayudarme durante todo ese proceso. También agradecer a todas las instituciones que han aportado financiación al grupo y al CiQUS y a todo su personal.

A todos mis compañeros del laboratorio, empezando por las que me acompañaron al principio de este viaje, Eva, Andrea y Nuria, pasando por los que se fueron incorporando más adelante como Pol, Andrés, Martín, Sergio, Patri y a nuestros muy confiables postdocs Irene, Balázs y Jaime a los cuales siempre podía acudir en caso de ayuda. Muchas gracias a todos por hacer de esta una experiencia, haciendo los días malos menos duros y los buenos aún mejores.

A mis amigos del pueblo, Diego, Pallas y Chedas, gracias por haberme aguantado y no olvidaros de mi pese a raramente ir por allí y a no tener tanto trato como antes, las partidas al LoL de las noches siempre eran una buena forma de desconectar después de un día duro.

Mi grupo de amigos de ingeniería, Javi, Samu, Hadri, Lucas y Carlos (aunque no empezaras ingeniería con nosotros y te unieras al grupo más adelante), sois la única razón por la que no me arrepiento de haber empezado ese grado, solamente el haberos conocido valió la pena y doy gracias de haber cometido ese error, porque habría perdido de conocer a unas personas maravillosas, gracias por siempre estar ahí cuando os necesito.

Mis amigos de las cerves, las dos Irenes, Pol, Alberto, Alfredo, Andrea y Ernesto, siempre se agradecía poder salir del laboratorio e ir a tomar unas cervezas al Bandullo y desahogarme o simplemente hablar de chorradas y desconectar.

No podrían faltar mis padres, gracias por apoyarme siempre en todas mis decisiones, no podría desear unos mejores padres, siempre habéis estado ahí para mí, incluso en los momentos más difíciles hicisteis lo posible para darme las mejores opciones y ayudarme en todo lo posible.

Me gustaría agradecer a Eugenia y a Guillermo por darme la oportunidad de trabajar con ellos utilizando este MOF en este proyecto, también agradecer a todas las personas con las que coincidí en mi breve estancia en el ICMol que me hicieron sentir como uno más durante esas dos semanas.

Por último, pero no menos importante sino al contrario, a Marcos, por acompañarme en esta aventura llena de buenos y malos momentos, siempre compartiendo y disfrutando los buenos y animándome en los malos, ya fuera simplemente escuchándome, apoyándome en lo posible o si hacía falta echándome la bronca y poniéndome las pilas. Una parte de esta tesis te pertenece, ya que muy posiblemente no habría sido capaz de continuarla sin ti, gracias por ser mi roca durante ella.

TABLE OF CONTENTS

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

1. ABBREVIATIONS

δ	Chemical shift
Ac	Acyl
APCI	Atmosphere-pressure chemical ionization
Ar	Aryl
Boc	*tert*-Butyloxycarbonyl
Cat	Catalyst
d	Doublet
DMA	Dimethylacetamide
DMF	Dimethylformamide
DMSO	Dimethyl sulfoxide
dr	Diastereomeric ratio
EDX	Energy Dispersive X-ray Analysis
equiv	Equivalent
GC-MS	Gas chromatography mass spectroscopy
hex	Hexyl
HRMS	High resolution mass spectrometry
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
J	Coupling constant
L	Ligand
m	Multiplet
M	Molar
M	Metal
MOF	Metal-organic framework
m/z	Mass charge relation
n.d.	Not determined
NHC	N-heterocyclic carbene
NMR	Nuclear Magnetic Resonance
Nu	Nucleophile
p	Pentet
Pd-PEPPSI-IPr	1,3-Bis(2,6-Diisopropylphenyl)imidazol-2-ylidene](3-chloropyridyl)palladium(II) dichloride
pin	Pinacol
ppm	Parts per million
q	Quadruplet
Ref.	Reference
r.t.	Room temperature
SBU	Secondary Building Unit
SN	Nucleophilic Substitution
t	Triplet
T	Temperature

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

TFA	Trifluoroacetic acid
THF	Tetrahydrofuran
XRPD	X-ray Powder diffraction

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

2. ABSTRACT

Catalysis is a powerful tool for the synthesis of a wide variety of compounds. A catalyst allows to increase the rate in which a chemical reaction reaches the equilibrium without being consumed in the process.

However, for the synthesis of more complex compounds usually homogeneous catalysis is needed. Nowadays the research of new heterogeneous catalysts that have both the advantages of heterogeneous and homogeneous catalysts has greatly increased.

On this field metal-organic frameworks have emerged as powerful catalyst that fulfill both the complexity of the homogeneous catalysts and the easy recyclability and robustness of the heterogeneous catalysts.

This thesis presents the principal results obtained in the investigation of the applications of a novel bimetallic framework with iron clusters and a palladium metalloligand in different palladium catalyzed reactions.

We focused in the carbon-carbon formation reactions. Focusing on reactions with interest for their potential to synthetize natural or bioactive compounds, while also trying to maximize the potential of the functionalities of the MOF.

We started with the allylic alkylation reaction, a well-known reaction that surprisingly was not explored using MOFs as catalysts, for this reaction we developed a methodology that not only to have a good generality of substrates, but that also allowed us to recuperate and reutilize the MOF up to five times without any reactivity drop.

After that we moved on to a more challenging reaction. The oxidative Heck reaction was chosen so we could take advantage of the other functionality of the MOF, using the iron clusters as an oxidant cocatalyst to enhance the oxidation step of the palladium under an air atmosphere. Also, very few reports of a heterogeneous version of this reaction are reported to the date and half of them are not even recyclable.

We could demonstrate hypothesis of the reoxidation of the Pd was happening. However, when we moved to test the recyclability, we could observe that the MOF was decomposing even after the first use.


USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

3. RESUMO

A catálise é unha ferramenta poderosa para a síntese de unha gran variedade de compostos, permite acelerar a velocidade na cal unha reacción acada o equilibrio sen que o catalizador sexa consumido no proceso. Os compostos que se poden sintetizar inclúen, dende compostos simples que son amplamente utilizados na industria como o amoníaco e o ácido sulfúrico, ata os produtos naturais ou activos bioloxicamente que son máis complexos e que constan de aplicacións médicas e farmacolóxicas. Hoxe en día, a maioría dos produtos químicos, máis dun 95%, son obtidos na industria mediante metodoloxías catalíticas.

Mentres que os compostos máis simples poden ser sintetizados mediante o uso de catálise heteroxénea en condicións extremas de presión e temperatura, cando a complexidade dos compostos aumenta a necesidade de catalizadores homoxéneos que teñan ligandos capaces de habilitar ditas transformacións.

Sen embargo, o uso de catálise homoxénea constitúe unha limitación a futuro para estas metodoloxías, isto é debido a que este tipo de catalizadores resultan complicados de recuperar resultando na perdida do catalizador. Algúns dos catalizadores máis usados están baseados en metais preciosos, que non só son economicamente custosos e con baixas abundancias na codia terrestre senón que tamén son tóxicos.

Pola outra banda, os catalizadores heteroxéneos máis comúns normalmente carecen da especificidade necesaria para realizar as transformacións máis complexas. Durante as últimas décadas fixéronse grandes avances neste campo, conseguindo empregar distintos materiais como ceolitas, sílice mesoporosa e outros materiais porosos como as redes metal-orgánicas (MOFs) como catalizadores para diferentes reaccións.

Os MOFs son redes cristalinas e porosas que se caracterizan polo seu carácter híbrido orgánico e inorgánico. Estas estruturas fórmanse mediante a coordinación de ligandos orgánicos a clústeres inorgánicos formando estruturas lineares, planares ou tridimensionais.

Debido a facilidade para modificar a súa estrutura a través de métodos de síntese orgánica, e gracias a posibilidade de predicir as súas propiedades e funcións a través de ferramentas de deseño molecular os MOFs emerxeron como catalizadores prometedores.

Os MOFs constan de características altamente desexables para catalizadores heteroxéneos, como tamaños grandes de poro ou a súa cristalinidade que permite un mellor e máis fácil da distribución dos sitios cataliticamente activos do MOF mediante técnicas cristalográficas.

Durante as ultimas tres décadas os MOFs foron gañando importancia tanto como materiais como catalizadores, isto último grazas ao mellor entendemento e control das técnicas para modular o tamaño e o entorno dos poros. O que tamén permitiu introducir catalizadores máis complexos dentro da estrutura do MOF.

Sen embargo, pese a seu gran potencial como catalizadores heteroxéneos, o feito de que as súas aplicacións eran buscadas despois da síntese e deseño do MOF limitou a súa aplicabilidade. Con todo o seu potencial foi demostrado con unha gran variedade de exemplos, incluso conseguindo levar a cabo reaccións que non eran posibles baixo catálise homoxénea.

As características que permiten que estas reaccións sexan posibles son: a protección do catalizador no interior da rede, protexéndoo de especies reactivas ou evadindo procesos de

USC

desactivación que involucran asociación ou agregación do catalizador; o tamaño controlado no interior dos poros que permite obter selectividades mellores ou alternativas; e a posibilidade de engadir diferentes funcionalidades dentro do MOF obtendo así os denominados MOFs multivariantes (MTV-MOFs) que poden dar lugar a reaccións non reportadas ata o momento.

Dentro dos MOFs hai diversos puntos nos cales se pode atopar o centro catalítico, o máis común reside nos nodos metálicos (representados como esferas azuis na figura 1), os cales se constan de vacantes de coordinación libres poden actuar como catalizadores. A actividade catalítica tamén se pode atopar nos ligandos (representados como unha barra negra na cal o centro catalítico está representado como unha esfera vermella na figura 1), actuando como organocatalizadores no caso de que o ligando sexa un ligando orgánico ou no caso de que sexa un metaloligando como un catalizador metálico. Unha vez sintetizado o MOF pódense engadir postsinteticamente os centros catalíticos, ben ancorando os centros metálicos en grupos coordinantes (representados como esferas verdes na figura 1) presentes tanto nos nodos como nos ligandos ou mediante a formación de nanopartículas dentro dos poros do MOF (representados como un conxunto de esferas grises no interior da cela do MOF).

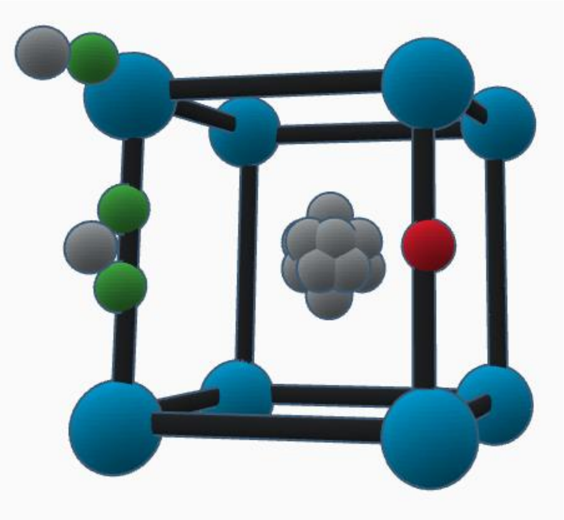


Figura 1. Representación esquemática dun MOF, os nodos representados como esferas azuis, ligandos como barras negras, grupos coordinantes como esferas verdes e centros metálicos externos como esferas grises.

Un dos metais máis amplamente utilizados como catalizador é o paladio, amplamente coñecido pola súa utilizade para formar enlaces carbono-carbono, como por exemplo as reaccións de acoplamento cruzado gañadoras do premio Nobel en 2010.

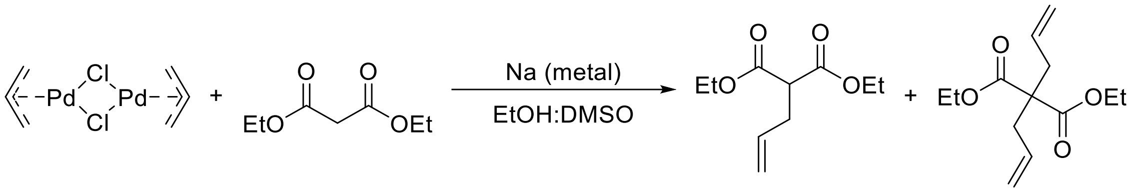
As reaccións catalizadas por paladio teñen en xeral unha ampla aplicación, sobre todo a hora da síntese de produtos naturais e bioloxicamente activos. Debido a súa escaseza na codia terrestre é de vital importancia o desenvolvemento de catalizadores heteroxéneos que teñan reactividade e selectividade comparables cos catalizadores homoxéneos coas vantaxe de ser reciclables e facilmente separables do medio de reacción.

O obxectivo de esta tese de doutoramento enfócase no estudio da reactividade e reciclabilidade dun MOF heterobimetálico (MUV-22) formado por nodos de ferro $[Fe_3(\mu_3O)(CH_3COO)_6]^+$ e un metaloligando de paladio $PdCl_2(H_2PDC)_2$, onde H_4PDC é o ácido piridin-3,5-dicarboxílico, sintetizado polo grupo do profesor Guillermo Minguez Espallargas no ICMOL na Universidad de Valencia en dúas reaccións catalizadas por paladio: a reacción

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

de alquilación alílica, tamén coñecida como a reacción de Tsuji-Trost e a reacción de Heck oxidativa.

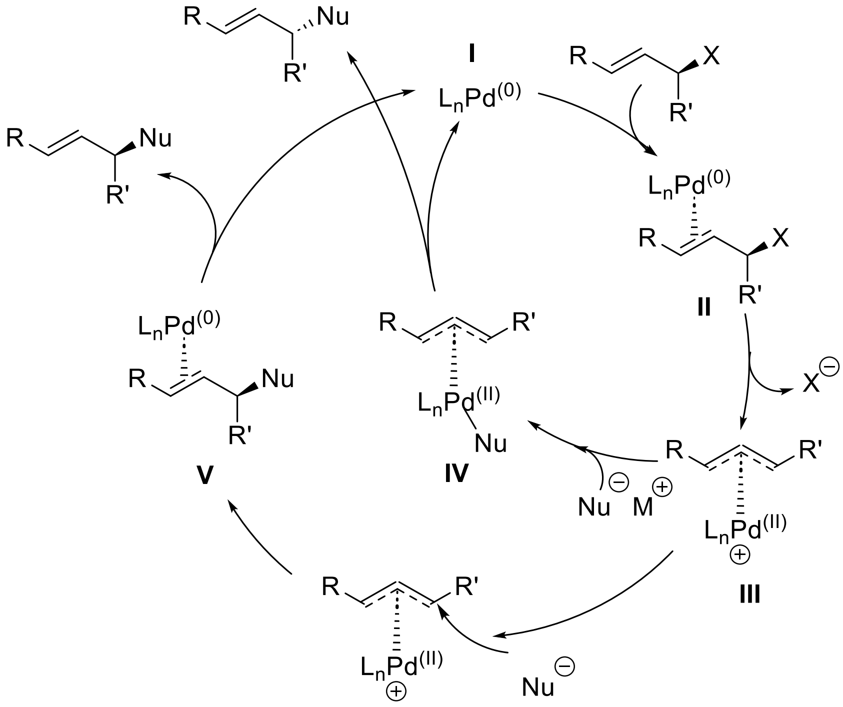
A reacción de alquilación alílica catalizada por paladio, amplamente coñecida como a reacción de Tsuji-Trost é unha reacción de substitución descuberta polo grupo de Tsuji en 1965 na cal un grupo saínte nunha posición alílica é trocado por un nucleófilo asistido por un complexo de paladio ben como reactivo estequiométrico ou como catalizador. Foi mellorada polo grupo de Trost gracias a adición de fosfinas como ligandos que permitían mellorar os rendementos e utilizar substratos non reactivos baixo as condicións normais.



Esquema 1. Primeira reacción de alquilación alílica asistida por paladio.

Ata o día de hoxe múltiples versións desta reacción foron descritas na literatura, mellorando as condicións, permitindo o uso de ligandos quirais conseguindo así produtos enantioenriquecidos e ampliando a variedade de compostos nos que se podían aplicar, por exemplo usando nucleófilos duros (compostos organometálicos) ou compostos alílicos con diferentes grupos saíntes.

O mecanismo de esta reacción (Esquema 2) empeza coa coordinación do complexo de paladio **I** ao dobre enlace do substrato alílico dando lugar ao intermedio **II**, seguido por unha adición oxidante do substrato ao paladio(0) que xera un complexo alilpaladio(II) **III**. A adición oxidante ocorre normalmente a través dun mecanismos tipo S_N2' onde o paladio se engade ao complexo en posición anti ao grupo saínte, isto implica que no caso de que o substrato sexa un derivado dun alcol alílico secundario esta etapa ocorre con unha inversión da configuración. O intermedio alilpaladio **III** pode reaccionar co nucleófilo mediante dous camiños diferentes, dependendo da natureza deste último: nucleófilos duros (pK_a do ácido conxugado >25) poden reaccionar mediante un mecanismo *inner-sphere* a través dunha etapa de transmetalación na cal a configuración do alilpaladio(II) é mantida para formar o intermedio **IV**. Unha posterior eliminación redutora libera o produto final cunha inversión neta da configuración e rexenera o complexo **I**. Pola contra, nucleófilos brandos segue un mecanismo *outer-sphere* onde o nucleófilo ataca a un dos átomos alílicos terminais do alilpaladio(II). Este ataque ocorre pola posición contraria do átomo de paladio, resultando en unha segunda inversión da configuración que da lugar ao intermedio **V**. Descoordinación do paladio rexenera o catalizador e libera o produto con unha retención neta da configuración.



Esquema 2. Mecanismo da reacción de substitución alílica con nucleófilos duros e brandos.

Tamén foron descritos numerosos exemplos da reacción de Tsuji-Trost empregando catalizadores heteroxéneos, a maioría utilizando como soporte sílice mesoporosa, diferentes polímeros orgánicos, ceolitas, montmorillonitas, entre outros. Sorprendentemente aínda que si que se utilizaron caixas orgánicas porosas (POCs) como soporte para esta reacción, non hai exemplos ata esta data de MOFs como catalizadores heteroxéneos para esta reacción.

Considerando que o MUV-22 presenta boa estabilidade química e térmica, gran porosidade e dispoñibilidade de centros de paladio(II) xunto coa ausencia de exemplos de MOFs empregados como catalizador para este tipo de reacción decidimos optimizar a reacción de substratos alílicos con ésteres de pinacol de ácidos borónicos en condicións adecuadas para a súa reciclabilidade.

Comezamos explorando o rol do grupo saínte da reacción, usando o éster de pinacol de ácidos borónicos metilo como nucleófilo (2 equiv), haluros ou derivados de alcoles de cinamilo, tolueno como disolvente a 150 ºC, carbonato de cesio (2 equiv) como base e fluoruro de potasio (1 equiv) como aditivo. Observouse que mentres que o grupo cloro da lugar a mellores rendementos a temperaturas altas, o MOF descompón. Baixando a temperatura a 120 ºC o bromo como grupo saínte da lugar a mellores rendementos comparando co cloro e o MOF podía recuperarse co seu aspecto orixinal.

Cando un disolvente máis polar como o 1,4-dioxano foi empregado os rendementos foron menores que usando un disolvente apolar como o tolueno, baixar a temperatura a 90 ºC en tolueno como disolvente da lugar aos rendementos máis altos. Cando se intentaron mellorar os rendementos modificando as estequiometrías de base e aditivo as cantidades iniciais resultaron óptimas.

Para demostrar o potencial do MUV-22 nesta reacción realizamos unha comparativa con diferentes catalizadores tanto homoxéneos como heteroxéneos, incluso comparando co metaloligando libre. En todos os casos o MOF deu lugar a resultados superiores.

A xeneralidade e as limitacións da reacción foron estudadas usando diferentes substratos alílicos e ésteres de pinacol de ácidos borónicos, dando lugar aos produtos correspondentes con bos resultados cando substratos alílicos con diferentes patróns de substitución no anel aromático son utilizados.

Respecto aos ésteres de pinacol de ácidos borónicos con aneis aromáticos dan lugar a excelentes resultados, mentres que os que teñen cadeas alquílicas dan lugar a resultados moderados ou no caso de que teñan hidróxenos na posición β da cadea fallan para dar lugar ao produto desexado.

Unha vez analizados a xeneralidade e as limitacións da reacción procedeuse a avaliar a estabilidade do MUV-22 no medio de reacción. Con este propósito realizamos varios experimentos e análises para asegurar que o MOF estaba mantendo a súa estrutura e non estaba descompoñendo.

Primeiro de todo, procedemos a comprobar a natureza heteroxénea do catalizador. Para iso realizamos un experimento de filtrado, no cal tras retirar o MOF do medio de reacción se comprobou que a reacción se paraba. Implicando isto que a catálise esta ocorrendo no MOF e non por unha posible paso de paladio do MOF a disolución homoxénea.

Sen embargo, isto non descarta unha posible perdida de paladio por descomposición do MOF, así que tamén se analizou o cru da reacción mediante ICP-MS para cuantificar a cantidade de paladio que estaba disolto, o resultado demostrou que a perdida de paladio era neglixible.

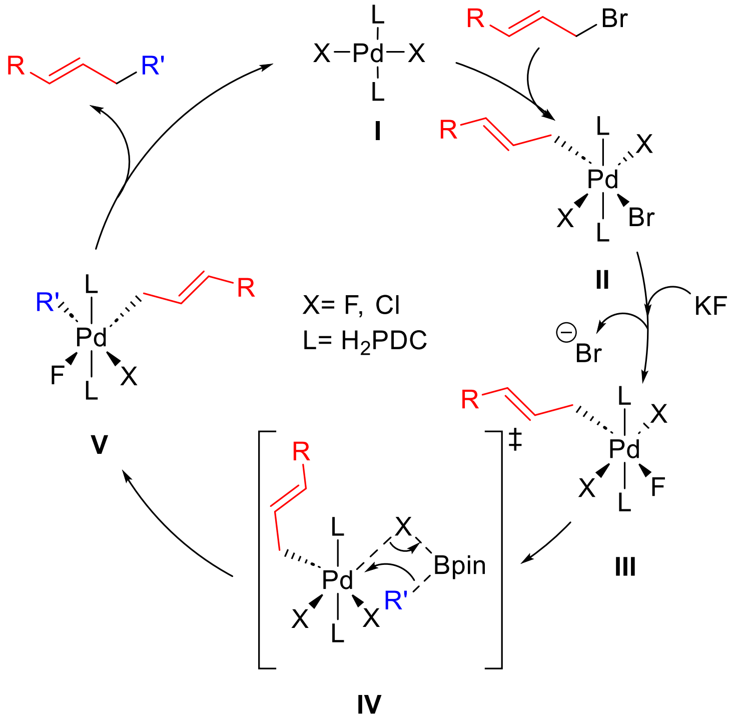
Procedeuse despois a realizar unha análise máis en detalle da estrutura do MOF despois da catálise, determinouse a estrutura cristalina do MOF mediante difracción de raios X de po. O difractrograma obtido correspondíase co da MOF fresco, indicando que O MOF non perde a estrutura cristalina durante a catálise.

O análise elemental por microanálise de raios X de enerxía dispersiva (EDX) deu lugar un resultado sorprendente, mentres que as proporcións entre os átomos de ferro e paladio se mantiñan constantes, indicando que non había descomposición, os átomos de cloro que estaban enlazados ao paladio do metaloligando desapareceron da estrutura do MOF, sendo substituídos por átomos de flúor. Sen embargo, cando o MOF foi mesturado nas condicións de reacción con fluoruro de potasio en ausencia dos substratos este cambio non foi observado. Isto puido ser debido a un intercambio de ligandos nun dos intermedios da reacción.

Para remarcar a utilidade do MUV-22 como catalizador heteroxéneo procedemos a estudar a súa reciclabilidade. Como estudo preliminar realizamos un análise dos rendementos ata conversión completa, para o noso deleite o MOF puido realizar ata cinco ciclos de reacción consecutivos sen unha perdida significativa de actividade. Cabe destacar que en ausencia de fluoruro potásico da reacción o MOF perdía a capacidade de ser reciclado, perdendo xa toda actividade a partir do primeiro ciclo. Cando o fluoruro potásico era engadido só na primeira reacción a actividade do MOF caia significativamente a partir do segundo ciclo e desactivándose totalmente a partir do cuarto.

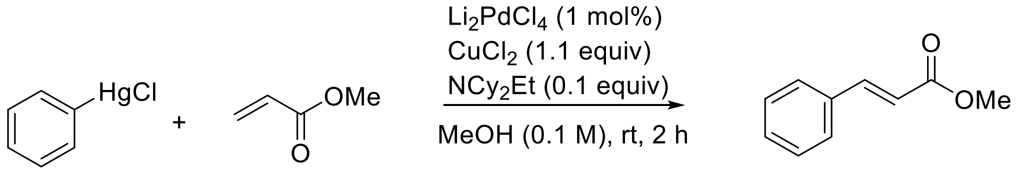
Pese a eses prometedores resultados, decidimos realizar un estudo cinético para asegurar que o MOF non estaba descompoñendo parcialmente no medio de reacción, o rendemento e a velocidade de reacción mantéñense constantes durante os ciclos o que indica que o MOF non descompón a medida que se vai reciclando.

Por último, para explicar os resultados observados, propuxemos o seguinte mecanismo de reacción (Esquema 3). Empeza coa coordinación do metaloligando de paladio **I** ao dobre enlace do substrato alílico seguido dunha adición oxidante da lugar ao intermedio **II**. Despois da adición oxidante, un intercambio de ligando ocorrería co fluoruro potásico presente no medio da reacción e liberando un ión bromuro para formar o intermedio **III**; esta etapa explicaría o intercambio dos átomos de cloro no MUV-22 polos átomos de flúor. A seguinte etapa sería unha transmetalación a través dun estado concertado de transición **IV** co éster de pinacol de ácido borónico para dar o intermedio **V** que finalmente evolucionaría mediante unha eliminación redutora para liberar o produto final e rexenerar o metaloligando **I**.



Esquema 3. Mecanismo proposto para a alilación tipo Suzuki-Miyaura.

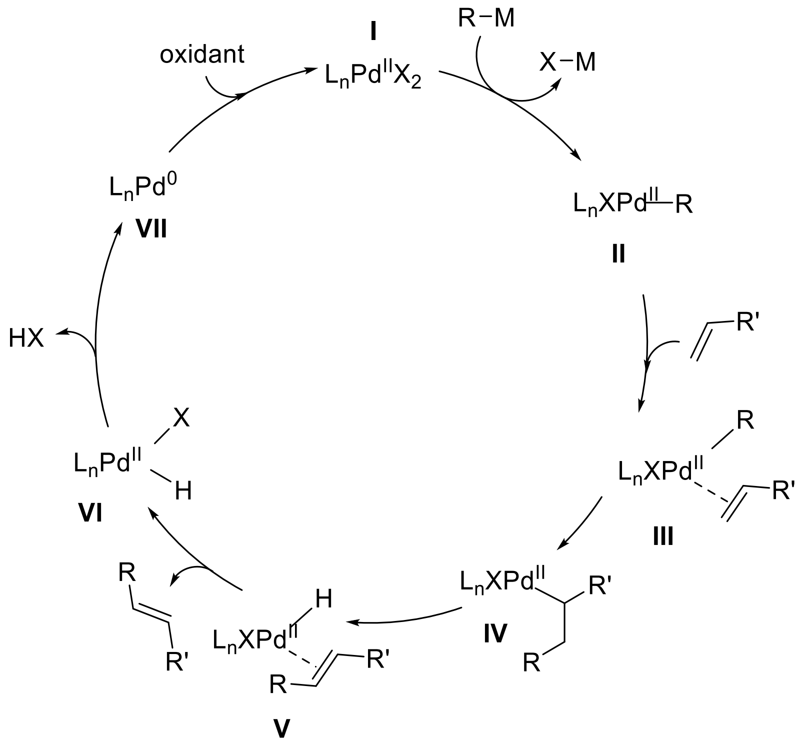
A seguinte reacción que procedemos a estudar era a reacción de Heck oxidativa, esta reacción foi descuberta en 1968 polo grupo de Heck e involucraba o acoplamento de olefinas con compostos organomercúricos de arilo con olefinas, nestas reaccións o catalizador de paladio necesita ser reoxidado por un axente externo.



Esquema 4. Primeira reacción de Heck oxidativa.

Os nucleófilos organometálicos que se poden empregar nesta reacción son moi diversos, como por exemplo os organosílices, organofósforos entre outros, pero destacan entre todos eles os compostos de organoboro que son os máis empregados.

O mecanismo de esta reacción comeza cunha transmetalación dende o composto organometálico ao complexo de paladio **I** dando lugar ao intermedio **II**, que se coordina ao alqueno para formar o intermedio **III**. Inserción migratoria na olefina conduce a la formación del alquilpaladio **IV**, que sofre unha eliminación β de hidruro xerando o hidruro de paladio coordinado ao alqueno **V**. O produto final libérase mediante disociación do alqueno resultando na especie de paladio **VI**, que evoluciona a través dunha eliminación redutora de HX ao intermedio de paladio(0) **VII**. Que necesita ser oxidado por un oxidante externo para rexenerar o complexo inicial **I** e cerrar o ciclo catalítico.



Esquema 5. Mecanismo da reacción de Heck oxidativa.

Un dos principais problemas desta reacción recae na necesidade de un oxidante externo para completar o ciclo catalítico, normalmente estes oxidantes adoitan ser sales de cobre ou derivados de benzoquinona, que producen unha gran cantidade de residuos, por iso é desexable evitar a formación de ditos residuos mediante o uso de oxidantes menos daniños para o medio ambiente, como o osíxeno ou idealmente o aire.

Mentres que os oxidantes foron migrando cara o uso dos menos daniños medioambientalmente o uso de catalizadores homoxéneos que non son recuperables continua sendo un problema de gran importancia. Sen embargo, a investigación do uso de catalizadores heteroxéneos para esta reacción segue estando a día de hoxe subdesenvolta. Actualmente só hai catro exemplos reportados, dos cales dous utilizan polímeros microporosos conxugados (CMPs), pero non presentan estudo da reciclabilidade nin do estado do catalizador despois da catálise. Os outros dous exemplos que si que son reciclables correspóndense cun polímero orgánico poroso (POP) con ligandos tipo carbenos N-heterocíclicos (NHC) na sua estrutura que coordinan o paladio e unha rede covalente orgánica (COF) con ligandos tipo base de Schiff.

Sen embargo, en todos os casos usan unha sal de cobre en cantidades altas como catalizador baixo atmosfera de osíxeno, debido a isto baseándonos nun traballo previo no que usan un cocatalizador de ferro para reoxidar o paladio nesta reacción en presencia de aire, o MUV-22 sería capaz de, cos seus nodos formados por ferro, reoxidar o paladio do metaloligando e despois el mesmo reoxidarse en presencia do aire de forma reciclable.

Con está hipótese e as vantaxes explicadas previamente do MUV-22, procedemos a buscar unhas condicións óptimas para a reacción de Heck oxidativa de forma reciclable. Comezamos usando estireno e o ácido fenil borónico (4 equivalentes) como substratos de partida e dimetilformamida (DMF) como disolvente baixo atmosfera de aire a 80 ºC dando lugar a excelentes resultados respecto o rendemento.

USC
UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Cambios ao disolvente, temperatura, número de equivalentes dos reactivos ou a cantidade de catalizador non resultaron en ningunha mellora no rendemento, polo que decidimos tomar as condicións iniciais como as condicións óptimas.

Coas condición óptimas na man, decidimos avaliar a xeneralidade da reacción e as súas limitacións, o uso de estirenos con diferentes patróns de substitución deu lugar a bos rendementos, menos nos casos de estirenos con substituíntes moi voluminosos na posición *orto* e con substituíntes fortemente dadores de carga, as olefinas con diferentes substitucións deron bos resultados en xeral, excepto no caso de aneis heteroaromáticos ou con substituíntes alifáticos no caso de que houbera hidróxenos na posición β da cadea.

Respecto aos ácidos borónicos os substituíntes arilo foron ben tolerados, aínda que con rendementos baixos para os substituíntes fortemente dadores de carga e non foron reactivos nin substituíntes heteroaromáticos nin aneis aromáticos con substitución na posición *orto*.

Unha vez avaliada a xeneralidade da reacción realizamos uns experimentos mecanísticos: o primeiro foi realizar a reacción baixo atmosfera de argon para elucidar se o ferro estaba tendo algún rol na reoxidación do paladio e o segundo unha comparativa cos compoñentes do MOF para ver se o efecto do confinamento dentro da rede do MOF estaba tendo algún efecto positivo sobre o rendemento da reacción. En ambos casos se confirma esa hipótese baseándonos nos datos obtidos.

Para avaliar a estabilidade, procedemos a comprobar a natureza heteroxénea do catalizador. Para iso realizamos un experimento de filtrado, no cal tras retirar o MOF do medio de reacción se comprobou que a reacción se paraba. Implicando isto que a catálise esta ocorrendo no MOF e non por unha posible paso de paladio do MOF a disolución homoxénea.

Unha vez descartado isto, pasamos a comprobar a reciclabilidade do catalizador nas condicións de reacción. Desafortunadamente a pesar de que o segundo ciclo funcionou como esperado a partir do terceiro ciclo obsérvase unha baixada dramática do rendemento. O sólido recuperado do primeiro ciclo foi analizado por EDX, observándose que neste caso as relacións entre os compoñentes do MOF non se manteñen, cunha perdida neta dun átomo de cloro da estrutura e certa perdida de paladio. Con estes datos permitíusenos propoñer un mecanismo que e similar ao xa explicado anteriormente, no cal o ferro estaría nun ciclo catalítico adxunto reoxidando o paladio e oxidándose na presenza do osíxeno atmosférico.

Finalmente tentamos unha serie de aditivos para solucionar o problema da reciclabilidade, sen embargo todos os resultados resultaron nulos.

4. INTRODUCTION

4.1 HETEROGENEOUS CATALYSIS IN MOFS

Catalysis is a powerful tool for the synthesis of a wide variety of compounds. A catalyst allows to increase the rate in which a chemical reaction reaches the equilibrium without being consumed in the process. The compounds that can be synthetized include, from simple compounds that are widely used in industry like ammonia or sulfuric acid, to the more complex natural or bioactive compounds that are used for medical and pharmacological applications. Nowadays chemicals obtained through catalytic methodologies constitute more than 95% of the total.[1]

While simple compounds are usually synthetized using heterogeneous catalysts in harsh temperature and pressure conditions, sometimes the complexity of the products that are obtained requires the use of homogeneous catalysts bearing different ligands that enable these transformations.

However, the use of homogeneous catalysts imposes a long-term limitation to these methodologies, since this type of catalysts are difficult to recover thus typically resulting in the loss of the catalyst. Some common metal catalysts are based on precious metals like gold,[2] palladium,[3] iridium,[4] among others.[5] These metals are not only expensive and with low abundances in nature, but some of them are toxic as well.[6]

On the other hand, common heterogeneous catalysts usually lack the specificity needed for performing more difficult transformations. During the last decades, important advances have been achieved in this field, allowing the use of different materials like zeolites,[7] mesoporous

---

[1] Hagen, J. Economic Importance of Catalysts. In Industrial Catalysis; Wiley, 2015; pp 459-462.

[2] a) Kashmi, A. S. K. *Chem. Rev.* **2007**, *107*, 3180-3211. b) Witzel, S.; Kashmi, A. S. K.; Xie, J. *Chem. Rev.* **2021**, *121*, 8868-8925. c) Hendrich, C. M.; Sekine, K.; Koshikawa, T.; Tanaka, K.; Kashmi, A. S. K. *Chem. Rev.* **2021**, *121*, 9113-9163.

[3] a) Yin, L.; Liebscher, J. *Chem. Rev.* **2007**, 107, 133-173. b) Biffis, A.; Centorno, P.; Del Zotto, A.; Zecca, M. *Chem. Rev.* **2018**, *118*, 2249-2295. c) Sarkar, S.; Cheung, K. P. S.; Gevorgyan, V. *Angew. Chem. Int. Ed.* **2024**, *63*, e202311972.

[4] a) Takeuchi, R.; Kezuka, S. *Synthesis* **2006**, *20*, 3349-3366. b) Cheng, Q.; Tu, H.-F.; Zheng, C.; Qu,J.-P.; Helmchen, G.; You, S.-L. *Chem. Rev.* **2019**, *119*, 1855-1969. c) Chauhan, D.; Prasad P.; Sasmal, P. K. *Coord. Chem. Rev.* **2024**, *520*, 216139.

[5] a) Fang, G.; Bi, X. *Chem. Soc. Rev.* **2015**, *44*, 8124-8173. b) Labinger, J. A. *Chem. Rev.* **2017**, *117*, 8483-8496. c) Gunanathan, C.; Milstein, D. *Chem. Rev*. **2014**, *114*, 12024-12087.

[6] Egorova, K. S.; Ananikov, V. *Organometallics* **2017**, *36*, 4071−4090.

[7] a) Shamzhy, M.; Opanasenko, M.; Concepción, P.; Martínez, A. *Chem. Soc. Rev.* **2019**, *48*, 1095-1149. b) Li, Y.; Yu, J. *Nature Reviews Materials* **2021**, *6*, 1156-1174. c) Zhang, Q.; Gao, S.; Yu, J. *Chem. Rev.* **2023**, *123*, 6039-6106.

silica[8] and different porous materials like metal organic frameworks (MOFs) as catalysts for different reactions.

MOFs are crystalline porous networks that are characterized by their hybrid inorganic and organic nature. They are formed through the coordination of organic linkers to inorganic clusters denominated secondary building units (SBUs) or nodes forming one-, two- or three-dimensional structures.

Due to the easy tunability of their structure through organic synthesis methods and the capacity of predicting their properties and controlling their functions through molecular design, MOFs have emerged as promising catalysts. Other properties such as the large pore size that allows substrate diffusion within the MOF or their crystallinity which facilitates the analysis of the distribution of the catalytic sites in the structure through crystallographic techniques are highly desirable for heterogeneous catalysts and would enable the synthesis of specific catalyst that can be reutilized.

MOFs have become increasingly important in the functional materials field during the last three decades. During those years, the catalytic applications of MOFs were steadily enhanced as the methods for controlling the size and environment of the pores improved. This allowed to introduce more complex catalysts in a controlled manner within the network of the MOF. Also, a better understanding of the structure was achieved thanks to the advances on *in situ* characterization methods.[9]

However, despite its incredible potential as heterogeneous catalysts, the fact the catalytic applications were usually searched off afterwards the design and synthesis of the MOFs limited their applicability. Nevertheless, important examples have been described, some of them even enabling reactions that were not possible to perform with homogeneous catalysts.

Some of these reactions were possible due to the intrinsic features of the MOF structure. The first one relays on the protective effect around the active center thanks to the confinement within the framework, protecting it from other reactive species, avoiding aggregation or self-association, and allowing improved lifetimes and turnovers. It is also remarkable that having an encapsulated catalyst not only protects the catalytic center, but it can also help to obtain better or alternative selectivity in ways that are difficult to achieve in a homogeneous regime.[10]

MOFs are not only interesting due to the possibility of the stabilization of fragile catalysts. Their incredible tunability facilitates control of the microenvironment of the catalyst, allowing to introduce different functionalities within the framework, thus opening the door to achieve unprecedented applications in catalytic transformations.

Moreover, it is possible to add more than two functionalities within the MOFs, they are known as multivariate MOFs (MTV-MOFs). This term was coined by the group of Yaghi that

---

[8] Yu. X.; Williams, C. T. *Catal. Sci. Technol*. **2022**, *12*, 5765-5794.

[9] *Chem. Soc. Rev*. **2010**, *39*, 4541-5072.

[10] a) Zhang, W.; Zheng, B.; Shi, W.; Chen, X.; Xu, Z.; Li, S.; Chi, Y. R.; Yang, Y.; Lu, J.; Huang, W.; Huo, F. *Adv. Mater.* **2018**, *30*, 1800643. b) Genna, D. T.; Pfund, L. Y.; Samblanet, D. C.; Wong-Foy, A. G.; Matzger, A. J.; Sanford, M. S. *ACS Catal*. **2016**, *6*, 3569-3574. c) Bauer, G.; Ongari, D.; Xi, X.; Tiana, D.; Smit, B.; Ranocchiari, M. *J. Am. Chem. Soc.* **2017**, *139*, 18166-18169. d) Liu, L.; Zhou, T. Y.; Telfer, S. G. *J. Am. Chem. Soc*. **2017**, *139*, 13936-13943.

in 2010[11] reported the first synthesis of MTV-MOFs based on the MOF-5[12] structure using up to eight different ligands within the MOF structure. When the uptake capacity of these variants was compared, a significant difference was observed between the different synthetized MTV-MOFs implying that the environment of the pore was being modified and there were more favorable interactions with the lattice depending on the functionalities of the ligand. This can be used also by adding different nodes, or post-synthetically adding to ligands bearing coordinating groups or within the pores as nanoparticles.

All these characteristics and possibilities position MOFs as very powerful platforms for heterogeneous catalysis. Moreover, the catalytic center can be distributed in several different locations through all the crystalline network of the MOF.

First, the nodes as they are formed by metal clusters, can usually act as catalysts by themselves (represented in blue in the figure 2). Second, the ligands in a similar fashion can act as catalysts also, both as organocatalysts or regular metal catalysts if they are metalloligands (represented in Figure 2 as a red sphere). Finally, the MOFs can be post-synthetically modified to introduce metal centers (represented as grey spheres in Figure 2) through coordinating groups that are (represented as green spheres in the Figure 2) present in their structures, both in the nodes or in the ligands or by introducing metal nanoparticles which can grow within the pores of the MOF (Represented as a group of grey spheres in the center of the structure in Figure 2).

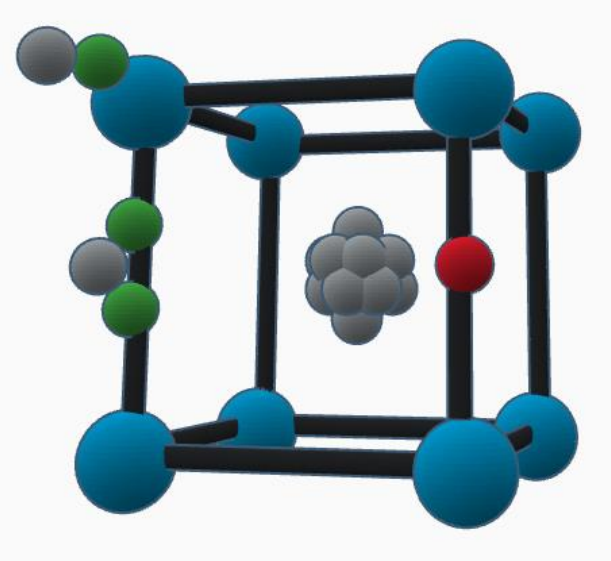


Figure 2. Schematic representation of a MOF, nodes represented as blue spheres, ligands as black lines, coordinating groups represented as green spheres and external metal centers as grey spheres.

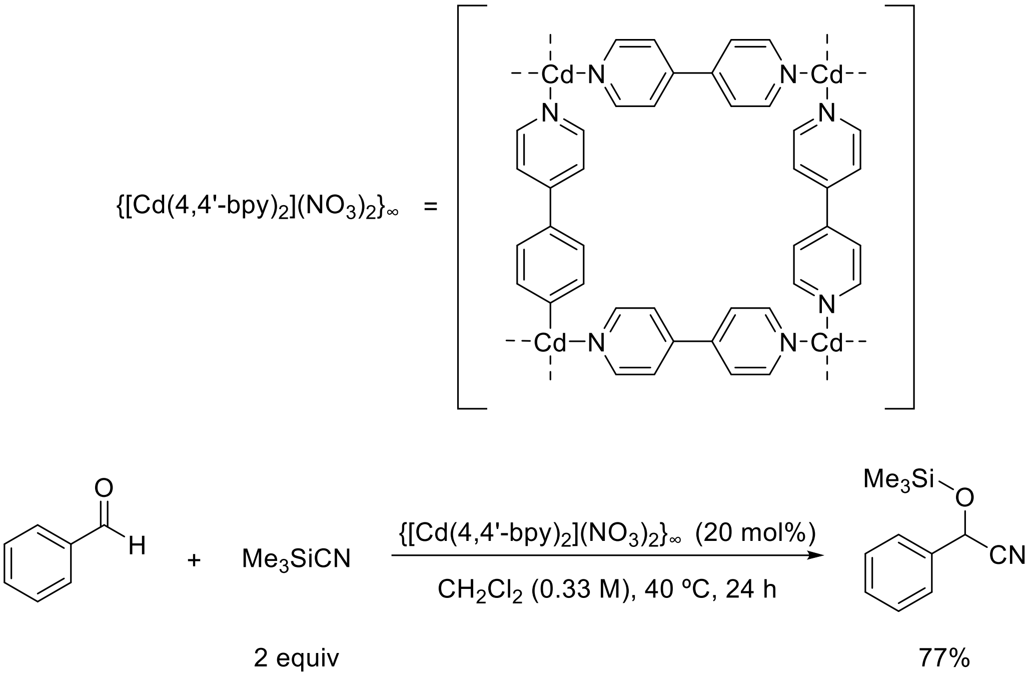
USC

[11] Deng, H.; Doonan, C. J.; Furukawa, H.; Ferreira, R. B.; Towne, J.; Knobler, C. B.; Wang, B.; Yaghi, O. M. *Science* **2010**, *327*, 846-850.

[12] Li, H.; Eddaoudi, M.; O'Keeffe, M.; Yaghi, O. M. *Nature* **1999,** *402*, 276-279.

4.1.1 Catalysis on MOFs nodes

The catalytic potential of MOFs was discovered early on in 1994 by Fujita and co-workers.[13] They discovered a Cd-4,4'-bipyridil two-dimensional MOF that showed off catalytic activity in the cyanosilylation of aldehydes demonstrating the accessibility of the active sites within the framework. However, when different aromatic aldehydes were used the yields dropped significantly due to shape specificities of the cavity (Scheme 6).



Scheme 6. Cyanosilylation of aldehydes catalyzed by a 2D Cd-MOF (counter anions are omitted in the structure for clarity).

After the first example reported by the group of Fujita the possibilities of the MOFs as catalysts were highlighted, open a new field of research. The catalytic potential of the MOFs usually relays in their metal nodes.

However, even though the nodes have the potential to act as catalysts in different reactions, these sites require to be geometrically undercoordinated to be accessible and available in order to be active in catalytic processes. Those sites are often referred to as open metal sites (OMSs).

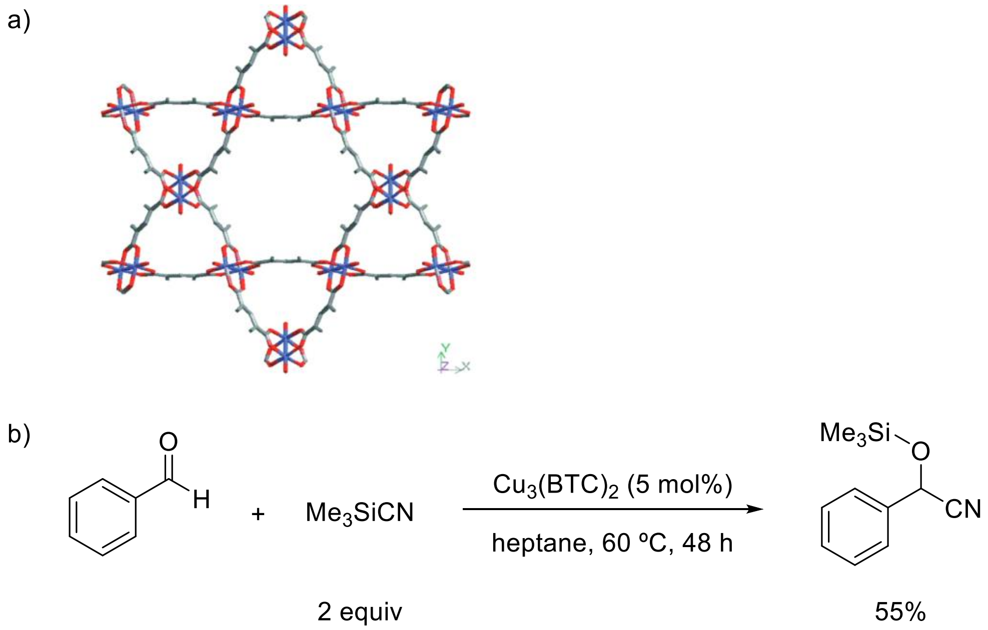
After 1999, there was already many examples of MOFs featuring open metal sites.[14] For instance, HKUST-1 formed by copper clusters and trimesic acid as ligands was synthetized by

---

[13] Fujita, M.; Kwon, Y. J.; Washizu, S.; Ogura, K. *J. Am. Chem. Soc.* **1994**, *116*, 1151-1152.

[14] Chen, B.; Eddaoudi, M.; Reineke, T. M.; Kampf, J. W.; O'Keeffe, M.; Yaghi, O. M.; *J. Am. Chem. Soc.* **2000**, *122,* 11559-11560.

the group of Williams[15] and later applied as a catalyst in a cyanosilylation of benzaldehyde by Kaskel[16] and coworkers in 2004. The open Lewis acid sites were obtained by removal of the water molecules bound to the copper centers, which can activate the benzaldehyde. However, even under the optimal conditions, the yields were moderate and when higher temperatures or other solvents were employed the MOF decomposed (Scheme 7).



Scheme 7. a) Structure of HKUST-1 from Chui, S. S.-Y.; Lo, S. M.-F.; Charmant, J. P. H.; Orpen, A. G.; Williams, I. D. *Science* 1999, *283*, 1148-1150. Reprinted with permission from AAAS. Cu in blue, C in grey and O in red. b) Cyanosilylation of aldehydes catalyzed by HKUST-1.

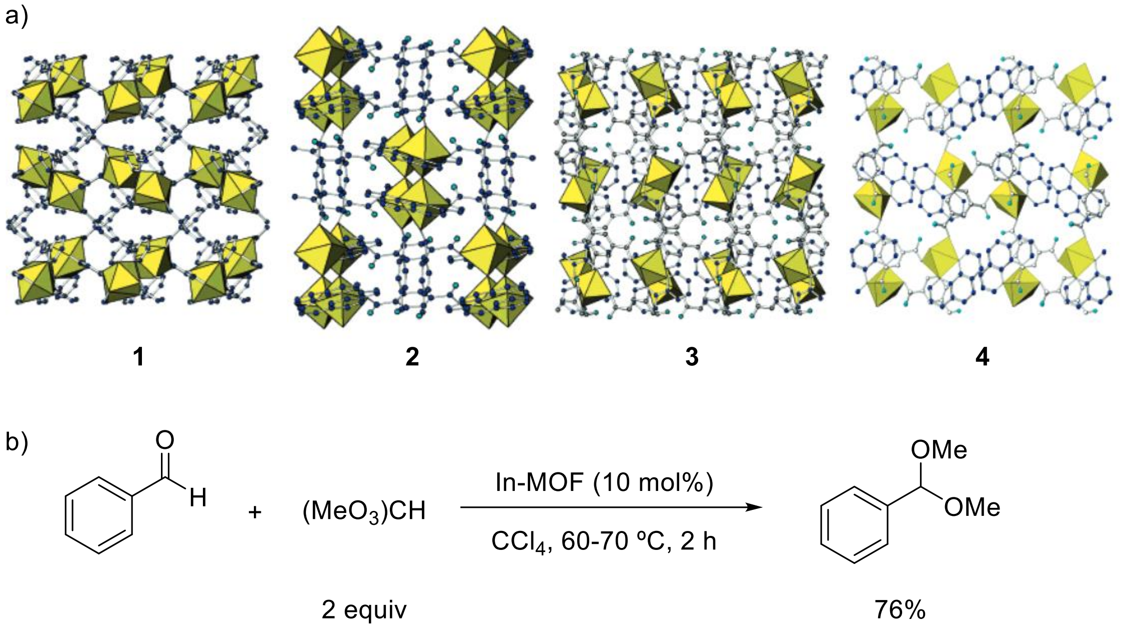
Closely after, the group of Snejko[17] reported the synthesis of a series of indium 2D and 3D MOFs. Among them one presented a saturated indium center. When these MOFs were tested as catalysts in the acetalization of benzaldehyde, the activity of the saturated indium MOF was an order of magnitude lower than the other ones leading to extremely low yields at same reaction times. This highlights the necessity of OMSs when looking toward metal catalysis on the nodes of a MOF (Scheme 8).

---

[15] Chui, S. S.-Y.; Lo, S. M.-F.; Charmant, J. P. H.; Orpen, A. G.; Williams, I. D. *Science* **1999**, *283*, 1148-1150.

[16] Schlichte, K.; Kratzke, T.; Kaskel, S. *Microporous Mesoporous Mater.* **2004**, *73*, 81-88.

[17] Gómez-Lor, B.; Gutiérrez-Puebla, E.; Iglesias, M.; Monge, M. A.; Ruiz-Valero, C.; Snejko, N. *Chem. Mater.* **2005**, *17*, 2568-2573.



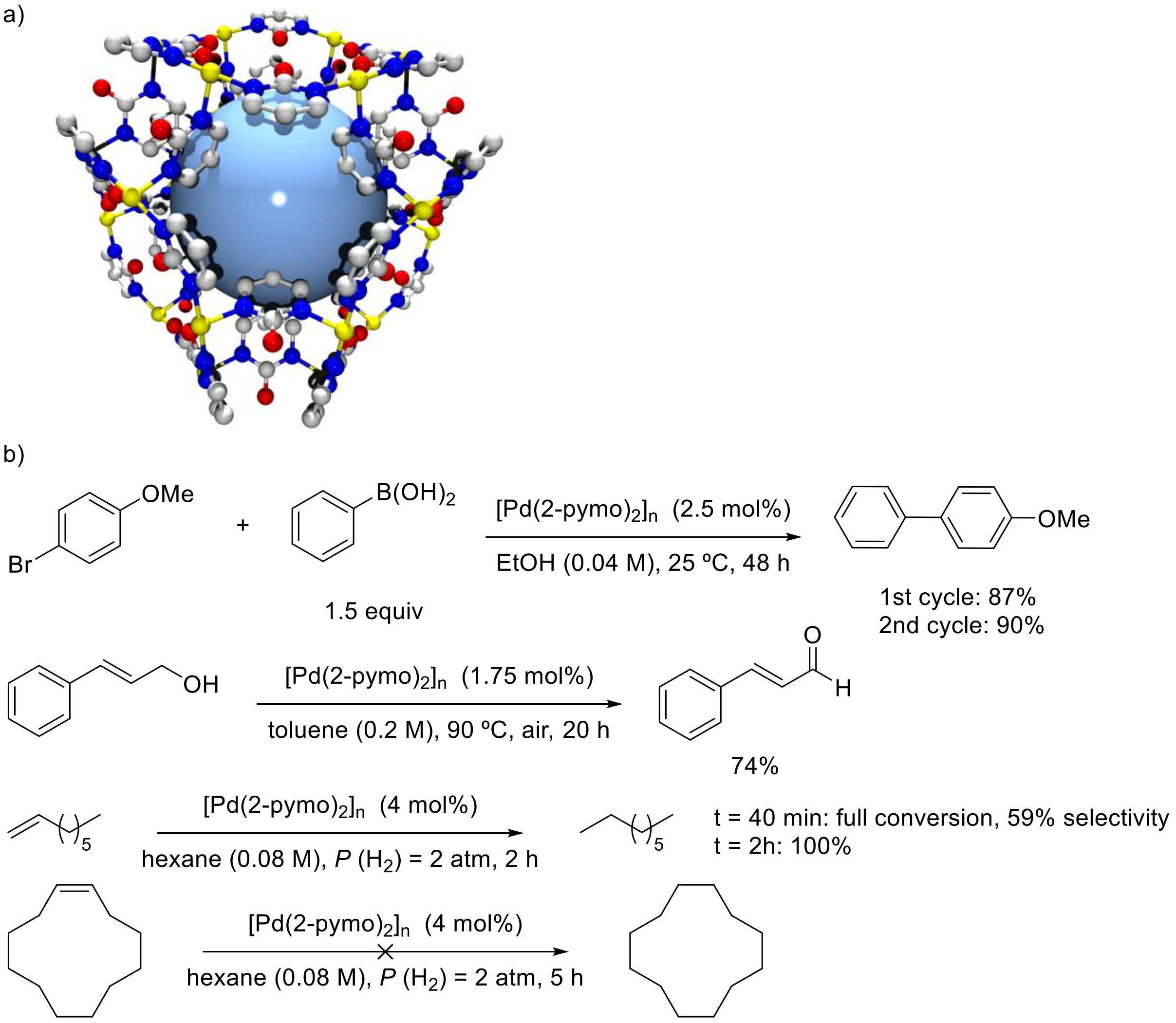
Scheme 8. a) Structure of indium MOFs: 1 (In(BDC)$_{1.5}$(bipy)), 2 (In$_2$(BDC)$_2$(OH)$_2$(phen)$_2$), 3 (In(BTC)(H$_2$O)(bipy)), 4 (In(BTC)(H$_2$O)(phen)), indium clusters represented by yellow polyhedral, (Reprinted with permission of Gómez-Lor, B.; Gutiérrez-Puebla, E.; Iglesias, M.; Monge, M. A.; Ruiz-Valero, C.; Snejko, N. *Chem. Mater.* 2005, *17*, 2568-2573). b) Acetalization of aldehydes catalyzed by In-MOFs.

The group of José B. Parra described the synthesis of a MOF containing palladium in its nodes and 2-hydroxypyrimidine as ligand.[18] It was later found by the group of Hermenegildo Garcia that this MOF [Pd(2-pymo)$_2$]$_n$ can be used as catalyst in several typical palladium-catalyzed reactions like Suzuki-Miyaura cross-coupling, oxidation of alcohols and hydrogenation with good yields and selectivities.[19] Interestingly, it was found that this MOF displays shape selectivity in the hydrogenation of different olefins. complete reduction of 1-octene to octane was observed in two hours while no reaction was observed for cyclododecene due to the bigger substrate inability to diffuse in the pores of the MOF. The MOF could be reused at least once for the Suzuki-Miyaura cross coupling reaction after filtration and washing of the catalyst, leading to same yields as in the first run (Scheme 9).

---

[18] Navarro, J.A.R.; Barea, E.; Salas, J.M.; Masciocchi, N.; Galli, S.; Sironi, A.; Ania, C.O.; Parra, J.B. *Inorg. Chem.* **2006**, *45*, 2397-2399.

[19] Llabrés i Xamena, F. X.; Abad, A.; Corma, A.; Garcia, H. *J. Catal*. **2007**, *250*, 294-298.



Scheme 9. a) Structure of [Pd(2-pymo)$_2$]$_n$ (Reprinted with permission of Navarro, J.A.R.; Barea, E.; Salas, J.M.; Masciocchi, N.; Galli, S.; Sironi, A.; Ania, C.O.; Parra, J.B. *Inorg. Chem.* 2006, *45*, 2397-2399). Pd in yellow, O in red, N in blue and C in grey. b) Typical palladium catalyzed reactions using [Pd(2-pymo)$_2$]$_n$ as catalyst.

More recently, in 2018, the group of Wang reported the use of the well-known MIL-100(Fe)[20] as catalyst for the decomposition of ozone as an air pollutant.[21] This MOF could work under high humidity conditions, which are the conditions commonly fpund where ozone is

---

[20] Canioni, R.; Roch-Marchal, C.; Sécheresse, F.; Horcajada, P.; Serre, C.; Hardi-Dan, M.; Férey, G.; Grenèche, J.-M.; Lefebvre, F.; Chang, J.-S.; Hwang, Y.-K.; Lebedev, O.; Turner, S.; Van Tendeloo, G. *J. Mater. Chem.* **2011**, *21*, 1226-1233.

[21] Wang, H.; Rassu, P.; Wang, X.; Li, H.; Wang, X.; Wang, X.; Feng, X.; Yin, A.; Li, P.; Jin, X.; Chen, S.L.; Ma, X.; Wang. B. *Angew. Chem. Int. Ed.* **2018**, *57*, 16416-16420.

found as pollutant. Also, the MOF could work without noticeable deactivation for more than 100 hours. All these characteristics in combination with the possibility of processing it into films that could be used for filters in a mask, makes MIL-100(Fe) in a highly desirable material not only as catalyst for the decontamination but also for protecting equipment necessary for operating in contaminated places.

4.1.2 Catalysis on MOFs ligands and metalloligands

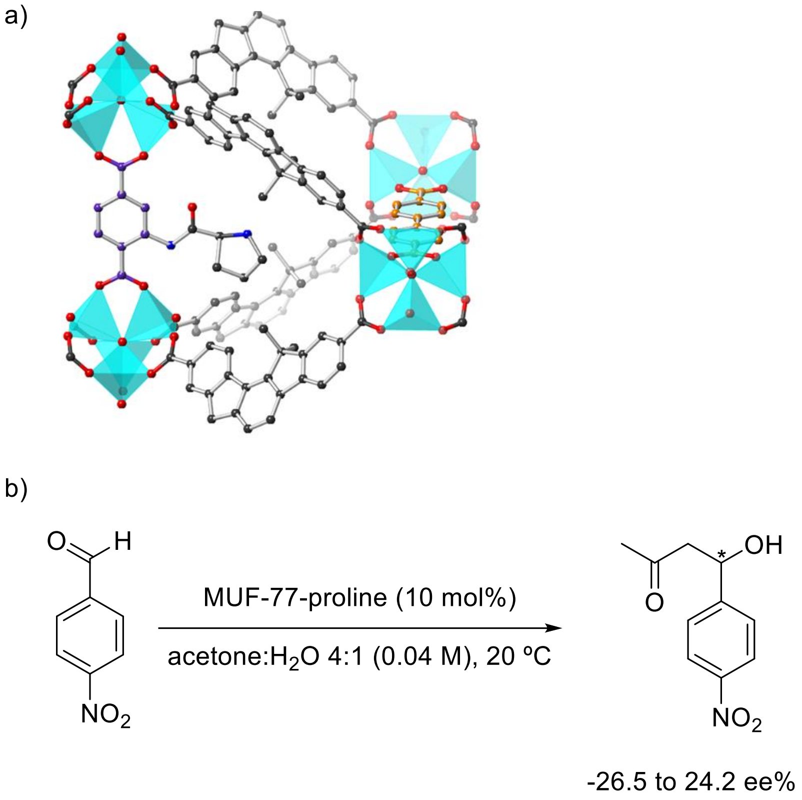
Even though heterogeneous catalysis with MOFs has been dominated by reactions in which the catalytic center is placed at a metal center with open metal sites present in the nodes, it is important to highlight that there are also examples in which the catalysis is performed by the MOF ligand. Depending on their nature they can act as organocatalysts or regular metal catalysts if they are metalloligands.

The group of Telfer synthetized a modified version of their MTV-MUF-77[22] containing a protected proline in one of their ligands and different ligands that acted as modulators.[23] After deprotection this bounded proline proved to be efficient to catalyze an aldol reaction, obtaining enantiomeric excesses and reaction rates similar to the free linkers. Interestingly, through modification of the environment of the pore with different modulators both enantiomers of the product could be obtained, even though the proline enantiomer remained the same. The catalyst could be reused for five subsequent reactions with similar results, also demonstrating the tolerance to the aqueous media in the reaction (Scheme 10).

---

[22] Liu, L.; Telfer, S. G. *J. Am. Chem. Soc.* **2015**, *137*, 3901-3909.

[23] Liu, L.; Zhou, T. Y.; Telfer, S. G *J. Am. Chem. Soc.* **2017**, *139*, 13936-13943.

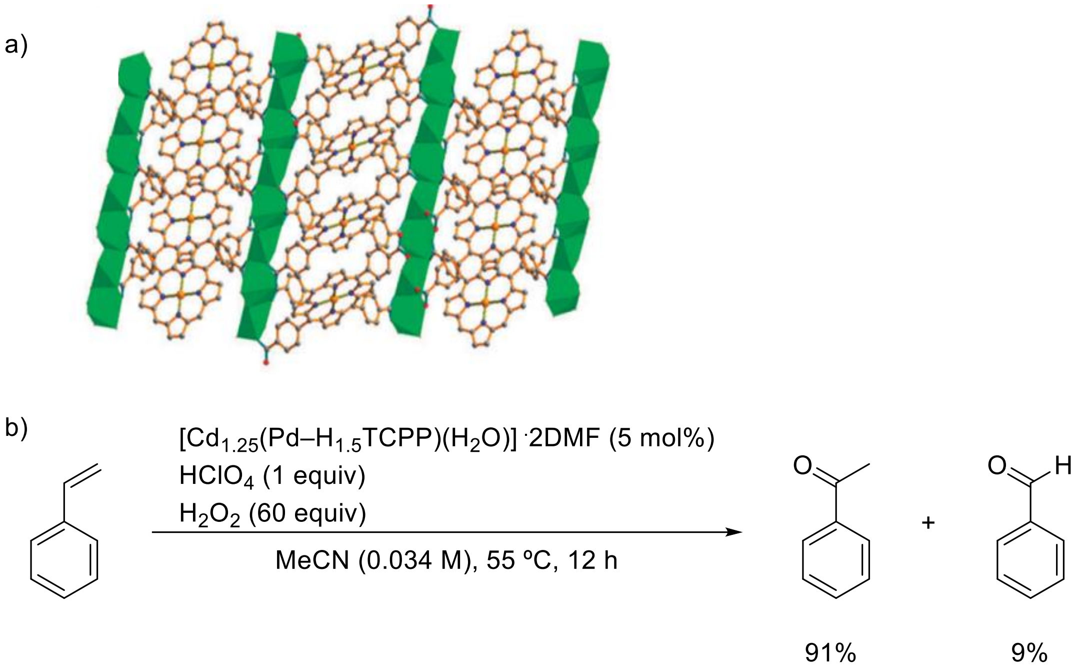


Scheme 10. a) Structure of one of the modified MUF-77 ([$Zn_4O(bdc\text{-}Pro)_{1/2}(bpdc)_{1/2}(hmtt)_{4/3}$]) (Reprinted with permission from Liu, L.; Zhou, T. Y.; Telfer, S. G *J. Am. Chem. Soc.* 2017, *139*, 13936-13943. Copyright 2017 American Chemical Society). Zr clusters in light blue, O in red, C in violet, black and orange, N in blue. b) Aldol reaction using different variants of the proline functionalized MUF-77.

Regarding MOFs with metalloligands active as catalysts, there are a few interesting examples. The oxidation of styrene to acetophenone was achieved by the group of Wu, by using a novel bimetallic MOF formed by Cd^{II} nodes and Pd^{II} porphyrin metalloligands.[24] This MOF showed to be active in the oxidation of styrene towards acetophenone with good selectivity and it could be recycled up to six times by simple filtration without any loss of activity or selectivity. They also confirmed the improvement of the reaction outcome compared with the homogeneous metalloligand in the same reaction conditions, which led to a diminished selectivity, probably due to the lack of the confinement effect that occurs within the framework of the MOF (Scheme 11).

USC
UNIVERSIDADE
DE SANTIAGO

[24] Xie, M.-H.; Yang, X.-L.; Wu, C.-D.; *Chem. Commun.* **2011**, *47*, 5521-5523.



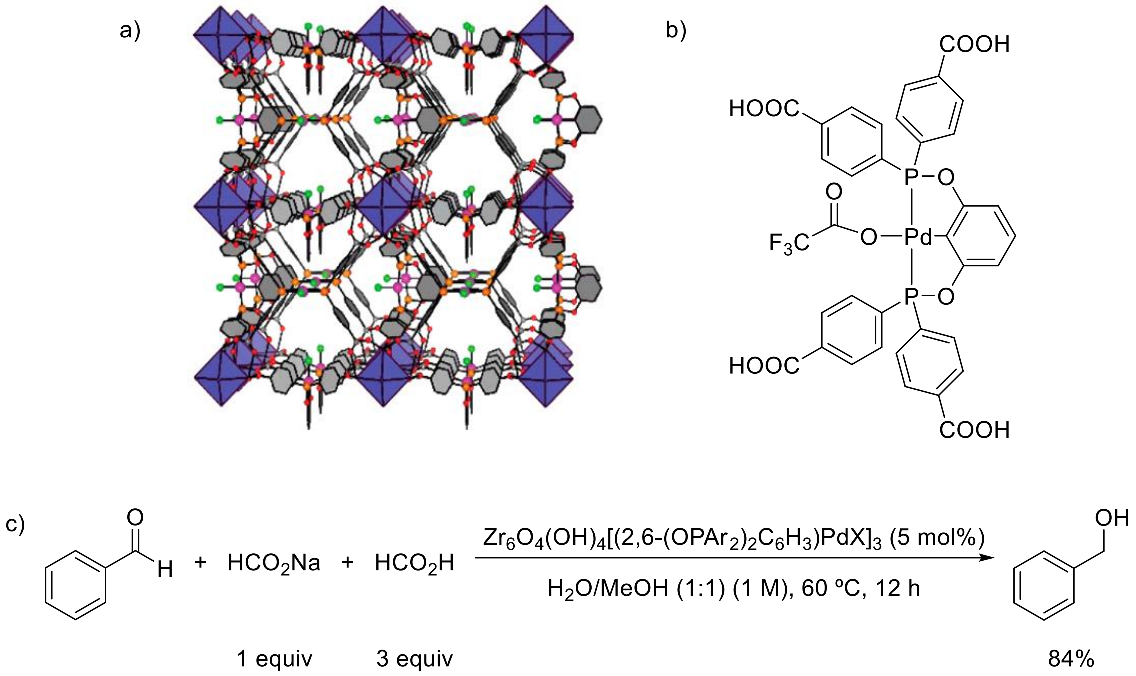
Scheme 11. a) Structure of the bimetallic Cd-Pd MOF (Reproduced from Xie, M.-H.; Yang, X.-L.; Wu, C.-D.; *Chem. Commun.* 2011, *47*, 5521-5523 with permission from the Royal Society of Chemistry). Cd clusters are green polyhedral, Pd in yellow, C in grey, O in red and N in blue. b) Styrene oxidation to acetophenone catalyzed by a bimetallic Cd-Pd MOF.

The group of Wade[25] described the use of a novel MOF bearing a diphosphinidite pincer palladium complex metalloligand active in the transfer hydrogenation of benzaldehydes. The use of the homogeneous diphosphinidite pincer palladium complex exhibited a deficient performance for this reaction. However, when a MOF with zirconium SBUs in which the linker acts as the ligand for the active metal center was used as catalyst for the reaction, excellent yields were observed. Even though substrates with sterically hindered substituents resulted in a dramatic drop of reactivity, it was demonstrated that the reaction was occurring with the framework and not only in the surface of the MOF. When a MOF bearing the same metallic cluster UiO-67[26] was used, no reaction occurred at all, demonstrating that the reaction was catalyzed by the pincer metalloligand and not by the zirconium cluster. Finally, recyclability experiments showed that MOF could be reused twice with satisfactory results albeit reactivity drop significantly in the third cycle, probably due to a partial decomposition of the pincer ligand within the MOF (Scheme 12).

---

[25] Burgess, S. A.; Kassie, A.; Baranowski, S. A.; Fritzsching, K. J.; Schmidt-Rohr, K.; Brown, C. M.; Wade, C. R. *J. Am. Chem. Soc.* **2016**, *138*, 1780-1783.

[26] Cavka, J. H.; Jakobsen, S.; Olsbye, U.; Guillou, N.; Lamberti,C.; Bordiga, S.; Lillerud, K. P. *J. Am. Chem. Soc.* **2008**, *130*, 13850-13851.

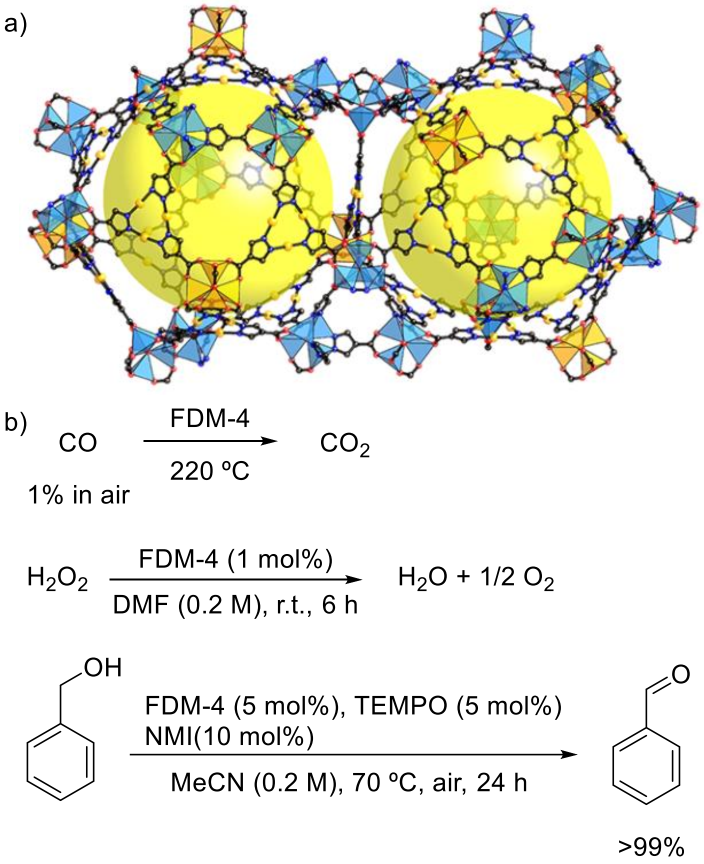


Scheme 12. a) Framework structure of the MOF, blue octahedra represents the $[Zr_6O_4(OH)_4]^{12+}$ SBUs, P in orange, Pd in pink, O in red, I in green. (Reprinted with permission of Burgess, S. A.; Kassie, A.; Baranowski, S. A.; Fritzsching, K. J.; Schmidt-Rohr, K.; Brown, C. M.; Wade, C. R. *J. Am. Chem. Soc.* 2016, *138*, 1780-1783. Copyright 2016 American Chemical Society). b) Metalloligand present in the structure of the MOF (H_4LPd). c) Hydrogenation of aldehydes catalyzed by a Zr-Pd-MOF.

The group of Li synthetized a variety of MOFs based on a triangular trinuclear Cu^{I} pyrazolate formed from 4-pyrazolecarboxylicacid as metalloligand and different combinations of Zn-based SBUs to form five different MTV-MOFs.[27] They envisioned that since the geometry of the reduced and oxidized metalloligand was the same, they would be able to perform redox catalysis without compromising the stability of the framework. The metalloligands proved to be active in different copper catalyzed redox reactions, such as CO oxidation to CO_2, and decomposition of H_2O_2 and the oxidation of benzyl alcohol to benzaldehyde. CO oxidation was successfully achieved on flow regime in a fixed-bed reactor with the MOFs supported on them without noticeable decomposition of the MOF. The decomposition of the hydrogen peroxide was performed five consecutive times in a row, however, even though the crystals retained its shape, the high crystallinity of the MOFs was lost. Finally, these MOFs also catalyzed the oxidation of benzyl alcohol to benzaldehyde. As for the hydrogen peroxide decomposition, the crystallinity was lost after benzyl alcohol oxidation (Scheme 13).

---

[27] Tu, B.; Pang, Q.; Xu, H.; Li, X.; Wang, Y.; Ma, Z.; Weng, L.; Li, Q. *J. Am. Chem. Soc.* **2017**, *139*, 7998-8007.



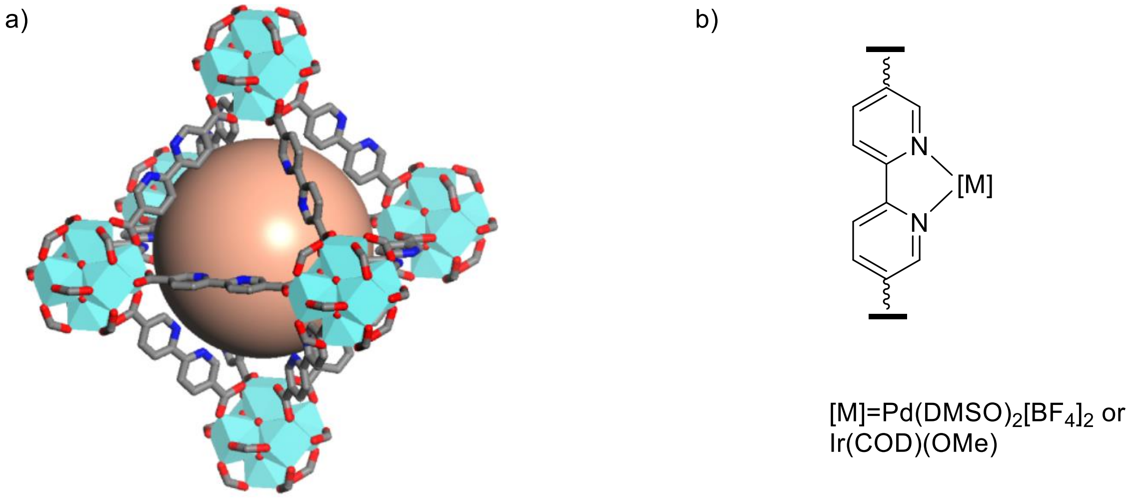
Scheme 13. a) Structure of the bimetallic Zn-Cu FDM-4, Zn (Reprinted with permission of Tu, B.; Pang, Q.; Xu, H.; Li, X.; Wang, Y.; Ma, Z.; Weng, L.; Li, Q. *J. Am. Chem. Soc.* 2017, *139*, 7998-8007. Copyright 2017 American Chemical Society). Cu in yellow, C in black, N in blue, O in red and Zn clusters as blue and yellow polyhedral. b) Different oxidation reactions catalyzed by a bimetallic Zn-Cu MOF.

4.1.3 Catalysis on MOFs postfunctionalized ligands and nodes

As explained before, another way to obtain suitable MOFs for catalysis consists in the post-synthetic modification of MOFs with metal catalysts that get coordinated within the framework.

A common strategy is the use of an organic ligand with coordinating atoms in their structure. They usually incorporate moieties coming from common homogeneous ligands, like phosphines,[28] bipyridines[29] and NHCs[30] among others.[11,31]

The work of the group of Lin[32] exemplifies the use of a MOF with a UiO type structure bearing 2,2'-bipyridil moiety (bpy-UiO) in catalysis. After the synthesis of the MOF, this was metalated separately with both iridium and palladium salts. The metalated MOFs were found to be highly active in different catalytic reactions and showed higher activity than their homogeneous counterparts. The bpy-UiO-Ir was employed in the C-H borylation of arenes with excellent results. The MOF was recyclable up to twenty times; however, the rates of reaction were slower after the ninth cycle. The bpy-UiO-Ir MOF was also successful as a catalyst in the *ortho*-silylation reaction of benzylsilyl ethers to benzoxasiloles without the need of a proton acceptor. And bpy-UiO-Pd led to excellent results in the dehydrogenation of cyclohexenones to phenols. However, when reused after 3 reaction cycles there was a slight decrease in activity (Scheme 14).



---

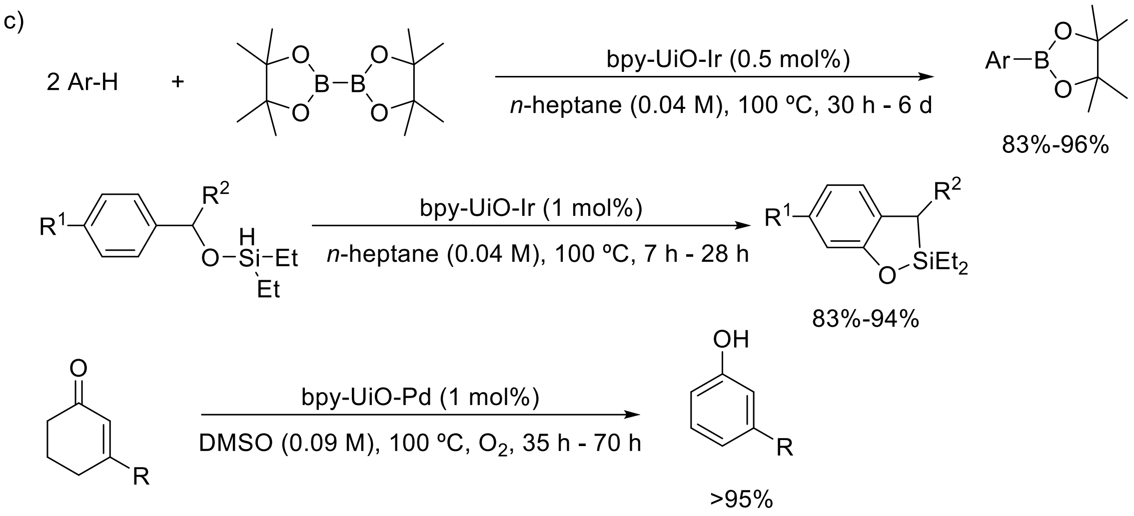
[28] Sawano, T.; Lin, Z.; Boures, D.; An, B.; Wang, C.; Lin, W. *J. Am. Chem. Soc.* **2016**, *138*, 9783-9786.

[29] a) Boller, T. M.; Murphy, J. M.; Hapke, M.; Ishiyama, T.; Miyaura, N.; Hartwig, J. F. *J. Am. Chem. Soc.* **2005**, *127*, 14263-14278. b) Manna, K.; Zhang, T.; Lin, W. *J. Am. Chem. Soc.* **2014**, *136*, 6566-6569. c) Manna, K.; Zhang, T.; Greene, F. X.; Lin, W. *J. Am. Chem. Soc.* **2015**, *137*, 2665-2673.

[30] a) Kong, G.-Q.; Xu, X.; Zou, C.; Wu, C.-D. *Chem. Commun.* **2011**, 47, 11005-11007. b) Kong, G.-Q.; Ou, S.; Zou, C.; Wu, C.-D. *J. Am. Chem. Soc.* **2012**, *134*, 19851-19857.

[31] a) Thacker, N. C.; Lin, Z.; Zhang, T.; Gilhula, J. C.; Abney, C. W.; Lin. *J. Am. Chem. Soc.* **2016**, *138*, 3501-3509. b) Manna, K.; Zhang, T.; Carboni, M.; Abney, C. W.; Lin, W. *J. Am. Chem. Soc.* **2014**, *136*, 13182-13185.

[32] Manna, K.; Zhang, T.; Lin, W. *J. Am. Chem. Soc.* **2014**, *136*, 6566-6569.



Scheme 14. a) Structure of the bpy-UiO (Reprinted with permission of Manna, K.; Zhang, T.; Lin, W. *J. Am. Chem. Soc.* 2014, *136*, 6566-6569. Copyright 2014 American Chemical Society). O in red, C in grey, N in blue and Zr SBUs in light blue. b) Metalated ligands within the structure of the MOF. c) Different reactions catalyzed by a metalated bpy-UiO.

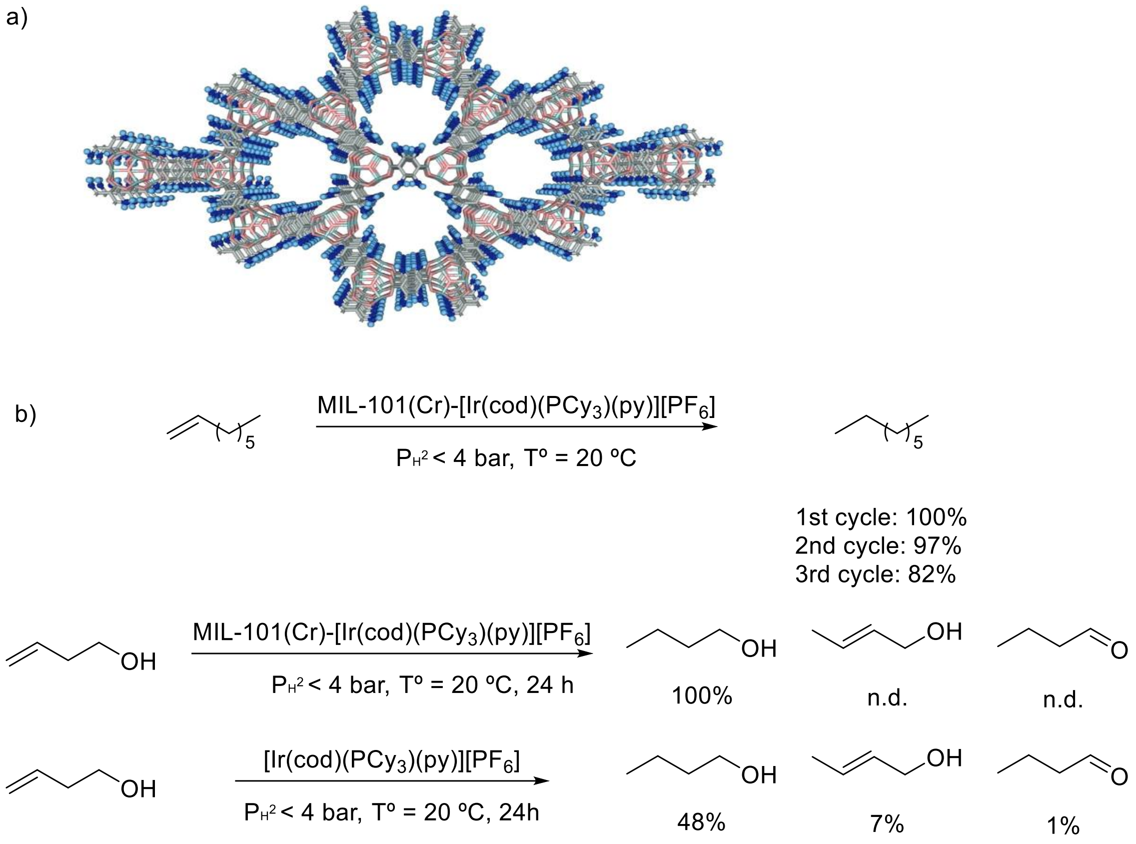
An elegant example of a selectivity improvement was the one reported by Weller, Rosseinsky and co-workers.[33] They immobilized the well-known Crabtree's cationic iridium hydrogenation catalyst[34] $[Ir(cod)(PCy_3)(py)][PF_6]$, inside of a sulfonated variant of the chromium terephthalate MIL-101.[35] Besides having similar TON and TOF than the homogeneous counterpart when applied to non-functionalized alkenes, the MOF catalyst could be recycled up to three times with just a slight activity loss in the last cycle. It also had six times higher activity when applied to a gas/solid reaction. And when used for the hydrogenation of olefinic alcohols a great enhancement of both selectivity and reactivity, especially with allylic and homoallylic alcohols that are prone to undergo olefin isomerization under homogeneous catalysis obtaining instead the different regioisomers of the olefin or the aldehyde (Scheme 15).

---

[33] Grigoropoulos, A.; McKay, A. I.; Katsoulidis, A. P.; Davies, R. P.; Haynes, A.; Brammer, L.; Xiao, J.; Weller, A. S.; Rosseinsky, M. J. *Angew. Chem. Int. Ed.* **2018**, *57*, 4532-4537.

[34] Crabtree, R. *Acc. Chem. Res.* **1979**, *12*, 331-337.

[35] Akiyama, G.; Matsuda, R.; Sato, H.; Takata, M.; Kitagawa, S. *Adv. Mater.* **2011**, *23*, 3294-3297.



Scheme 15. a) Structure of the sulfonated variant of MIL-101(Cr) (Reproduced from Akiyama, G.; Matsuda, R.; Sato, H.; Takata, M.; Kitagawa, S. *Adv. Mater.* 2011, *23*, 3294-3297 with permission from John Wiley and Sons). Cr in green, O in red, SO_3^- in dark (S) and light blue (O), C in grey. b) Selected examples of the hydrogenation by an encapsulated iridium complex within a MOF.

As explained before, MOFs can lead to better results compared to their homogeneous counterparts. Ligands can be incorporated within the structure of the MOF to obtain improved reactivities or selectivities due to the confinement effect and the microenvironment of the pore.

It is well known that iridium complexes bearing phenanthroline ligands are active in the borylation reaction of methane.[36] However, it lacks the control to discriminate totally between the methane, the already borylated product and the solvent, leading to mixtures of mono- and diborylated products together with the borylation of the solvent.

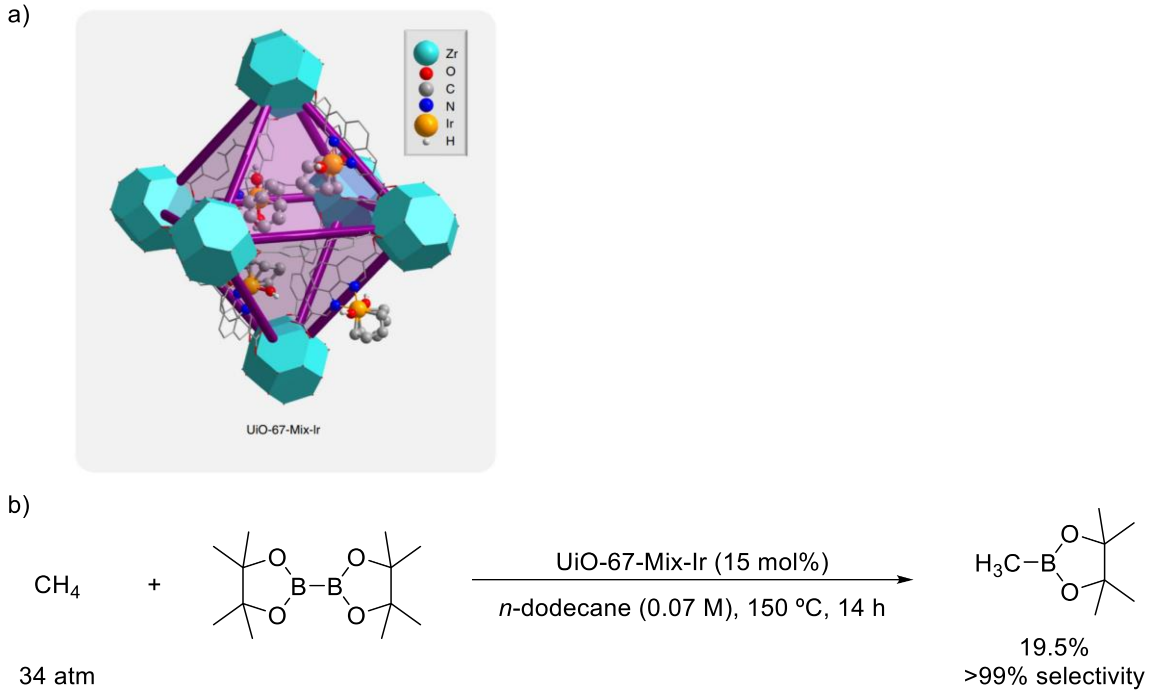
The group of Farha[37] overcame this issue by incorporating the phenanthroline moiety within the MOF UiO-67, to coordinate $[Ir(COD)(\mu\text{-}Cl)]_2$. Under optimal conditions, the

---

[36] a) Cook, A. K.; Schimler, S. D.; Matzger, A. J; Sanford, M. S. *Science* **2016**, *351*, 1421-1424. b) Smith, K. T.; Berritt, S.; González-Moreiras, M.; Ahn, S.; Smith, M. R.; Baik, M.-H.; Mindiola, D. J. *Science* **2016**, *351*, 1424-1427.

[37] Zhang, X., Huang, Z., Ferrandon, M.; Yang, D.; Robison, L.; Li, P.; Wang, T. C.; Delferro, M.; Farha, O. M. *Nat Catal* **2018**, *1*, 356-362.

resulting MOF was able to provide exclusively the monoborylated product. The reason behind the selective borylation could be due to the intrinsic confinement effect that occurs in the pores of the MOF(Scheme 16).



Scheme 16. a) Structure of the UiO-67-Mix-Ir (Reproduced from Zhang, X., Huang, Z., Ferrandon, M.; Yang, D.; Robison, L.; Li, P.; Wang, T. C.; Delferro, M.; Farha, O. M. *Nat Catal* 2018, *1*, 356-362 with permission from Springer Nature). b) Methane borylation catalyzed by UiO-67-Mix-Ir.

Even though is a less common strategy, the metallic clusters can also be post-synthetically modified if they are bearing free coordinating groups available to coordinate other metallic centers.[38] For example, MOFs bearing Zr nodes are well known for having abundant and structurally well-defined free -OH and -OH_2 that can act as coordinating groups for other metals.[39] The group of Farha reported the atomic metalation on the NU-1000 MOF[40] through atomic layer deposition of Ni in its nodes. After activation, it showed great activity towards the

---

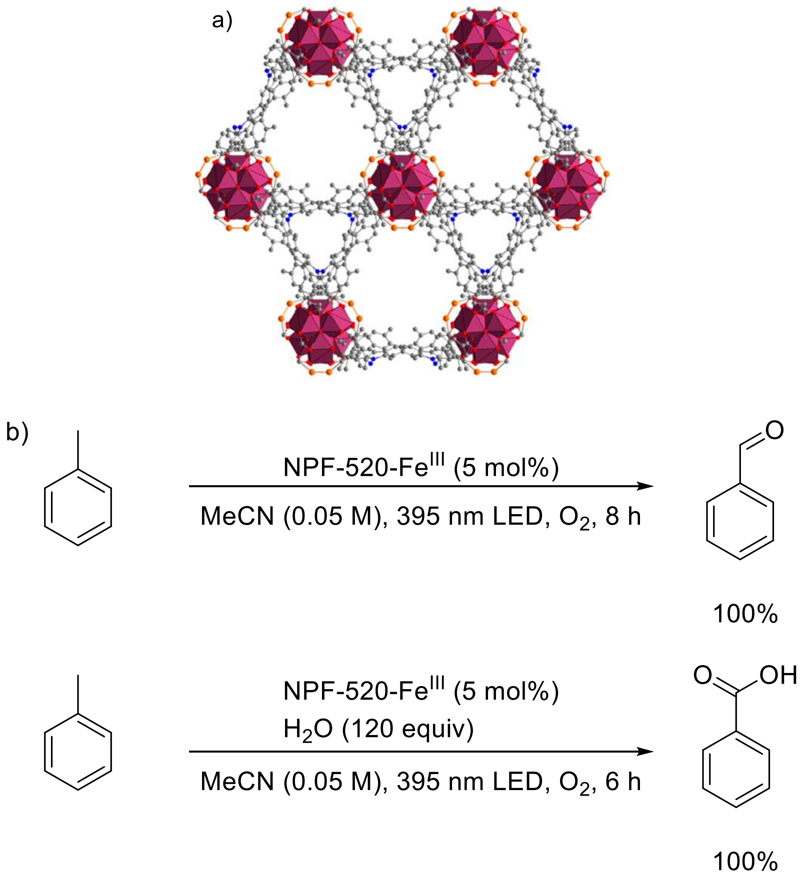
[38] Feng, X.; Song, Y.; Lin, W. *Trends in Chemistry* **2020**, *2*, 965-979.

[39] a) Planas, N.; Mondloch, J. E.; Tussupbayev, S.; Borycz, J.; Gagliardi, L.; Hupp, J. T.; Farha, O. K.; Cramer, C. J. *J. Phys. Chem. Lett.* **2014**, *5*, 3716-3723. b) Nguyen, H. G. T.; Schweitzer, N. M.; Chang, C.-Y.; Drake, T.L.; So, M. C.; Stair, P. C.; Farha, O. K.; Hupp, J. T.; Nguyen, S. T. *ACS Catal.* **2014**, *4*, 2496-2500. c) Manna, K.; Ji, P.; Greene, F. X.; Lin, W. *J. Am. Chem. Soc.* **2016**, *138*, 7488-7491. d) Ji, P.; Manna, K.; Lin, Z.; Urban, A.; Greene, F. X.; Lan, G.; Lin, W. *J. Am. Chem. Soc.* **2016**, *138*, 12234-12242. e) An, B.; Li, Z.; Song, Y.; Zhang, J.; Zeng, L.; Wang, C.; Lin, W. *Nat. Catal* **2019**, *2*, 709-717.

[40] Mondloch, J. E.; Bury, W.; Fairen-Jimenez, D.; Kwon, S.; DeMarco, E. J.; Weston, M. H.; Sarjeant, A. A.; Nguyen, S. T.; Stair, P.C.; Snurr, R. Q.; Farha, O. K.; Hupp, J. T. *J. Am. Chem. Soc.* **2013**, *135*, 10294-10297.

hydrogenation of ethylene with minimal deactivation during two weeks in a stream of ethylene, hydrogen and argon mixture in flow.[41]

MOFs can also have utility as photocatalysts, as recently demonstrated by the group Zhang. They synthetized the novel NPF-520 bearing nonanuclear Zr nodes, that was later metalated with Fe. The metalated MOF was suitable for the C-H oxidation of toluene under aerobic conditions, being able to selectively oxidize it to the aldehyde or the carboxylic acid depending on the reaction conditions under blue light excitation (Scheme 17).[42]



Scheme 17. a) Structure of NPF-520-Fe^{III} (Reproduced from Khoo, R. S. H.; Fiankor, C.; Yang, S.; Hu, W.; Yang, C.; Lu, J.; Morton, M. D.; Zhang, X.; Liu, Y.; Huang, J.; Zhang, J. *J. Am. Chem. Soc.* 2023, *145*,

---

[41] Li, Z.; Schweitzer, N. M.; League, A. B.; Bernales, V.; Peters, A. W.; Getsoian, A. B.; Wang, T. C.; Miller, J. T.; Vjunov, A.; Fulton, J. L.; Lercher, J. A.; Cramer, C. J.; Gagliardi, L.; Hupp, J. T.; Farha, O. K. *J. Am. Chem. Soc.* **2016**, *138*, 1977-1982.

[42] Khoo, R. S. H.; Fiankor, C.; Yang, S.; Hu, W.; Yang, C.; Lu, J.; Morton, M. D.; Zhang, X.; Liu, Y.; Huang, J.; Zhang, J. *J. Am. Chem. Soc.* **2023**, *145*, 24052-24060.

24052-24060. Copyright 2023 American Chemical Society). Fe in orange, O in red, C in grey, N in blue and Zr_9 clusters in dark pink polyhedral. b) Toluene oxidation catalyzed by NPF-520-Fe^{III}.

4.1.4 Catalysis on MOFs bearing embedded metal nanoparticles

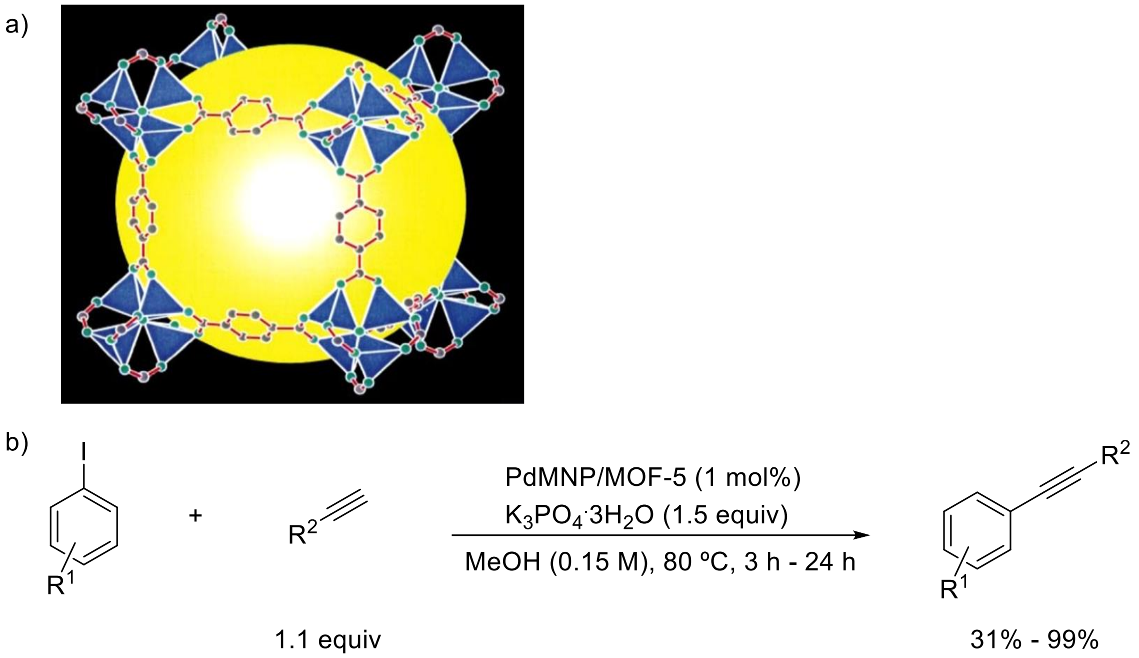
The last strategy to obtain catalytically active MOF is to build up metal nanoparticles within the pores of the framework.[43] Due to its high porosity and crystalline structure MOFs have emerged during the last years as a versatile support for metal nanoparticles, as they provide interesting properties to the composites, such as control of the particle sizes and the distribution along the structure of the nanoparticles; a better control of the reaction selectivity by sieving and blocking molecules by their size; the possibility of modulating the electronic density and the electron charge transfer by modifying the microenvironment of the pores. Moreover, MOFs embedded with metal nanoparticles can also catalyze one-pot tandem reactions in which both reactions are catalyzed separately by the active sites of both the MOF and the nanoparticles.

The group of Che[44] reported a copper-free Sonogashira coupling using the well-known MOF-5[12] loaded with palladium nanoparticles. In this case, the growth of the nanoparticles did not occur within the framework but in the surface of the MOF. The resulting material was active in the coupling of aryl iodides and terminal phenyl acetylenes, achieving excellent yields in a broad scope of substrates. However, since it was highly sensitive to oxidation, to the point it could ignite under air, its activity dropped after being recycled two times, due to partial oxidation and aggregation of the nanoparticles (Scheme 18).

---

[43] Yang, Q.; Xu, Q.; Jiang, H.-J. *Chem. Soc. Rev.* **2017**, *46*, 4774-4808.

[44] Gao, S.; Zhao, N.; Shu, M.; Che, S. *Appl. Catal. A* **2010**, *388*, 196-201.



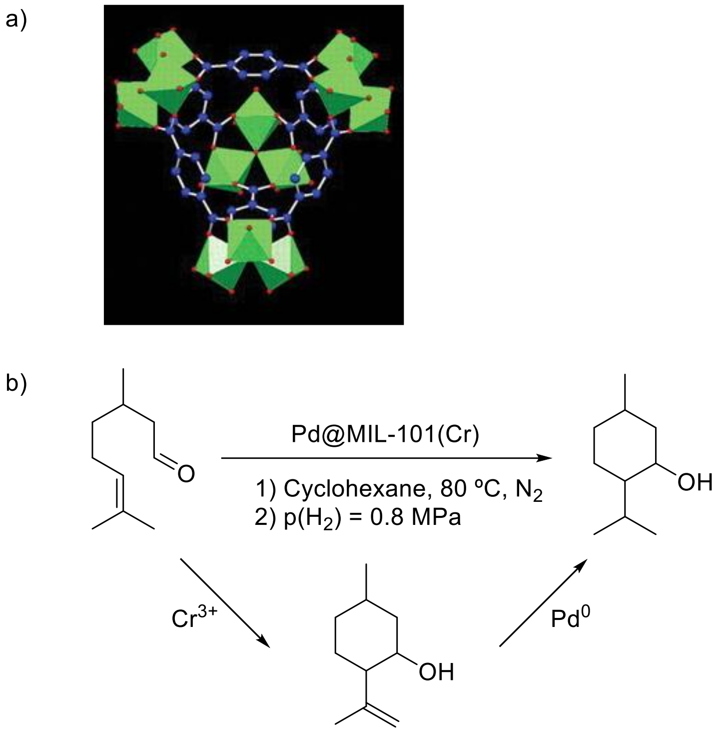
Scheme 18. a) Structure of MOF-5 (Reproduced from Gao, S.; Zhao, N.; Shu, M.; Che, S. *Appl. Catal. A* 2010, *388*, 196-201 with permission from Springer Nature). C in grey, O in green, Zn in blue and Zn clusters in blue tetrahedra. b) Copper-free Sonogashira coupling catalyzed by PdMNP/MOF-5.

A bifunctional MOF was obtained two years later by the group of Corma and Llabrés I Xamena[45] using MIL-101[46] as support and impregnating it using an aqueous solution of palladium (II) nitrate, after a reduction palladium nanoparticles were formed within the framework. It was a suitable catalyst for the synthesis of menthol from citronellal. The Cr^{3+} ions catalyzed the cyclization of the citronellal to isopulegol and then the palladium nanoparticles in the presence of a hydrogen atmosphere catalyzed the isomerization/hydrogenation of the isopulegol to menthol (Scheme 19).

---

[45] Cirujano, F. G.; Llabrés i Xamena, F. X.; Corma, A. *Dalton Trans.* **2012**, *41*, 4249-4254.

[46] Ferey, G.; Mellot-Draznieks, C.; Serre, C.; Millange, F.; Dutour, J.; Surble, S.; Margiolaki, I. *Science* **2005**, *309*, 2040-2042.



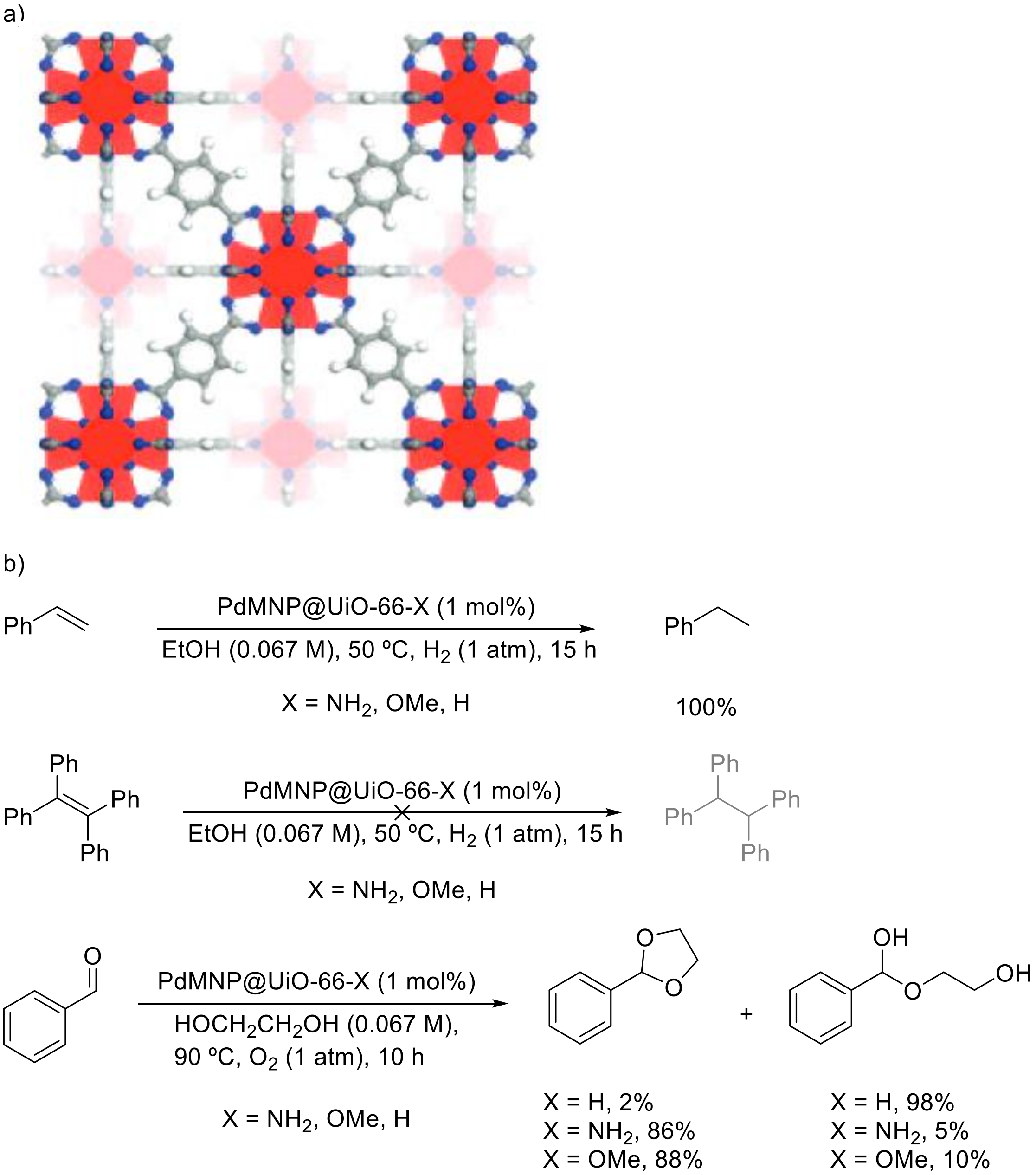
Scheme 19. a) Structure of MIL-101 from Ferey, G.; Mellot-Draznieks, C.; Serre, C.; Millange, F.; Dutour, J.; Surble, S.; Margiolaki, I. *Science* 2005, *309*, 2040-2042. Reprinted with permission from AAAS. C in blue, O in red, Cr clusters in green polyhedra. b) Tandem cyclization/hydrogenation catalyzed by bifunctional MIL-101.

An example of a system comprising nanoparticles encapsulated into the MOFs pores and employed as catalyst was reported by the group of Huang.[47] Using different functionalized UiO-66[48] supports and palladium nanoparticles, they could perform the size selective hydrogenation of alkenes and also selectively obtain the acetal of benzaldehyde or the ester depending on the functional groups present on the support with perfect recyclability during five reaction cycles (Scheme 20).

---

[47] Li, X.; Goh, T. W.; Li, L.; Xiao, C.; Guo, Z.; Zeng, X. C.; Huang, W. *ACS Catal.* **2016**, *6*, 3461-3468.

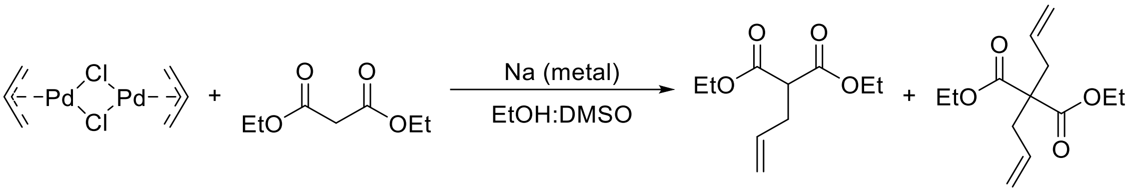
[48] Cavka, J. H.; Jakobsen, S.; Olsbye, U.; Guillou, N.; Lamberti, C.; Bordiga, S.; Lillerud, K. P. *J. Am. Chem. Soc.* **2008**, *130*, 13850-13851.



Scheme 20. a) Structure of UiO-66 (Reprinted with permission from Cavka, J. H.; Jakobsen, S.; Olsbye, U.; Guillou, N.; Lamberti, C.; Bordiga, S.; Lillerud, K. P. *J. Am. Chem. Soc.* 2008, *130*, 13850-13851. Copyright 2008 American Chemical Society). Zr clusters in red, O in blue, C in grey and H in white. b) Palladium catalyzed reactions by PdMNP@UiO-66-X.

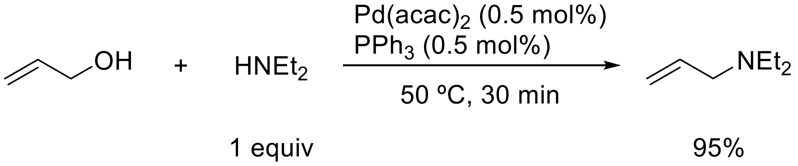
4.2 PD-CATALYZED ALLYLIC ALKYLATION

The Pd-catalyzed allylic alkylation, also known as the Tsuji-Trost reaction, is a substitution reaction in which a leaving group present at an allylic position is replaced by a nucleophile by the aid of a palladium complex either as stoichiometric reagent or in a catalytic amount. This transformation was first discovered in 1965 by the group of Tsuji.[49] It was performed in a stoichiometric manner, in which the palladium complex reacted with soft nucleophiles to obtain the alkylated products (Scheme 21).



Scheme 21. First Pd-mediated allylic alkylation reaction.

Closely after, these methodologies were further improved with the use of palladium in a catalytic manner. The first example of the catalytic use of palladium in an allylation reaction was the work of Atkins and co-workers in 1970,[50] using secondary amines as nucleophiles and alcohols or carbonates as allylic substrates to obtain the corresponding allylic tertiary amines (Scheme 22).



Scheme 22. First Pd-catalyzed allylic substitution.

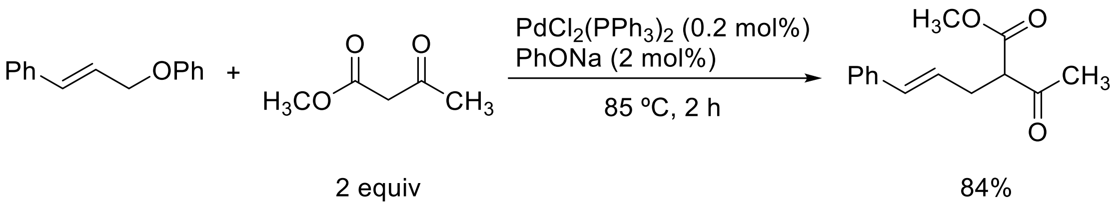
Two years later, in 1972, Takahashi and co-workers[51] described the first allylic alkylation in catalytic conditions, using allylic ethers as allylic substrates and activated methylene compounds as nucleophiles. Primary and secondary amines, alcohols, phenols and carboxylic acids were also successfully employed as nucleophiles in the allylation reaction (Scheme 23).

---

[49] Tsuji, J.; Takahashi, H.; Morikawa, M. *Tetrahedron Lett.* **1965**, *6*, 4387-4388.

[50] Atkins, K.; Walker, W.; Manyik, R. *Tetrahedron Lett.* **1970**, *11*, 3821-3824.

[51] Takahashi, K.; Miyaki, A.; Hata, G. *Bull. Chem. Soc. Jpn.* **1972**, *45*, 230-236.



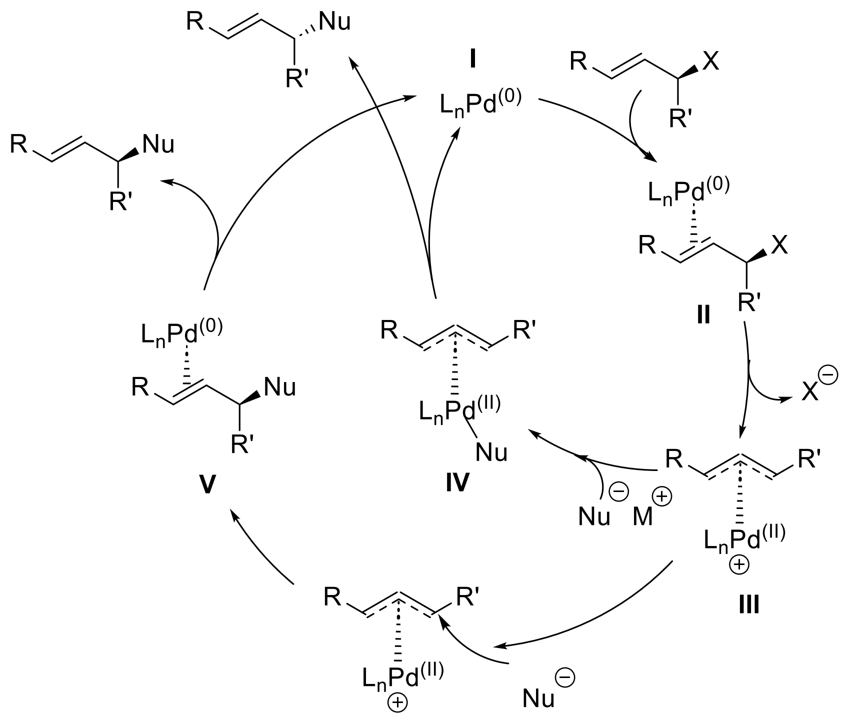
Scheme 23. First catalytic allylic alkylation reaction.

In 1973 the group of Trost contributed to the field with the addition of phosphine ligands, which allowed to expand the scope of the reaction to less reactive allylic substrates.[52] This breakthrough also enabled asymmetric versions of the reaction by the use of chiral phosphine ligands.[53] A few years later, in 1976 the group of Trost also demonstrated the utility of the allylic alkylation in the synthesis of natural products.[54] They could apply this catalytic methodology to the synthesis of steroids, obtaining a different stereoselectivity than using the allylic alkylation reaction in a stoichiometric approach.

The reaction mechanism of the Pd-catalyzed allylic alkylation (Scheme 24) starts with the coordination of the palladium complex **I** to the double bond of the allylic substrate to give the intermediate **II**, followed by an oxidative addition of the allylic substrate to the palladium(0) that generates allylpalladium(II) complex **III**. Oxidative addition typically occurs through an S_N2'-type mechanism where the Pd atom adds anti to the leaving group, i.e. if the substrate is a chiral secondary alcohol derivative this step occurs with an inversion of configuration. Allylpalladium intermediate **III** can react with the nucleophile through two different pathways, depending on the nature of the latter: hard nucleophiles (pK_a of the conjugate acid >25) react through an inner-sphere mechanism by a transmetalation step in which the configuration of the allyl moiety is maintained to form the intermediate **IV**. Subsequent reductive elimination releases the final product with a net inversion of the configuration and regenerates the palladium(0) complex **I**. On the other hand, soft nucleophiles follow an outer-sphere mechanism when the nucleophile attacks one of the allylic termini of the allylpalladium(II) intermediate. This attack occurs at the opposite site of the Pd atom thus resulting in a second inversion of the configuration that leads to intermediate **V**. Palladium discoordination regenerates the catalyst and releases the product with net retention of configuration.

---

[52] Trost, B. M.; Fullerton. T. J. *J. Am. Chem. Soc.* **1973**, *95*, 292-294.
[53] Trost, B. M.; Van Vranken, D. L. *Chem. Rev.* **1996**, *96*, 395-422.
[54] Trost, B. M.; Verhoeven, T. R. *J. Am. Chem. Soc.* **1976**, *98*, 630-632.



Scheme 24. Mechanism of the Tsuji-Trost allylic substitution reaction with hard and soft nucleophiles.

During the last decades, the allylic substitution reaction has been widely studied, allowing it to be performed using different metals, like nickel,[55] ruthenium,[56] iridium,[57] even merging regular metal catalysis with photocatalysis[58] or organocatalysis.[59] Its versatility also allowed asymmetric versions of the reaction to be developed, that is broadly known as Asymmetric Allylic Alkylation (AAA).[60]

---

[55] a) Minami, I.; Shimizu, I.; Tsuji, J. *J. Organomet. Chem.* **1985**, *296*, 269-280. b) Trost, B. M.; Spagnol, M. D. *J. Chem. Soc., Perkin Trans. 1* **1995**, 2083-2097. c) Gomez-Bengoa, E.; Heron, N. M.; Didiuk, M. T.; Luchaco, C. A.; Hoveyda, A. H. *J. Am. Chem. Soc.* **1998**, *120*, 7649-7650.

[56] a) Kondo, T.; Ono, H.; Satake, N.; Mitsudo, T.; Watanabe, Y. *Organometallics* **1995**, *14*, 1945-1953. b) Zhang, S.; Mitsudo, T.; Kondo, T.; Watanabe, Y. J. *Organomet. Chem*. **1993**, *450*, 197-207.

[57] a) Takeuchi, R.; Kashio, M. *J. Am. Chem. Soc.* **1998**, *120*, 8647-8655. b) Graening, T.; Hartwig, J. F. *J. Am. Chem. Soc.* **2005**, *127*, 17192-17193.

[58] a) Wang, ZJ.; Zheng, S.; Romero, E.; Matsui, J. K.; Molander, G. A. *Org. Lett.* **2019**, 21, 6543-6547. b) Martínez-Balart, P.; Tóth, B. L.; Velasco-Rubio, A.; Fañanás-Mastral, M. *Org. Lett.* **2022**, *24*, 6874-6879.

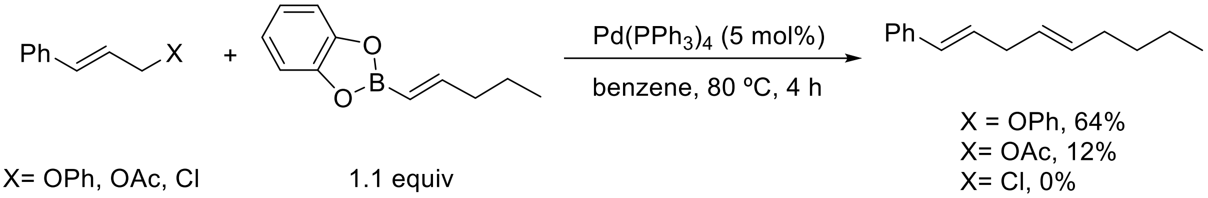
[59] Ibrahem, I.; Córdova, A. *Angew. Chem. Int. Ed.*, **2006**, *45*, 1952-1956.

[60] a) Crawley, M. L.; Trost, B. M. *Chem. Rev.* **2003**, *103*, 82921-2944. b) Pàmies, O.; Margalef, J.; Cañellas, S.; James, J.; Judge, E.; Guiry, P. J.; Moberg, C.; Bäckvall, J.-E.; Pfaltz, A.; Pericàs, M. A.; Diéguez, M. *Chem. Rev.* **2021**, *121*, 4373-4505.

4.2.1 Allylic alkylation with organoboron compounds

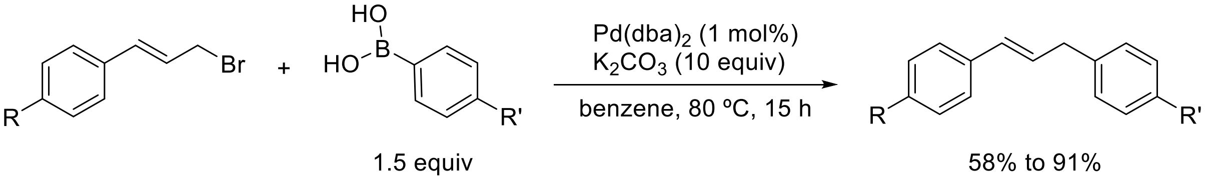
While the use of soft nucleophiles in palladium catalyzed-allylic alkylation is well stablished,[61] transformations using hard nucleophiles[62] have been less explored. Among them, there are some examples using organoboron reagents.

The first example was reported by Suzuki and coworkers in 1985.[63] They could achieve the coupling between boronic acid esters and allylic phenyl ethers with good yields. However, the scope of the reaction was limited to this type of allylic substrate, since the use of other leaving groups like acetates or chlorides led to a dramatic drop of reactivity (Scheme 25).



Scheme 25. First Suzuki-Miyaura allylic substitution with boron nucleophiles.

In 1995, the group of Moreno Mañas[64] published a more robust coupling of allylic bromides with aryl boronic acids. This methodology was more general, and it allowed to efficiently use a broader scope of allylic substrates (Scheme 2.6).



Scheme 26. Suzuki-Miyaura allylic arylation with boronic acids and allylic bromides.

Even though there are more examples of the use of arylboron reagents in allylic substitution reactions,[65] to the best of our knowledge only one example employing alkylboron reagents has

---

[61] a) Trost, B. M. *Acc. Chem. Res.* **1980**, *13*, 385-393. b) Van Vranken, D. L.; Trost, B. M. *Chem. Rev.* **1996**, *96*, 395-422.

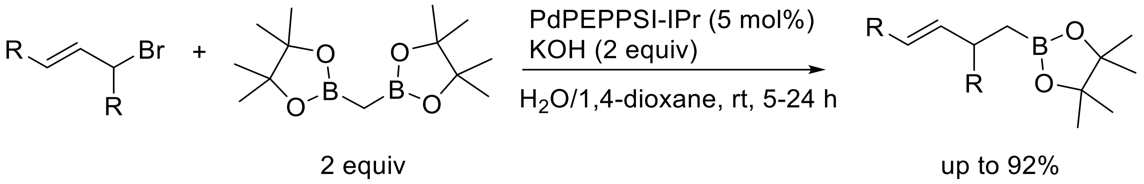
[62] a) Moineau, C.; Bolitt, V., Sinou, D. *J. Org. Chem.* **1998**, *63*, 582-591. b) Rosales, V.; Zambrano, J. L.; Demuth, M. *J. Org. Chem.* **2002**, *67*, 1167-1170. b) Volla, C. M. R.; Dubbaka, S. R.; Vogel, P. *Tetrahedron* **2009**, *65*, 504-511. d) Negishi, E.; Fang, L. in Handbook of Organopalladium Chemistry for Organic Synthesis; Wiley, New 2002, vol. 1, ch. III.2.9. e) Mao, J.; Zhang, J.; Jiang, H.; Bellomo, A.; Zhang, M.; Walsh, P. J. *Angew. Chem., Int. Ed.* **2016**, *55*, 2526-2530. f) Zhang, J.; Stanciu, C.; Wang, B.; Hussain, M. M.; Da, C.-S.; Carroll, P. J.; Dreher, S. D.; Walsh, P. J. *J. Am. Chem. Soc.* **2011**, *133*, 20552-20560. g) Chaves-Pouso, A.; Rivera-Chao, E.; Fañanas-Mastral, M. *ACS Catal.* **2023**, *13*, 12656-12664.

[63] Miyaura, N.; Yamada, K.; Suginome, H.; Suzuki, A. *J. Am. Chem. Soc.* **1985**, *107*, 972-980.

[64] Moreno-Manas, M.; Pajuelo, F.; Pleixats, R. *J. Org. Chem.* **1995**, *60*, 8, 2396-2397.

[65] a) Botella, L.; Nájera, C. *J. Organomet. Chem.* **2002**, 663, 46-57. b) Singh, R.; Viciu, M. S.; Kramareva, N.; Navarro, O.; Nolan, S. P. *Org. Lett.* **2005**, *7*, 1829-1832. c) Alacid, E.; Nájera, C. *Org. Lett.* **2008**, *10*, 5011-5014. d) Ghosh, R.; Adarsh, N. N.; Sarkar, A. *J. Org. Chem.* **2010**, *75*, 5320-5322. e) Lipshutz, B. H.; Ghorai, S.; Abela, A. R.; Moser, R.; Nishikata, T.; Duplais, C.; Krasovskiy, A.; Gaston, R. D.; Gadwood, R. C. *J. Org. Chem.* **2011**, *76*, 4379-4391.

been reported to the date. This work was reported by Shibata and co-workers,[66] and it is based on the use of diborylmethane as nucleophile, in the regioselective coupling with allylic bromides and benzyl bromides. In this case, a Pd/HNC catalyst proved to be efficient to render the methylboration products in good yields under mild reaction conditions (Scheme 27).

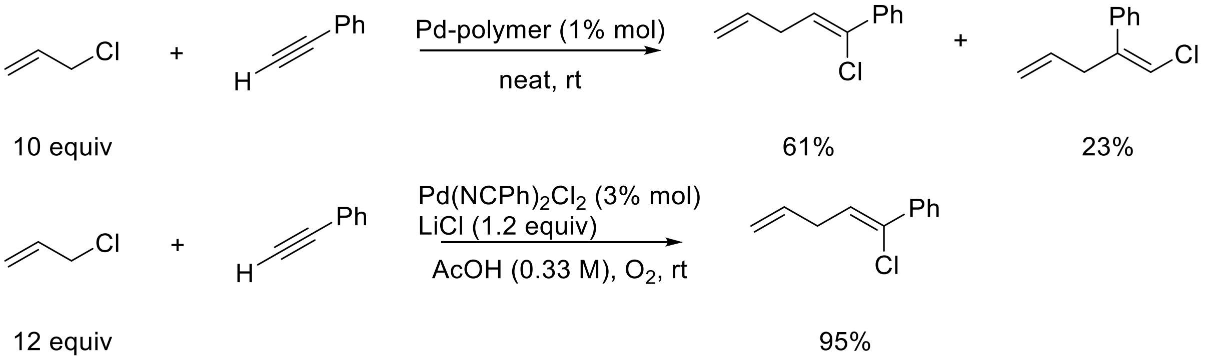


Scheme 27. Suzuki-Miyaura allylic alkylation of diborylmethane.

4.2.2 Heterogeneous Pd-catalyzed allylic alkylation

Pd-catalyzed allylic alkylation reactions have been also described under heterogeneous catalysis conditions. Examples have been mainly based on the use of polymer or silica supported palladium catalysts.

The first example of a heterogeneous Pd-catalyzed allylic substitution was reported in 1976 by the group of Kaneda.[67] It was based on a polymeric diphenylbenzyl phosphine structure, which was not described in detail. It allowed them to perform the allyl chlorination of phenyl acetylene. Although the heterogeneous system proved to be successful, it was also demonstrated that the reaction was more efficient and selective when a homogeneous palladium catalyst was used (Scheme 28).



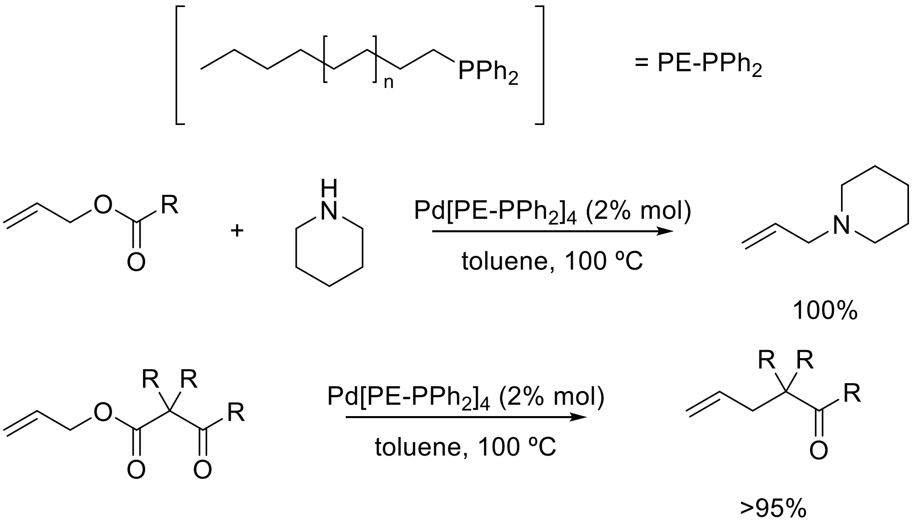
Scheme 28. Pd-catalyzed allyl chlorination of phenyl acetylene

---

[66] Endo, K.; Ohkubo, T.; Ishioka, T.; Shibata, T. *J. Org. Chem.* **2012**, *77*, 4826-4831.

[67] Kaneda, K.; Uchiyama, T.; Terasawa, M.; Imanaka, T.; Teranishi, S. *Chem. Lett.* **1976**, 449-452.

A few years later, Bergbreiter and Weatherford described a heterogeneous catalyst for the allylation of secondary amines with allylic esters.[68] The allylated amine products were obtained in nearly quantitative yields by using a polyethylene oligomer bounded Pd^0/phosphine complex that is soluble at the reaction conditions and can be recovered by centrifugation under inert atmosphere after the crude is cooled down. The recovered catalyst could be used again up to four times; however, it is extremely sensitive to adventitious oxygen resulting in the deactivation of the catalyst due to oxidation of the phosphine ligands. This methodology proved to be effective also in the allylic alkylation via decarboxylative allylation of allyl esters of β-keto esters (Scheme 29).



Scheme 29. First heterogeneous allylic substitution.

During the last years further investigation about this type of polymer-supported heterogeneous palladium catalysts has been carried out,[69] especially by the group of Uozumi.[70]

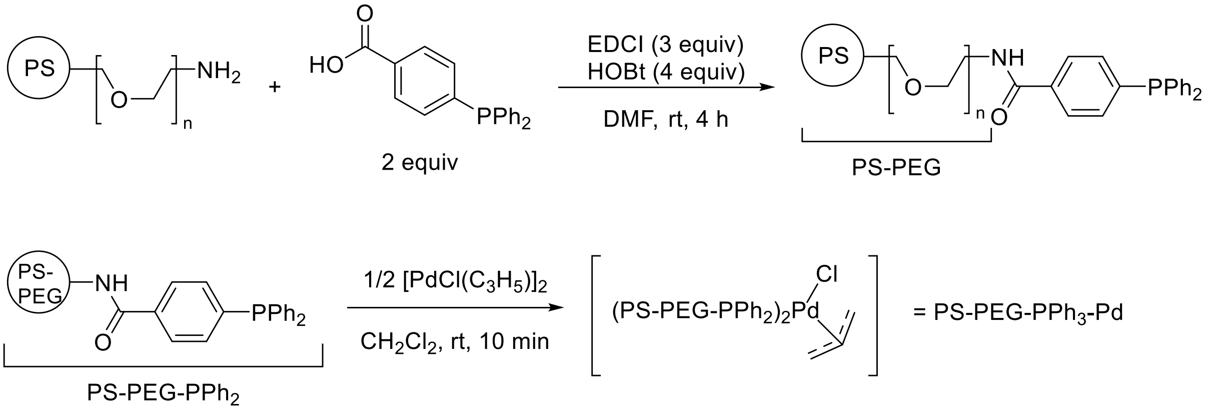
---

[68] Bergbreiter, D. E.; Weatherford, D. A. *J. Org. Chem.* **1989**, *54*, 2726-2730.

[69] a) Song, C. E.; Yang, J. W.; Roh, E. J.; Lee, S.; Ahn, J. H.; Han, H. *Angew. Chem. Int. Ed*. **2002**, *41*, 3852-3854. b) Kim, S.; Kim, G.; *J. Ind. Eng. Chem.* **2006**, *12*, 643-647. c) Swennenhuis, B. H. G.; Chen, R.; van Leeuwen, P. W. N. M.; de Vries, J. G.; Kamer, P. C. J. *Eur. J. Org. Chem*. **2009**, 5796-5803. c) Wagh, Y. S.; Tambade, P. J.; Sawant, D. N.; Bhanage, B. M. *Eur. J. Org. Chem.* **2010**, 5071-5076. d) Wagh, Y. S.; Sawant, D. N.; Dhake, K. P.; Deshmukh, K. M.; Bhanage, B. M. *Tetrahedron Lett*. **2011**, *52*, 5676-5679.

[70] a) Danjo, H.; Tanaka, D.; Hayashi, T.; Uozumi, Y. *Tetrahedron* **1999**, *55*, 14341-14352. b) Uozumi, Y.; Shibatomi, K. *J. Am. Chem. Soc*. **2001**, *123*, 2919-2920. c) Uozumi, Y.; Tanaka, H.; Shibatomi, K. *Org. Lett.* **2004**, *6*, 281-283. d) Uozumi, Y.; Kimura, M.; *Tetrahedron: Asymmetry* **2006**, *17*, 161-166. e) Kobayashi, Y.; Tanaka, D.; Danjo, H.; Uozumi, Y. *Adv. Synth. Catal.* **2006**, *348*, 1561-1566. f) Uozumi, Y.; Suzuka, T.; Kawade, R.; Takenaka, H. *Synlett* **2006**, 2109-2113. g) Uozumi, Y.; Suzuka, T. *J. Org. Chem.* **2006**, *71*, 8644-8646. h) Uozumi, Y. *Pure Appl. Chem.* **2007**, *79*, 1481-1489. i) Uozumi, Y.; Takenaka, H.; Suzuka, T. *Synlett* **2008**, 1557-1561. j) Uozumi, Y.; Suzuka, T. *Synthesis* **2008**, 1960-1964. k) Sarkar, S. M.; Y. Uozumi, Y.; Yamada, M. A. *Angew. Chem. Int. Ed.* **2011**, *50*, 9437-9441. l) Yamada, Y. M. A.; Sarkar, S. M.; Uozumi, Y. *J. Am. Chem. Soc*. **2012**, *134*, 3190-3198.

Their first example, reported in 1997,[71] was the application of a commercially available functionalized polyethylene glycol-polystyrene graft copolymer. The polymer features free amino groups at the end of the polyethylene glycol chains that were further functionalized by condensation with benzoic acids that possess phosphine groups, suitable to generate a palladium complex after reacting with allylpalladium(II) chloride dimer (Scheme 30).



Scheme 30. Synthesis of a palladium catalyst supported on polymer-based materials bearing a phosphine ligand.

This catalyst was employed for the allylic substitution of allylic acetates with soft nucleophiles in aqueous media. Products were obtained in excellent yields, and recyclability was demonstrated by running the reaction over six reaction cycles without loss of activity. The polymer was easily recovered by filtration (Scheme 31a).

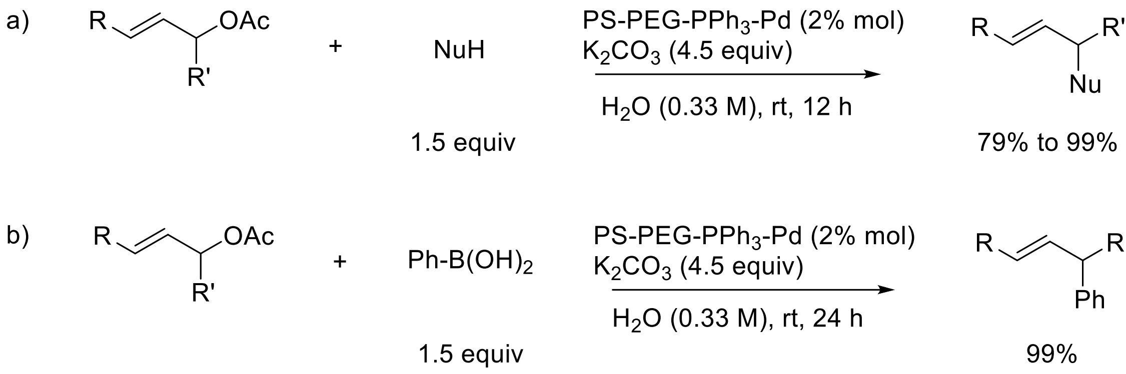
This same polymer was later applied to the allylic alkylation of aryl boronic acids with similar reaction conditions and procedure (Scheme 31b).[72] This transformation could also be performed under flow conditions.[73]

---

[71] Uozumi, Y.; Danjo, H.; Hayashi, T. *Tetrahedron Lett*. **1997**, *38*, 3557-3560.

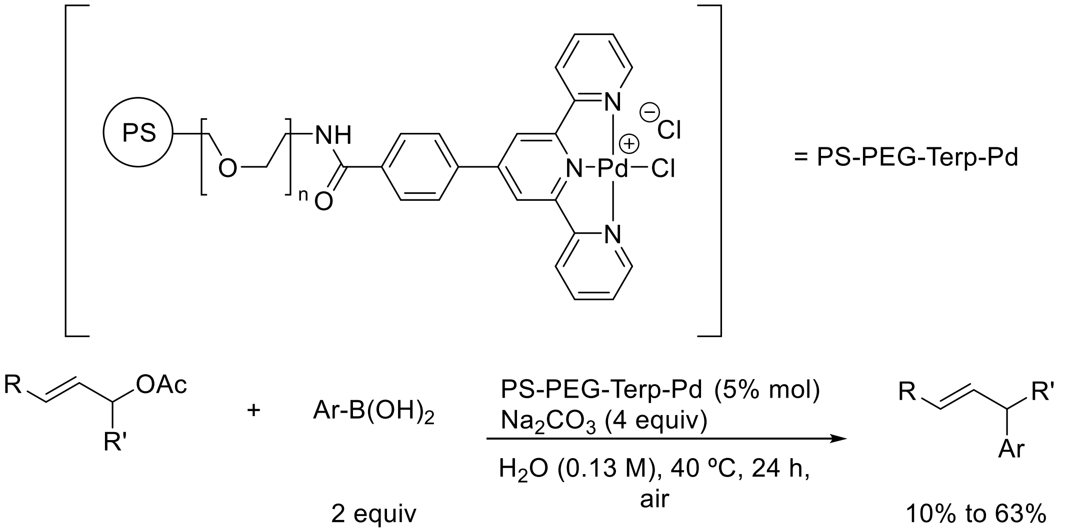
[72] Uozumi, Y.; Danjo, H.; Hayashi, T. *J. Org. Chem.* **1999**, *64*, 3384-3388.

[73] Yamada, Y. M. A.; Watanabe, T.; Torii, K.; Uozumi. Y. *Chem. Commun*. **2009**, 5594-5596.



Scheme 31. Heterogeneous allylic alkylation on palladium supported on polymer-based materials bearing a phosphine ligand.

A similar polymer bearing a terpyridine ligand loaded with bis(benzonitrile)palladium(II) chloride was also proven to be active and recyclable over three reaction cycles in the same reaction under aerobic conditions, even though products were obtained in lower yields (Scheme 32).[74]



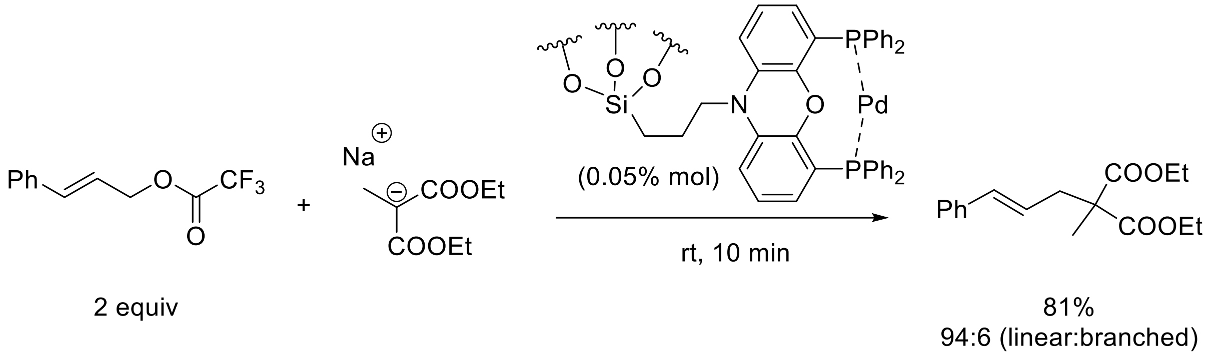
Scheme 32. Heterogeneous allylic alkylation on palladium supported on polymer-based materials bearing a terpyridine ligand.

The other main family of heterogeneous palladium catalysts are those supported in silica. The first example of a palladium-catalyzed allylic alkylation using silica as support was

---

[74] Suzuka, T.; Takayama, N.; Unten, M.; Onda, K.; Ogihara, K. *Trans. Mater. Res. Soc. Jpn*. **2019**, *44*, 41-44.

reported in 2001 by Sandee and co-workers.[75] They supported bis(dibenzylideneacetone)palladium(0) in mesoporous molecular sieves through trialkoxysilane functionalized phosphine ligands. The particles were loaded after stirring in the presence of the palladium source and they could be used to catalyze the allylic alkylation of malonate derivatives with good yields and good selectivity. The catalyst could be recycled by a simple filtration without loss of activity after four reaction cycles (Scheme 33).



Scheme 33. First heterogeneous allylic alkylation on palladium supported on silica.

Closely after, Chung and co-workers published in 2002 the synthesis of compounds with four five membered rings fused through a common quaternary carbon atom.[76] This methodology consisted in a three-step one-pot reaction involving two Pauson-Khand cyclizations and an allylic alkylation catalyzed by a combination of cobalt nanoparticles and allylpalladium(II) chloride dimer.

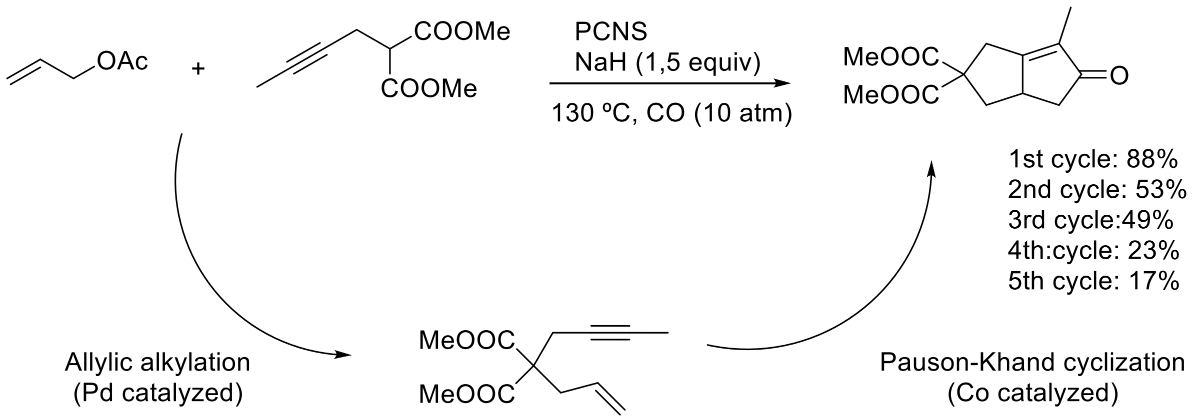
The same year they reported a cascade reaction involving an allylic alkylation followed by a Pauson-Khand cyclization to form bicyclic enones.[77] As heterogeneous catalyst, cobalt and palladium nanoparticles supported in colloidal silica (PCNS) were used. Products were obtained in excellent yields. However, the yields significantly dropped after recycling the catalyst due to palladium leaching, which was around a 30% of the initial amount only from the first to the second cycle (Scheme 34).

---

[75] Sandee, A. J.; Dimitrijevic, D.; van Haaren, R. J.; Reek, J. N. H.; Kamer, P. C. J.; van Leeuwen, P. W. N. M. *J. Mol. Catal. A* **2002**, 309-317.

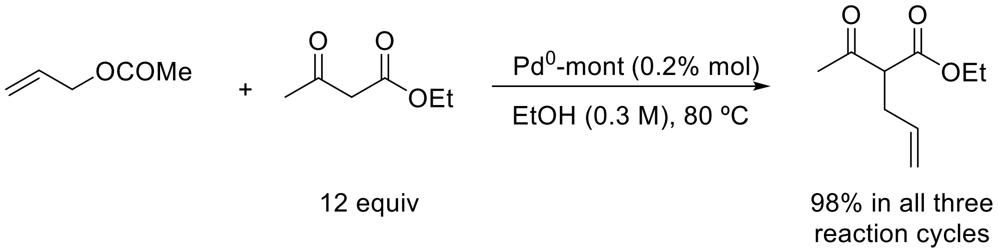
[76] Son, S. U.; Park, K. H.; Chung, Y. K. *J. Am. Chem. Soc.* **2002**, *124*, 6838-6839.

[77] Park, K. H.; Son, S. U.; Chung, Y. K. *Org. Lett.*, **2002**, *4*, 4361-4363.



Scheme 34. Cascade allylic alkylation followed by a Pauson-Khand cyclization to form bicyclic enones catalyzed by silica supported cobalt and palladium nanoparticles.

Other palladium-based materials supported in silica have been explored for the allylic alkylation reaction. The group of Kaneda reported the use of a palladium-doped montmorillonites.[78] Montmorillonites are hydrophilic clays formed by two types of different sheets forming a sandwich type structure: the first one negatively charged formed by silica and a second layer positively charged formed by alumina. In this second layer the cations can be easily interchanged for other cationic species. In this example after loading the Na^+-montmorillonite with calcium cations through treatment with aqueous calcium hydroxide, the obtained Ca^{2+}-montmorillonite is loaded with bis(dibenzylideneacetone)palladium(0) in DMA as solvent under aerobic conditions to afford the Pd^{II}-montmorillonite (Pd^{II}-mont). Finally, a reduction led to the formation of palladium clusters within the mineral (Pd^0-mont), which under the reaction conditions could perform the reaction of allylic carbonates and ethyl acetoacetate in excellent yields and with perfect recyclability by simple filtration after three uses in aqueous media (Scheme 35).

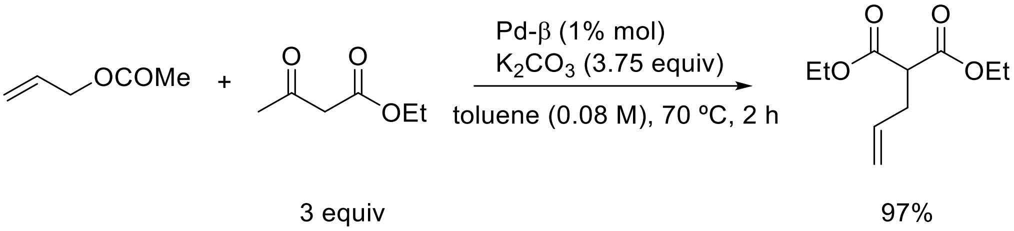


Scheme 35. Allylic alkylation catalyzed by palladium supported on montmorillonite.

---

[78] Mitsudome, T.; Nose, K.; Mori, K.; Mizugaki, T.; Ebitani, K.; Jitsukawa, K.; Kaneda, K. *Angew. Chem. Int. Ed.* **2007**, *46*, 3288-3290.

Aluminosilicates could also be used as a support for palladium catalysts. Zeolite β was employed by Okumura and co-workers,[79] which was found to be effective in the Tsuji-Trost allylation of ethyl acetoacetate. Allylation products were obtained in excellent yields and the catalysts could be reutilized up to four times without noticeable deactivation (Scheme 36).



Scheme 36. Allylic alkylation catalyzed by palladium supported on zeolite.

Different silica supported catalysts have been used during last years in allylic alkylation reactions,[80] even hybrid materials combining polymers extending from the silica surface that later function as palladium ligands.[81] There are also examples of the activation of allylic alcohols, which are less reactive than other common allylic substrates as halides and carbonates, via hydrogen bonding of the hydroxyl groups present in the silica surface.[82] In this publication from the group of Tanaka[34a] they reported the allylic alkylation of soft nucleophiles with allylic alcohols in good yields. However, the selectivity was poor, leading to mixtures of mono- and di- allylated products, also the recyclability of the catalyst was not proven (Scheme 37).

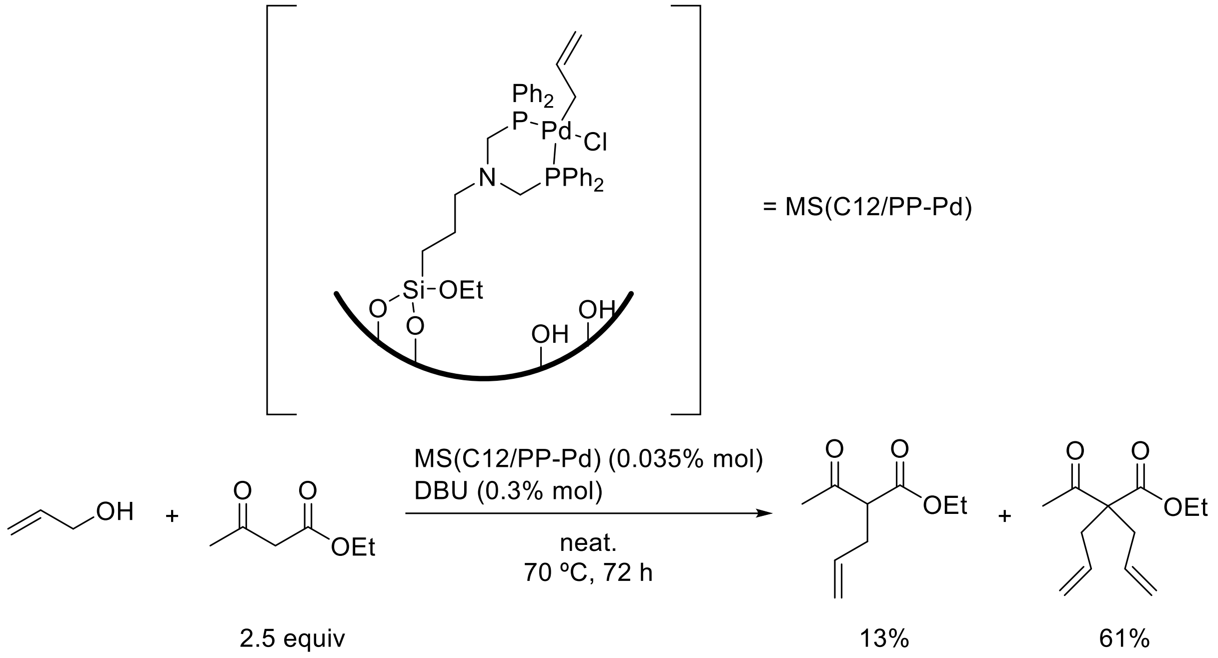
---

[79] Okumura, K.; Sato, K.; Kamioka, K.; Koga, Y. *Microporous Mesoporous Mater.* **2019**, *288*, 109571.

[80] a) Dickschat, A. T.; Behrends, F.; Surmiak, S.; Weiß, M.; Eckert, H.; Studer, A. *Chem. Commun.* **2013**, *49*, 2195-2197. b) Noda, H.; Motokura, K.; Miyaji, A.; Baba, T. *Angew. Chem. Int. Ed.* **2012**, *51*, 8017-8020. c) Noda, H.; Motokura, K.; Miyaji, A.; Baba, T. *Adv. Synth. Catal.* **2013**, *355*, 973-980. d) Motokura, K.; Saitoh, K.; Noda, H.; Chun, W.; Miyaji, A.; Yamaguchi, S.; Baba, T. *Catal. Sci. Technol.* **2016**, *6*, 5380-5388. e) Motokura, K.; Saitoh, K.; Noda, H.; Uemura, Y.; Chun, W.; Miyaji, A.; Yamaguchi, S.; Baba, T. *ChemCatChem* **2016**, *8*, 331-335. f) Motokura, K.; Ikeda, M.; Nambo, M.; Chun, W.; Nakajima, K.; Tanaka, S. *ChemCatChem* **2017**, *9*, 2924-2929. g) Motokura, K.; Ikeda, M.; Kim, M.; Nakajima, K.; Kawashima, S.; Nambo, M.; Chun, W.; Tanaka, S. *ChemCatChem* **2018**, *10*, 4536-4544. h) Motokura, K.; Kawashima, S.; Nambo, M.; Manaka, Y.; Chun, W.-J. *ChemCatChem* **2020**, *12*, 2783-2791.

[81] a) Cai, M.; Huang, Y.; Zhao, H.; Zhang, R. *J. Organomet. Chem.* **2004**, *689*, 2436-2440. b) Zhao, H.; Cai, M. *Chin. J. Chem.* **2006**, *24*, 1669-1673.

[82] a) Motokura, K.; Ikeda, M.; Kim, M.; Nakajima, K.; Kawashima, S.; Nambo, M.; Chun, W.-J.; Tanaka, S. *ChemCatChem* **2018**, *10*, 4536-4544. b) Ding, S.; Manaka, Y.; Nambo, m.; Chun, W-J.; Tomita, I.; Motokura, K. *Catal. Sci. Technol.* **2023**, *13*, 3047-3059.

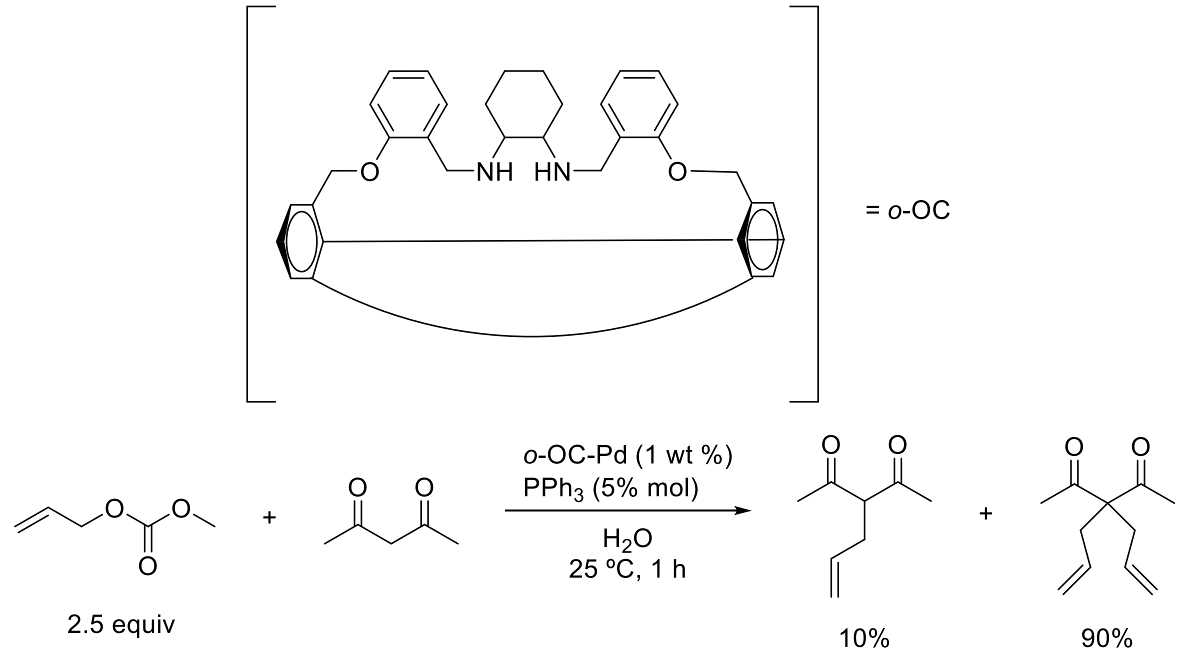


Scheme 37. Allylic alkylation of allylic alcohols catalyzed by palladium supported on silica.

Other types of materials have been utilized as support for palladium catalysts, like graphene,[83] graphene and polymer hybrid materials[84], magnetic and silica hybrid materials[85] or dendrimer and silica hybrid materials[86]. Surprisingly, to the best of our knowledge, no example of the use of a MOF as heterogeneous catalyst for a Tsuji-Trost type allylation has been reported to date, even though similar materials as porous organic cages (POCs) have been successfully used as support of palladium nanoparticles which could be later applied to this reaction. Bharadwaj and co-workers synthetized these organic cages (*o*-OC) that were embedded with palladium through treatment with palladium(II) chloride and posterior reduction.[87] The nanoparticles formed inside had a particle size around 2.7 nm and were able to catalyze the allylic alkylation of allylic carbonates and soft nucleophiles in excellent yields, even though a lack of selectivity towards mono- or di- allylated products was observed. Also, the recyclability of the material was examined during four different reaction cycles without noticeable activity loss, while the catalyst was easily recovered by centrifugation (Scheme 38).

---

[83] Zhao, Q.; Zhu, Y.; Sun, Z.; Li, Y.; Zhang, G.; Zhang, F.; Fan, X. *J. Mater. Chem. A* **2015**, *3*, 2609-2616.
[84] Liu, J.; Huo, X.; Li, T.; Yang, Z.; Xi, P.; Wang, Z.; Wang, B. *Chem. Eur. J.* **2014**, *20*, 11549-11555.
[85] Nasir Baig, R. B.; Varma, R. S. *Ind. Eng. Chem. Res.* **2014**, *53*, 18625-18629.
[86] Touzani, R.; Alper, H. *J. Mol. Catal. A* **2005**, *227*, 197-207.
[87] Sharma, V.; R. Saha, D. De; Chattaraj, P. K.; Bharadwaj. P. K. *ACS Appl. Mater. Interfaces* **2020**, *12*, 8539-8546.

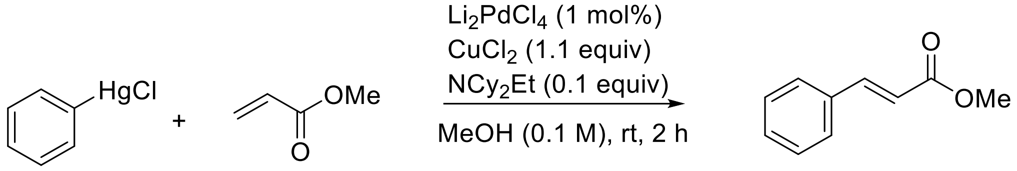


Scheme 38. Allylic alkylation catalyzed by palladium supported on a POC.

4.3 PD-CATALYZED OXIDATIVE BORON HECK REACTION

The Mizoroki-Heck reaction consists in the cross-coupling of aryl and vinyl (pseudo)halides with alkenes. It was parallelly discovered by the groups of Heck[88] and Mizoroki[89] in 1972 and it has been widely employed in organic synthesis.[90] The mechanism for this reaction involves an oxidative addition of the organic halide to the palladium(0) complex, further reacting with the alkene to release the coupling product and regenerating the catalyst.

Curiously, a few years before, in 1968, Heck reported an oxidative alternative of the reaction known as the oxidative Heck coupling.[91] An organometallic compound is used instead of the aryl bromide, and in particular for this example, arylmercurial salts were used. This reagent underwent a transmetalation with lithium tetrachloropalladate(II), further reacting with the alkene to release the final product. At the final step of this reaction the palladium needed to be oxidized by an external oxidant, in this case copper(II) chloride to regenerate the starting catalyst and close the catalytic cycle (Scheme 39).



Scheme 39. First oxidative Heck reaction.

After this initial discovery, different organometallic coupling partners have been used as coupling partners for this reaction like organomercurials,[92] organosilicones,[93] organotins,[94] organophosphorus[95] among others.[96]

---

[88] Heck, R. F.; Nolley, Jr., J. P. *J. Org. Chem*. **1972**, *37*, 2320-2322.

[89] Mizoroki, T.; Mori, K.; Ozaki, A. *Bull. Chem. SOC. Jpn*. **1972**, *44*, 581-581.

[90] a) Prashad, M. *Top. Organmet. Chem*. **2004**, *6*, 181-203. b) Nicolaou, K. C.; Bulger P. G.; Sarlah, D. *Angew. Chem., Int. Ed.* **2005**, *44*, 4442-4489. c) Kobetic R.; Biliskov, N.; *Kem. Ind*. **2007**, *56*, 391-402. d) Tietze, L. F.; Kinzel, T. *Pure Appl. Chem*. **2007**, *79*, 629-650.

[91] a) Heck, R. F. *J. Am. Chem. Soc.* **1968**, *90*, 5518-5526. b) Heck, R. F. *J. Am. Chem. Soc.* **1968**, *90*, 5538-5542. c) Heck, R. F. *J. Am. Chem. Soc.* **1968**, *91*, 6707-6714.

[92] a) Trost, B. M.; Burgess, K. *J. Chem. Soc., Chem. Commun*. **1985**, 1084-1086. b) Larock, R. C.; Stinn, D. E.; Mann-Yan, K. *Tetrahedron Lett.* **1990**, 31, 17-20.

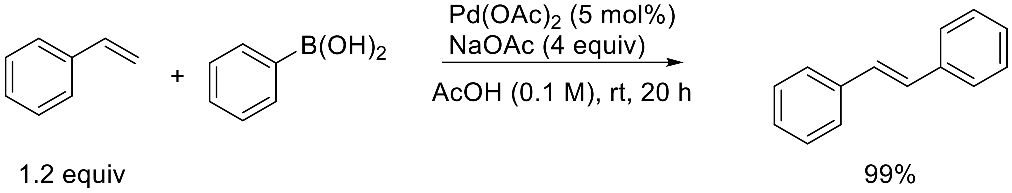
[93] a) Yoshida, J.-i.; Tamao, K.; Yamamoto, H.; Kakui, T.; Uchida, T.; Kumada, M. *Organometallics* **1982**, *1*, 542-549. b) Hirabayashi, K.; Nishihara, Y.; Mori, A.; Hiyama, T. *Tetrahedron Lett*. **1998**, *39*, 7893-7896.

[94] a) Tamaru, Y.; Hojo, M.; Kawamura, S.-i.; Yoshida, Z.-i. *J. Org. Chem*. **1986**, *51*, 4089-4090. b) Hirabayashi, K.; Ando, J.-i.; Nishihara, Y.; Mori, A.; Hiyama, T. *Synlett 1999*, **1999**, 99-101. c) Parrish, J. P.; Jung, Y. C.; Shin, S. I.; Jung, K. W. *J. Org. Chem*. **2002**, *67*, 7127-7130.

[95] a) Inoue, A.; Shinokubo, H.; Oshima, K. *J. Am. Chem. Soc*. **2003**, *125*, 1484-1485. b) Hwang, L. K.; Na, Y.; Lee, J.; Do, Y.; Chang, S. *Angew. Chem. Int. Ed.* **2005**, *44*, 6166-6169.

[96] a) Kjonaas, R. A. *J. Org. Chem*. **1986**, *51*, 3708-3710. b) Moiseev, D. V.; Gushchin, A. V.; Shavirin, A. S.; Kursky, Y. A.; Dodonov, V. A. *J. Organomet. Chem*. **2003**, *667*, 176-184. c) Hirabayashi, K.; Nara, Y.; Shimizu, T.; Kamigata, N. *Chem. Lett.*

Nowadays the most widely used organometallic nucleophiles for this reaction are organoboron compounds. Heck and Dieck reported the first example of this type of coupling in 1975,[97] using stoichiometric palladium(II) acetate, vinyl boronic acids and alkenes. Two decades later in 1994, Uemura and co-workers[98] improved this reaction by using acetic acid as solvent and a base, allowing stilbenes to be obtained from arylboronic acids and alkenes in excellent yields and selectivities, using catalytic amounts of palladium acetate as catalyst (Scheme 40).



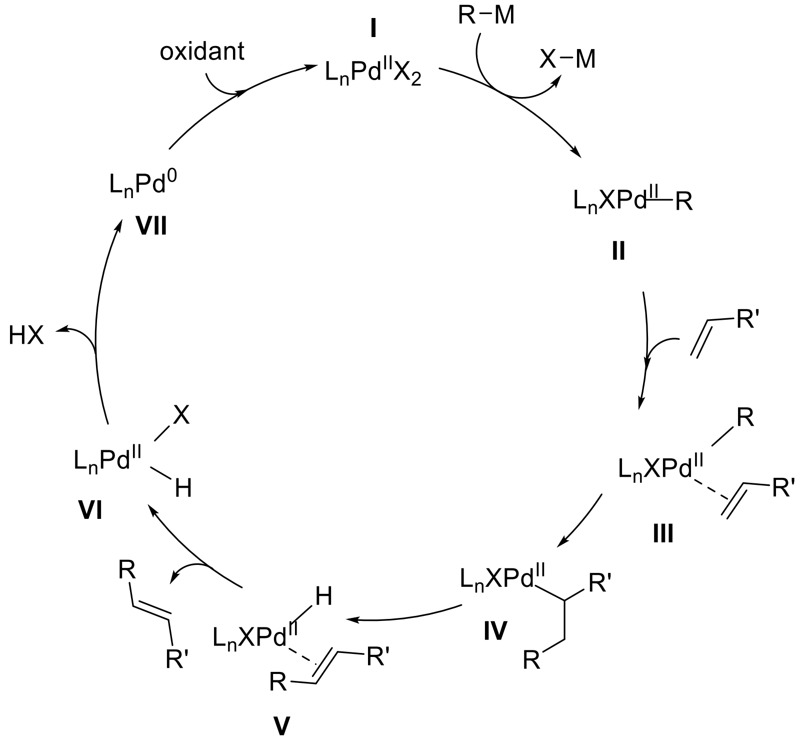
Scheme 40. First oxidative boron Heck reaction.

The mechanism of this reaction (Scheme 41) somewhat resembles the mechanism of the original Mizoroki-Heck reaction. It starts with the transmetalation from the organometallic reagent to the palladium(II) complex **I** leading to the intermediate **II**, which coordinates to the alkene giving rise to the intermediate **III**. Migratory insertion into the olefin leads to the alkylpalladium **IV**, that undergoes β-hydride elimination generating the alkene coordinated palladium hydride **V**. The final product is released through alkene dissociation resulting in the palladium species **VI**, which after reductive elimination of HX provides palladium(0) intermediate **VII**. Final oxidation of **VII** closes the catalytic cycle regenerating the initial palladium complex **I**.

2004, *33*, 1280-1281. d) Malysheva, Y. B.; Gushchin, A. V.; Mei, Y.; Lu, Y.; Ballauff, M.; Proch, S.; Kempe, R. *Eur. J. Inorg. Chem.* **2008**, *3*, 379-383.

[97] Dieck, H. A.; Heck, R. F. *J. Org. Chem.* **1975**, *40*, 1083-1090.

[98] Cho, C. S.; Uemura, S.; *J. Organomet. Chem.* **1994**, *465*, 85-92.



Scheme 41. Mechanism of the oxidative Heck reaction.

The main difference between both couplings is the necessity of an oxidant so that the catalyst is regenerated in the last step of the mechanism. Metallic salts, usually copper (II) salts[99,100] or benzoquinone derivatives[101] are among the most used oxidants. However, they lead to the production of big amounts of waste, so it is highly desirable to use environmentally friendly oxidants such as molecular oxygen[13,102] or, even better, air[103] as sole oxidants.

A very interesting example of an elegant use of air as oxidant is the one proposed by the group of Itami,[104] in which they could perform the coupling of difficult hindered arylboronic acids with heteroaromatic rings and olefins using palladium acetate with a sulfoxide-oxazoline

---

[99] a) Du, X.; Suguro, M.; Hirabayashi, K.; Mori, A.; Nishikata, T.; Hagiwara, N.; Kawata, K.; Okeda, T.; Wang, H. F.; Fugami, K.; Kosugi, M. *Org. Lett.* **2001**, *3*, 3313-3316.

[100] Parrish, J. P.; Jung, Y. C.; Shin, S. I.; Jung K. W. *J. Org. Chem.* **2002**, *67*, 7127-7130.

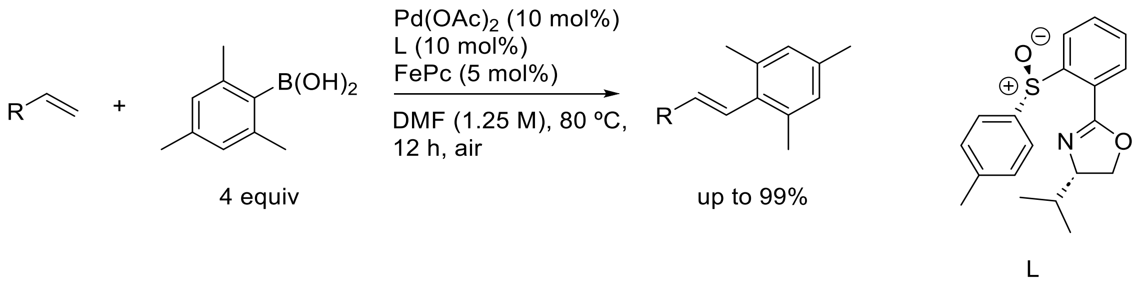
[101] a) Yoo, K. S.; Yoon, C. H.; Mishra, R. K.; Jung, Y. C.; Yi, S. W.; Jung, K. W. *J. Am. Chem. Soc.* **2006**, *128*, 16384-16393. b) Crowley, J. D.; Hänni, K. D.; Lee, A.-L.; Leigh, D. A. *J. Am. Chem. Soc.* **2007**, *129*, 12092-12093. c) Delcamp, J.H.; Gormisky, P. E.; White, M. C. *J. Am. Chem. Soc*. **2013**, *135*, 8460−8463.

[102] a) Jung, Y. C.; Mishra, R. K.; Yoon, C. H.; Jung, K. W. *Org. Lett.* **2003**, *5*, 2231-2234. b) Andappan, M. M. S.; Nilsson, P.; Larhed, M. *Chem. Commun.* **2004**, 218-219. c) Andappan, M. M. S.; Nilsson, P.; von Schenck, H.; Larhed, M. *J. Org. Chem.* **2004**, *69*, 5212-5218. d) Akiyama, K.; Wakabayashi, K.; Mikami, K. *Adv. Synth. Catal*. **2005**, *347*, 1569-1575.

[103] a) Enquist, P.-A.; Lindh, J.; Nilsson, P.; Larhed, M. *Green Chem*. **2006**, *8*, 338-343. b) Lindh, J.; Enquist, P.-A.; Pilotti, Å.; Nilsson, P.; Larhed, M. *J. Org. Chem.* **2007**, *72*, 7957-7962.

[104] Yamaguchi, K.; Kondo, H.; Yamaguchi, J.; Itami, K. *Chem. Sci***. 2013**, *4*, 3753-3757.

ligand and an iron phthalocyanine as a catalytic oxidant. The iron complex oxidizes Pd(0) to Pd(II) while it gets reoxidized by molecular oxygen (Scheme 42).



Scheme 42. Iron-mediated oxidation in an oxidative boron Heck reaction.

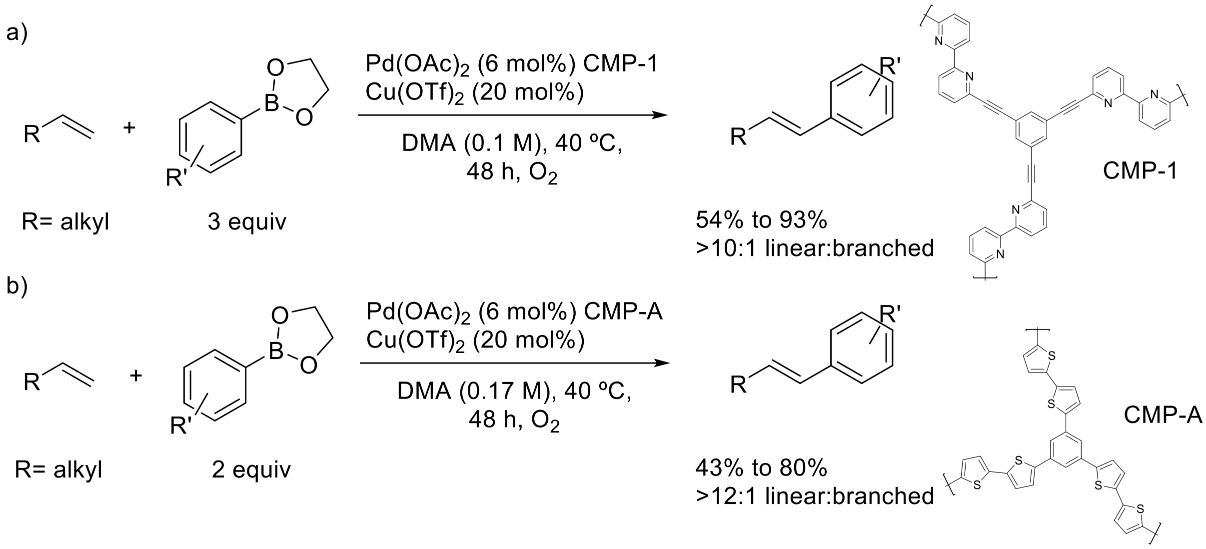
4.3.1 Heterogeneous Palladium catalyzed oxidative Heck reaction

While research on the field of the oxidative Heck reaction has evolved towards the use of less environmentally harmful oxidants, the use of homogeneous non-recyclable palladium catalysts remains a problem of high importance. Little investigation has been carried out in the field of heterogeneous oxidative Heck reactions. Indeed, there are only four known examples of applications of heterogeneous catalysts to this reaction to date. Two examples were reported by the group of Zhan in 2017, both using different Conjugated Microporous Polymers (CMPs) as heterogeneous ligands for palladium. These materials are characterized for having extended π-conjugation and have good thermal and chemical stability. In the first example (Scheme 43a),[105] a bipyridine based ligand was used while in the second one (Scheme 43b)[106] the catalyst was based on a bithiophene ligand. In both cases similar results were obtained, with good yields and regioselectivities towards the linear products using simple alkyl substituted olefins. However, no study of the recyclability, or analysis of the state of the catalyst after the reaction were performed.

---

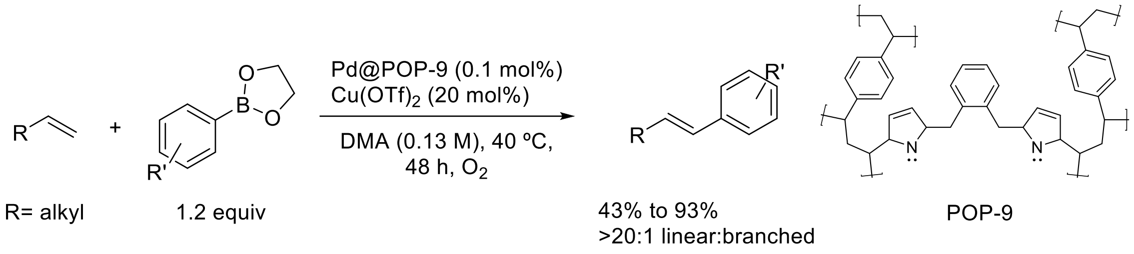
[105] Zhou, Y. B.; Wang, Y. Q.; Ning, L. C.; Ding, Z. C.; Wang, W. L.; Ding, C. K.; Li, R. H.; Chen, J. J.; Lu, X.; Ding, Y. J.; Zhan, Z. P. *J. Am. Chem. Soc*. **2017**, *139*, 3966-3969.

[106] Li, R. H.; Ding, Z. C.; Li, C. Y.; Chen, J. J.; Zhou, Y. B.; An, X. M.; Ding, Y. J.; Zhan, Z. P. *Org. Lett.* **2017**, *19*, 4432-4435.



Scheme 43. Heterogeneous oxidative Heck reaction using CMPs as ligands.

Ding and co-workers[107] synthetized a heterogeneous porous organic polymer (POP) bearing two NHC ligands, that act as a chelate ligand for palladium. In this case, they could achieve good yields and excellent regioselectivities using unbiased olefins. It is remarkable that they could recycle this material up to 10 times with no drop of the yield or the regioselectivity. The catalyst was easily recovered by vacuum evaporation and sequential washings with various solvents (Scheme 44).



Scheme 44. Heterogeneous oxidative Heck reaction using POPs as ligands.

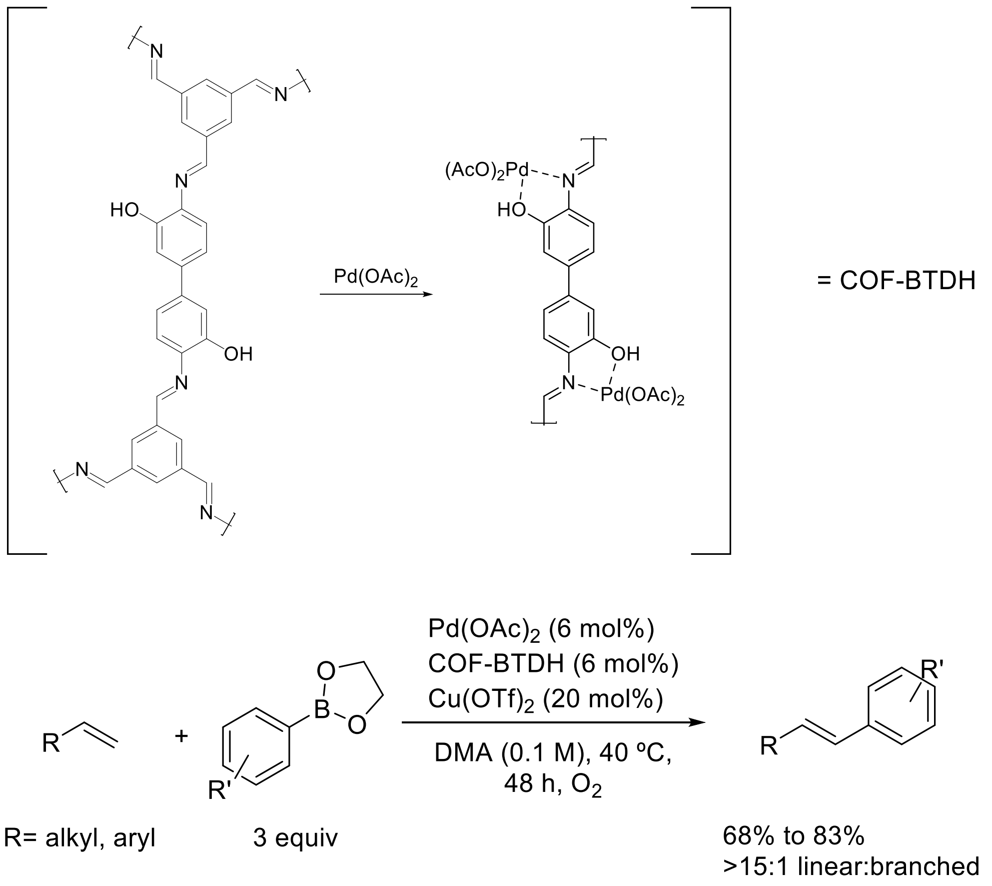
Finally, the group of Ji reported the use of covalent organic frameworks (COFs) as ligands for the oxidative Heck reaction.[108] They synthetized a Schiff base-COF, that could coordinate the palladium present on the reaction media to catalyze the oxidative Heck reaction with good yields and good selectivity. The catalyst could be used over nine times without losing any

---

[107] Li, W. H.; Li, C. Y.; Xiong, H. Y.; Liu, Y.; Huang, W. Y.; Ji, G. J.; Jiang, Z.; Tang, H. T.; Pan, Y. M.; Ding, Y. J. *Angew. Chem. Int. Ed.* **2019**, *58*, 2448-2453.
[108] Han, J.; Sun, X.; Wang, X.; Wang, Q.; Hou, S.; Song, X.; Wei, Y.; Wang, R.; Ji, W. *Org. Lett.* **2020**, *22*, 1480-1484.

activity by single filtration (Scheme 45). However, at the tenth cycle both yield and selectivity dropped significantly even though no palladium leaching was found by ICP. The authors reported that this was due to the collapse of the crystalline structure of the COF.

Interestingly, despite this report on the use a COF catalyst for the oxidative Heck reaction, to the best of our knowledge, no example of a MOF acting as heterogeneous catalyst for this transformation has been reported to date.



Scheme 45.eterogeneous oxidative Heck reaction using POPs as ligands.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

5. OBJECTIVES

As mentioned above in the introduction, the development of new methodologies that allow to perform reactions with heterogeneous catalysts is of high importance. Moreover, the C-C forming reactions are crucial in the synthesis of bioactive and natural compounds and many of those reactions involve palladium as catalyst. So, it's highly important to develop heterogenous catalyst based on palladium that can perform those reactions.

The group of Prof. Guillermo Mínguez Espallargas (ICMOL, Univ. Valencia) developed a MOF (Figure 3) consisting of triangular $[Fe_3(\mu_3O)(COO)_6]^+$ as nodes and a square planar Pd^{II} metalloligand $PdCl_2(H_2PDC)_2$ where H_4PDC is the pyridine-3,5-dicarboxylic acid. The structure of the obtained MOF is a cubic system isoreticular to the MIL-127.[109] Some interesting features of this MOF are its high chemical stability towards different organic solvents and temperature; its porous nature and the availability of the palladium(II) centers.

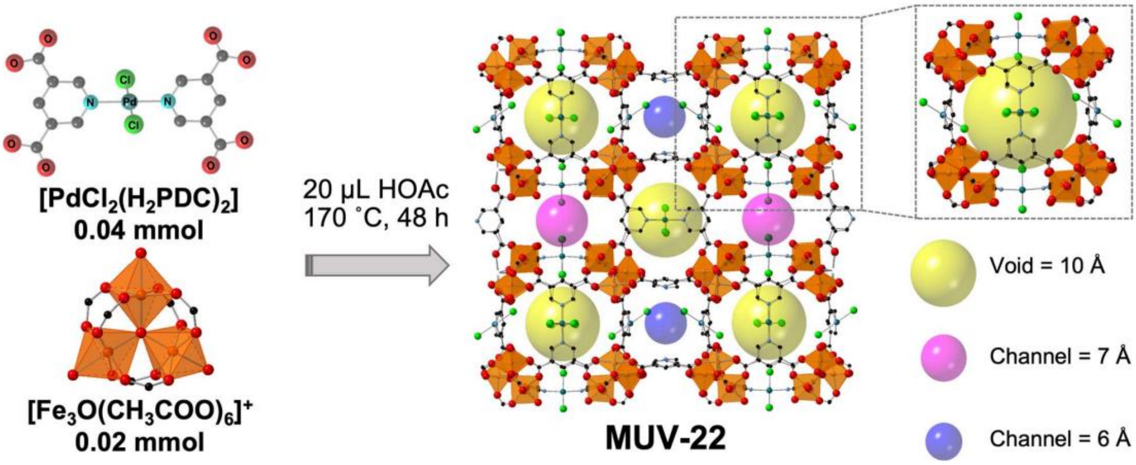


Figure 3. Synthesis and structure of MUV-22 (Reproduced from Miguel-Casañ, E.; Darawsheh, M. D.; Fariña-Torres, V.; Vitórica-Yrezábal, I. J.; Andres-Garcia, E.; Fañanás-Mastral, M.; Mínguez Espallargas, G.; *Chem. Sci*. 2023, 14, 179-185 with permission from the Royal Society of Chemistry).

---

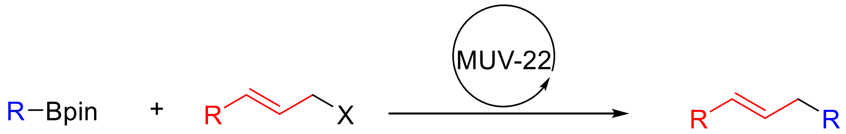
[109] Chevreau, H.; Permyakova, A.; Nouar, F.; Fabry, P.; Livage, C.; Ragon, F.; Garcia-Marquez, A.; Devic, T.; Steunou, N.; Serre, C.; Horcajada, P. *CrystEngComm* **2016**, *18*, 4094-4101.

Considering these structural features and properties, we envisioned that this bimetallic Fe/Pd MOF bearing a palladium metalloligand could be suitable for palladium-catalyzed reactions.

The repercussion of the allylic substitution reaction during the last decades and its utility in the synthesis of natural and bioactive products were also highlighted. So, due to its great impact, the access to recyclable heterogeneous catalysts that can perform the allylic alkylation is highly desirable.

It is interesting to note that even though the use of heterogeneous catalysts for this reaction has been explored, there are not known examples of the use of MOFs to date. In addition, examples in the literature of the allylic substitution reaction involving organoboron reagents are not widely common and there is only one known example using alkylboron reagents effectively.

The first objective of this thesis is to optimize the reaction of the allylic substrates and boronic acid pinacol esters using MUV-22 as catalyst (Scheme 46) in suitable reaction conditions for its recyclability.



Scheme 46. Proposed allylic alkylation reaction catalyzed by MUV-22.

As a second objective for this thesis the oxidative Heck reaction seemed an interesting option due to its oxidative nature, that could open a way to research into other different oxidative reactions interesting to the industry like the Wacker[110] process for the oxidation of ethylene to acetaldehyde, that nowadays remains one of the few industrial processes relying in homogeneous catalysis.

Based on the work of Itami and co-workers (Scheme 42),[105] we hypothesized that the iron clusters of the MUV-22 could promote the oxidation of the palladium centers in the oxidative Heck reaction. Two of the iron (III) ions present in the nodes of the MOF would get reduced to iron (II) through a single electron transfer (SET) to oxidize the palladium center from Pd^0 to Pd^{II}. After that the iron (II) formed would get oxidized in the presence of oxygen, regenerating the initial state of the MOF.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

[110] Smidt, J.; Hafner, W.; Jira, R.; Sedlmeier, J.; Sieber, R.; Kojer, H.; Rttinger, R. *Angew. Chem.* **1959**, *71*, 176-182.

So, the second objective of this thesis is to optimize the reaction between simple alkenes and boronic acids using MUV-22 as heterogeneous catalyst by finding suitable reaction conditions for its recyclability (Scheme 47).

Scheme 47. Proposed oxidative Heck reaction catalyzed by MUV-22.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA


USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

6. RESULTS AND DISCUSSION


USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

6.1 HETEROBIMETALLIC MOF-CATALYZED SUZUKI-MIYAURA ALLYLATION*

*The results from this section have already been published:

Miguel-Casañ, E.;[a] Darawsheh, M. D.;[a] Fariña-Torres, V.;[b] Vitórica-Yrezábal, I. J.;[c] Andres-Garcia, E.;[a] Fañanás-Mastral, M.;[b] Mínguez Espallargas, G.[a] Chem. Sci. **2023**, *14*, 179-185.

[a]Instituto de Ciencia Molecular (ICMol), Universidad de Valencia, 46980, Paterna, Spain.

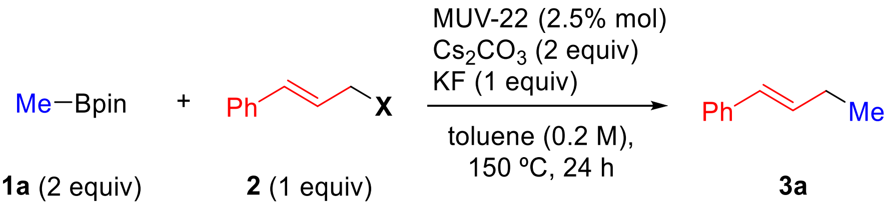
[b]Centro Singular de Investigación en Química Biolóxica e Materiais Moleculares (CiQUS), Departamento de Química Orgánica, Universidade de Santiago de Compostela, 15782, Santiago de Compostela, Spain.

[c]School of Chemistry, University of Manchester, Oxford Road, Manchester M13 9PL, UK.

6.1.1 Optimization

We first explored the role of the allyl substrate's leaving group in the proposed transformation (Table 1). By running the reaction at 150 ºC and using toluene as solvent, cesium carbonate (2 equiv) as base and potassium fluoride (1 equiv) as additive, the use of cinnamyl bromide led to the desired product in 35% yield (entry 1). The use of cinnamyl chloride led to an increased 50% yield (entry 2). In contrast, diminished reactivity was observed when acetate or carbonate were used as leaving groups (entries 3 and 4). Despite product being obtained in these preliminary reactions, in all cases MUV-22 was recovered with a color change (it became a black solid), likely meaning that it was decomposing under these reaction conditions. Based on this observation, we ran the reaction with the two best performing substrates at a lower temperature (120 ºC). Under these new conditions, cinnamyl chloride gave rise to the product in 37% yield with incomplete conversion (entry 5). A better performance was observed for cinnamyl bromide which furnished the product in 47% yield (entry 6). The positive observation was that at this lower temperature MUV-22 could be recovered in its original shape.

Table 1. Screening of leaving groups



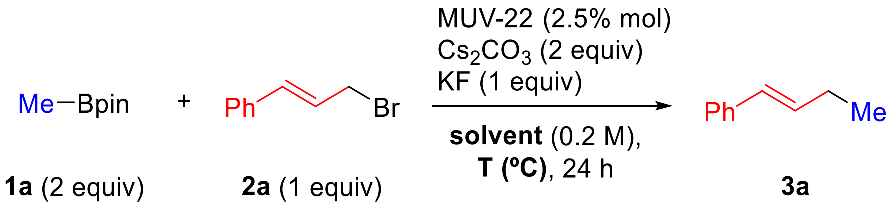
1a (2 equiv) **2** (1 equiv) **3a**

Entry	*T⁰ (ºC)*	*Leaving group*	*Conversion (%)^b*	*Yield (%)^b*
1	150	Br	Full	35
2	150	Cl	Full	50
3	150	OAc	35	22
4	150	OBoc	59	7
5	120	Cl	87	37
6	120	Br	Full	47

[a]Reactions were performed on a 0.2 mmol scale. [b]Determined by ^{1}H-NMR analysis using 1,3,5-trimethoxybenzene as internal standard.

With that information in hand, we selected cinnamyl bromide as the model allylic substrate and proceeded to evaluate the effect different solvents at different temperatures (Table 2). The use of 1,4-dioxane generally resulted in lower yields when compared with toluene. Best result was observed when reaction was carried out at 90 ºC, obtaining the product in 58% yield (entry 5).

Table 2. Screening of solvents and temperatures

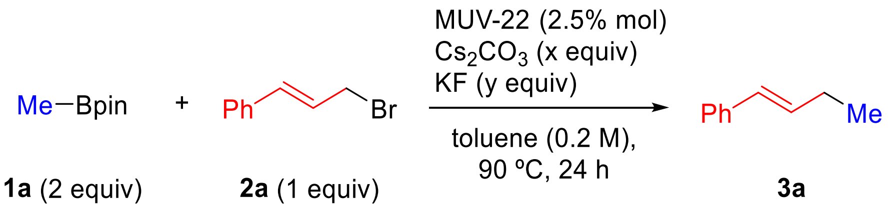


Entry	*Solvent*	*T^{0} (^{0}C)*	*Conversion (%)^{b}*	*Yield (%)^{b}*
1	1,4- dioxane	60	47	8
2	1,4- dioxane	90	96	23
3	1,4- dioxane	120	Full	32
4	toluene	60	31	-
5	toluene	90	96	58

[a]Reactions were performed on a 0.2 mmol scale. [b]Determined by ^{1}H-NMR analysis using 1,3,5-trimethoxybenzene as internal standard.

Finally, base and additive stoichiometry was examined (Table 3). These screening studies revealed that 2 equivalents of Cs_2CO_3 and 1 equivalent of KF is the optimal combination. Nevertheless, it is interesting to note that the reaction does not work in the absence of base, while it does so in the absence (or with less amount of KF) albeit in lower yields (entries 2 and 4).

Table 3. Screening of additive amounts



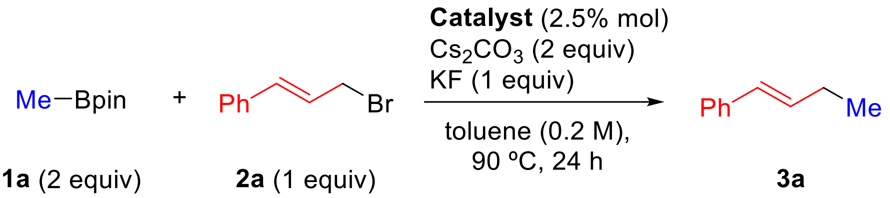
Entry	*Cs_2CO_3 equivalents*	*KF equivalents*	*Conversion (%)^{b}*	*Yield (%)^{b}*
1	2	1	100	58
2	2	0	100	45
3	0	1	3	-
4	2	0,5	100	40
5	1	1	55	41
6	1	0	49	33
7	3	0	100	44

[a]Reactions were performed on a 0.2 mmol scale. [b]Determined by ^{1}H-NMR analysis using 1,3,5-trimethoxybenzene as internal standard.

6.1.2 Comparison with different Pd catalysts

To highlight the value of using MUV-22 as a catalyst for this reaction, we run out a comparison with different homogeneous and heterogeneous palladium catalysts (Table 4), as well as with MUV-22 monomers, the iron cluster and the palladium metalloligand. When palladium homogeneous catalysts were used lower yields were observed, despite of using a four times higher catalyst loading (entry 3). Pd-PEPPSI-IPr was tested due to its efficacy in the allylic alkylation of diborylmethane reagents (See Introduction) but lower yields were obtained. The use of other heterogeneous catalysts such as palladium hydroxide over carbon also resulted also in lower yields (entry 5). Interestingly, when the palladium metalloligand (entry 6) and the iron cluster (entry 7) were used separately, allylation product was obtained in significantly lower yield. Similarly, the combination of both metallic monomers led to a diminished yield (entry 8). Although bimetallic catalysis in which the iron metallic cluster activates the allylic substrate as a Lewis acid catalyst[111] cannot be discarded at this point, these results suggest that the superior catalytic activity of MUV-22 might be due to a structural confinement effect.

Table 4. Comparison of different catalysts.



1a (2 equiv) **2a** (1 equiv) **3a**

Entry	*Catalyst (x mol%)*	*Conversion (%)*^{a}	*Yield (%)*^{a}
1	**MUV-22 (2.5 mol%)**	100	58
2	None	75	-
3	$Pd(OAc)_2$ (10 mol%)	100	20
4	Pd-PEPPSI-IPr (2.5 mol%)	100	41
5	$Pd(OH)_2/C$ (2.5 mol%)	100	43
6	$PdCl_2(H_2PDC)_2$ (2.5 mol%)^b	100	42
7	$Fe_3O(OAc)_6(ClO_4)$ (1.7 mol%)^c	87	18
8	$PdCl_2(H_2PDC)_2$ (2.5 mol%)^b $Fe_3O(OAc)_6(ClO_4)$ (1.7 mol%)^c	100	41

^{a}Determined by ^{1}H-NMR analysis using CH_2Br_2 as internal standard. ^{b}Linker of MUV-22. ^{c}Metal cluster of MUV-22.

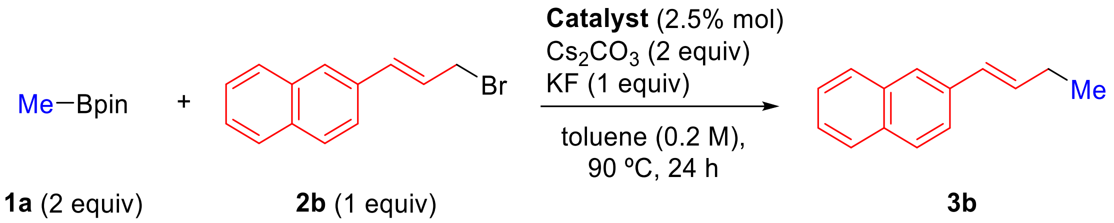
Furthermore, comparison of the catalytic activity in the coupling of Me-Bpin with a larger substrate (i.e. (*E*)-2-(3-bromoprop-1-en-1-yl) naphthalene) demonstrates a more drastic difference in reactivity probably due to the confinement effect (Table 5).

---

[111] Rivera-Chao, E.; Mitxelena, M.; Varela, J. A.; Fañanás-Mastral, M. *Angew. Chem. Int. Ed.* **2019**, *58*, 18230-18234.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Table 5. Comparison of MUV-22 vs monomers with a larger substrate.



Entry	*Catalyst (x mol%)*	*Conversion (%)^a*	*Yield (%)^a*
1	MUV-22 (2.5 mol%)		45
2	$PdCl_2(H_2PDC)_2$ (2.5 mol%)^b $Fe_3O(OAc)_6(ClO_4)$ (1.7 mol%)^c		18

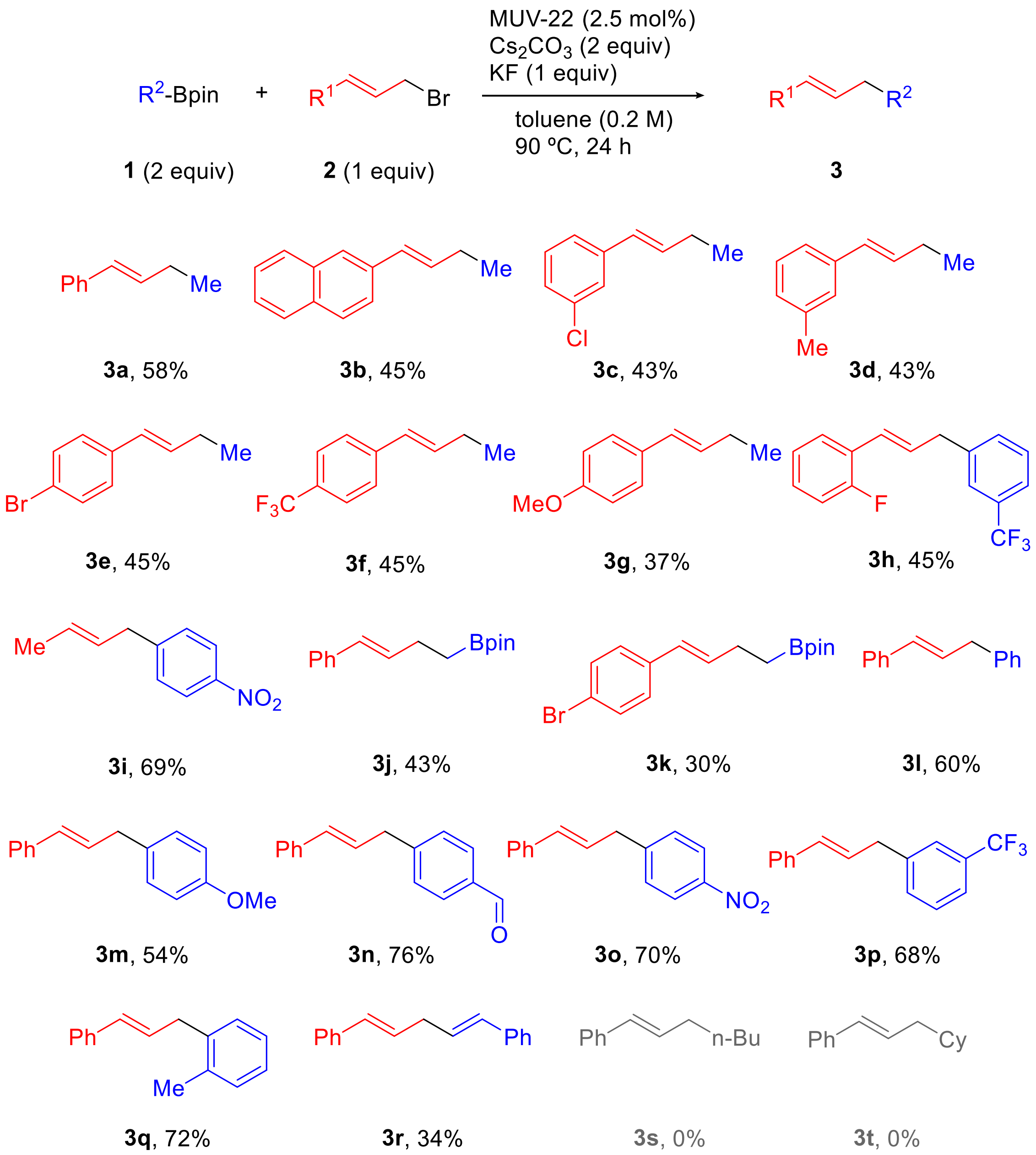
^{a}Determined by ^{1}H-NMR analysis using CH_2Br_2 as internal standard. ^{b}Linker of MUV-22. ^{c}Metal cluster of MUV-22.

6.1.3 Reaction scope

Having established the optimal conditions for the reaction (Table 3, entry 1), we proceeded to study the generality and the limitations of the system (Scheme 2.20). Different allylic bromides bearing all kind of substitution patterns in the aryl ring were used obtaining moderate yields for *meta*- and *para*- substitution (**3a-3g**). However, *ortho*- substitution (**3h**) led to moderate yields even in the presence of a more reactive aromatic boronic pinacol acid ester. Crotyl bromide was used as an example of alkyl allylic bromide and gave rise to the product in good yields, but in a mixture 2:1 of regioisomers (**3I-3I'**).

Then, we explored different boronic pinacol acid esters. Other alkyl boronic acid esters could be used such as diborylmethane obtaining homoallylboronates (**3j-3k**). However, aliphatic groups bearing hydrogen atoms in the β-position of the chain failed to provide the corresponding products, likely due to competitive β-hydride elimination pathways. Aryl boronic acid esters bearing all kinds of substitution in the aryl ring led to the products in good yields (**3l-3q**) and to our delight a skipped diene (**3r**) could be synthetized from an alkenyl boronic pinacol acid ester even in low yields.

Scheme 48. Scope and limitations of the reaction.



6.1.4 Stability studies

Next, we moved on to evaluate the stability of the MUV-22 in the reaction media. For this purpose, we performed several analyses to ensure the MOF was maintaining its structure and it was not decomposing.

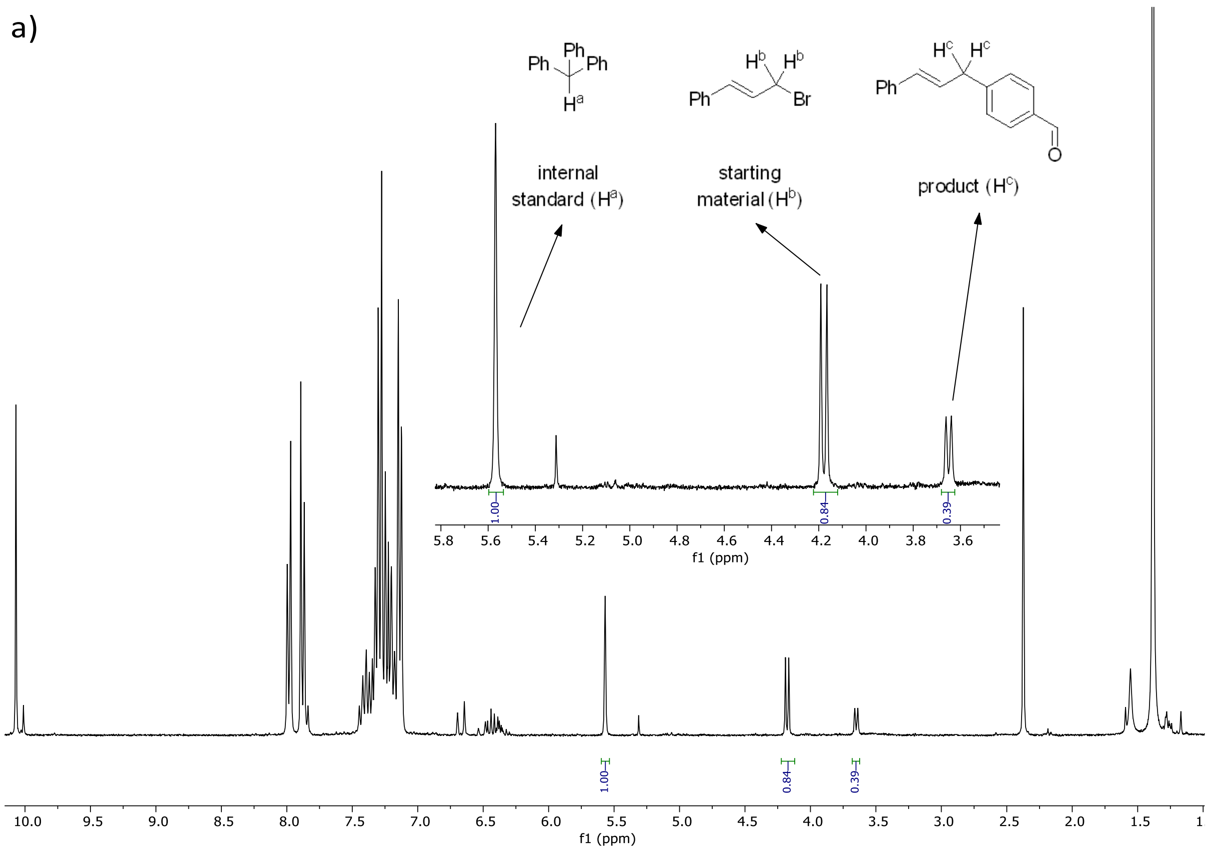
6.1.4.1 Leaching experiments

To test the heterogeneous nature of the catalyst, we performed a series of leaching test experiments.

For this purpose, we analyzed in different ways the reaction crude, to know if any palladium coming from the MUV-22 was dissolving in the solvent, meaning that palladium would be working as a homogeneous catalyst.

6.1.4.2 Hot filtration test

First of all, we performed a hot filtration test, in which we performed the reaction using 4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzaldehyde as substrate in the adding triphenylmethane as internal standard. After one hour (Figure 4a), we filtered the reaction crude via canula to a new reaction vessel. Treatment of the filtrate with more base and additive under the same reaction conditions did not lead to any further formation of the product (Figure 4b), as analyzed by ^{1}H-NMR, thus establishing that no palladium leaches out of the MOF and excluding any homogeneous pathway.



USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

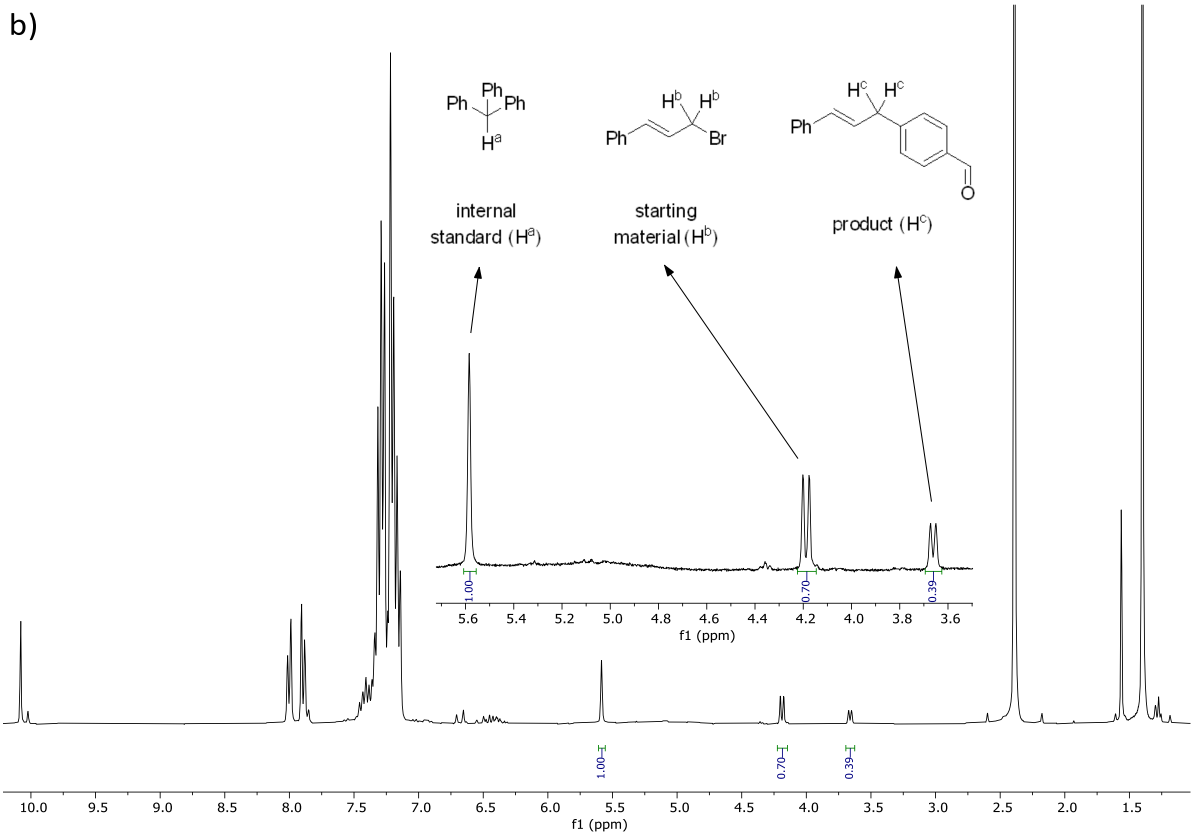


Figure 4. a) ^{1}H-NMR spectra of the reaction after 1 hour b) ^{1}H-NMR spectra of the reaction after 2 hours after filtration.

This allowed us to conclude that homogeneous palladium was not working as catalyst for the reaction. However, this experiment was not conclusive to elucidate whether the MUV-22 was decomposing or not in the reaction media, so further studies needed to be done.

6.1.4.3 ICP-MS test

We also performed an analysis of the reaction crude and measure the amount of the palladium that was dissolved. After the analysis by ICP-MS in which the sample was atomized and ionized in plasma to determine which ions were present in the solution. A palladium concentration of 219 mg/L was found. This value would correspond to a 0.04% of the initial palladium amount added with the MUV-22. This result allowed us to conclude that no palladium leaching was occurring during the reaction.

6.1.4.4 XRPD and EDX analysis

In collaboration with the group of Prof. Guillermo Mínguez Espallargas (ICMOL, Univ. Valencia), we determined the crystalline structure of the recovered MUV-22 after catalysis by X-ray powder diffraction. This technique provides the diffractogram of the sample which successfully compared with the freshly synthetized MUV-22 monocrystal (Figure 5).

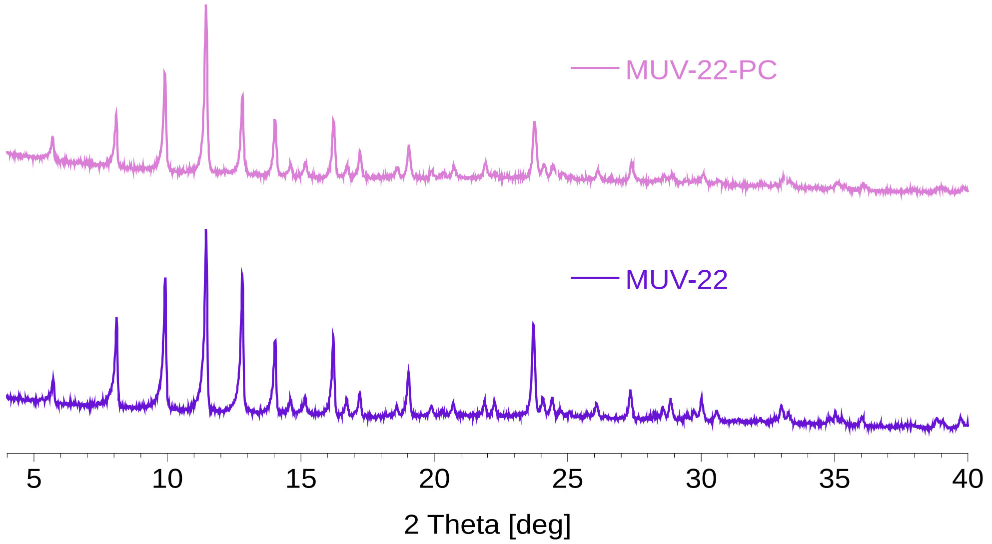


Figure 5. XRPD of MUV-22-PC (post catalysis) compared with as synthetized MUV-22 (Reproduced from Miguel-Casañ, E.; Darawsheh, M. D.; Fariña-Torres, V.; Vitórica-Yrezábal, I. J.; Andres-Garcia, E.; Fañanás-Mastral, M.; Mínguez Espallargas, G.; *Chem. Sci*. 2023, 14, 179-185 with permission from the Royal Society of Chemistry).

The EDX microanalysis is an elemental analysis technique that allows to know the ratios of the different elements in the sample by exciting it with X-ray radiation and analyzing its emission spectra. Surprisingly, when the analysis of the recovered solid was performed a change was observed (also done in collaboration with the group of Prof. Guillermo Mínguez). The chlorine atoms in the structure disappeared and they were substituted by fluorine atoms (Figure 6). Curiously, when the MOF was mixed with KF in the reaction conditions without substrate the exchange was not observed. Thus, this phenomenon could be due to a ligand exchange in one of the reaction intermediates.

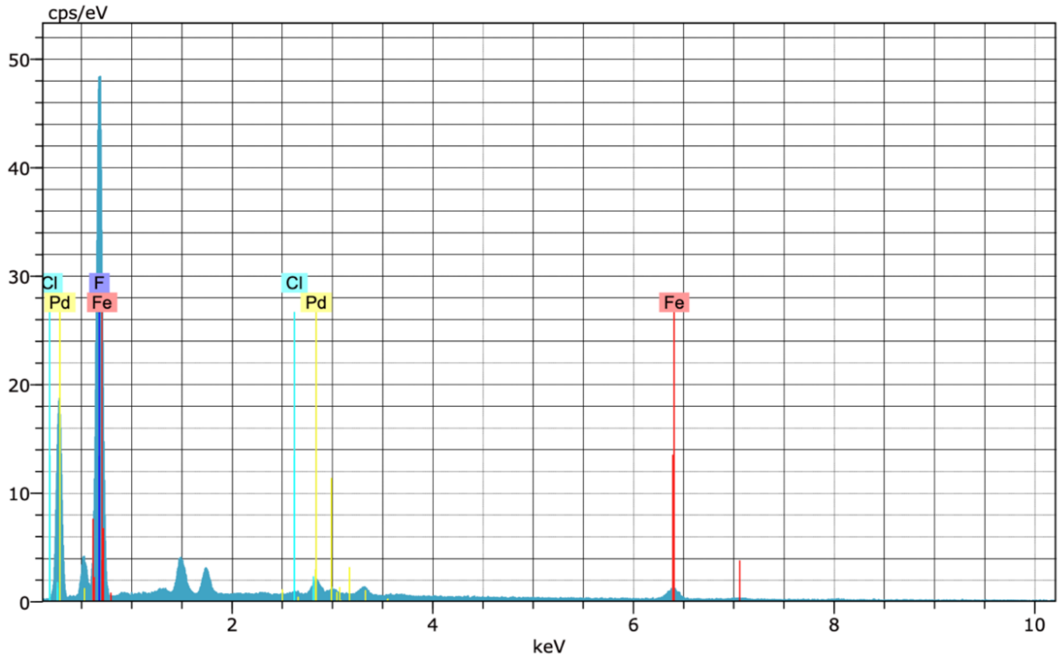
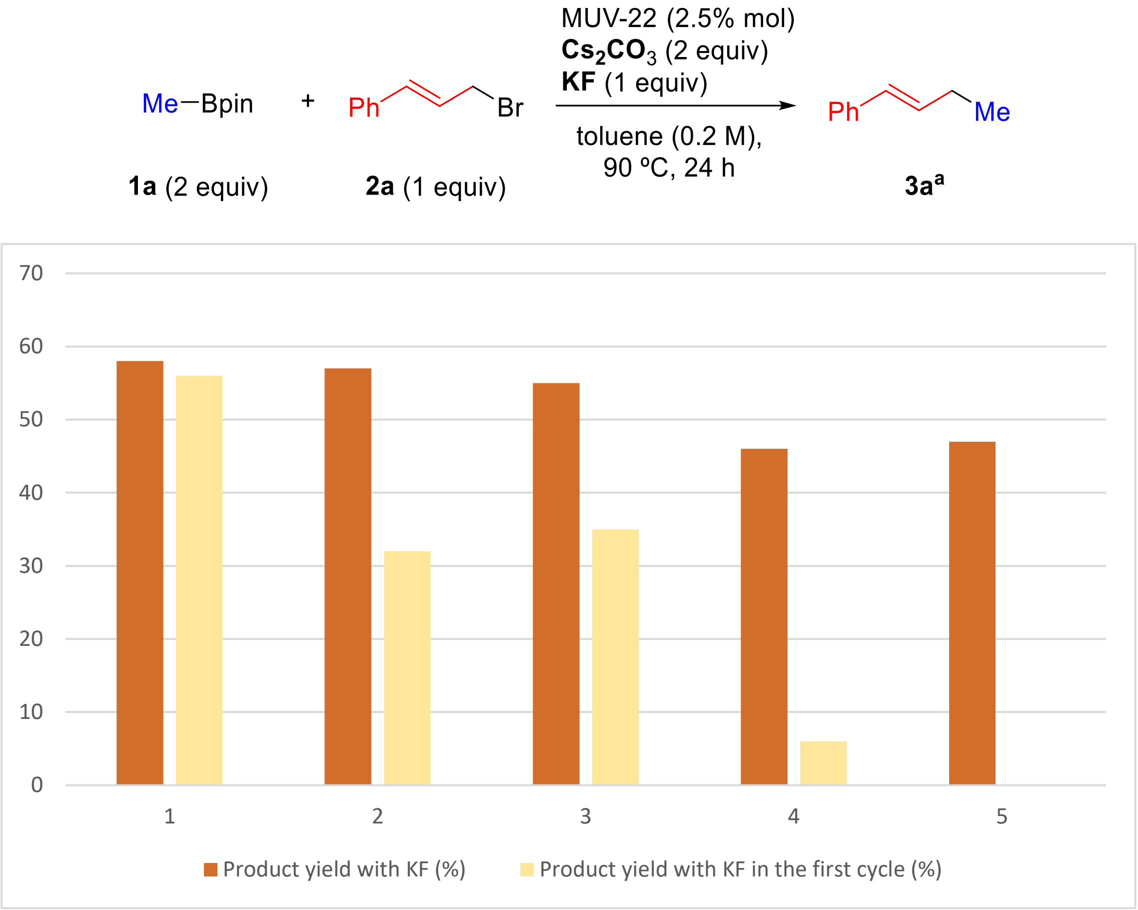


Figure 6. EDS of MUV-22-PC showing fluorine exchange with chlorine. The Pd:Fe ratio remains as 1.0:2.0. The blue line indicates where the peak of the chlorine atoms should be observed (Reproduced from Miguel-Casañ, E.; Darawsheh, M. D.; Fariña-Torres, V.; Vitórica-Yrezábal, I. J.; Andres-Garcia, E.; Fañanás-Mastral, M.; Mínguez Espallargas, G.; *Chem. Sci*. 2023, 14, 179-185 with permission from the Royal Society of Chemistry).

6.1.4.5 Recycling experiments

To highlight the utility of the MUV-22 as catalyst we proceeded to test its recyclability.

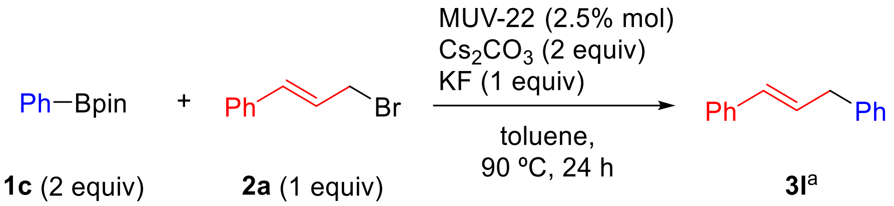
To our delight, we found out that MUV-22 could perform up to 5 reaction cycles without significant loss of activity (Figure 7, brown bars). Surprisingly, the use of KF was essential to keep the level of recyclability. When KF was not renewed after the first cycle a significant decrease in catalytic efficiency was observed after the second cycle, which ended up in catalyst deactivation after the fourth cycle (Figure 7, yellow bars). Furthermore, when the first reaction was run in the absence of KF, no product formation was observed already in the second cycle.

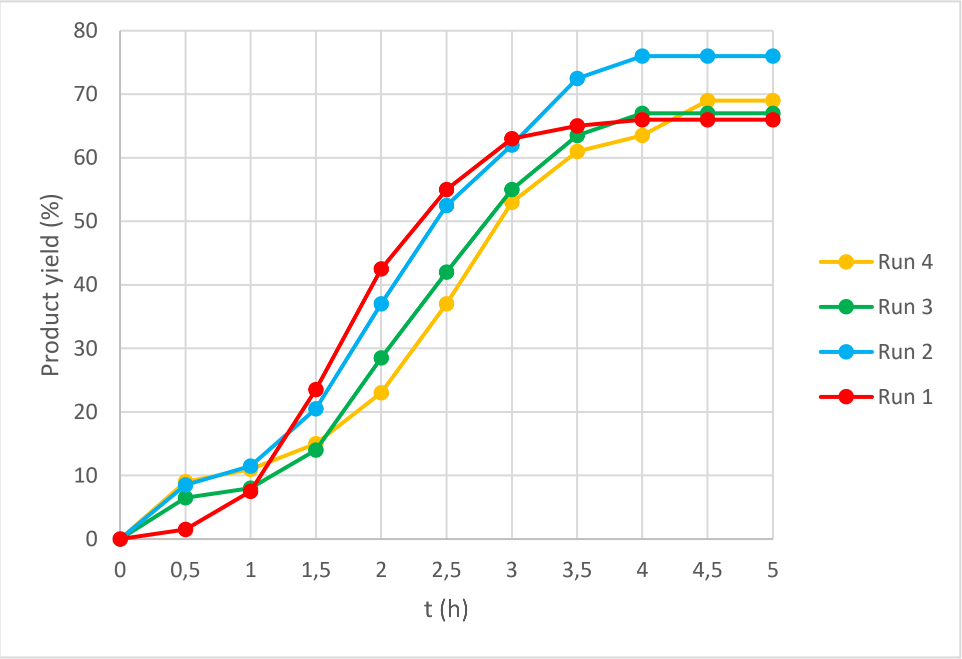


[a]Yields determined by ^{1}H-NMR analysis using 1,3,5-trimethoxybenzene as internal standard.

Figure 7. Consecutive reaction cycles.

To ensure that the catalyst was not partially decomposing in the reaction media, we performed a kinetic study, taking aliquots from the reaction media at different times for each reaction cycle to compare them. For making these experiments we chose the reaction involving the use of phenyl boronic pinacol acid ester due to its shorter reaction times, so the reactions could be followed easier. These kinetic studies (Figure 8) revealed that the rate and yield of the reaction are essentially maintained between these four runs, which demonstrates that MUV-22 is robust and maintains its activity.



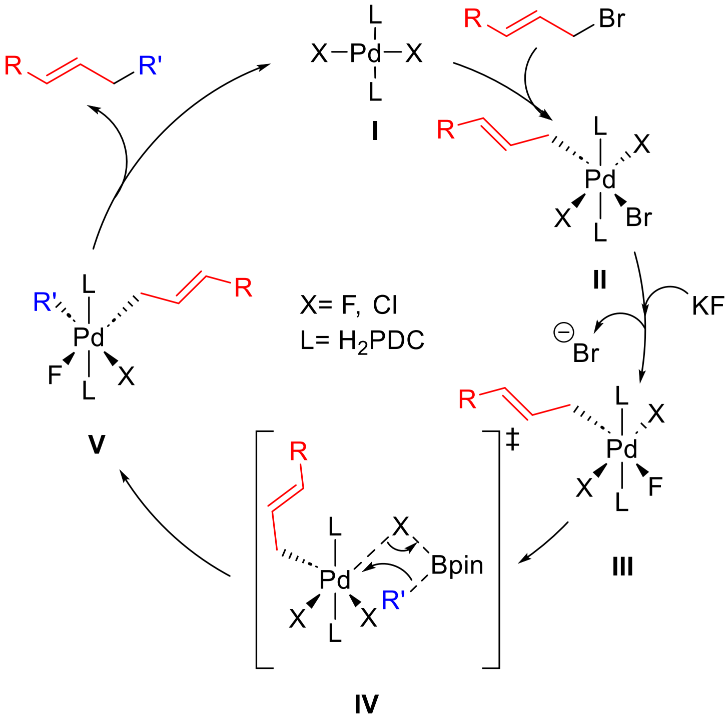


[a]Yields determined by ^{1}H-NMR analysis using 1,3,5-trimethoxybenzene as internal standard.

Figure 8. Kinetic study for consecutive runs.

6.1.5 Mechanistic proposal

To explain the observed results, we proposed the following reaction mechanism (Scheme 48). It starts with the coordination of the palladium metalloligand **I** to the double bond of the allylic substrate followed by an oxidative addition giving intermediate **II**. After the oxidative addition, a ligand exchange would occur with the KF present in the reaction media and liberating a bromine ion to form intermediate **III**, this step would explain the exchange of the original chlorine atoms in the MUV-22 by fluorine atoms observed in the EDX microanalysis after the catalysis.[112] Next, a transmetalation would happen likely through a concerted transition state **IV** with the boronic acid pinacol ester to give the intermediate **V**. Finally, this intermediate suffers a reductive elimination releasing the final product and regenerating the metalloligand **I**. Even the mechanism could operate through both Pd^0/Pd^{II} or Pd^{II} /Pd^{IV} the absence of Pd^0 in the XPS analysis makes the Pd^{II} /Pd^{IV} cycle more likely.



Scheme 48. Proposed mechanism for the Suzuki-Miyaura type allylation reaction.

---

[112] Amatore, C.; Le Duc, G.; Jutand, A. *Chem. Eur. J.* **2013**, *19*, 10082-10093.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

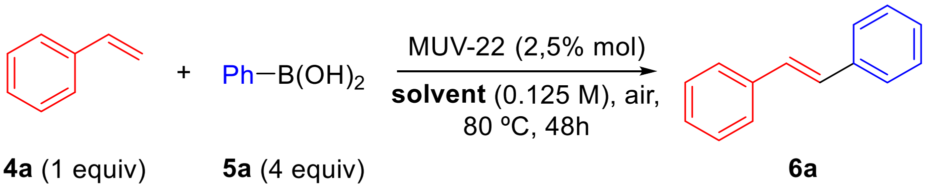
6.2 HETEROBIMETALLIC MOF-CATALYZED OXIDATIVE BORON HECK COUPLING

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

6.2.1 Optimization

We began our investigation by exploring the reaction between styrene and phenyl boronic acid in a 1:4 ratio at 80 ºC in dimethylformamide as solvent under air atmosphere with a balloon. To our delight, after 48 hours we obtained the corresponding product in 80% yield. After this promising result, we decided to try to improve the reaction times and efficiency, so we started the optimization studies with a screening of solvents (Table 6). We found out that other polar solvents like 1,4-dioxane (entry 3), acetonitrile (entry 4), dimethylacetamide (entry 5), 1,2-dichloroethane (entry 6) and gave worse results. A more polar solvent like dimethyl sulfoxide (entry 7) led to a similar yield. However, under these conditions all the solid was dissolved meaning that the MUV-22 decomposed in the reaction media. Protic and apolar solvents like isopropanol (entry 8) and toluene (entry 2) respectively did not work well for the transformation. Finally, a mixture of DMF and water (entry 9) was tested, with no reaction after 48 hours and partial MOF decomposition.

Table 6. Screening of solvents.

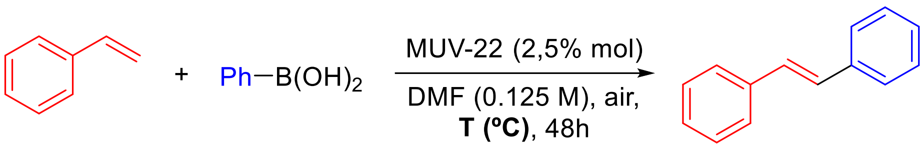


Entry	*Solvent*	*Conversion (%)*^{b}	*Yield (%)*^{b}
1	DMF	90	83(80)
2	Toluene	7	5
3	1,4-dioxane	28	25
4	MeCN	50	45
5	DMA	12	10
6	DCE	5	-
7	DMSO	91	82
8	IPA	35	31
9	DMF:H_2O (1:1)	3	-

^{a}Reactions were performed on a 0.1 mmol scale. ^{b}Determined by ^{1}H-NMR analysis using 1,3,5-trimethoxybenzene as internal standard. Isolated yield in brackets.

We moved on and proceeded next with a screening of different temperatures (Table 7). Lower temperature led to lower yields (entry 1). When temperature was increased to 100 ºC (entry 3) a similar outcome than the reaction at 80 ºC (entry 2) was observed. When the temperature was further increased to 120ºC (entry 4) the yield decreased dramatically to a 35%. This could be due to the decomposition of the MUV-22 or the substrates in the reaction media.

Table 7. Screening of temperatures.



4a (1 equiv) **5a** (4 equiv) **6a**

Entry	*T^0 (ºC)*	*Conversion (%)^b*	*Yield (%)^b*
1	60	42	37
2	80	90	83(80)
3	100	80	75
4	120	94	35

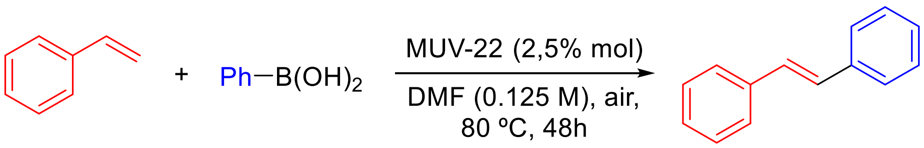
^{a}Reactions were performed on a 0.1 mmol scale. ^{b}Determined by ^{1}H-NMR analysis using 1,3,5-trimethoxybenzene as internal standard. Isolated yield in brackets.

Next, we tried an oxygen atmosphere instead of air. No significative change was observed in the reaction times or yield (Table 3.3, entry 2). Based on this, and for practical reasons, we decided to continue with air atmosphere.

Reducing the amount of boronic acid to a half of the initial resulted in a dramatic drop of yield and conversion (Table 8, entry 3).

Finally, increase in catalyst loading to a 4% mol did not lead to any improvement, so we decided to set the optimal catalyst loading at 2.5% mol (Table 3.3, entry 4).

Table 8. Variations on the reaction conditions.



4a (1 equiv) **5a** (4 equiv) **6a**

Entry	*Variation*	*Conversion (%)^b*	*Yield (%)^b*
1	None	90	83(80)
2	O_2 instead of air	92	85
3	2 equiv of $PhB(OH)_2$	29	25
4	4% mol MUV-22	91	82

^{a}Reactions were performed on a 0.1 mmol scale. ^{b}Determined by ^{1}H-NMR analysis using 1,3,5-trimethoxybenzene as internal standard. Isolated yield in brackets.

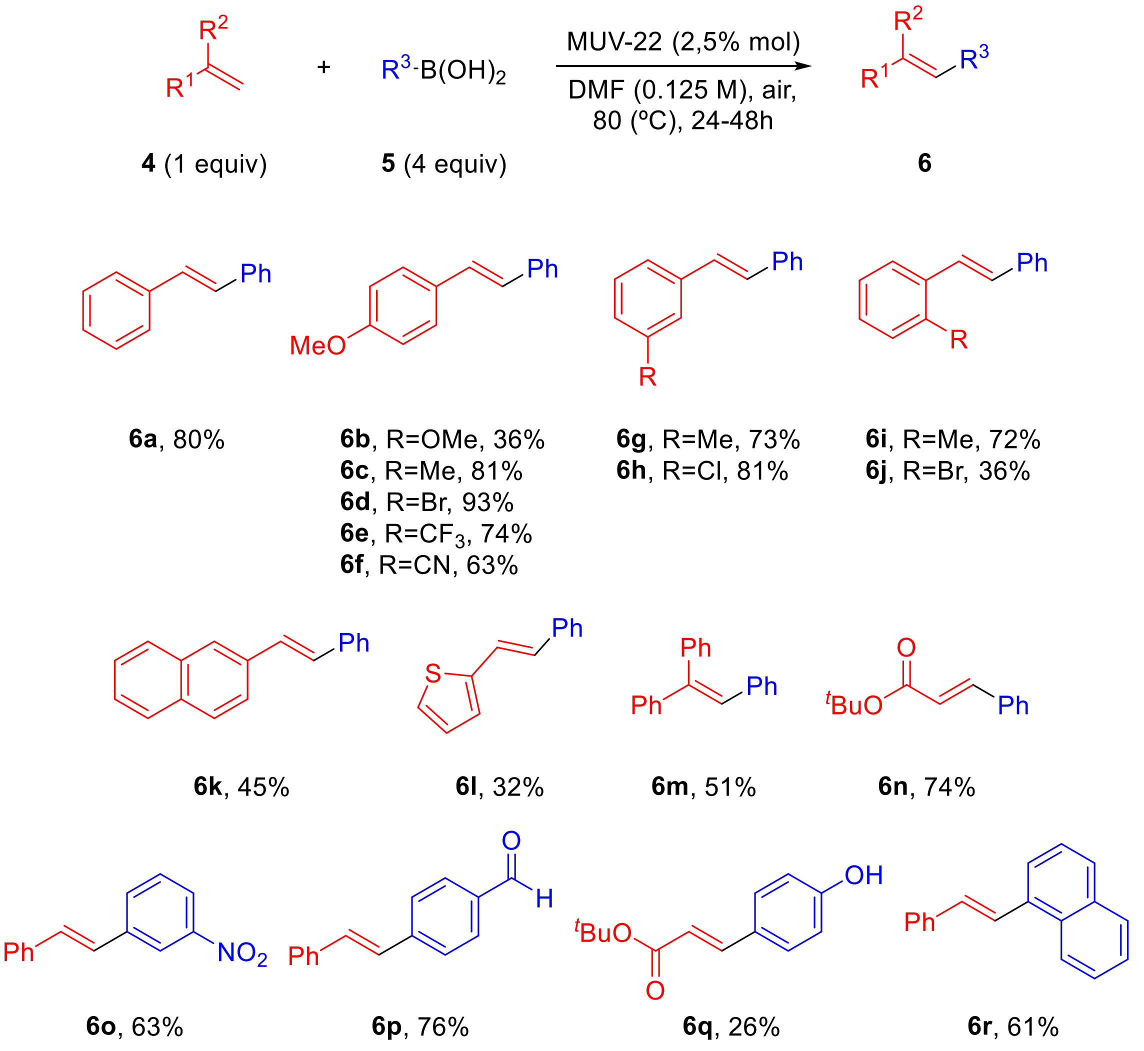
6.2.2 Reaction scope and limitations.

Having established the optimal conditions for the reaction, we proceeded to study the generality and the limitations of the system (Scheme 49).

Different aromatic alkenes bearing all kinds of substitution patterns in the aryl ring were tested (**6a-6j**). Good to excellent yields were obtained in almost all cases regardless the nature or the position of the substituent. Yield was only compromised in cases when there is a strong electron-donating group at the para-position (**6b**) or a bulky substituent in the ortho position (**6j**). Extended aromatic groups (**6k**) or heteroaryl substituent (**6l**) were also tolerated, albeit products were obtained in slightly diminished yield. 1,1-disubstituted olefins (**6m**) proved also efficient for this transformation, as well as acrylates (**6n**).

We next explored different boronic acids. Aryl boronic acids bearing sensitive groups such as nitro (**6o**), aldehyde (**6p**) or even a hydroxy group (**6q**) were compatible with the reaction and afforded the corresponding products in moderate to good yields, besides, the product **6r** is a precursor of the natural product *p*-coumaric acid after a deprotection of the ester group. Similarly, a sterically demanding naphthalene-derived boronic acid (**6r**) proved efficient for this transformation.

Scheme 49. Scope of the reaction.



4 (1 equiv) **5** (4 equiv) **6**

6a, 80%

6b, R=OMe, 36%
6c, R=Me, 81%
6d, R=Br, 93%
6e, R=CF$_3$, 74%
6f, R=CN, 63%

6g, R=Me, 73%
6h, R=Cl, 81%

6i, R=Me, 72%
6j, R=Br, 36%

6k, 45%

6l, 32%

6m, 51%

6n, 74%

6o, 63%

6p, 76%

6q, 26%

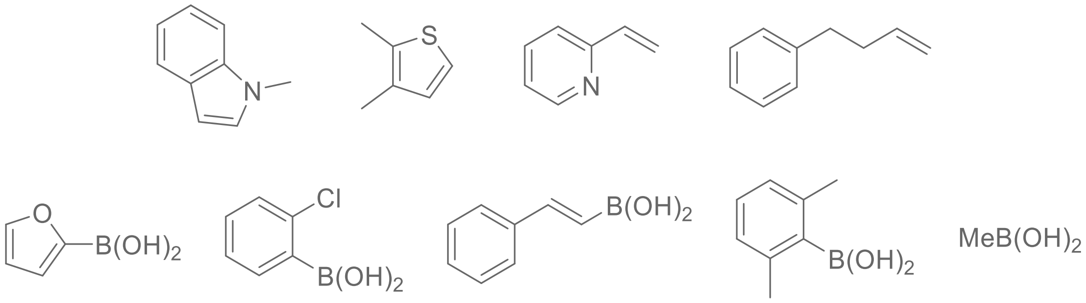
6r, 61%

Unfortunately, heteroaromatic compounds and 2-ethenylpyridine did not show any reactivity. Olefins bearing alkyl substituents with hydrogens in β-position resulted in a complex mixture of isomers probably due to chain walking events. Boronic acids bearing heteroaryl and

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

sterically hindered aryl rings, alkenyl groups or methyl boronic acid were not reactive either (Scheme 50).

Scheme 50. Limitations of the reaction.

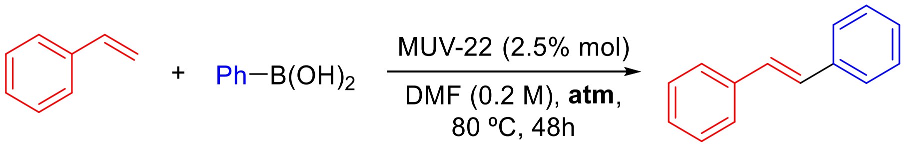


6.2.3 Mechanistic studies

For acquiring better knowledge about the reaction and the possible cooperativity between the two metals present in MUV-22 we run out two different experiments.

The first one consisted in carrying out the standard reaction in Argon atmosphere. Under these conditions the product was obtained in a 10% of yield. However, it is noticeable that in the absence of an oxidant the palladium should only be able to do one catalytic turnover leading to a maximum 2.5% of the product. The higher yield obtained could be explained if the Fe^{III} ions of the metallic cluster were reoxidizing the palladium center as we hypothesized.

Table 9. Comparison of the reaction under air and inert atmosphere.



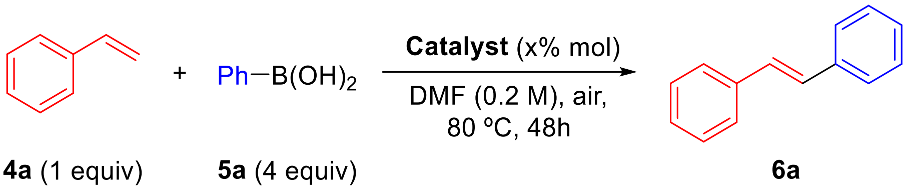
4a (1 equiv) **5a** (4 equiv) **6a**

Entry	*Atmosphere*	*Conversion (%)^b*	*Yield (%)^b*
1	Air	100	83(80)
2	Ar	12	10

^{a}Reactions were performed on a 0.1 mmol scale. ^{b}Determined by ^{1}H-NMR analysis using 1,3,5-trimethoxybenzene as internal standard. Isolated yield in brackets.

The second one consisted of a comparison between the catalytic activity of the MUV-22 itself, the metallic cluster, the metalloligand and both in conjunction (Table 10). This allowed us to know if the structure of the MOF was contributing to the catalytic activity. After setting up the reaction with the monomers, we observed that for the same conditions the amounts of product obtained were lower. This difference could be due to the confinement effect occurring inside the MOF enhancing the reactivity.

Table 10. Comparison of different catalysts.

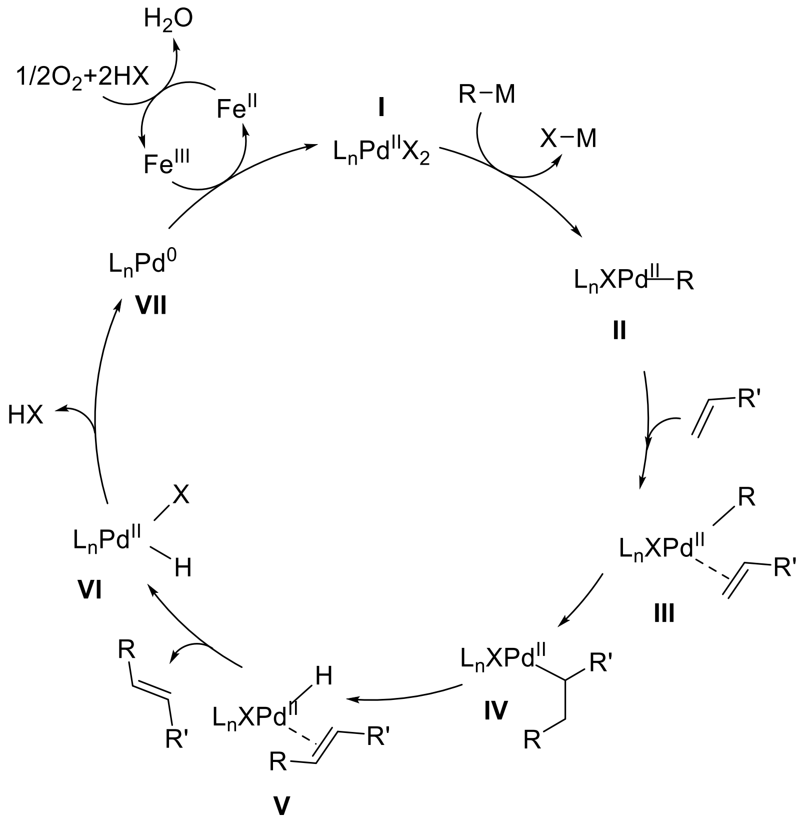


Entry	*Catalyst (x mol%)*	*Conversion (%)*^{b}	*Yield (%)*^{b}
1	MUV-22 (2.5 mol%)	100	83(80)
2	$PdCl_2(H_2PDC)_2$ (2.5 mol%)^{c}	65	53
3	$Fe_3O(OAc)_6(ClO_4)$ (1.7 mol%)^{d}	10	-
4	$PdCl_2(H_2PDC)_2$ (2.5 mol%)^{c} $Fe_3O(OAc)_6(ClO_4)$ (1.7 mol%)^{d}	51	45

^{a}Reactions were performed on a 0.1 mmol scale. ^{b}Determined by ^{1}H-NMR analysis using 1,3,5-trimethoxybenzene as internal standard. Isolated yield in brackets. ^{c}Linker of MUV-22. ^{d}Metal cluster of MUV-22.

6.2.4 Mechanistic proposal

To explain the observed results, we propose the following reaction mechanism (Scheme 51). It starts with the transmetalation from the boronic acid to the palladium to give intermediate **II**. After coordination of the alkene, intermediate **III** is obtained, the palladium undergoes migratory insertion into the olefin leading to the alkylpalladium **IV**, β-hydride elimination gives the alkene coordinated palladium hydride **V**. The release of the final product occurs via alkene dissociation forming the palladium species **VI**, after reductive elimination of HCl, which results in a net loss of a chlorine ligand, a palladium(0) complex **VII** is formed, two SET from the palladium (0) center to two iron(III) ions of the metallic cluster would regenerate the palladium(II) center, and the iron(II) ions would be oxidized by the molecular oxygen present in the air to regenerate the iron(III) ions.



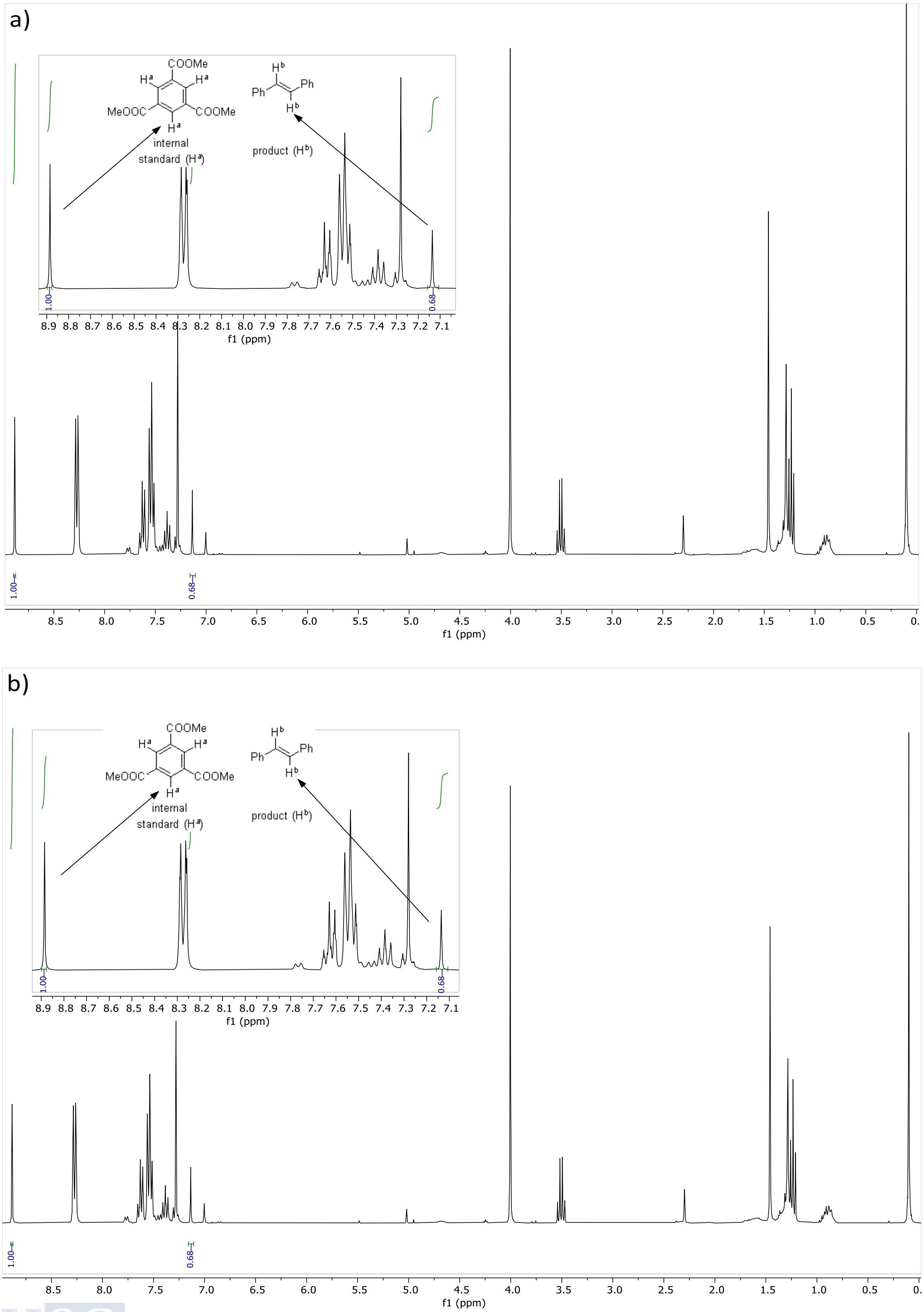
Scheme 51. Proposed mechanism for the oxidative-Heck reaction catalyzed by MUV-22.

6.2.5 Stability studies

Next, we moved on to evaluate the stability of the MUV-22 in the reaction media. For this purpose, we performed several analyses to ensure the MOF was maintaining its structure and it was not decomposing.

6.2.5.1 Leaching experiment

As we did for the allylation reaction described in chapter II, we performed a hot filtration test to rule out that palladium leaches out to the solution and becomes a homogeneous catalyst. Using the standard conditions and adding trimethyl benzene-1,3,5-tricarboxylate as internal standard, at 24 hours the reaction crude was filtered to a new vessel, an aliquot was taken and analyzed by ^{1}H-NMR and GC-MS and after an additional 24 hours was analyzed again (Figure 9). For both reaction times the conversion remained a 55% and the product yield a 35% meaning that a homogenous pathway was not occurring for the reaction.

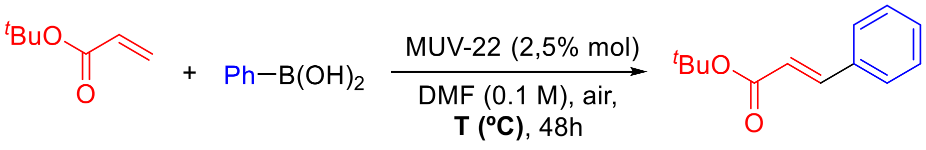


USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

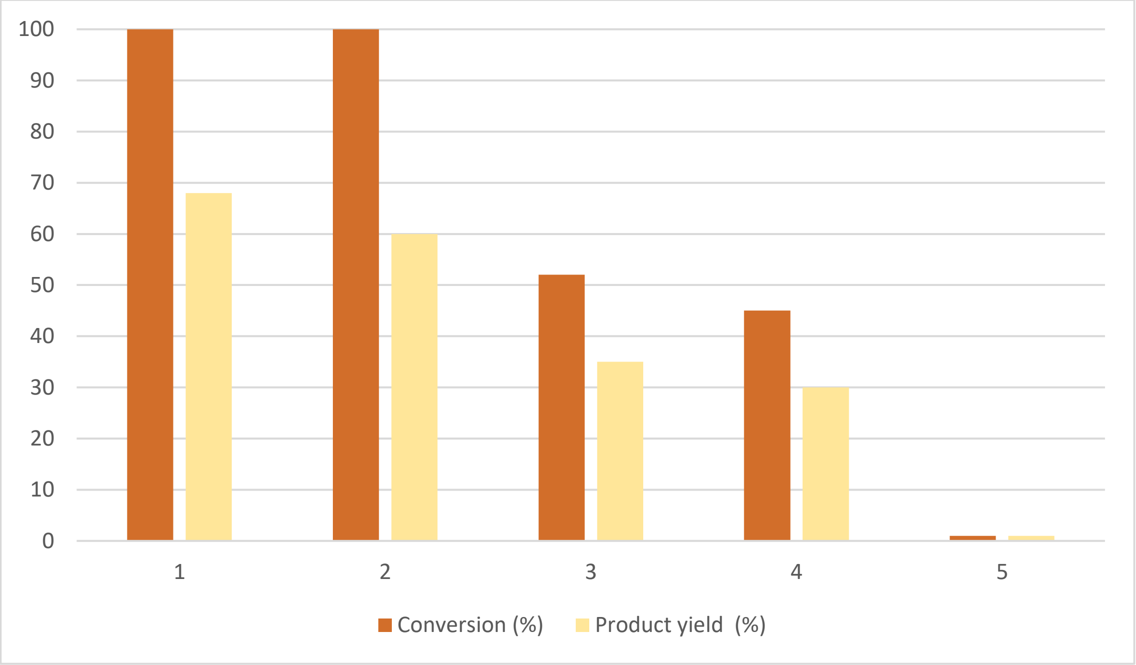
Figure 9. a) ^{1}H-NMR spectra of the reaction after 24 hours b) ^{1}H-NMR spectra of the reaction after 48 hours after filtration.

6.2.5.2 Recycling experiments

Next, to ensure that MUV-22 was not decomposing under reaction conditions, we proceeded to test its recyclability. We performed the experiment during several reaction cycles at 24 hours. While the catalytic activity remained intact after two cycles, unfortunately, when the reaction was set for the third time the product yield dropped (Figure 10). This could be due to the decomposition of the MUV-22 in the reaction media. Thus, we decided to perform further analysis to get insight into this issue and discard any other factors that may be affecting the reactivity of the MOF.



4a (1 equiv) **5a** (4 equiv) **6a**[a]



[a]Yields determined by ^{1}H-NMR analysis using 1,3,5-trimethoxybenzene as internal standard.

Figure 10. Consecutive reaction cycles.

6.2.5.3 EDX analysis

In collaboration with the group of Prof. Guillermo Mínguez Espallargas (ICMOL, Univ. Valencia), we measured the elemental ratios of the palladium, iron and chlorine atoms in the sample recovered after the catalysis (Figure 11). Pitifully, the ratios indicated that a partial decomposition of the MUV-22 was occurring after the catalysis, one out of the two chlorine atoms bounded to the palladium were lost and some palladium leached out from the structure.

This confirms an intrinsic problem in the reductive elimination step of the proposed mechanism, in which one of the chlorine bonds is lost in every catalytic turnover, likely causing the collapse of the MOF's structure.

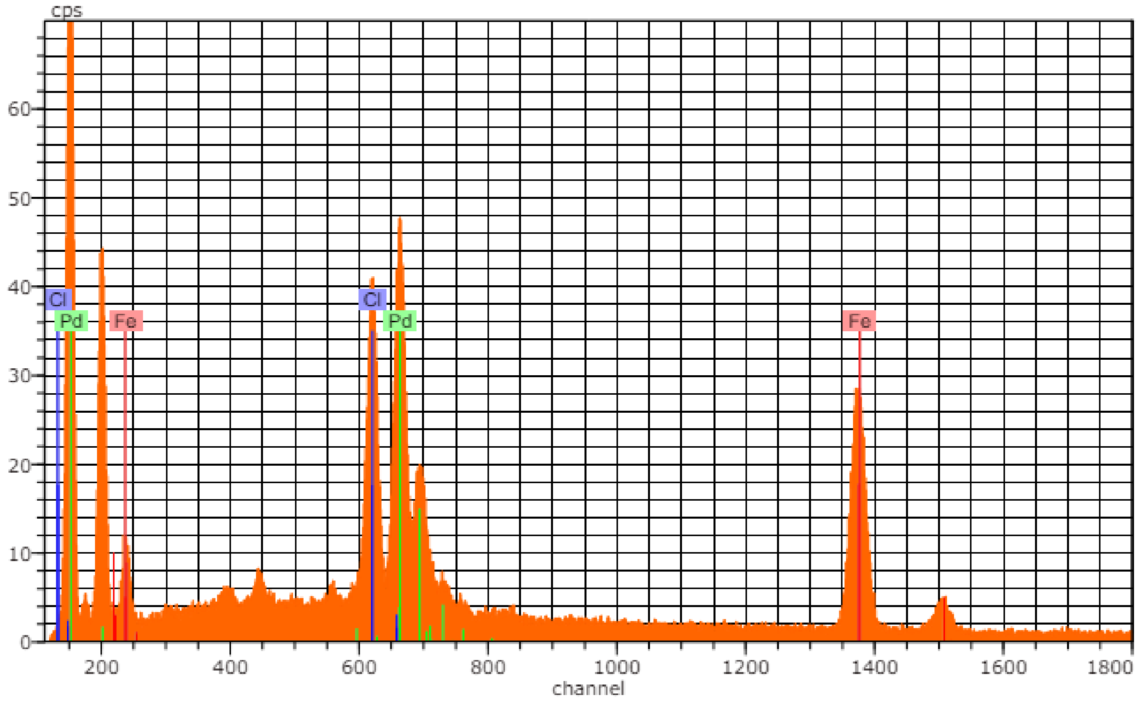


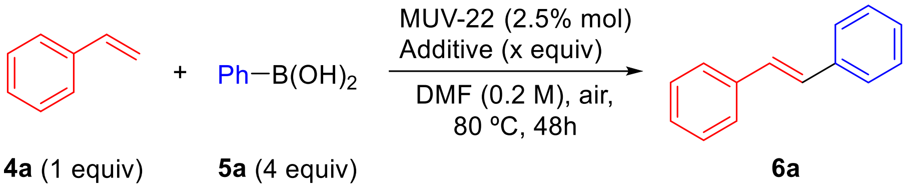
Figure 11. EDS of MUV-22-PC for the oxidative Heck reaction. The Pd:Fe:Cl ratio shifts from the original 1.0:2.0:2.0 to 1.0:2.4:1.0 indicating decomposition.

6.2.6 Additive screening

Even though the MUV-22 was decomposing in the reaction media, we envisioned that maybe with some additives we could overcome this problem as for the allylic alkylation reaction (Table 10).

According to the proposed mechanism, one of the chlorine ligands is eliminated through the reductive elimination step. We thought that adding an anion source to the reaction media could help to fix this loss. When lithium chloride was added no reaction was observed and the MUV-22 was dissolved leading to a yellow solution (Table 10, entry 1). The use of potassium fluoride led to low reactivity(Table 10, entry 2). Acetic acid led to same results as standard conditions (Table 10, entry 3), but when recyclability was evaluated with using it as additive reactivity was dramatically decreased in the second cycle (Table 10, entry 4). Other acids sources such as trifluoroacetic acid resulted in excellent yields but decomposition of the catalyst in a yellow solution (Table 10, entry 5). Finally, as we found that the acid media likely was accelerating the rate of decomposition of the MOF, we decided to add a base to neutralize the acid formed in the reaction media, but no reaction occurred (Table 10, entry 6).

Table 10. Additive screening.



Entry	*Additive*	*Conversion (%)*[b]	*Yield (%)*[b]
1	LiCl	-	-
2	KF	9	6
3	AcOH	Full	86
4[c]	AcOH	20	15
5	TFA	Full	91
6	Cs_2CO_3	<5	<5

[a]Reactions were performed on a 0.1 mmol scale. [b]Determined by ^{1}H-NMR analysis using 1,3,5-trimethoxybenzene as internal standard. Isolated yield in brackets. [c]Second run using the recovered solid.


USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

7. CONCLUSIONS

Regarding the first objective, we have developed a methodology that allows the allylic alkylation, arylation and alkenylation of allylic bromides using boronic pinacol acid esters using a bimetallic Fe/Pd MOF as catalyst.

The catalyst could be used up to five times without any loss in activity. Characterization after the catalysis confirmed that the structure was not compromised during the reaction. The recyclability was analyzed by kinetic studies showing no variability of the yield during the reaction time for the different reaction cycles.

Curiously, the EDX analysis showed a substitution of the chlorine atoms by fluorine atoms. This observation helped us to postulate a feasible mechanism for the reaction.

A comparison was performed with other common palladium catalysts showing that under our conditions MUV-22 was the more efficient catalyst for this transformation.

Regarding the second objective, we have developed a methodology that allows the oxidative Heck reaction with alkenes and boronic acids using a bimetallic Fe/Pd MOF as catalyst with air as sole oxidant probably improved by the iron clusters of the MUV-22 acting as intermediate for the oxidation step.

The catalyst was recycled up to four times. However, the efficiency decreases during each of the runs, and it was demonstrated that the structure of the MOF was compromised after the first cycle through EDX analysis.

Different additives were evaluated in order to overcome the recyclability issue with negative results.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

8. EXPERIMENTAL PART

8.1 GENERAL METHODS

All reactions were performed under argon atmosphere unless otherwise noted using oven dried glassware and using standard Schlenk techniques. Solvents were dried using an MBraun SPS 800 system. All chemicals were purchased from Acros Organics Ltd., Aldrich Chemical Co. Ltd., Alfa Aesar, Apollo, Strem Chemicals Inc., Fluorochem Ltd. or TCI Europe N.V. chemical companies and used without further purification, unless otherwise noted.

Analytical thin layer chromatography was carried out on silica-coated aluminum plates (silica gel 60 F254 Merck) and components were visualized by UV light and $KMnO_4$ staining. Flash column chromatography was performed on silica gel 60 (Merck, 230-400 mesh).

GC-MS analyses were performed in an Agilent instrument GC-8890 equipped with Chemical Ionization (CI) MS-5977B detector.

High Resolution Mass spectrometry was carried out on a Bruker microTOF spectrometer using APCI.

^1H, ^{13}C and ^{19}F NMR spectra were recorded using a Bruker DPX300 (300 MHz), Varian Mercury 300 MHz or Agilent VNMRS-300 MHz NMR spectrometer and Me_4Si as an internal standard. ^{11}B spectra were recorded using a Bruker AVIII 500 MHz. Chemical shift values are reported in ppm with the solvent resonance as the internal standard ($CHCl_3$: δ 7.26 for ^1H, δ 77.16 for ^{13}C). Coupling constants (J) are given in Hertz (Hz). Multiplicities are reported as follows: s = singlet, d = doublet, t = triplet, q = quartet, p = pentet, m = multiplet or as a combination of them.

High-resolution (MALDI-TOF/TOF) mass spectra were recorded in a 5800 MALDI TOF/TOF (ABSciex) in positive reflector mode.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

8.2 HETEROBIMETALLIC MOF-CATALYZED SUZUKI-MIYAURA ALLYLATION

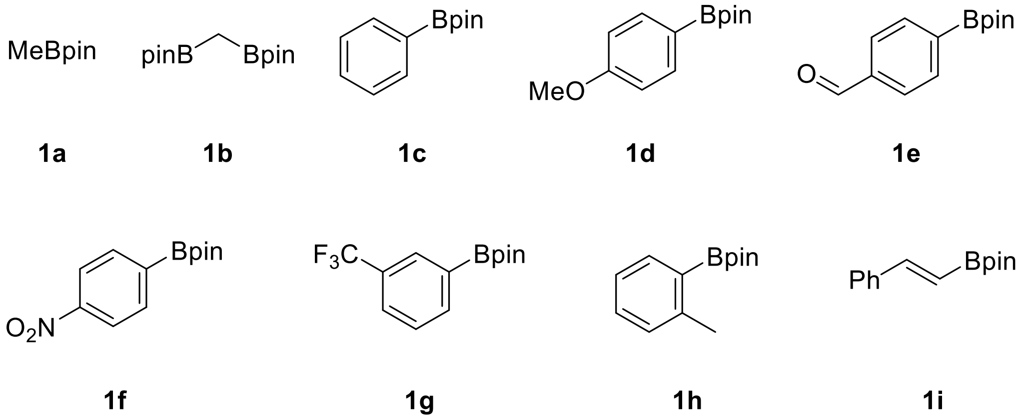
8.2.1 General procedure for the MUV-22 catalyzed Suzuki-Miyaura allylation

A 5 mL pressure tube equipped with a magnetic stirring bar was charged with **MUV-22** (2.5 mol%), Cs_2CO_3 (0.4 mmol), KF (0.2 mmol). Boronic acid pinacol ester (0.4 mmol) and cinnamyl bromide (0.2 mmol) were dissolved in the corresponding solvent (0.8 mL and 0.2 mL, respectively) and subsequently added to the reaction vessel. The reaction mixture was stirred at the designed temperature for 24 hours. Then, Et_2O (2 mL) was added, and the mixture was decanted. This treatment was repeated 4 times solid. The combined organic layers were filtered through a pad of silica and the solvent was removed under vacuum. Yield was determined by ^{1}H-NMR using dibromomethane as internal standard. The reaction crude was purified by column chromatography with silica gel and isolated yield was obtained.

8.2.2 List of starting materials

Boronic acid pinacol esters **1a-1h** and allyl bromides **2a** and **2b** were purchased from commercial sources. Boronic acid pinacol ester **1i**[113] and allyl bromides **2c**[114], **2d**[115], **2e**[116], **2f**[115], **2g**[117], **2h**[118], **2i**[119], were prepared according to reported methods.

8.2.2.1 Boronic acid pinacol esters



1a **1b** **1c** **1d** **1e**

1f **1g** **1h** **1i**

Scheme 52. Boronic acid pinacol esters used in the scope.

---

[113] Lee, J.-E.; Kwon, J.; Yun, J. *Chem. Commun*. **2008**, 733-734.

[114] Yang, W.; Chen C.; Chan, K. S. *Dalton Trans*. **2018**, *47*, 12879-12883.

[115] Lin, Q.; Hu, B.; Xu, X.; Dong, S.; Liu, X.; Feng, X.; *Chem. Sci*. **2020**, *11*, 3068-3073.

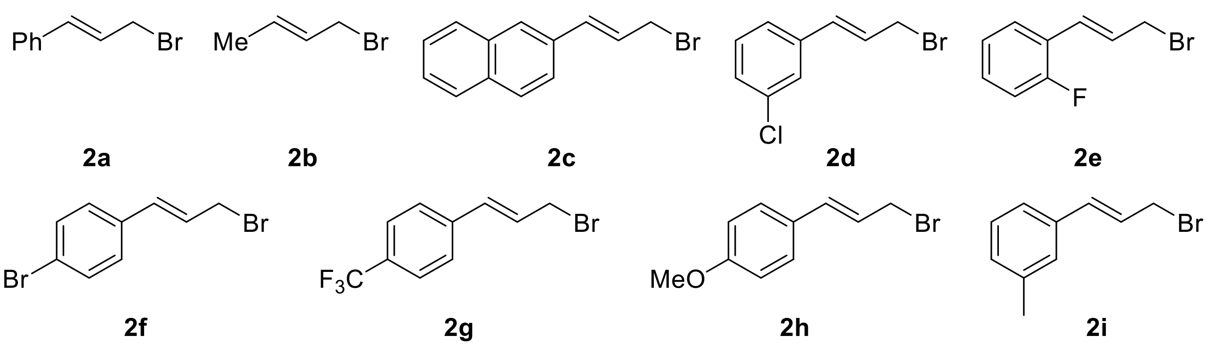
[116] Liu, X.; Liu, S.; Wang, Q.; Zhou, G.; Yao, L.; Ouyang, Q.; Jiang, R.; Lan Y.; Chen, W. *Org. Lett*. **2020**, *22*, 3149-3154.

[117] Guduguntla, S.; Hornillos, V.; Tessier, R.; Fañanas-Mastral, M.; Feringa, B. L. *Org. Lett*. **2016**, *18*, 252-255.

[118] He, J.; Jia, Z.; Tan, H.; Luo, X.; Qiu, D.; Shi, J.; Xu, H.; Li, Y. *Angew. Chem. Int. Ed*. **2019**, *58*, 18513-18518.

[119] Gao, S.; Niggemann, M.; *Adv. Synth. Catal*. **2019**, *361*, 1549-1553.

8.2.2.2 Allyl bromides



Scheme 53. Allyl bromides used in the scope.

8.2.1 Characterization data

(*E*)-But-1-en-1-ylbenzene (3a). Synthesized following the general procedure, obtained as a colorless oil in 58% yield after column chromatography (pentane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.40-7.21 (m, 5H), 6.43 (d, J = 15.8 Hz, 1H), 6.32 (dt, J = 15.8, 6.1 Hz, 1H), 2.28 (m, 2H), 1.15 (t, J = 7.4 Hz, 3H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 138.1, 132.7, 128.9, 128.6, 126.8, 125.9, 26.0, 13.6. Spectroscopic data are in accordance to reported literature.[120]

(*E*)-2-(but-1-en-1-yl)naphthalene (3b). Synthesized following the general procedure, obtained as a colorless oil in 45% yield after column chromatography (pentane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.78 (m, 3H), 7.68 (m, 1H), 7.58 (m, 1H), 7.43 (m, 2H), 6.55 (d, J = 15.8 Hz, 1H), 6.40 (dt, J = 15.8, 6.2 Hz, 1H), 2.30 (m, 2H), 1.14 (t, J = 7.4 Hz, 3H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 135.6, 133.9, 133.3, 132.8, 129.1, 128.2, 128.0, 127.8, 126.2, 125.6, 125.4, 123.8, 26.3, 13.8. Spectroscopic data are in accordance to reported literature.[121]

(*E*)-1-(But-1-en-1-yl)-3-chlorobenzene (3c). Synthesized following the general procedure, obtained as a colorless oil in 43% yield after column chromatography (pentane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.33 (s, 1H), 7.22-7.14 (m, 3H), 6.36-6.28 (m, 2H), 2.28-2.19 (m, 2H), 1.09 (t, J = 7.5 Hz, 3H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 139.6, 134.2, 134.0, 129.4, 127.4, 126.4, 125.6, 123.9, 25.7, 13.2. Spectroscopic data are in accordance to reported literature.[15]

(*E*)-1-(But-1-en-1-yl)-3-methylbenzene (3d). Synthesized following the general procedure, obtained as a colorless oil in 43% yield after column chromatography (pentane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.17 (m, 3H), 7.01 (d, J = 7.0 Hz, 1H), 6.36 (d, J = 16.0 Hz, 1H), 6.25 (dt, J = 15.8, 6.0 Hz, 1H), 2.34 (s, 3H), 2.23 (m, 2H), 1.09 (t, J = 7.4 Hz, 3H). **^{13}C NMR**

---

[120] Hill, E. A.; Engel, M. R. *J. Org. Chem*. **1971**, *36*, 1356-1360.

[121] Kumar, R.; Sharma, A.; Sharma, N.; Kumar, V.; Sinha, A. K. *Eur. J. Org. Chem*. **2008**, *33*, 5577-5582.

(75 MHz, $CDCl_3$) δ 138.0, 137.9, 132.5, 128.9, 128.4, 127.5, 126.7, 123.1, 26.1, 21.4, 13.7. Spectroscopic data are in accordance to reported literature.[122]

(*E*)-1-Bromo-4-(but-1-en-1-yl)benzene (3e). Synthesized following the general procedure, obtained as a colorless oil in 45% yield after column chromatography (pentane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.33 (d, *J* = 8.6 Hz, 2H), 7.13 (d, *J* = 8.6 Hz, 2H), 6.29 – 6.12 (m, 2H), 2.15 (m, 2H), 1.02 (t, *J* = 7.5 Hz, 3H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 136.6, 133.2, 131.2, 128.8, 127.4, 127.2, 120.1, 25.8, 13.2. Spectroscopic data are in accordance to reported literature.[123]

(*E*)-1-(But-1-en-1-yl)-4-(trifluoromethyl)benzene (3f). Synthesized following the general procedure, obtained as a colorless oil in 45% yield after column chromatography (pentane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.53 (d, *J* = 8.4 Hz, 2H), 7.42 (d, *J* = 8.0 Hz, 2H), 6.47 – 6.30 (m, 2H), 2.26 (m, 2H), 1.11 (t, *J* = 7.5 Hz, 3H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 141.4, 135.5, 127.7, 126.0, 125.4 (q, *J* = 3.9 Hz), 29.7, 13.4. **^{19}F NMR** (282 MHz, $CDCl_3$) δ -62.4. Spectroscopic data are in accordance to reported literature.[123]

(*E*)-1-(But-1-en-1-yl)-4-methoxybenzene (3g). Synthesized following the general procedure, obtained as a colorless oil in 37% yield after column chromatography (pentane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.27 (d, *J* = 8.3 Hz, 2H), 6.83 (d, *J* = 8.7 Hz, 2H), 6.32 (d, *J* = 15.9 Hz, 1H), 6.12 (dt, *J* = 15.8, 6.4 Hz, 1H), 3.80 (s, 3H), 2.21 (m, 2H), 1.08 (t, *J* = 7.4 Hz, 3H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 158.6, 130.8, 130.5, 128.1, 127.0, 113.9, 55.3, 26.0, 13.8. Spectroscopic data are in accordance to reported literature.[124]

(*E*)-1-Fluoro-2-(3-(3-(trifluoromethyl)phenyl)prop-1-en-1-yl)benzene (3h). Synthesized following the general procedure, obtained as a colorless oil in 45% yield after column chromatography (hexane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.53 – 7.40 (m, 5H), 7.19 (t, *J* = 6.8 Hz, 1H), 7.14 – 6.97 (m, 2H), 6.66 (d, *J* = 15.9 Hz, 1H), 6.49 – 6.33 (m, 1H), 3.64 (d, *J* = 7.0 Hz, 2H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 159.8 (d, *J* = 248.7 Hz), 140.6, 131.8, 130.4 (d, *J* = 4.6 Hz), 130.0 (q, *J* = 34.1 Hz), 128.7, 128.3 (d, *J* = 8.4 Hz), 127.5 (q, *J* = 265.6 Hz), 127.0 (d, *J* = 3.8 Hz), 125.1 (q, *J* = 3.9 Hz), 124.6 (d, *J* = 12.4 Hz), 124.1 (d, *J* = 3.5 Hz), 123.8 (d, *J* = 3.6 Hz), 122.9 (q, *J* = 3.9 Hz), 115.5 (d, *J* = 22.2 Hz), 39.2.**^{19}F NMR** (282 MHz, $CDCl_3$) δ -62.6, -118.4. **HRMS (APCI)** Calc. for $C_{16}H_{11}F_4$ [M+H^{+}]: 279.0787, found 279.0791.

(*E*)-1-(But-2-en-1-yl)-4-nitrobenzene (3i) + 1-(but-3-en-2-yl)-4-nitrobenzene (3i'). Synthesized following the general procedure, obtained as a pale yellow oil in 69% yield after column chromatography (hexane:DCM 50:50). Obtained as a 2:1 mixture of regioisomers. **^{1}H**

---

[122] Zhu, N.; Zhao, J.; Bao, H.; *Chem. Sci.* **2017**, *8*, 2081-2085.

[123] Yu, X.; Zhao, H.; Li, P.; Koh, M. J. *J. Am. Chem. Soc.* **2020**, *142*, 18223-18230.

[124] Zhang, R. K.; Chen, K.; Huang, X.; Wohlschlager, L.; Renata, H.; Arnold, F. H. *Nature* **2019**, *565*, 67-72.

NMR (300 MHz, $CDCl_3$) *δ* 8.17 (m, 2H **3i** + 2H **3i’**), 7.37 (m, 2H **3i** +2H **3i’**), 6.00 (ddd, *J* = 16.7, 10.4, 6.4 Hz, 1H **3i’**), 5.71 – 5.50 (m, 2H **3i**), 5.17 – 5.07 (m, 2H **3i’**), 3.61 (p, *J* = 6.9 Hz, 1H **3i’**), 3.44 (m, 2H **3j**), 1.76 – 1.70 (m, 3H **3i**), 1.42 (d, *J* = 7.0 Hz, 3H **3i’**). **^{13}C NMR** (75 MHz, $CDCl_3$) *δ* 153.2 (**3i’**), 148.9 (**3i**), 146.5 (**3i’**), 141.4 (**3i’**), 129.2 (**3i**), 129.1 (**3i**), 128.2 (**3i’**), 128.1 (**3i**), 128.1 (**3i**), 127.0 (**3i**), 123.7 (**3i**), 123.7 (**3i’**), 123.6 (**3i**), 114.5 (**3i’**), 43.1 (**3i’**), 38.8 (**3i**), 20.5 (**3i’**), 17.87 (**3i**). **HRMS (APCI)** Calc. for $C_{10}H_{12}NO_2$ [M+H$^+$]: 178.0863, found 178.0863. Spectroscopic data are in accordance to reported literature.[125]

(*E*)-4,4,5,5-Tetramethyl-2-(4-phenylbut-3-en-1-yl)-1,3,2-dioxaborolane (3j). Synthesized following the general procedure, obtained as a colorless oil in 43% yield after column chromatography (hexane:Et_2O 99:1). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.39 – 7.17 (m, 5H), 6.41 (d, *J* = 15.9 Hz, 1H), 6.30 (dt, *J* = 15.9, 6.1 Hz, 1H), 2.37 (q, *J* = 7.2 Hz, 2H), 1.27 (s, 12H), 1.01 (t, *J* = 7.7 Hz, 2H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 138.0, 132.8, 128.9, 128.4, 126.7, 125.9, 83.1, 27.3, 24.9. **^{11}B NMR** (160 MHz, $CDCl_3$) δ 33.88. Spectroscopic data are in accordance to reported literature.[126]

(*E*)-2-(4-(4-Bromophenyl)but-3-en-1-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (3k). Synthesized following the general procedure, obtained as a colorless oil in 30% yield after column chromatography (hexane:Et_2O 99:1). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.41 (d, *J* = 7.9 Hz, 2H), 7.20 (d, *J* = 8.4 Hz, 2H), 6.39 – 6.22 (m, 2H), 2.34 (q, *J* = 7.5 Hz, 2H), 1.26 (s, 12H), 0.99 (t, *J* = 7.7 Hz, 2H). **^{13}C NMR** (75 MHz, $CDCl_3$) 137.1, 133.8, 131.6, 127.9, 127.6, 120.4, 83.3, 27.5, 25.0. **^{11}B NMR** (160 MHz, $CDCl_3$) δ 33.88. Spectroscopic data are in accordance to reported literature.[127]

***(E)-Prop-1-ene-1,3-diyldibenzene* (3l).** Synthesized following the general procedure, obtained as a colorless oil in 60% yield after column chromatography (hexane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.45 – 7.17 (m, 10H), 6.51 (d, *J* = 15.9 Hz, 1H), 6.40 (dt, *J* = 15.8, 6.4 Hz, 1H), 3.59 (d, *J* = 6.4 Hz, 2H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 139.9, 137.2, 130.8, 128.9, 128.4, 128.3, 128.2, 128.1, 126.8, 126.1, 125.9, 125.8, 39.1. Spectroscopic data are in accordance to reported literature.[128]

1-Cinnamyl-4-methoxybenzene (3m). Synthesized following the general procedure, obtained as a colorless oil in 54% yield after column chromatography (hexane:Et_2O 99:1). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.41 – 7.13 (m, 7H), 6.87 (d, *J* = 8.0 Hz, 2H), 6.45 (d, *J* = 15.9 Hz, 1H), 6.35 (dt, *J* = 16.1, 6.5 Hz, 1H), 3.80 (s, 3H), 3.50 (d, *J* = 6.2 Hz, 2H). **^{13}C NMR** (75 MHz,

---

[125] Yasunori, Y.; Shingo, T.; Norio, M.; *Chem. Lett.* **2006**, *35*, 704-705.

[126] Endo, K.; Ohkubo, T.; Ishioka, T.; Shibata, T.; *J. Org. Chem.* **2012**, *77*, 4826-4831.

[127] Zhang, Z.-Q.; Zhang, B.; Lu, X.; Liu, J.-H.; Lu, X.-Y.; Xiao, B.; Fu, Y. *Org. Lett.* **2016**, *18*, 952-955.

[128] Wang, Y.; Shao, Z.; Zhang, K.; Liu, Q. *Angew. Chem. Int. Ed*. **2018**, *57*, 15143-15147.

$CDCl_3$) δ 157.8, 137.3, 131.9, 130.5, 129.4, 129.3, 128.2, 126.8, 125.8, 113.6, 55.0, 38.2. Spectroscopic data are in accordance to reported literature.[129]

4-Cinnamylbenzaldehyde (3n). Synthesized following the general procedure, obtained as a colorless oil in 76% yield after column chromatography (hexane:Et_2O 99:1). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 10.01 (s, 1H), 7.85 (d, J = 8.2 Hz, 2H), 7.47 – 7.17 (m, 9H), 6.51 (d, J = 15.8 Hz, 1H), 6.35 (dt, J = 15.8, 6.7 Hz, 1H), 3.65 (d, J = 6.7 Hz, 2H).**^{13}C NMR** (75 MHz, $CDCl_3$) δ 192.1, 147.7, 137.2, 135.0, 132.3, 130.2, 129.7, 128.7, 127.7, 127.6, 126.3, 39.6. Spectroscopic data are in accordance to reported literature.[130]

1-Cinnamyl-4-nitrobenzene (3o). Synthesized following the general procedure, obtained as a colorless oil in 70% yield after column chromatography (hexane:Et_2O 99:1). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 8.12 – 8.03 (m, 2H), 7.36 – 7.11 (m, 7H), 6.41 (d, J = 15.8 Hz, 1H), 6.23 (dt, J = 15.8, 6.8 Hz, 1H), 3.57 (d, J = 6.7 Hz, 2H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 148.0, 146.7, 136.9, 132.6, 129.5, 128.7, 127.6, 127.0, 126.2, 123.8, 39.1. Spectroscopic data are in accordance to reported literature.[131]

1-Cinnamyl-3-(trifluoromethyl)benzene (3p). Synthesized following the general procedure, obtained as a colorless oil in 68% yield after column chromatography (hexane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.54 – 7.19 (m, 9H), 6.50 (d, J = 15.8 Hz, 1H), 6.34 (dt, J = 15.8, 6.7 Hz, 1H), 3.62 (d, J = 6.7 Hz, 2H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 141.2, 137.3, 132.2 (q, J = 1,3 Hz), 132.1, 131.0 (q, J = 32.1 Hz), 129.0, 128.7, 128.1, 127.5, 126.3, 125.5 (q, J = 3.7 Hz), 124.4 (q, J = 272.3 Hz), 123.3 (q, J = 3.9 Hz), 39.2. Spectroscopic data are in accordance to reported literature.[132]

1-Cinnamyl-2-methylbenzene (3q). Synthesized following the general procedure, obtained as a colorless oil in 72% yield after column chromatography (hexane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.30 – 7.03 (m, 11H), 6.34 – 6.15 (m, 2H), 3.45 (d, J = 5.0 Hz, 2H), 2.26 (s, 3H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 138.4, 137.7, 136.6, 131.0, 130.4, 129.4, 128.7, 128.6, 127.2, 126.5, 126.2, 126.2, 37.0, 19.6. Spectroscopic data are in accordance to reported literature.[133]

(1*E*,4*E*)-1,5-Diphenylpenta-1,4-diene (3r). Synthesized following the general procedure, obtained as a colorless oil in 34% yield after column chromatography (hexane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.44 – 7.21 (m, 11H), 6.52 (d, J = 15.9 Hz, 2H), 6.33 (dt, J = 15.8, 6.5 Hz, 2H),

---

[129] Yang, B.; Wang, Z.-X. *J. Org. Chem.* **2017**, *82*, 4542-4549.

[130] Tsukamoto, H.; Uchiyama, T.; Suzuki, T.; Kondo, Y. *Org. Biomol. Chem.* **2008**, *6*, 3005- 3013.

[131] Lee, Y.; Shabbir, S.; Lee, S.; Ahn, H.; Rhee, H. *Green Chem*. **2015**, *17*, 3579-3583.

[132] Qiu, J.; Zhang, R.; *Org. Biomol. Chem*. **2013**, *11*, 6008-6012.

[133] Lipshutz, B. H.; Ghorai, S.; Abela, A. R.; Moser, R.; Nishikata, T.; Duplais, C.; Krasovskiy, A.; Gaston, R. D.; Gadwood, R. C. *J. Org. Chem*. **2011**, *76*, 4379-4391.

3.17 (t, *J* = 6.5 Hz, 2H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 137.6, 131.2, 128.5, 128.2, 127.1, 126.1, 36.2. Spectroscopic data are in accordance to reported literature.[134]

---

[134] Alacid, E.; Nájera, C. *J. Org. Chem*. **2009**, *74*, 2321-2327.

8.2.2 ^{1}H-NMR and ^{13}C-NMR Spectra

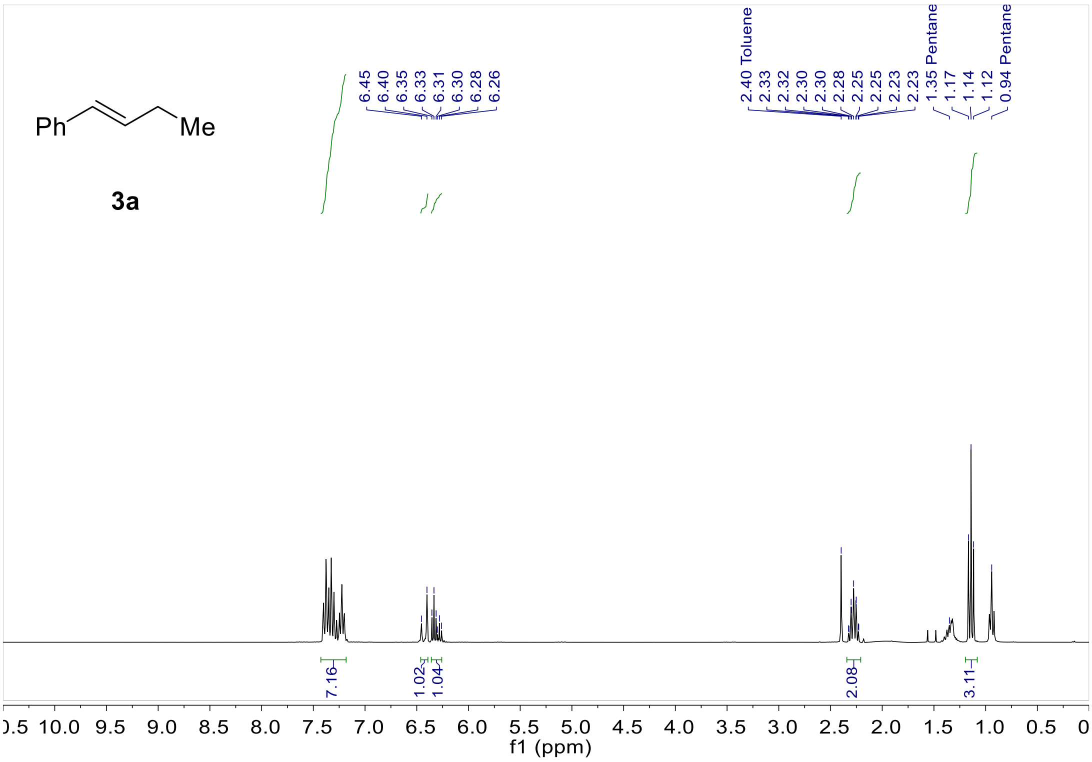


Figure 12. ^{1}H NMR spectra of product 3a.

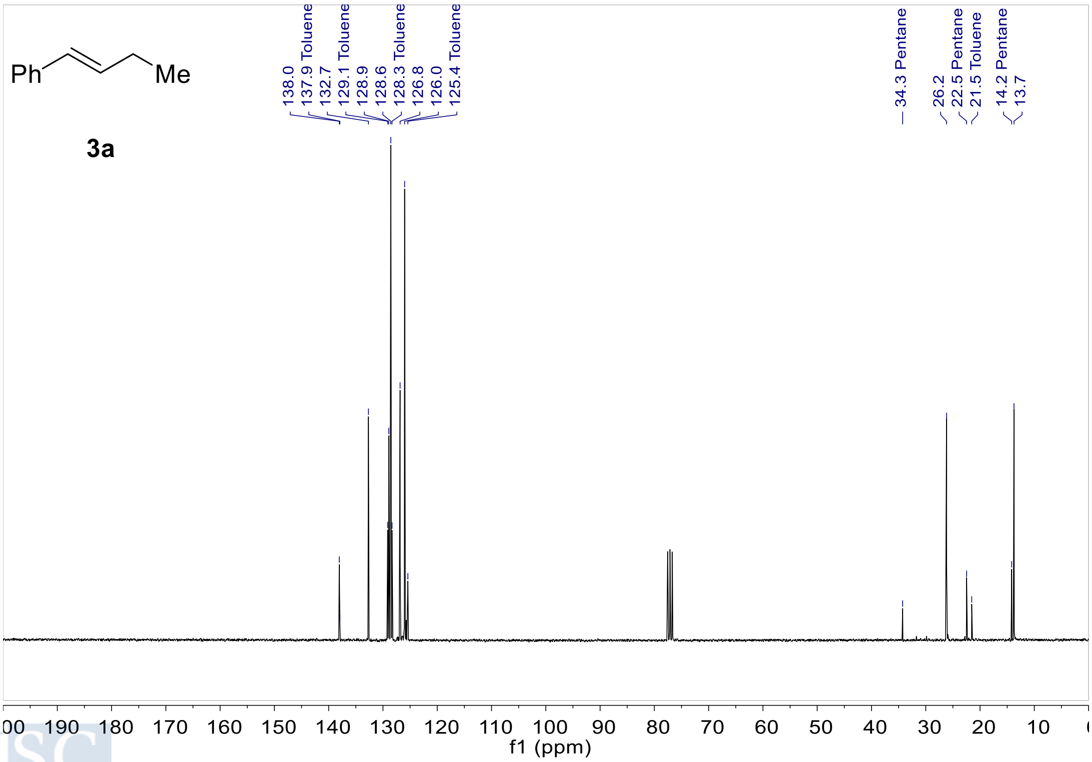
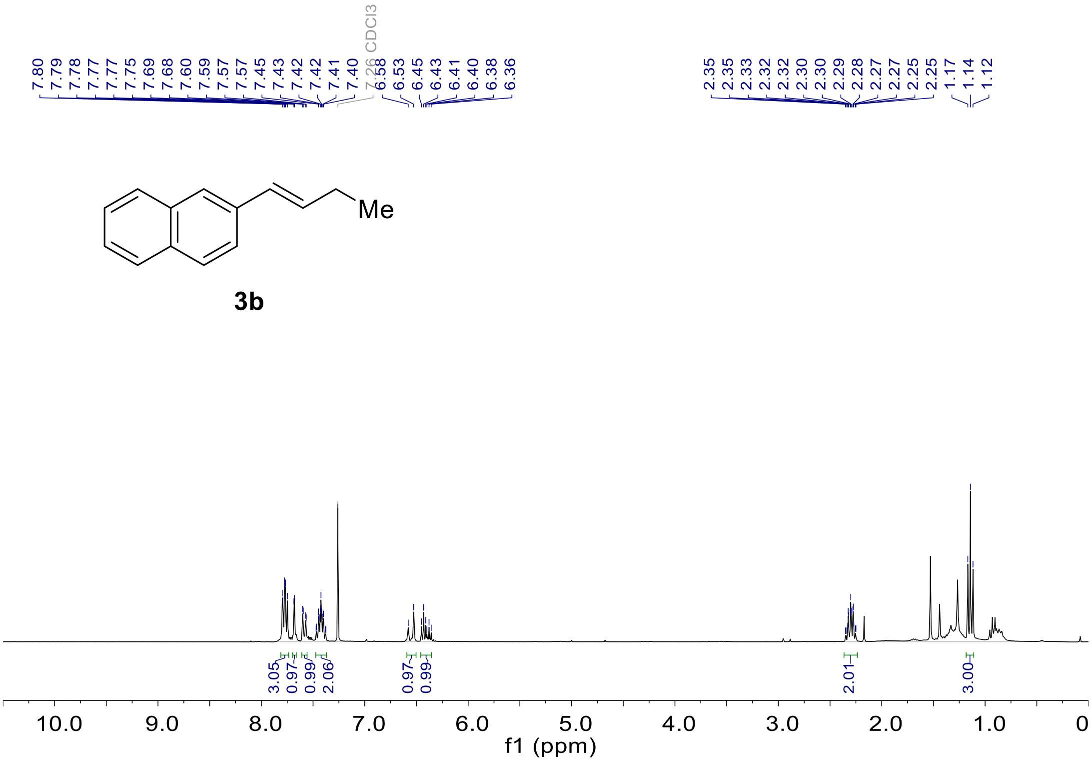


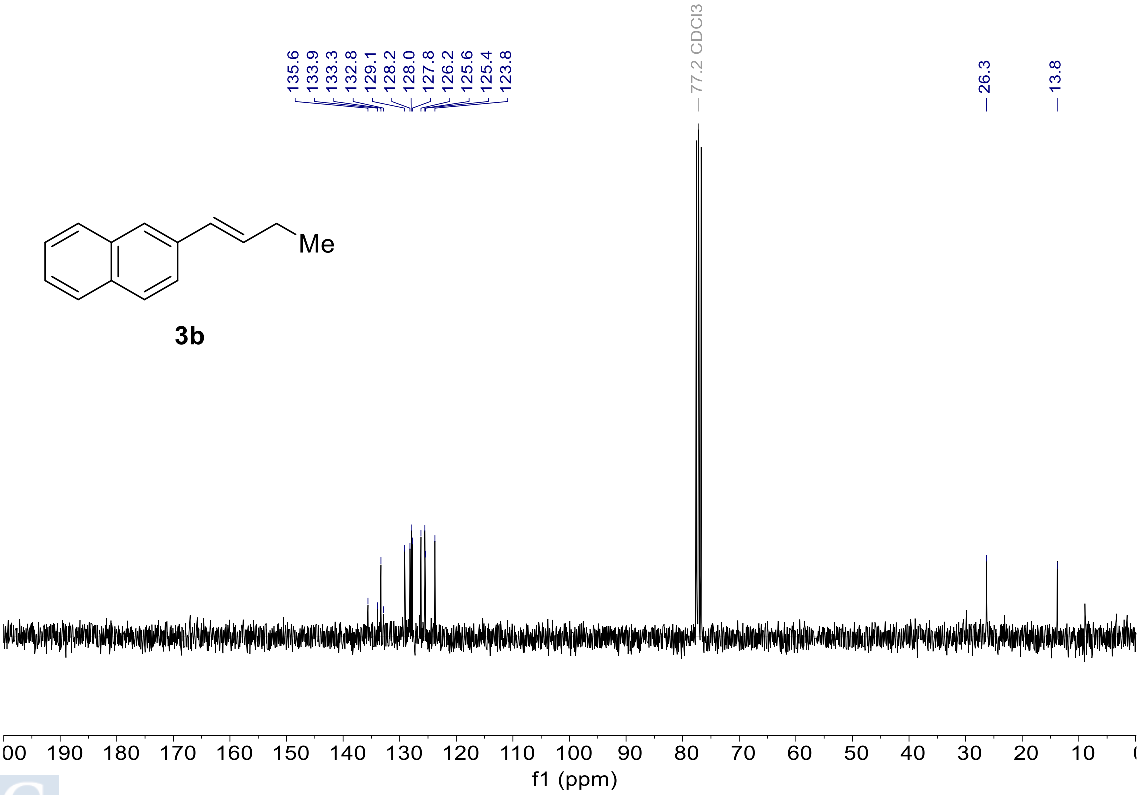
Figure 13. ^{13}C NMR spectra of product 3a.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA



3b

Figure 14. ^{1}H NMR spectra of product 3b.



3b

Figure 15. ^{13}C NMR spectra of product 3b.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

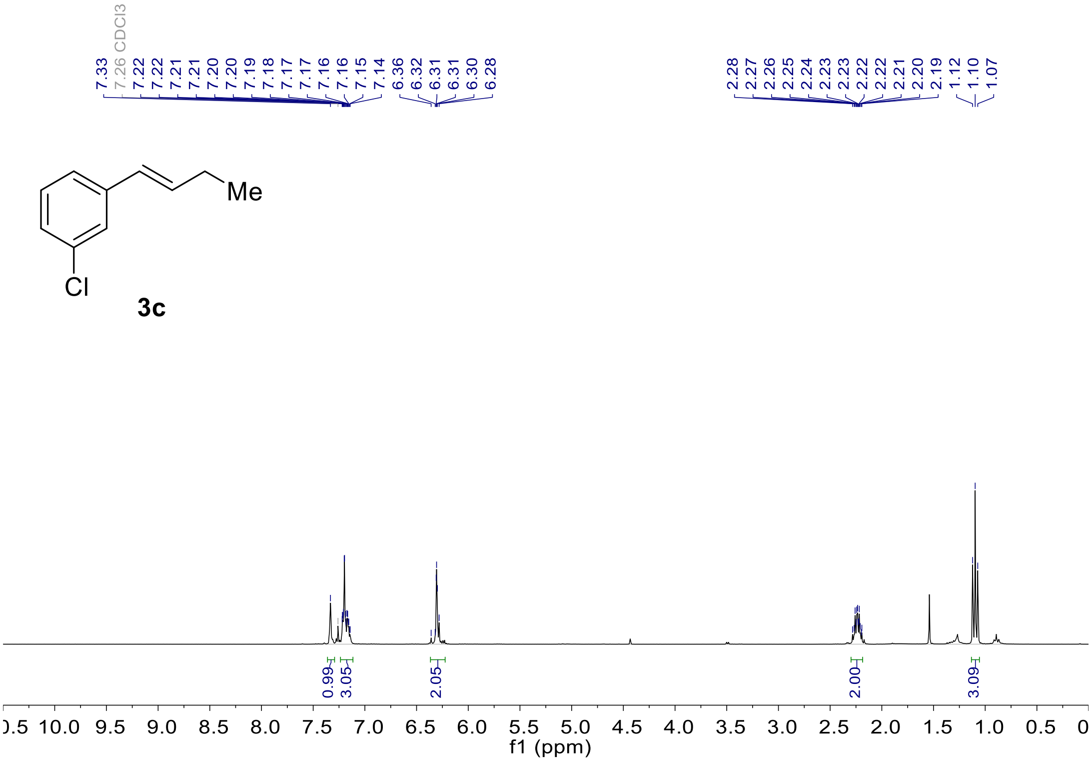


Figure 16. ^{1}H NMR spectra of product 3c.

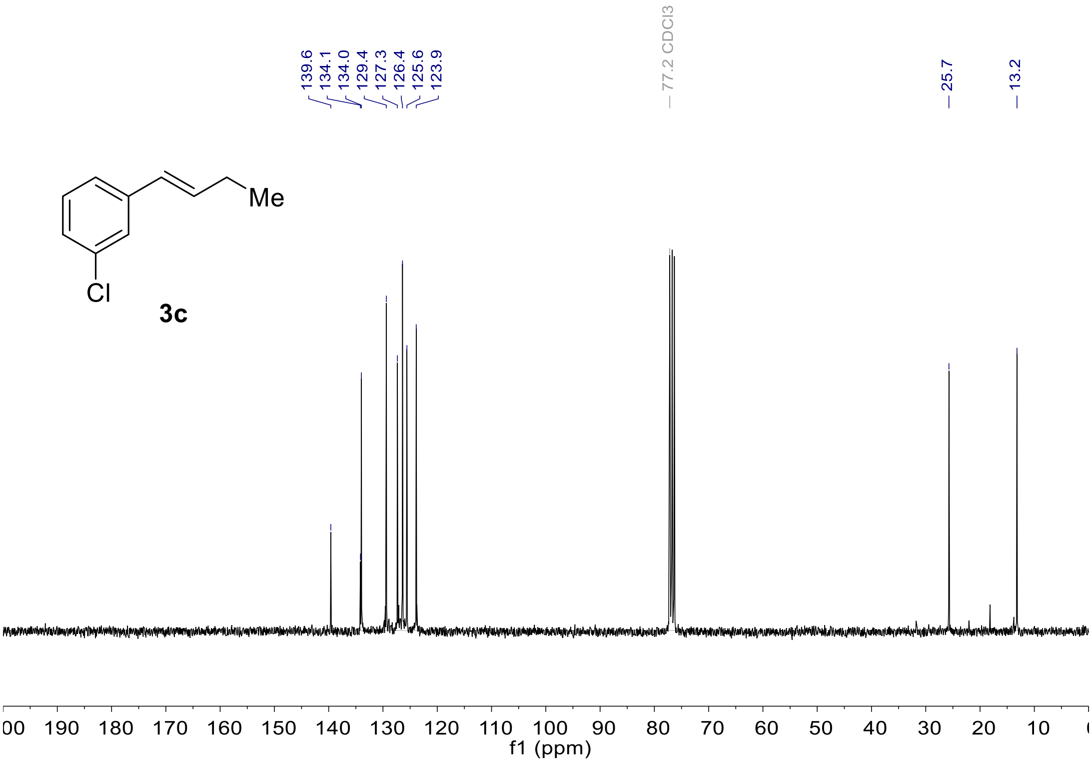


Figure 17. ^{13}C NMR spectra of product 3c.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

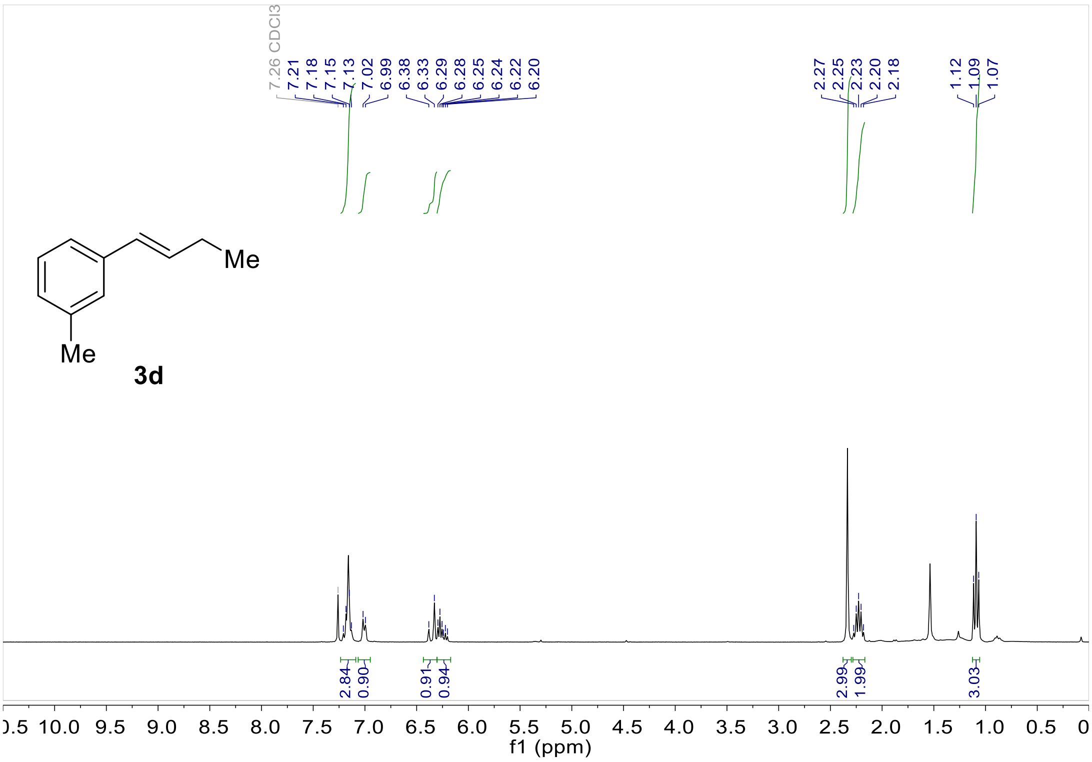


Figure 18. ^{1}H NMR spectra of product 3d.

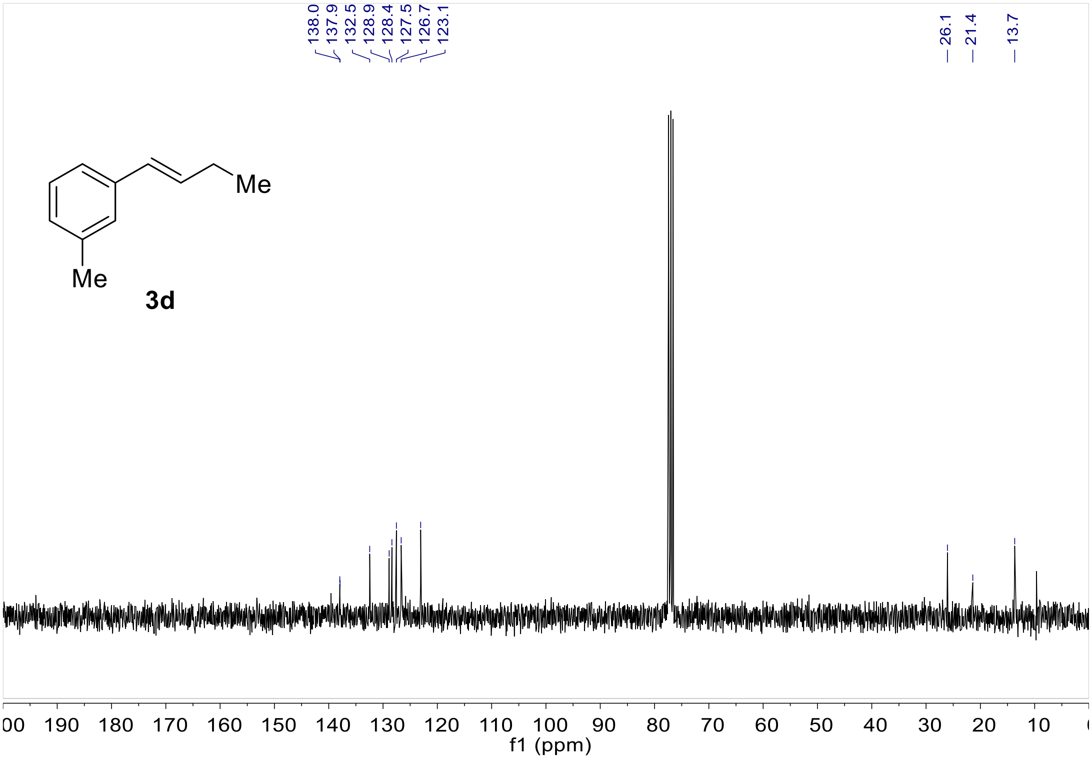


Figure 19. ^{13}C NMR spectra of product 3d.

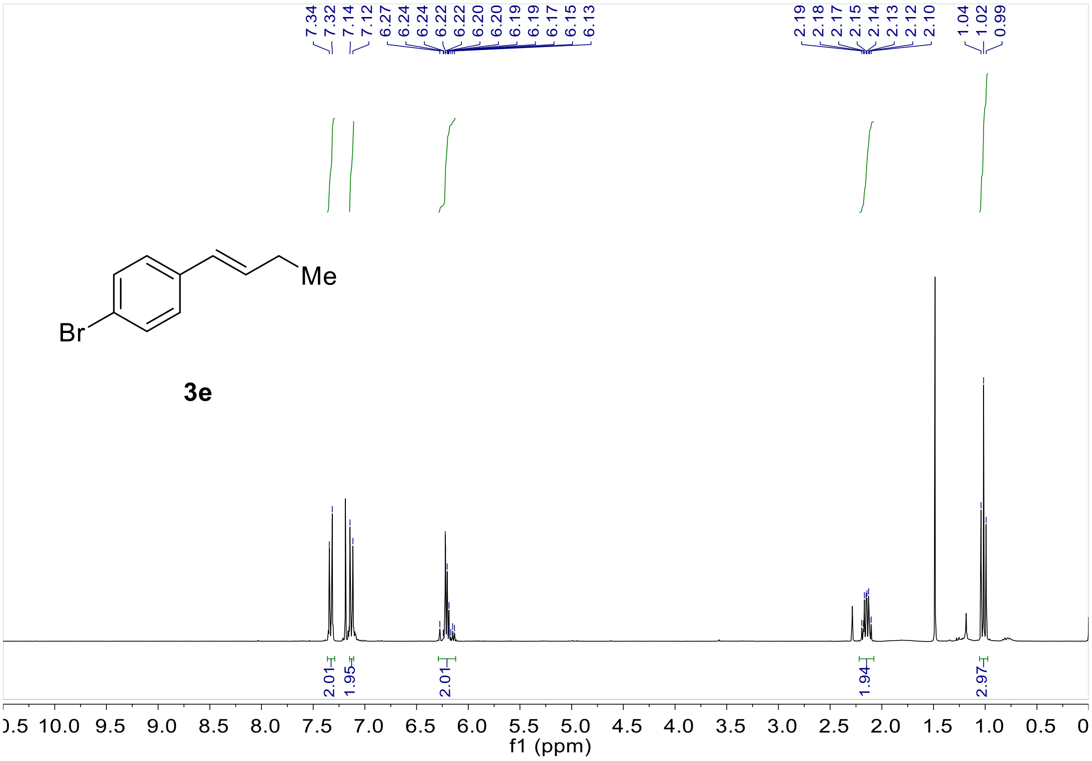


Figure 20. ^{1}H NMR spectra of product 3e.

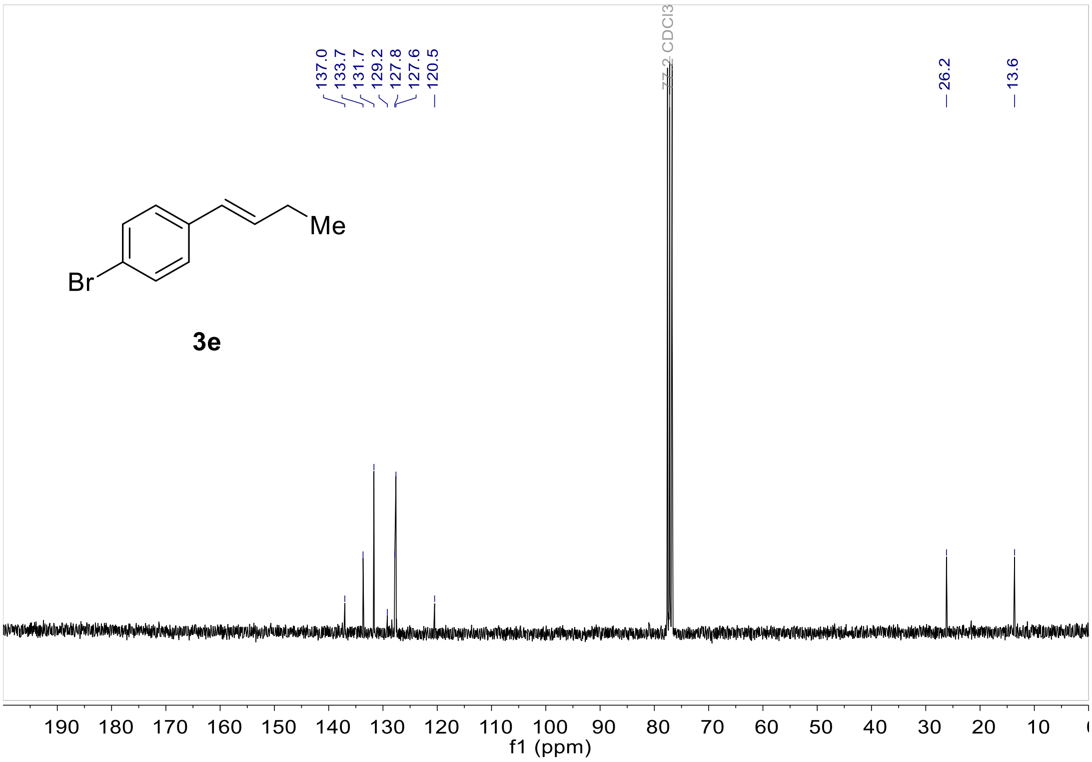


Figure 21. ^{13}C NMR spectra of product 3e.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

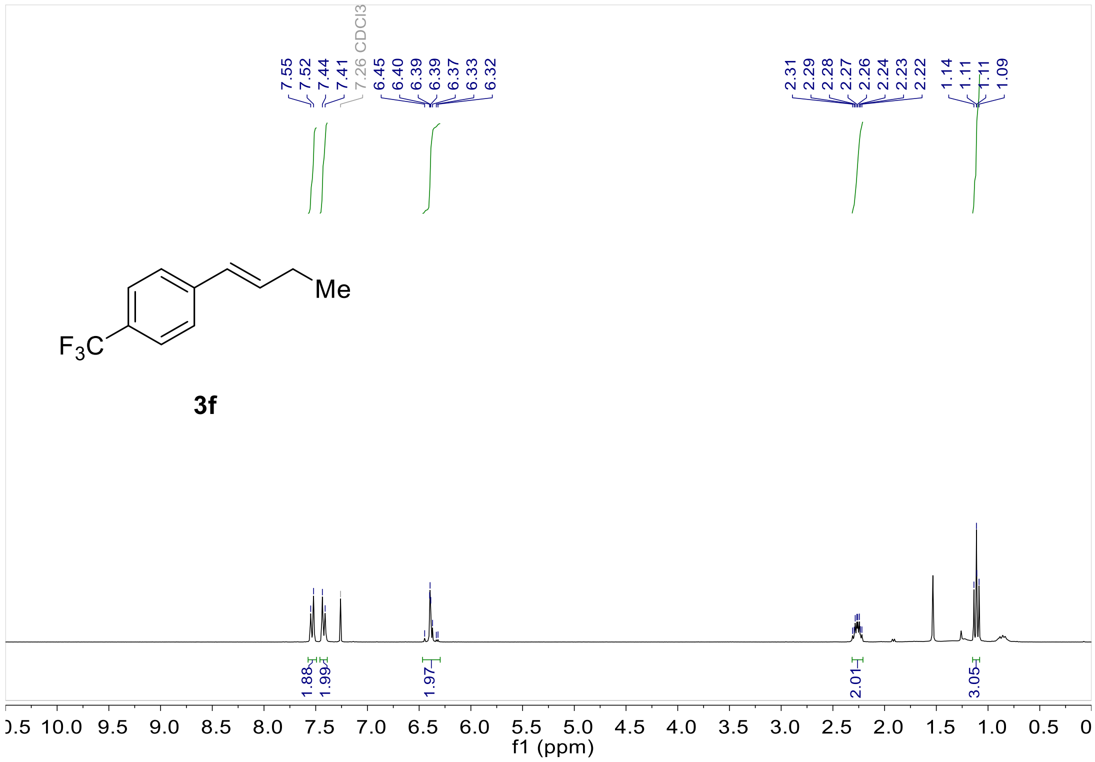


Figure 22. ^{1}H NMR spectra of product 3f.

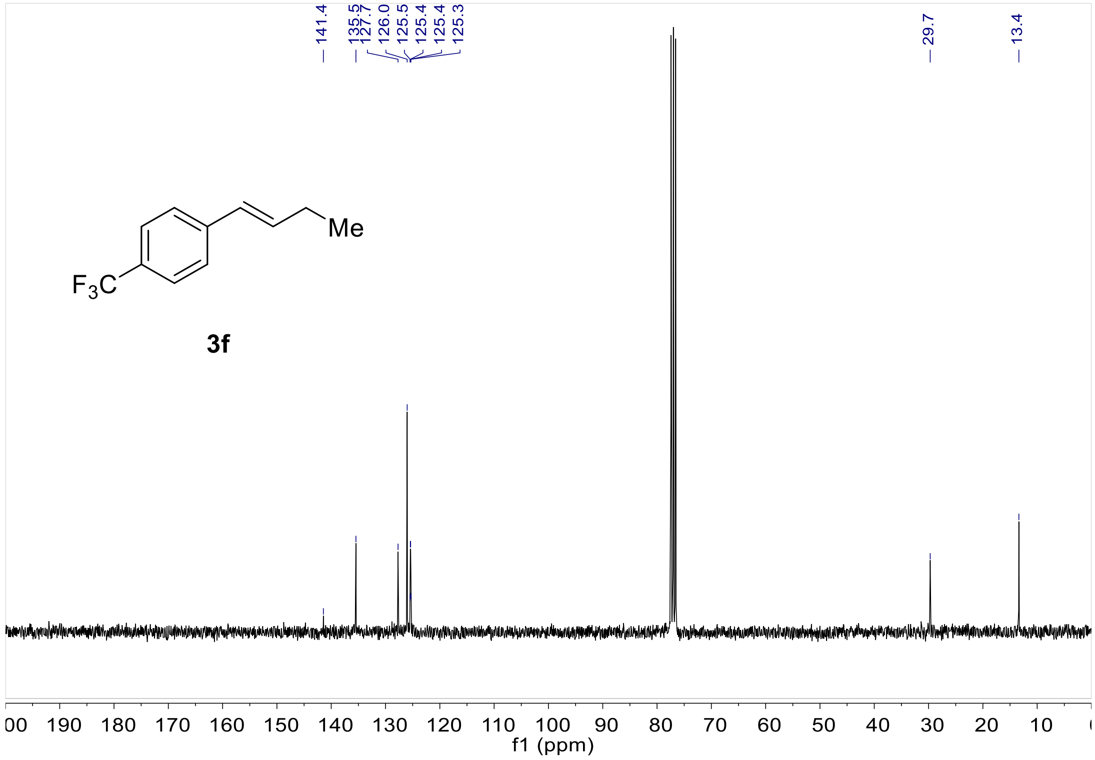


Figure 23. ^{13}C NMR spectra of product 3f.

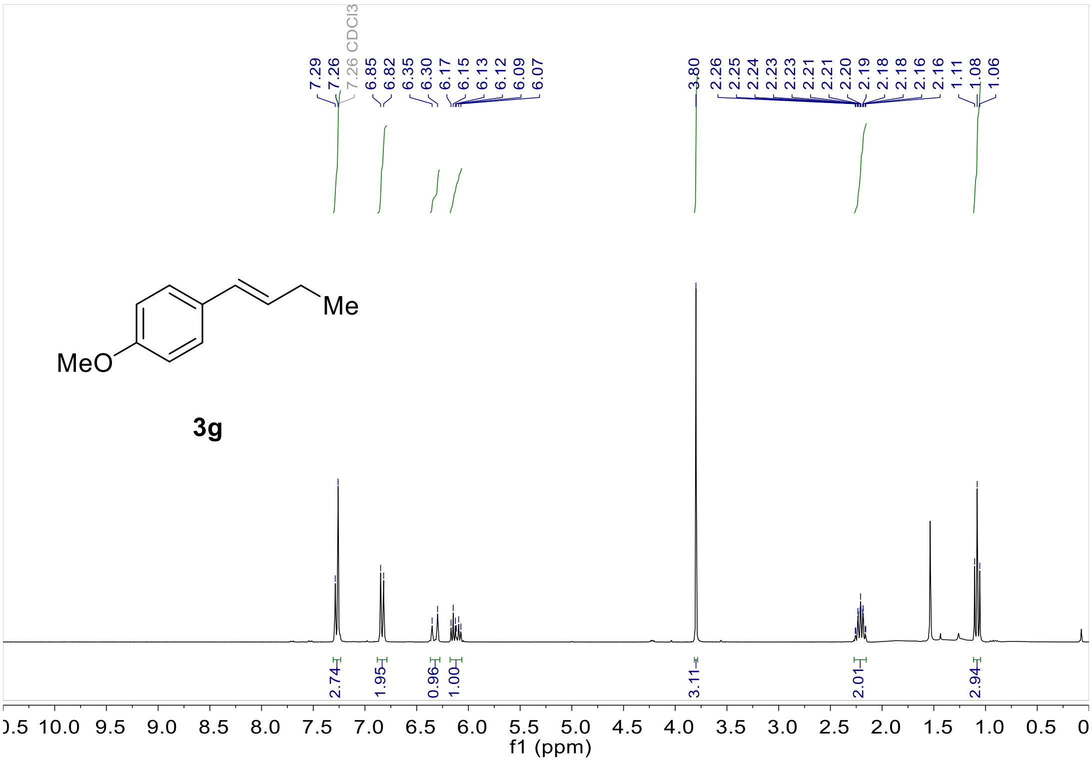


Figure S24. ^{1}H NMR spectra of product 3g.

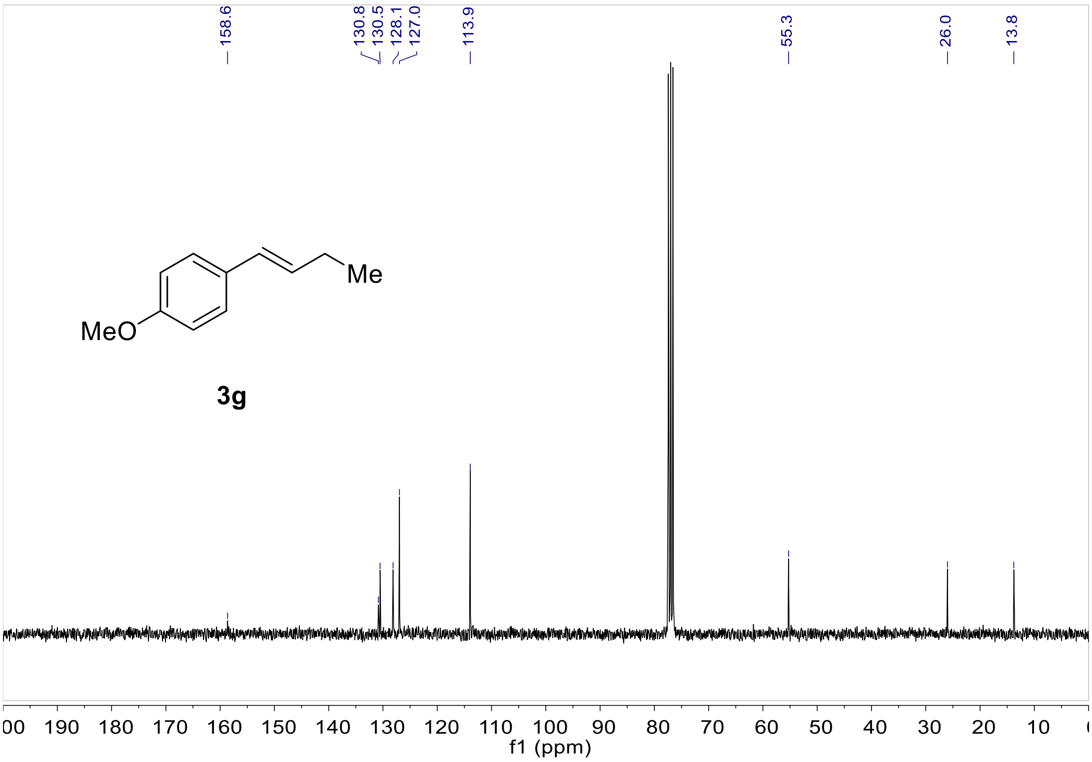


Figure S25. ^{13}C NMR spectra of product 3g.

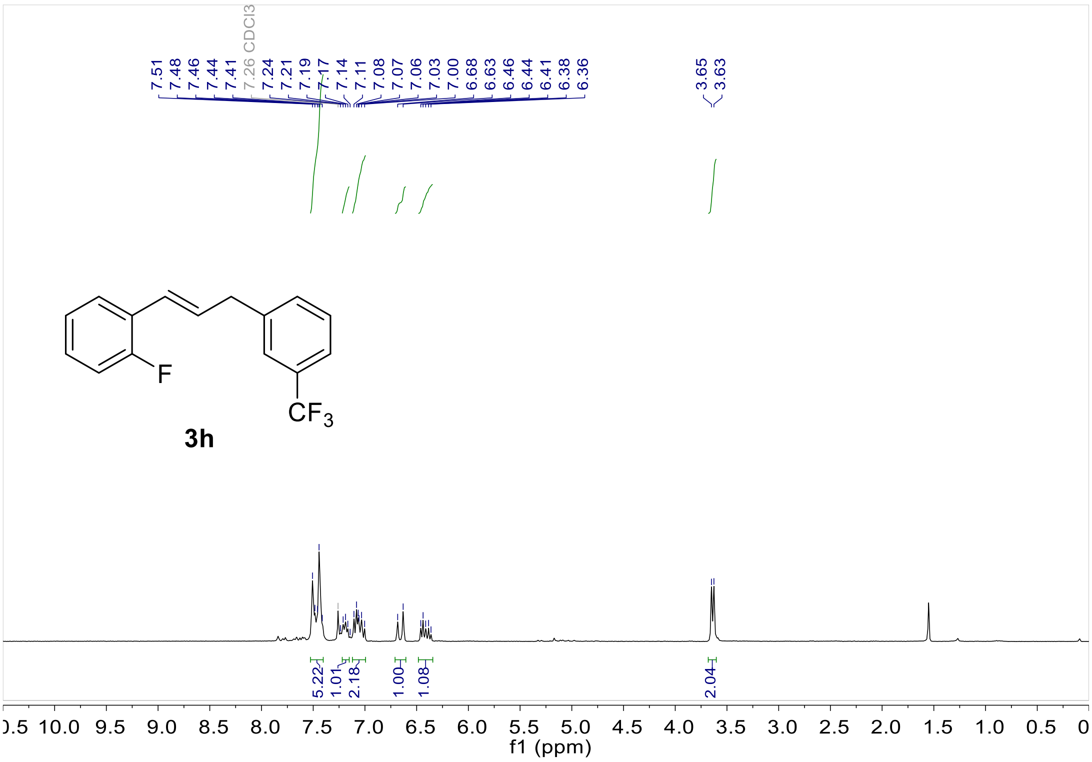


Figure 26. ^{1}H **NMR spectra of product 3h.**

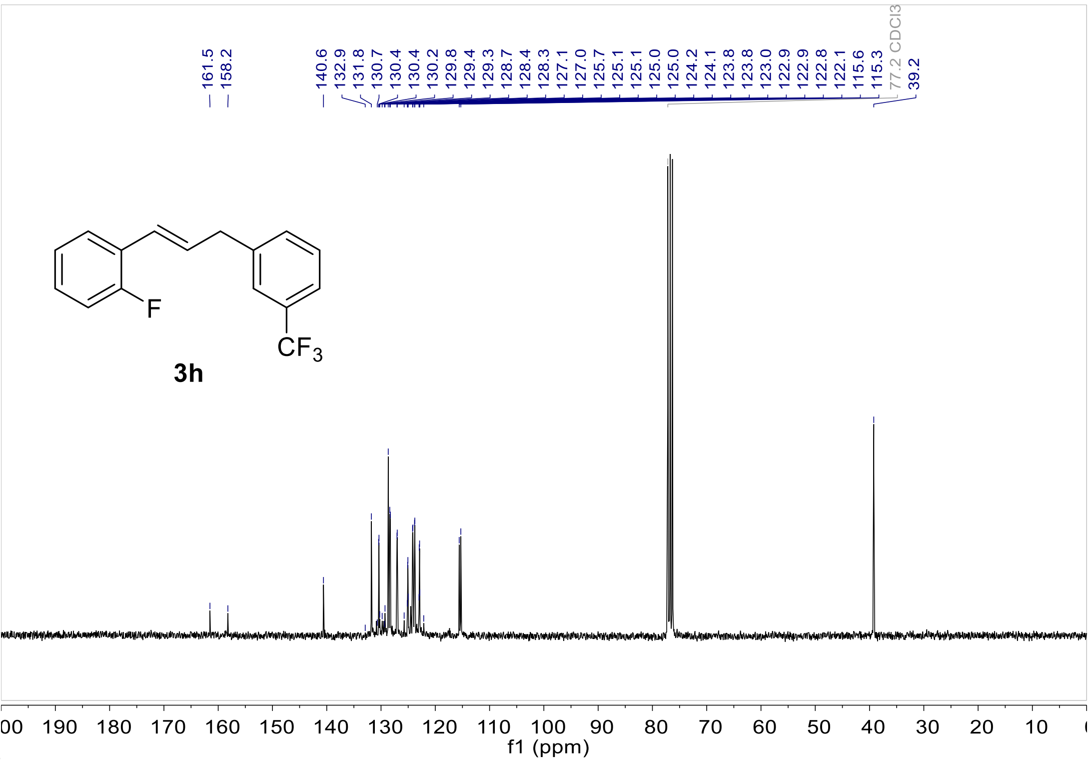


Figure 27. ^{13}C **NMR spectra of product 3h.**

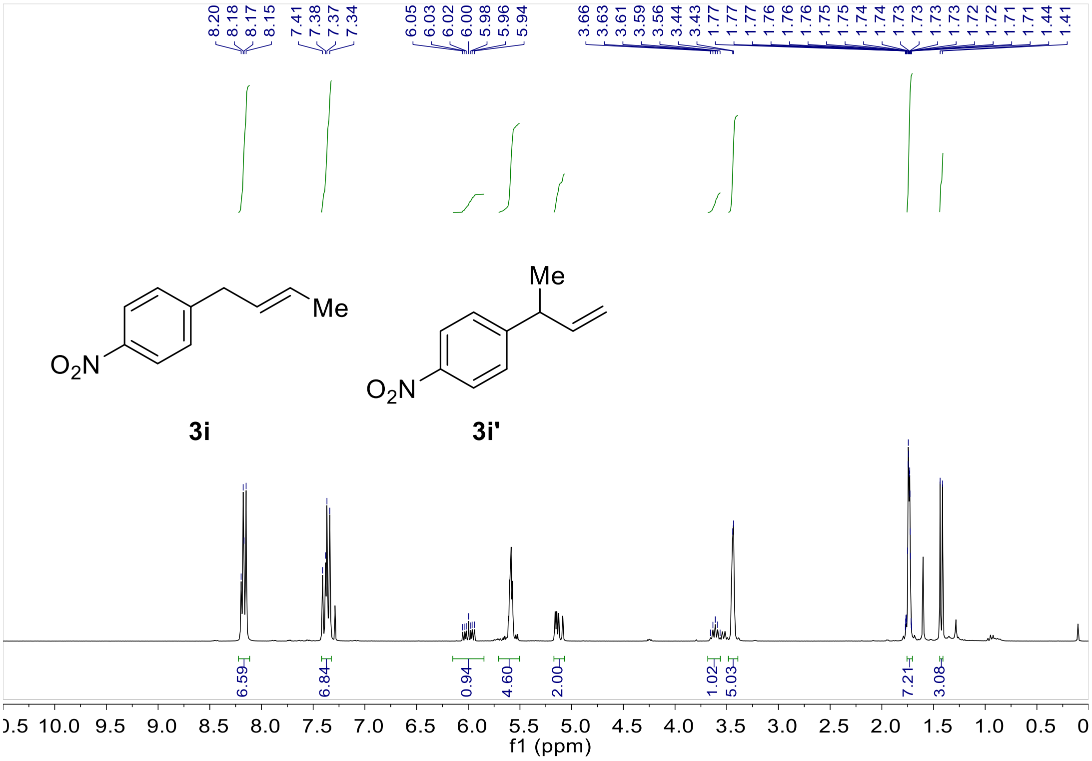


Figure 28. ^{1}H NMR spectra of products 3i and 3i'.

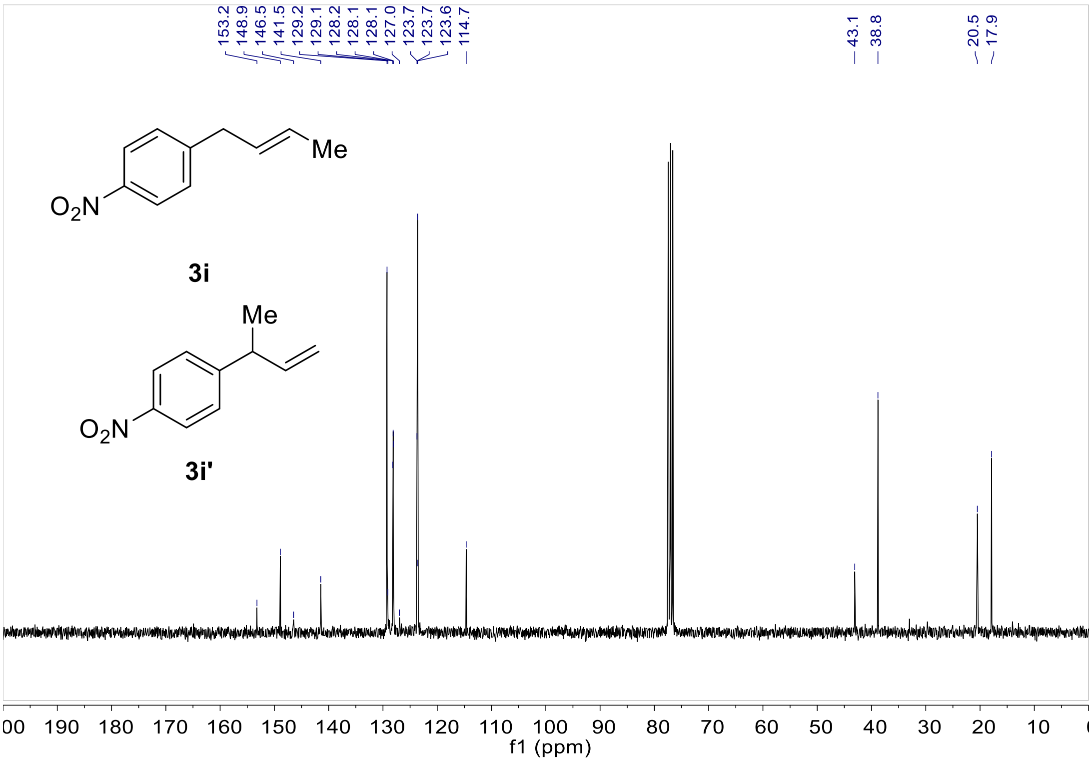


Figure 29. ^{13}C NMR spectra of products 3i and 3i'.

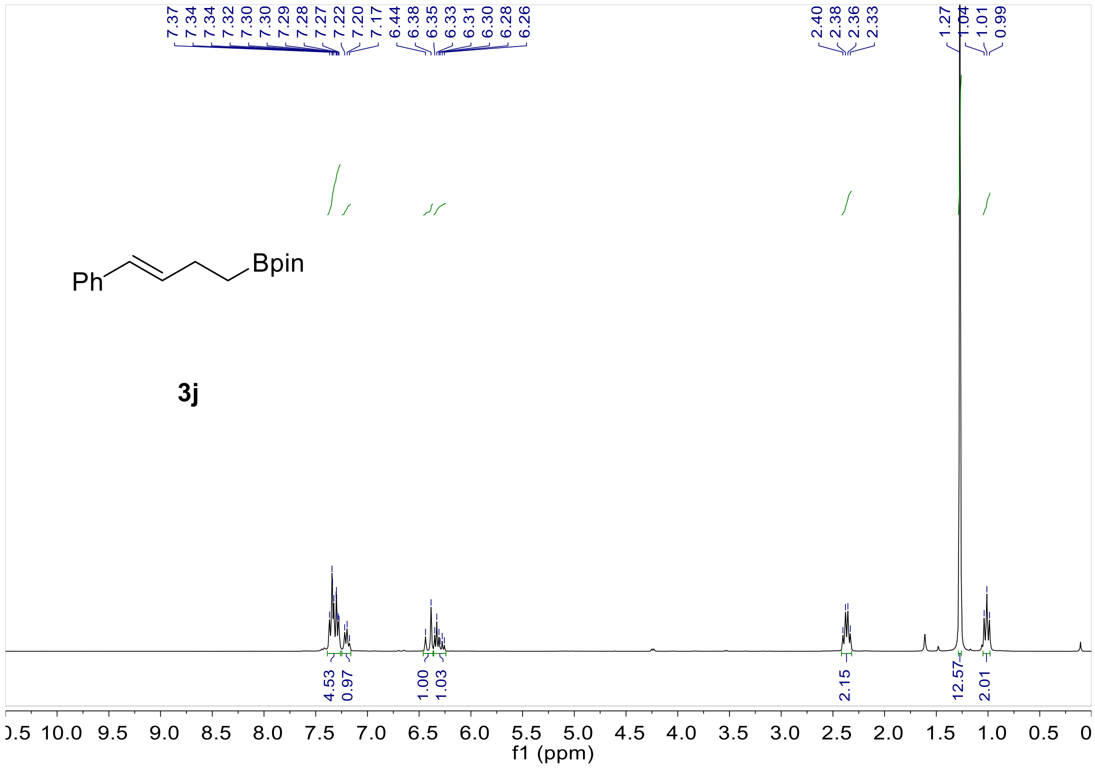


Figure 30. ^{1}H NMR spectra of product 3j.

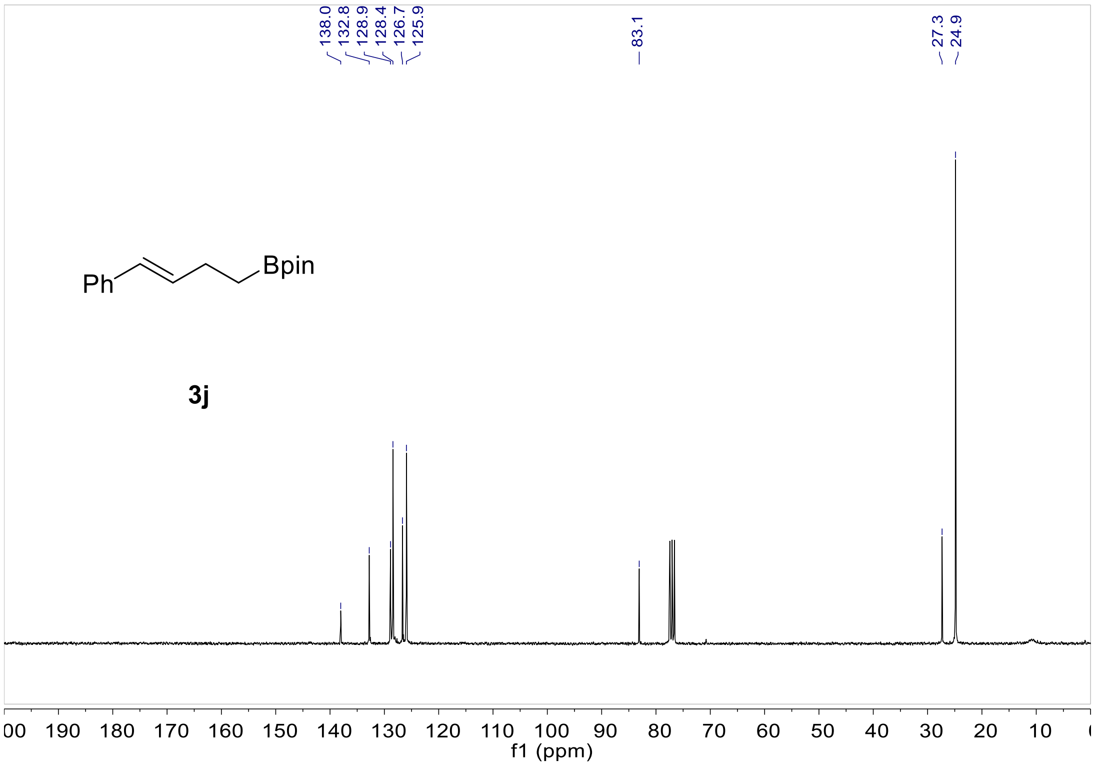


Figure 31. ^{13}C NMR spectra of product 3j.

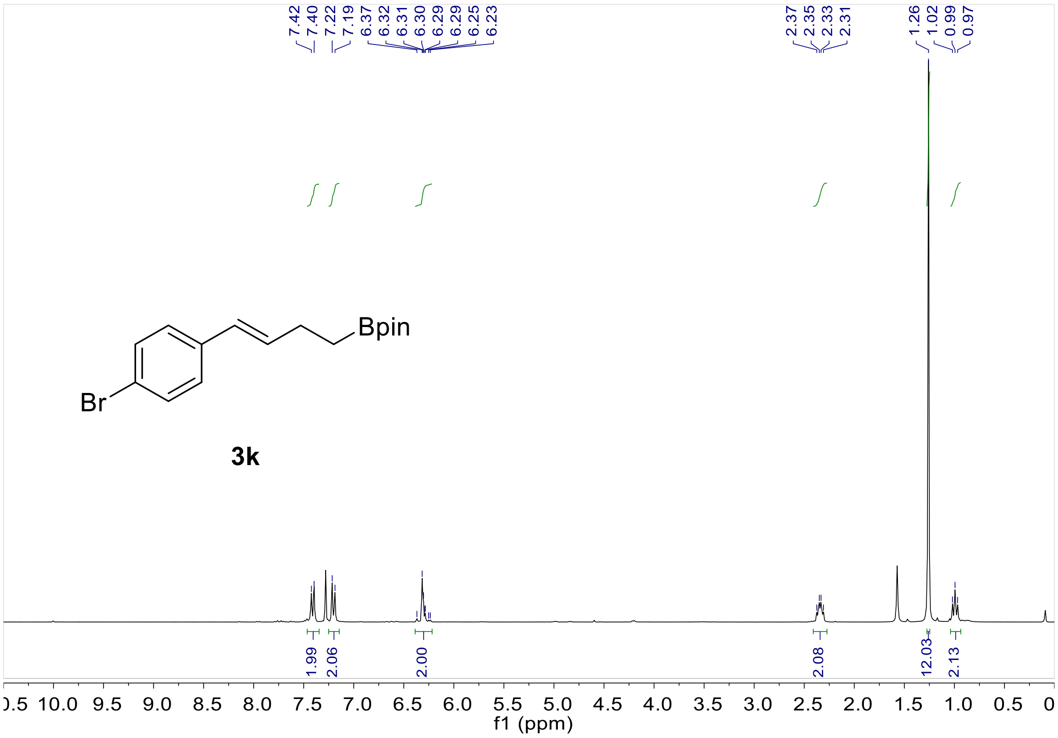


Figure 32. ^{1}H NMR spectra of product 3k.

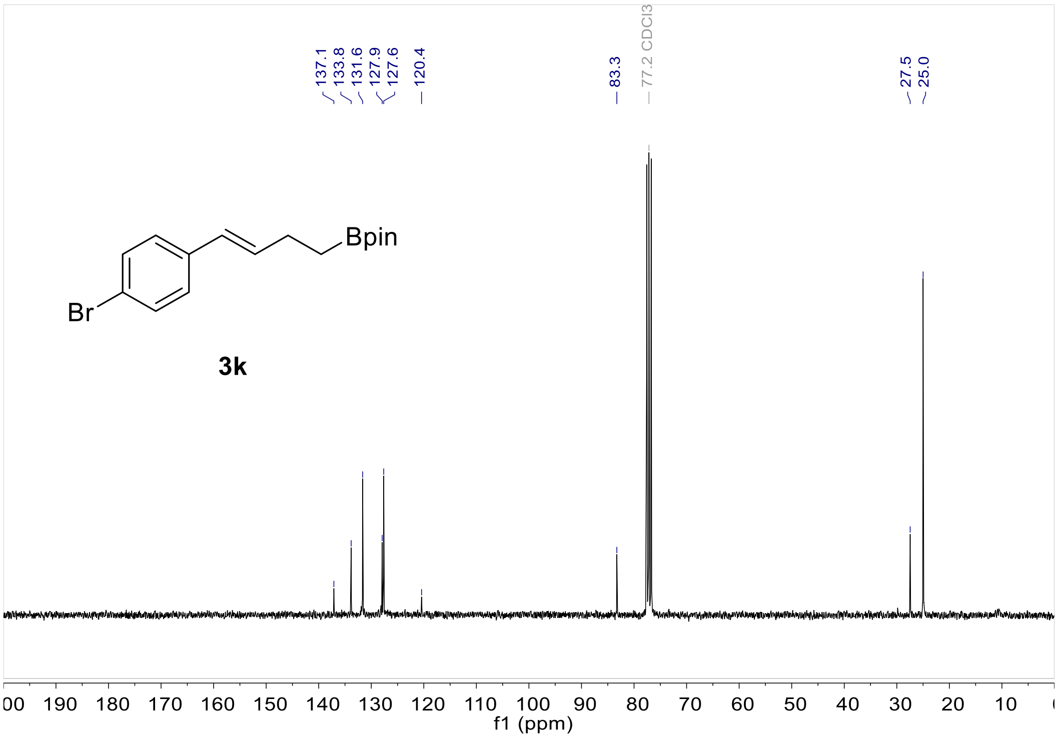


Figure 33. ^{13}C NMR spectra of product 3k

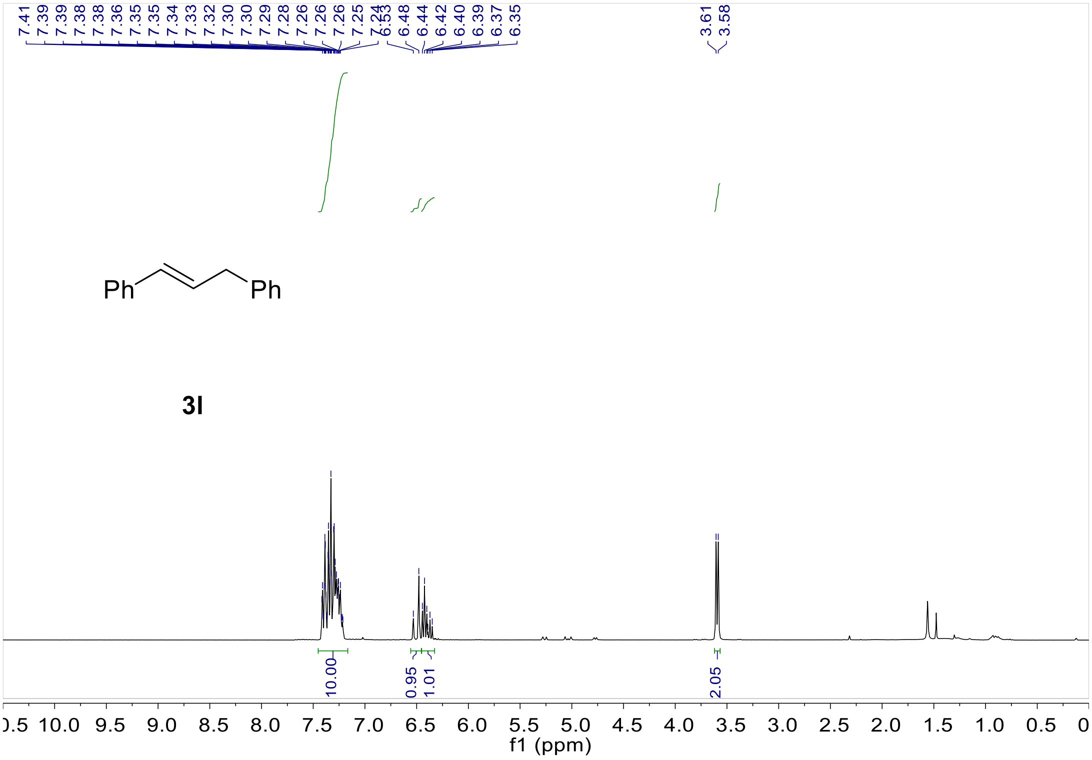


Figure 34. **^{1}H NMR spectra of product 3l.**

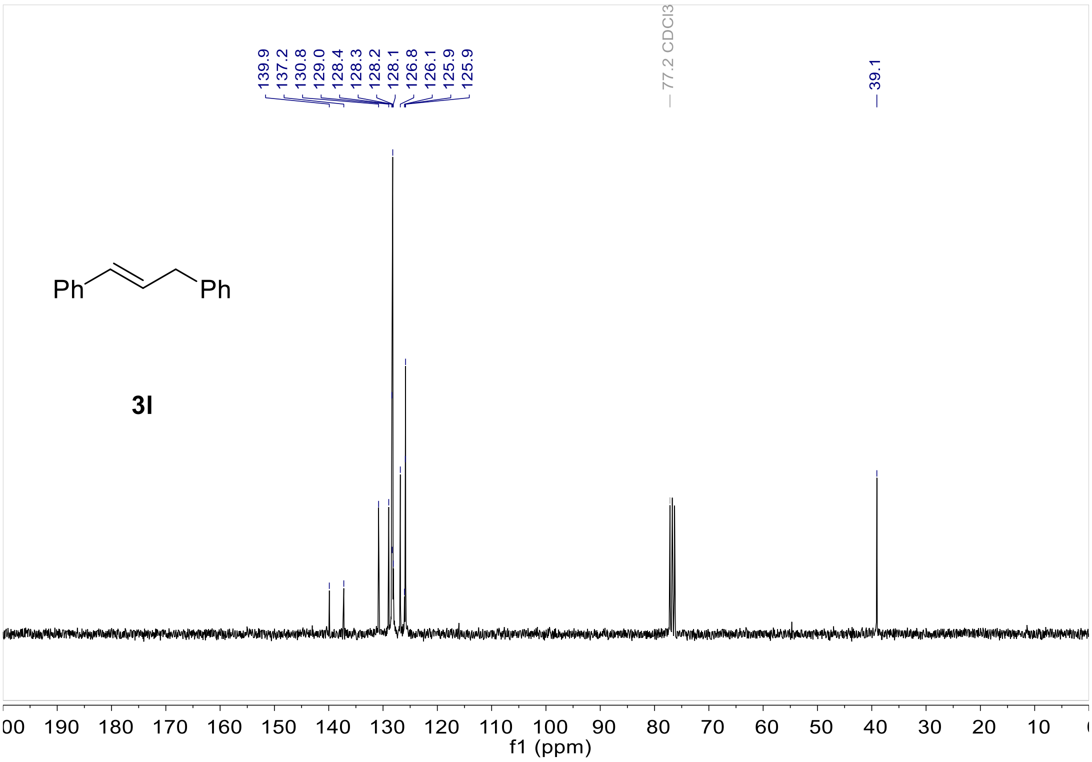


Figure 35. **^{13}C NMR spectra of product 3l.**

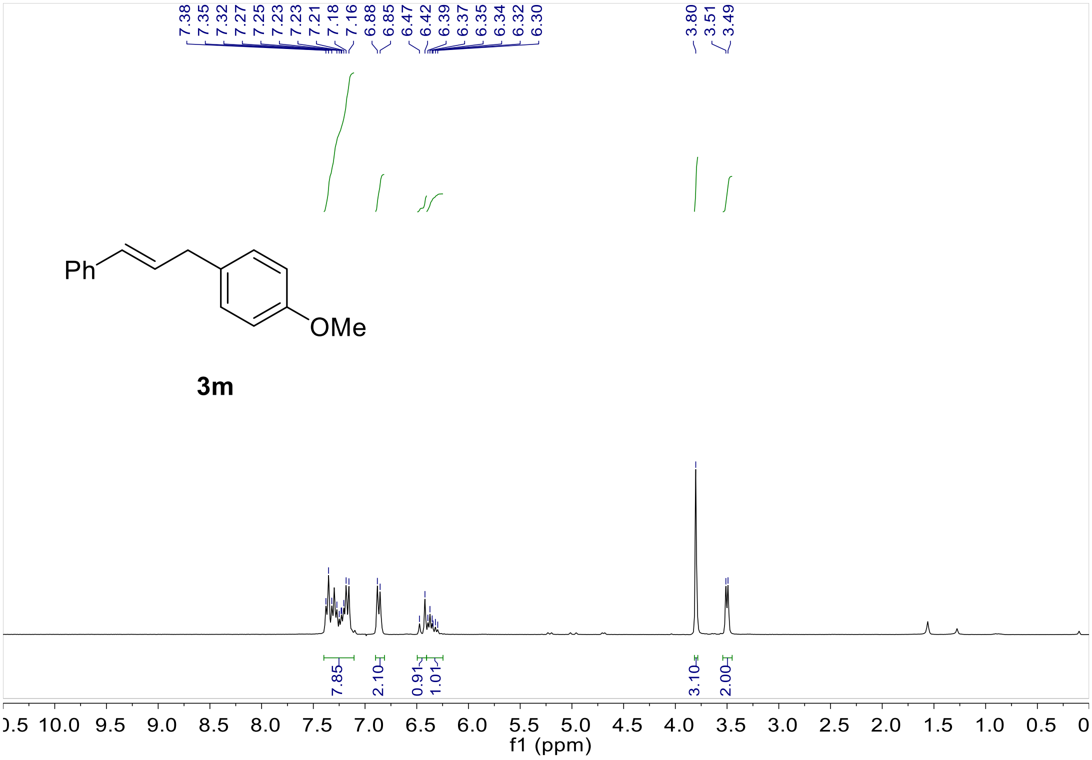


Figure 36. ^{1}H NMR spectra of product 3m.

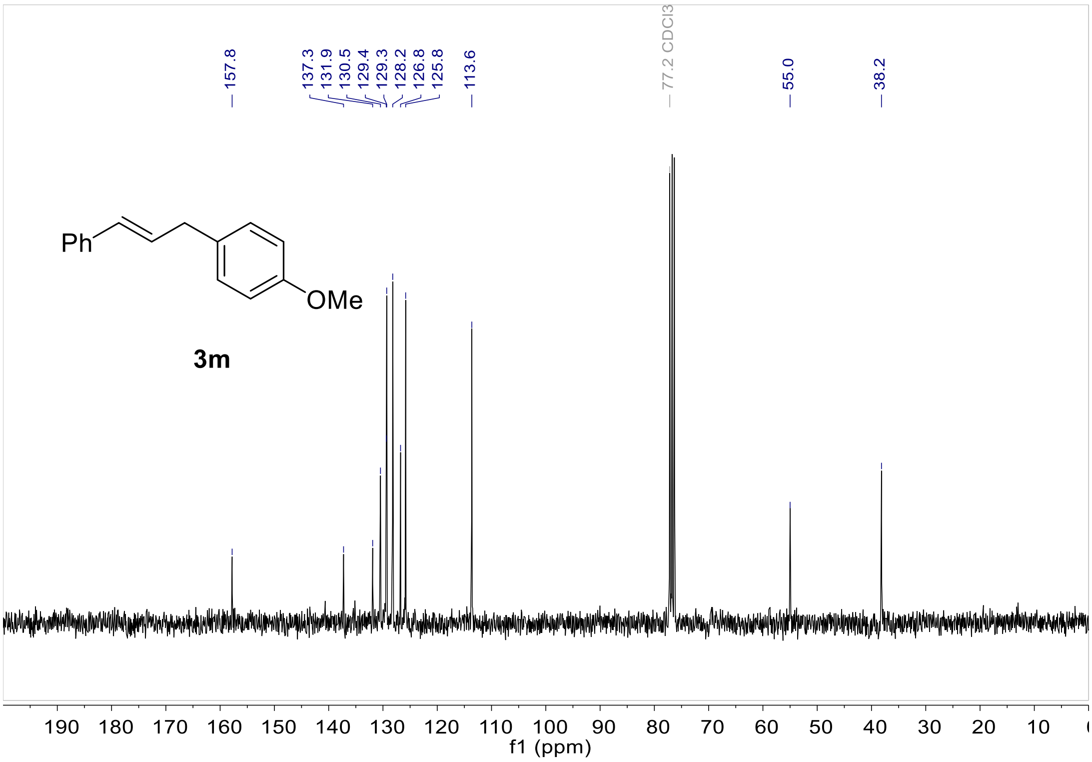


Figure 37. ^{13}C NMR spectra of product 3m.

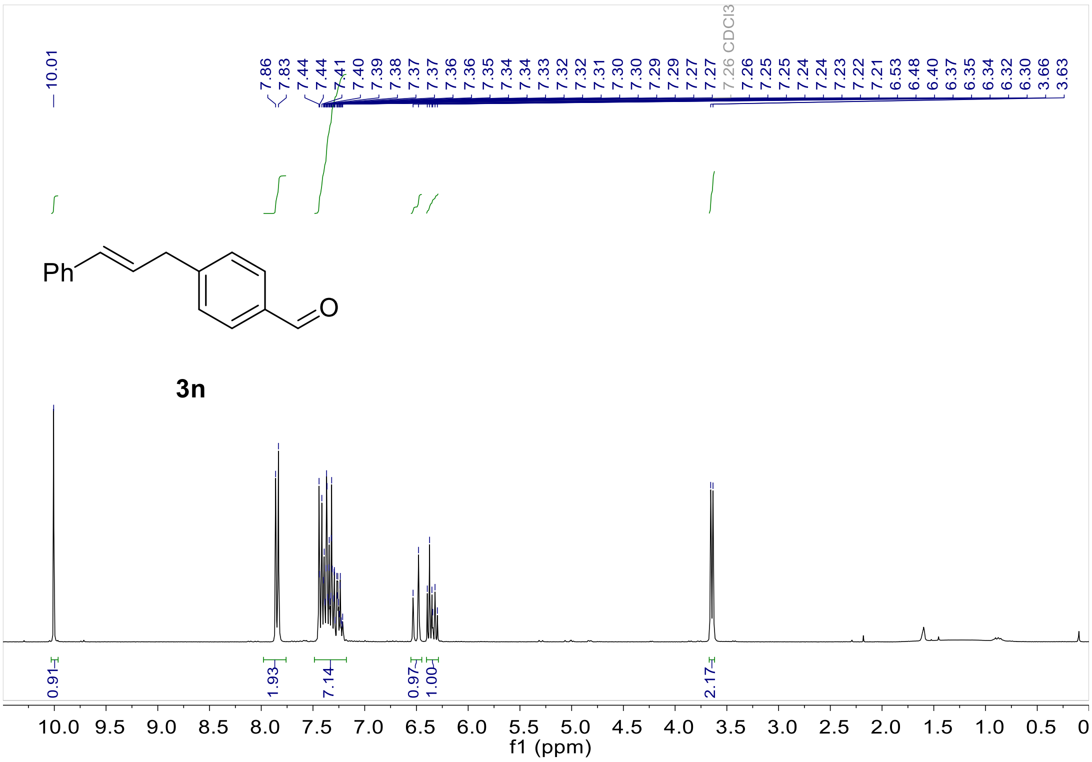


Figure 38. ^{1}H NMR spectra of product 3n.

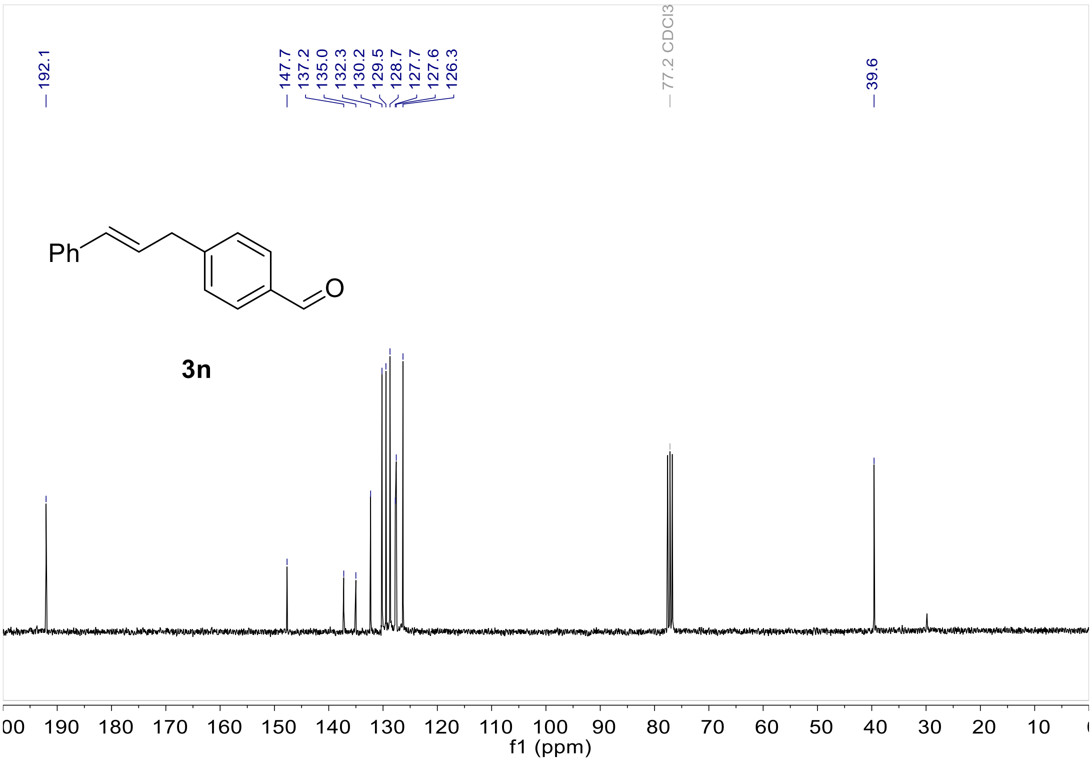


Figure 39. ^{13}C NMR spectra of product 3n.

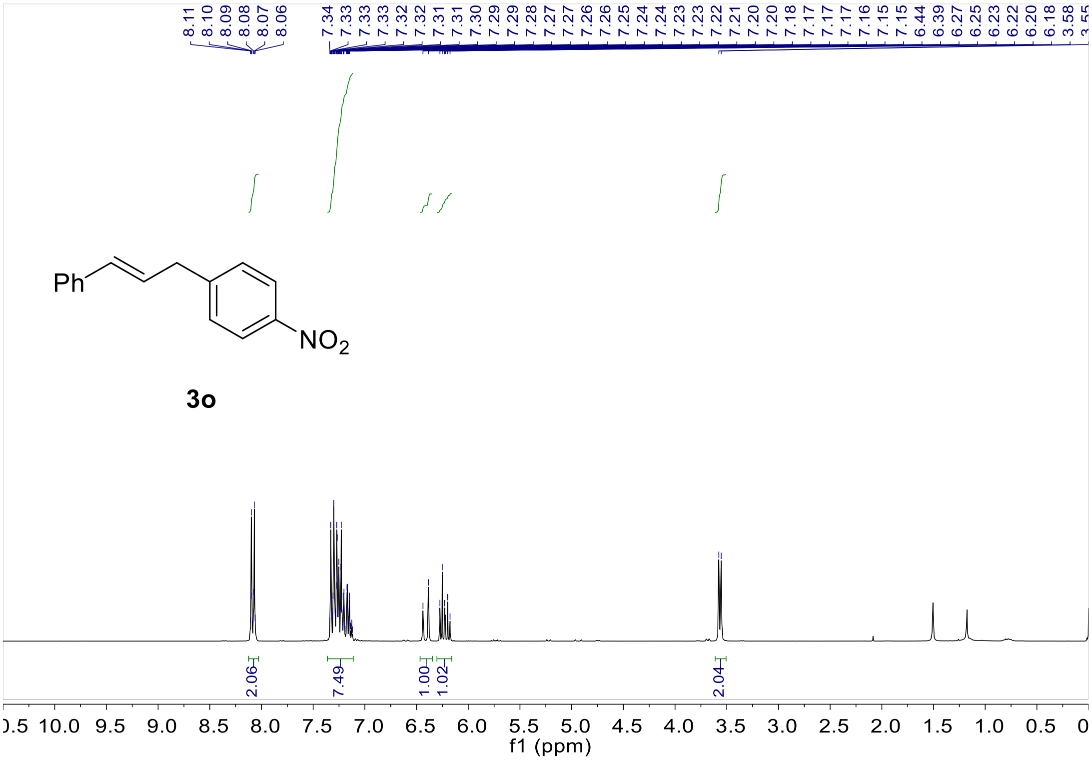


Figure 40. ^{1}H NMR spectra of product 3o.

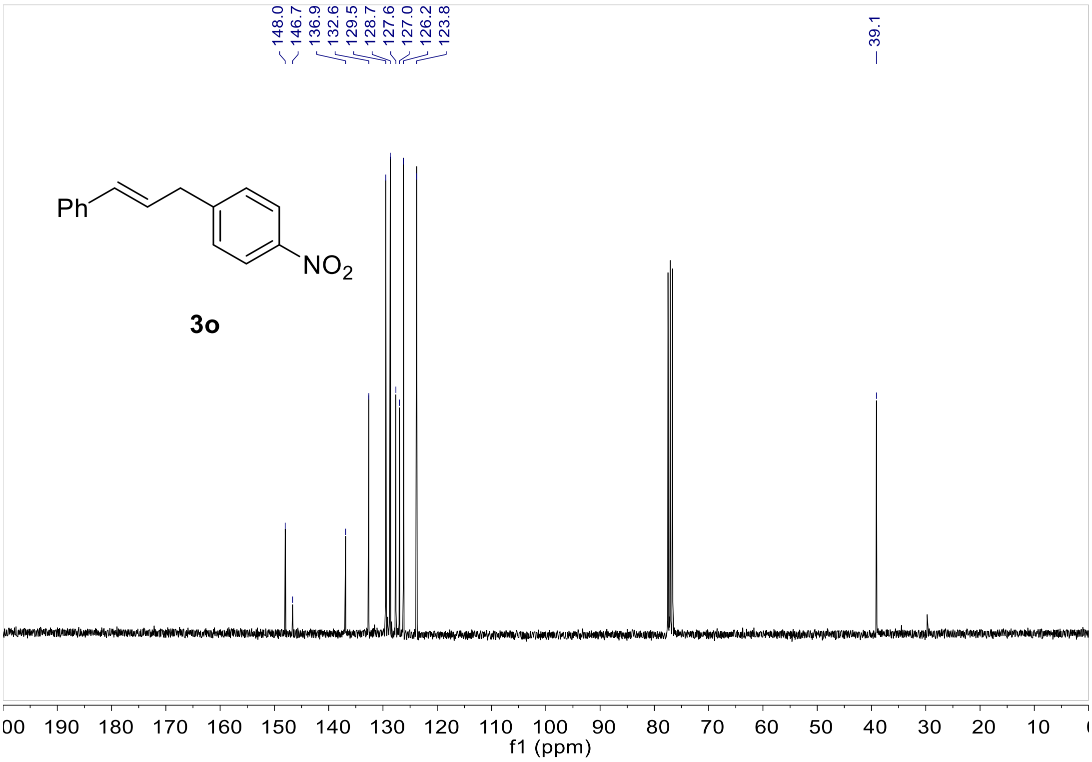


Figure 41. ^{13}C NMR spectra of product 3o.

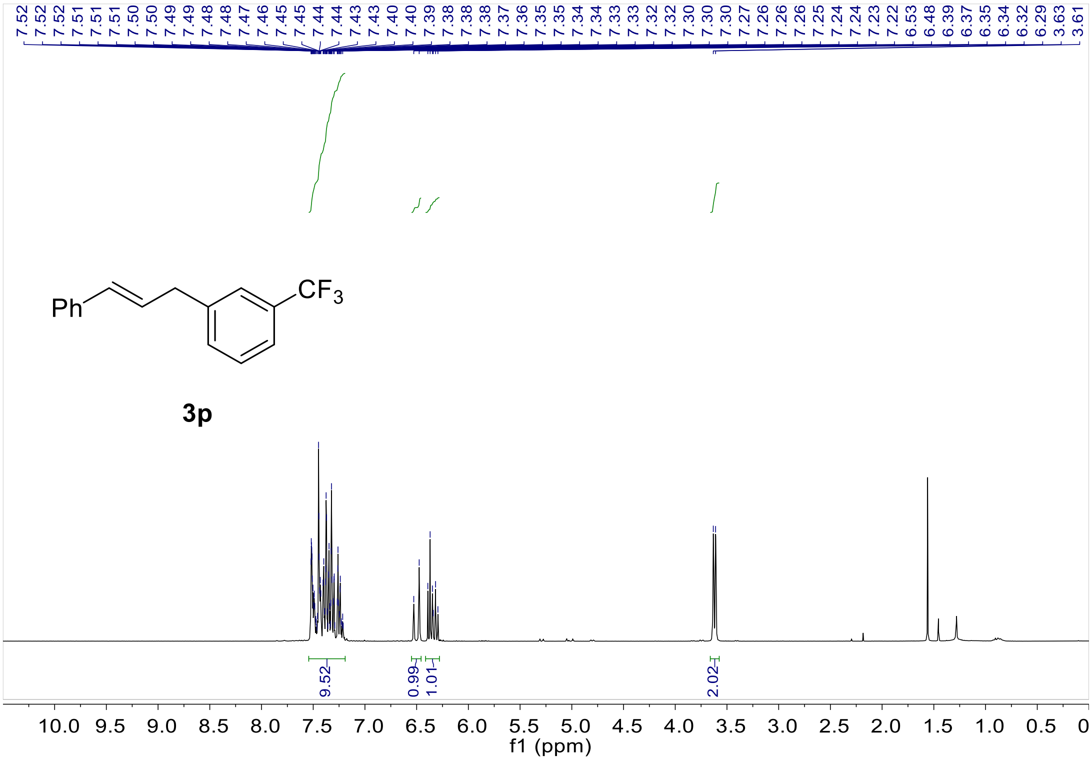


Figure 42. ^{1}H NMR spectra of product 3p.

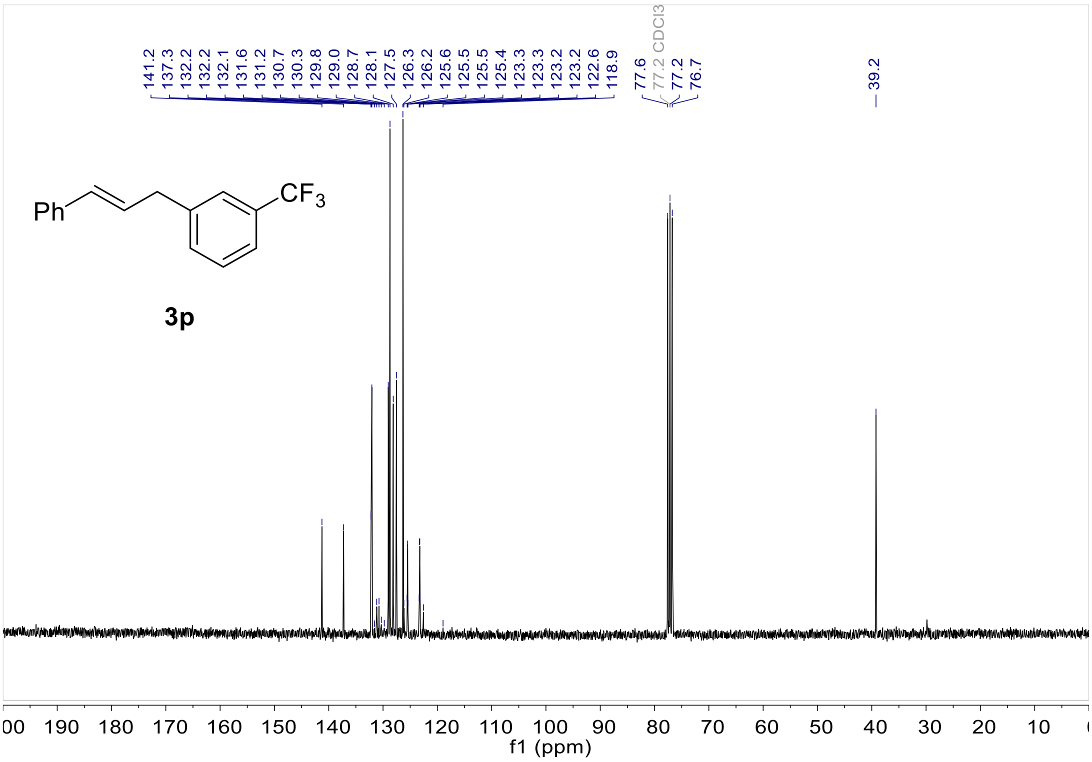


Figure 43. ^{13}C NMR spectra of product 3p.

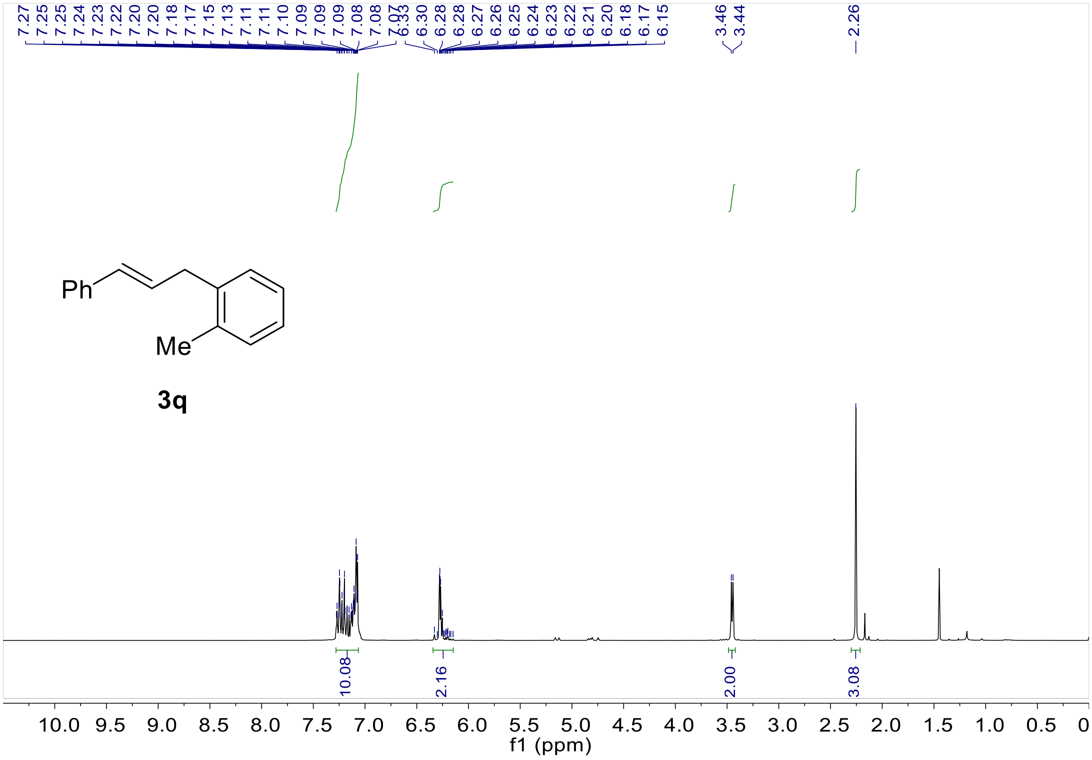


Figure 44. ^{1}H NMR spectra of product 3q.

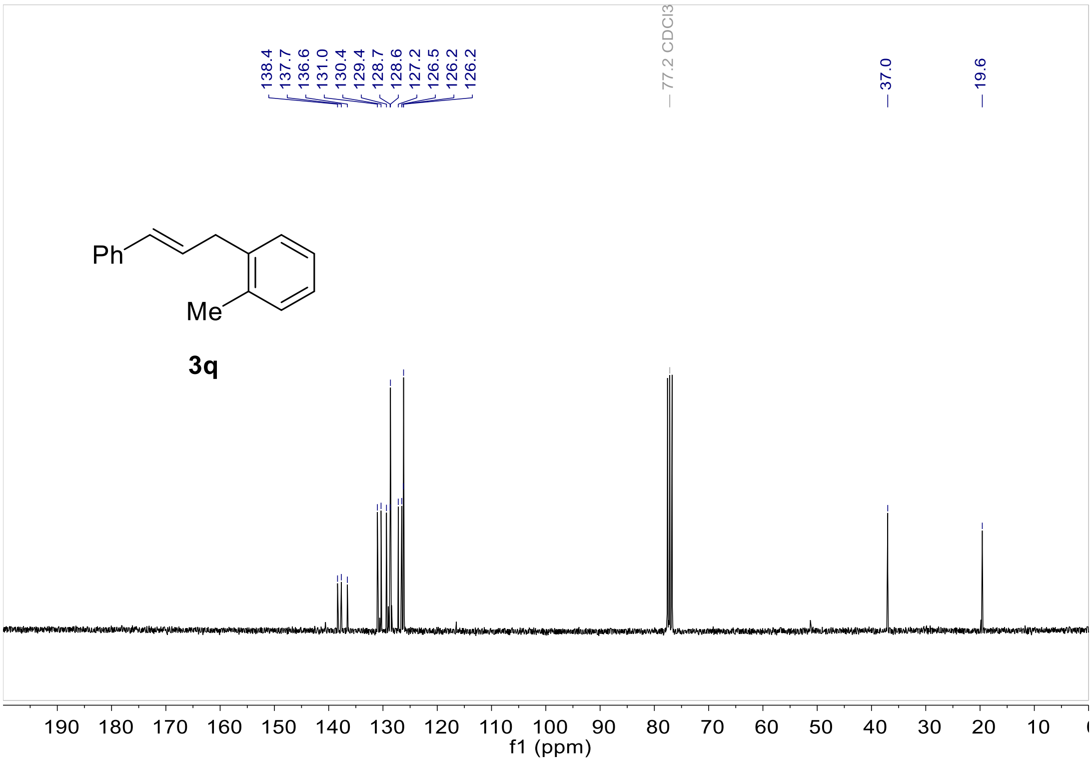


Figure 45. ^{13}C NMR spectra of product 3q.

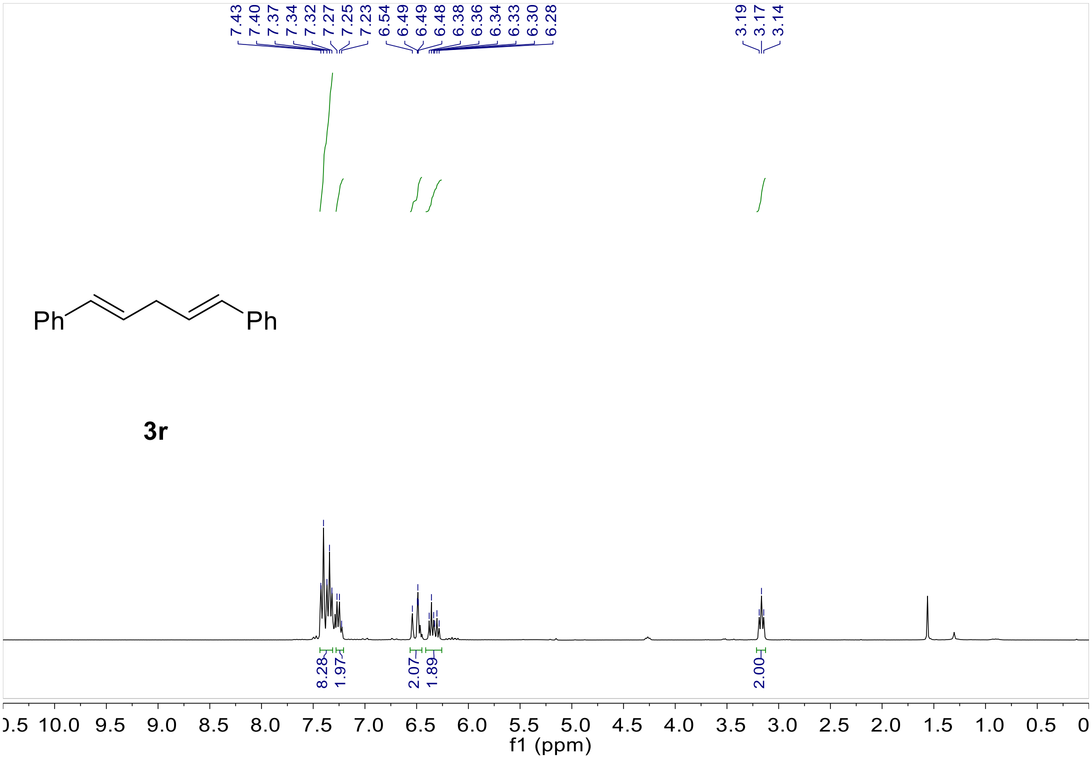


Figure 46. ^{1}H NMR spectra of product 3r.

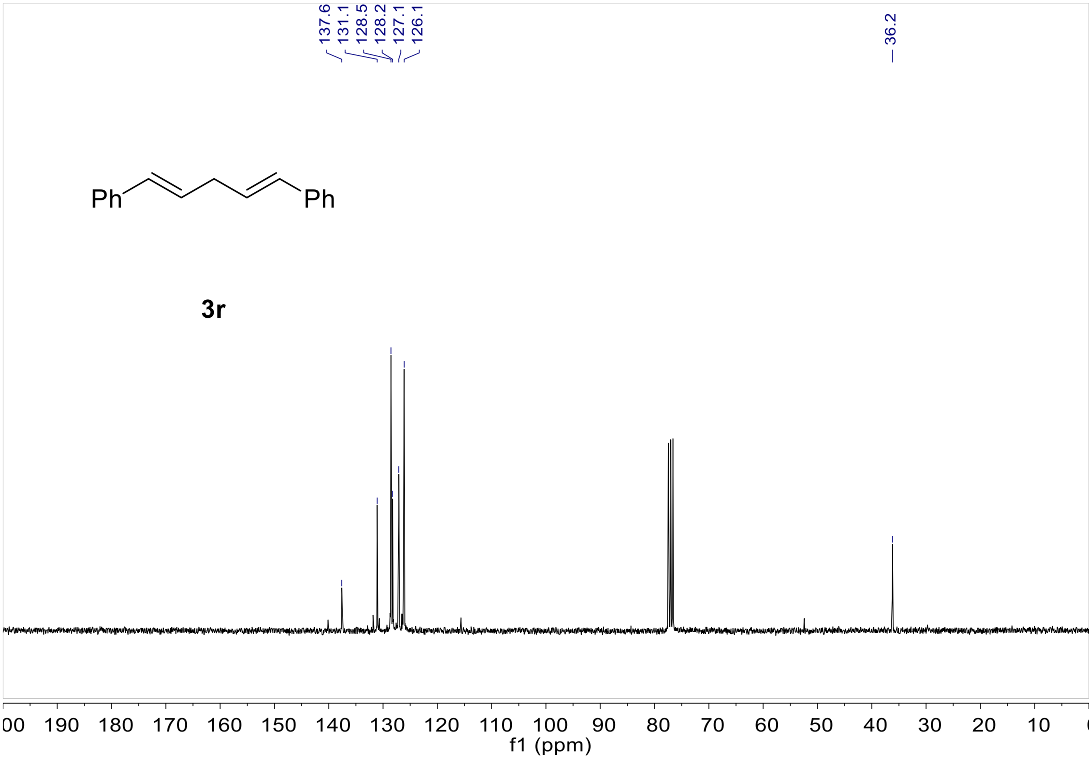


Figure 47. ^{13}C NMR spectra of product 3r.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

8.3 HETEROBIMETALLIC MOF-CATALYZED OXIDATIVE HECK COUPLING

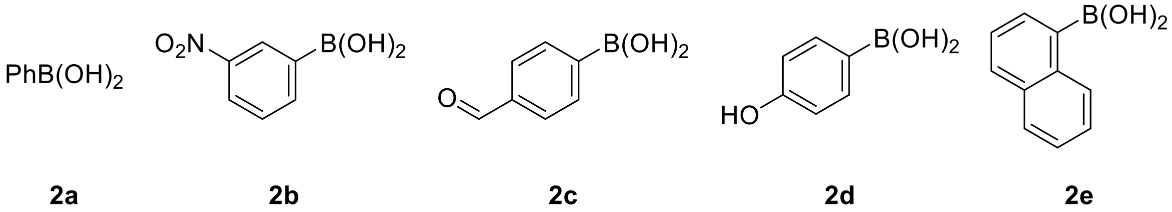
8.3.1 General procedure for the MUV-22 catalyzed oxidative Heck coupling.

A vial equipped with a magnetic stirring bar was charged with **MUV-22** (2.5 mol%). Boronic acid (0.4 mmol) and the alkene (0.1 mmol) were dissolved in the corresponding solvent (0.4 mL and 0.4 mL, respectively) and subsequently added to the reaction vessel. The reaction mixture was stirred at the designed temperature for until reaching full conversion by TLC or 48 hours. Then, Et_2O (2 mL) was added, and the mixture was decanted. This treatment was repeated 4 times solid. The combined organic layers were extracted with $NaCl_{(sat)}$ and the solvent was removed under vacuum. Yield was determined by ^{1}H-NMR using 1,3,5-trimethoxybenzene as internal standard. The reaction crude was purified by column chromatography with silica gel and isolated yield was obtained.

8.3.2 List of starting materials

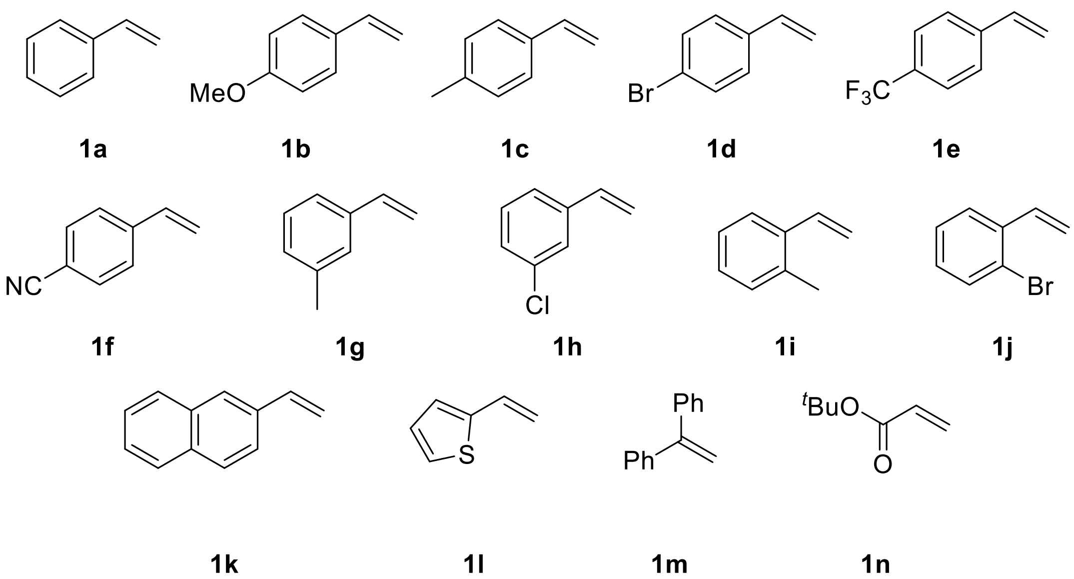
Alkenes **1a-1o** and boronic acids **2a-2e** were purchased from commercial sources.

8.3.2.1 Boronic acids



Scheme 54. Boronic acids used in the scope.

8.3.2.2 Alkenes



Scheme 55. Alkenes used in the scope.

8.3.3 Characterization data

(*E*)-1,2-Diphenylethylene (6a). Synthesized following the general procedure, obtained as a white solid in 80% yield after column chromatography (hexane). ^{1}**H NMR** (300 MHz, $CDCl_3$) δ 7.58 (d, *J* = 7.6 Hz, 4H), 7.42 (t, *J* = 7.6 Hz, 4H), 7.36-7.28 (t, *J* = 7.3 Hz, 2H), 7.17 (s, 2H). ^{13}**C NMR** (75 MHz, $CDCl_3$) δ 137.5, 128.8, 127.8, 126.7. Spectroscopic data are in accordance to reported literature.[135]

(*E*)-1-methoxy-4-styrylbenzene (6b). Synthesized following the general procedure, obtained as a white solid in 36% yield after column chromatography (hexane). ^{1}**H NMR** (300 MHz, CDl_3) δ 7.54-7.40 (m, 4H), 7.35 (t, *J* = 7.4 Hz, 2H), 7.26-7.19 (m, 1H), 7.08 (d, *J* = 16.3 Hz, 1H), 6.98 (d, *J* = 16.3 Hz, 1H), 6.91 (d, *J* = 8.7 Hz, 2H), 3.84 (s, 3H). ^{13}**C NMR** (75 MHz, $CDCl_3$) δ 159.5, 137.8, 130.3, 128.8, 128.4, 127.9, 127.4, 126.8, 126.4, 114.3, 55.5. Spectroscopic data are in accordance to reported literature.[136]

(*E*)-1-methyl-4-styrylbenzene (6c). Synthesized following the general procedure, obtained as a white solid in 81% yield after column chromatography (hexane). ^{1}**H NMR** (300 MHz, $CDCl_3$) δ 7.56 (d, *J* = 7.3 Hz, 2H), 7.47 (d, *J* = 8.1 Hz, 2H), 7.40 (t, *J* = 7.6 Hz, 2H), 7.35 – 7.24 (m, 1H), 7.22 (d, *J* = 8 Hz, 2H), 7.15 (d, *J* = 16.5 Hz, 1H), 7.09 (d, *J* = 16.5 Hz, 1H), 2.42 (s, 3H). ^{13}**C NMR (**75 MHz, $CDCl_3$) δ 137.7, 134.7, 129.5, 128.8, 127.9, 127.5, 126.6, 126.6, 21.4. Spectroscopic data are in accordance to reported literature.[136]

(*E*)-1-bromo-4-styrylbenzene (6d). Synthesized following the general procedure, obtained as a white solid in 93% yield after column chromatography (hexane). ^{1}**H NMR** (300 MHz, $CDCl_3$) δ 7.57-7.44 (m, 4H), 7.43-7.33 (m, 4H), 7.32-7.27 (m, 1H), 7.11 (d, *J* = 16.3 Hz, 1H), 7.03 (d, *J* = 16.3 Hz, 1H). ^{13}**C NMR** (75 MHz, $CDCl_3$) δ 137.1, 136.5, 131.9, 129.6, 128.9, 128.1, 128.1, 127.6, 126.7, 121.5. Spectroscopic data are in accordance to reported literature.[137]

(*E*)-1-styryl-4-(trifluoromethyl)benzene (6e). Synthesized following the general procedure, obtained as a white solid in 74% yield after column chromatography (hexane). ^{1}**H NMR** (300 MHz, $CDCl_3$) δ 7.61 (s, 4H), 7.55 (d, *J* = 7.6 Hz, 2H), 7.39 (t, *J* = 7.3 Hz, 2H), 7.35-7.27 (m, 1H), 7.21 (d, *J* = 16.3 Hz, 1H), 7.12 (d, *J* = 16.3 Hz, 1H).^{13}**C NMR** (75 MHz, $CDCl_3$) δ 140.9, 136.7, 131.3, 129.26 (q, *J* = 32.6 Hz), 128.9, 128.4, 127.2, 126.9, 126.7, 125.7 (q, *J* = 3.8 Hz), 124.3 (q, *J* = 271.6 Hz). ^{19}**F NMR** (282 MHz, $CDCl_3$) δ -62.47. Spectroscopic data are in accordance to reported literature.[138]

---

[135] Dai, M.; Liang, B.; Wang, C.; Chen, J.; Yang, Z. *Org. Lett*. **2004**, *6*, 221-224.
[136] Iwasaki, T.; Miyata, Y.; Akimoto, R.; Fujii, Y.; Kuniyasu, H.; Kambe. *J. Am. Chem. Soc*. **2014**, *136*, 9260-9263.
[137] Aydin, J.; Larsson, J. M.; Selander, N.; Szabó, K. J. *Org. Lett*. **2009**, *11*, 2852-2854.
[138] Selvakumar, K.; Zapf, A.; Beller, M. *Org. Lett*. **2002**, *4*, 3031-3033.

(*E*)-4-styrylbenzonitrile (6f). Synthesized following the general procedure, obtained as a white solid in 63% yield after column chromatography (hexane:Et_2O 96:4). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.69-7.48 (m, 6H), 7.39 (t, *J* = 7.2 Hz, 2H), 7.32 (m, 1H), 7.22 (d, *J* = 16.3 Hz, 1H), 7.09 (d, *J* = 16.3 Hz, 1H).**^{13}C NMR** (75 MHz, $CDCl_3$) δ 142.0, 136.5, 132.6, 132.6, 129.0, 128.8, 127.1, 127.0, 126.9, 119.1, 110.8. Spectroscopic data are in accordance to reported literature.[139]

(*E*)-1-methyl-3-styrylbenzene (6g). Synthesized following the general procedure, obtained as a colorless oil in 73% yield after column chromatography (hexane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.52 (d, *J* = 7.9 Hz, 2H), 7.42-7.29 (m, 4H), 7.29-7.21 (m, 2H), 7.13-7.05 (m, 3H), 2.39 (s, 3H).**^{13}C NMR** (75 MHz, $CDCl_3$) δ 138.4, 137.6, 137.5, 129.0, 128.8, 128.7, 128.7, 128.6, 127.7, 127.4, 126.6, 123.9, 21.6. Spectroscopic data are in accordance to reported literature.[137]

(*E*)-1-chloro-3-styrylbenzene (6h). Synthesized following the general procedure, obtained as a white solid in 81% yield after column chromatography (hexane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.59-7.50 (m, 3H), 7.46-7.36 (m, 3H), 7.36-7.21 (m, 3H), 7.15 (d, *J* = 16.3 Hz, 1H), 7.06 (d, *J* = 16.3 Hz, 1H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 139.4, 137.0, 134.8, 130.3, 130.0, 128.9, 128.2, 127.6, 127.4, 126.8, 126.5, 124.9. Spectroscopic data are in accordance to reported literature.[140]

(*E*)-1-methyl-2-styrylbenzene (6i). Synthesized following the general procedure, obtained as a colorless oil in 72% yield after column chromatography (hexane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.64 (d, *J* = 6.3 Hz, 1H), 7.57 (d, *J* = 7.1 Hz, 2H), 7.47-7.15 (m, 7H), 7.04 (d, *J* = 16.1 Hz, 1H), 2.48 (s, 3H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 137.9, 136.6, 135.9, 130.5, 130.2, 128.8, 127.7, 127.7, 126.7, 126.7, 126.3, 125.5, 20.0. Spectroscopic data are in accordance to reported literature.[141]

(*E*)-1-bromo-2-styrylbenzene (6j). Synthesized following the general procedure, obtained as a white solid in 36% yield after column chromatography (hexane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.68 (dd, *J* = 7.8, 1.7 Hz, 1H), 7.58 (m, 3H), 7.48 (d, *J* = 16.2 Hz, 1H), 7.39 (t, *J* = 7.4 Hz, 2H), 7.38-7.24 (m, 2H), 7.12 (td, *J* = 7.7, 1.7 Hz, 1H), 7.05 (d, *J* = 16.2 Hz, 1H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 137.3, 137.2, 133.2, 131.6, 128.9, 128.9, 128.2, 127.7, 127.7, 127.0, 126.9, 124.3. Spectroscopic data are in accordance to reported literature.[142]

---

[139] Khalafi-Nezhad, A.; Panahi, F. *ACS Sustainable Chem. Eng.* **2014**, *2*, 1177-1186.

[140] Zhang, J.-Q.; Cao, J.; Li, W.; Li, S.-M.; Li, Y.-K.; Wang, J.-T.; Tang, L. *New J. Chem.* **2017**, *41*, 437-441.

[141] Tanaka, S.; Mori, A. *Eur. J. Org. Chem.* **2014**, *2014*, 1167-1171.

[142] Krasovkskiy, A. L.; Haley, S.; Voigtritter, K.; Lipshutz, B. H. *Org. Lett.* **2014**, *16*, 4066-4069.

(*E*)-2-styrylnaphthalene (6k). Synthesized following the general procedure, obtained as a white solid in 45% yield after column chromatography (hexane:Et_2O 99:1). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.98-7.83 (m, 4H), 7.79 (d, J = 8.6 Hz, 1H), 7.61 (d, J = 8.0 Hz, 2H), 7.54-7.48 (m, 2H), 7.43 (t, J = 7.6 Hz, 2H), 7.38-7.23 (m, 3H). **^{13}C NMR** (75 MHz, CDCl3) δ 137.5, 135.0, 133.9, 133.2, 129.2, 129.0, 128.9, 128.5, 128.2, 127.8, 126.8, 126.7, 126.5, 126.1, 123.7. Spectroscopic data are in accordance to reported literature.[137]

(*E*)-2-styrylthiophene (6l). Synthesized following the general procedure, obtained as a yellow solid in 32% yield after column chromatography (hexane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.47 (d, J = 7.8 Hz, 2H), 7.35 (t, J = 7.7 Hz, 2H), 7.27-7.15 (m, 2H), 7.07 (d, J = 3.7 Hz, 1H), 7.03-6.98 (m, 1H), 6.93 (d, J = 16.1 Hz, 1H).**^{13}C NMR** (75 MHz, $CDCl_3$) δ 143.1, 137.1, 128.8, 128.5, 127.7, 126.5, 126.2, 124.5, 121.9. Spectroscopic data are in accordance to reported literature.[143]

ethene-1,1,2-triyltribenzene (6m). Synthesized following the general procedure, obtained as a white solid in 51% yield after column chromatography (hexane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.43-7.28 (m, 8H), 7.28-7.22 (m, 2H), 7.20-7.11 (m, 3H), 7.10-7.03 (m, 2H), 7.01 (s, 1H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 143.6, 142.8, 140.5, 137.6, 130.5, 129.7, 128.8, 128.3, 128.3, 128.1, 127.8, 127.6, 127.5, 126.9. Spectroscopic data are in accordance to reported literature.[144]

(*E*)-tert-butyl cinnamate (6n). Synthesized following the general procedure, obtained as a colorless oil in 74% yield after column chromatography (hexane:Et_2O 97:3). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.59 (d, J = 16.0 Hz, 1H), 7.54-7.45 (m, 2H), 7.37 (m, 3H), 6.37 (d, J = 16.0 Hz, 1H), 1.54 (s, 9H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 166.5, 143.7, 134.9, 130.1, 129.0, 128.1, 120.4, 80.6, 28.4. Spectroscopic data are in accordance to reported literature.[145]

(*E*)-1-nitro-3-styrylbenzene (6o). Synthesized following the general procedure, obtained as a yellow solid in 63% yield after column chromatography (hexane:Et_2O 93:7). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 8.39 (t, J = 2.0 Hz, 1H), 8.12 (ddd, J = 8.2, 2.3, 1.0 Hz, 1H), 7.87- 7.77 (d, J = 7.8 Hz ,1H), 7.62-7.49 (m, 3H), 7.48-7.37 (m, 2H), 7.35 (m, 1H), 7.27 (d, J = 16.3 Hz, 1H), 7.16 (d, J = 16.3 Hz, 1H).**^{13}C NMR** (75 MHz, $CDCl_3$) δ 148.9, 139.4, 136.5, 132.4, 132.0, 129.7, 129.0, 128.7, 127.0, 126.3, 122.2, 121.1. Spectroscopic data are in accordance to reported literature.[136]

---

[143] Mennecke, K.; Kirschning, A. *Beilstein J. Org. Chem*. **2009,** 5, No. 21.
[144] Cahiez, G.; Moyeux, A.; Poizat, M. *Chem. Commun*. **2014**, 50, 8982-8984.
[145] Zhou, X.; Luo, J.; Liu, J.; Peng, S.; Deng, G.-J. *Org. Lett.* **2011**, 13, 1432-1435.

(*E*)-4-styrylbenzaldehyde (6p). Synthesized following the general procedure, obtained as a white solid in 76% yield after column chromatography (hexane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 10.00 (s, 1H), 7.87 (d, J = 8.2 Hz, 2H), 7.66 (d, J = 8.3 Hz, 3H), 7.55 (d, J = 7.3 Hz, 1H), 7.39 (t, J = 7.3 Hz, 2H), 7.32 (d, J = 7.4 Hz, 1H), 7.27 (d, J = 16.3 Hz, 1H), 7.14 (d, J = 16.3 Hz, 2H).**^{13}C NMR** (75 MHz, $CDCl_3$) δ 191.6, 143.4, 136.6, 135.4, 132.2, 130.2, 128.8, 128.5, 127.4, 126.9. Spectroscopic data are in accordance to reported literature.[146]

tert-butyl(*E*)-4-(4-hydroxystyryl)benzoate (6q). Synthesized following the general procedure, obtained as a white solid in 26% yield after column chromatography (hexane:Et_2O 95:5). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 7.53 (d, J = 16.0 Hz, 1H), 7.40 (d, J = 8.6 Hz, 2H), 6.83 (d, J = 8.6 Hz, 2H), 6.23 (d, J = 16.0 Hz, 1H), 5.46 (br s, 1H), 1.53 (s, 9H).**^{13}C NMR** (75 MHz, $CDCl_3$) δ 157.6, 143.4, 129.9, 127.7, 117.9, 116.0, 80.5, 28.4. Spectroscopic data are in accordance to reported literature.[147]

(*E*)-1-styrylnaphthalene (6r). Synthesized following the general procedure, obtained as a white solid in 61% yield after column chromatography (hexane). **^{1}H NMR** (300 MHz, $CDCl_3$) δ 8.23 (d, J = 7.5 Hz, 1H), 7.96-7.85 (m, 2H), 7.81 (d, J = 8.2 Hz, 1H), 7.75 (d, J = 7.3 Hz, 1H), 7.61 (d, J = 7.2 Hz, 3H), 7.58-7.46 (m, 3H), 7.41 (t, J = 7.4 Hz, 2H), 7.35-7.27 (m, 1H), 7.16 (d, J = 16.0 Hz, 1H). **^{13}C NMR** (75 MHz, $CDCl_3$) δ 137.8, 135.2, 133.9, 131.9, 131.6, 128.9, 128.8, 128.2, 127.9, 126.8, 126.2, 126.0, 125.8, 123.9, 123.8. Spectroscopic data are in accordance to reported literature.[148]

---

[146] Huang, M.-H.; Liang, L.-C. *Organometallics* **2004**, *23*, 2813-2816.

[147] Szewczyk, S. M.; Zhao, Y.; Sakai, H. A.; Dube, P.; Newhouse, T. R. *Tetrahedron* **2018,** *74*, 3293-3300.

[148] Alacid, E.; Nájera, C. *J. Org. Chem.* **2009**, *74*, 8191-8195.

USC

8.3.4 ^{1}H-NMR and ^{13}C-NMR Spectra

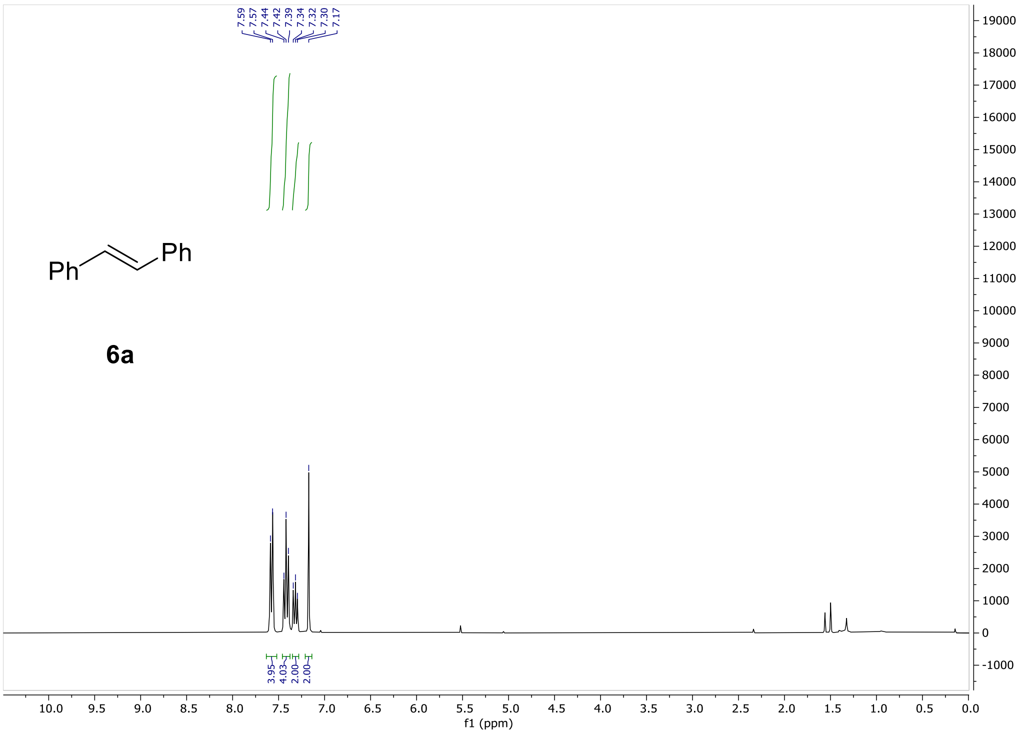


Figure 48. ^{1}H NMR spectra of product 6a.

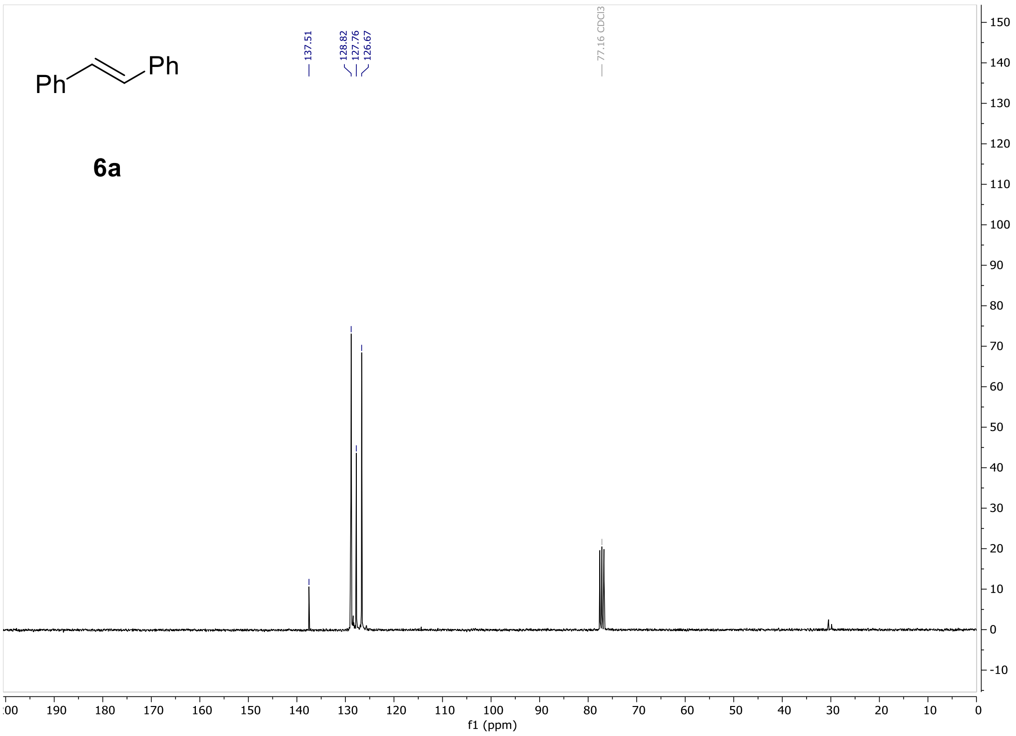


Figure 49. ^{13}C NMR spectra of product 6a.

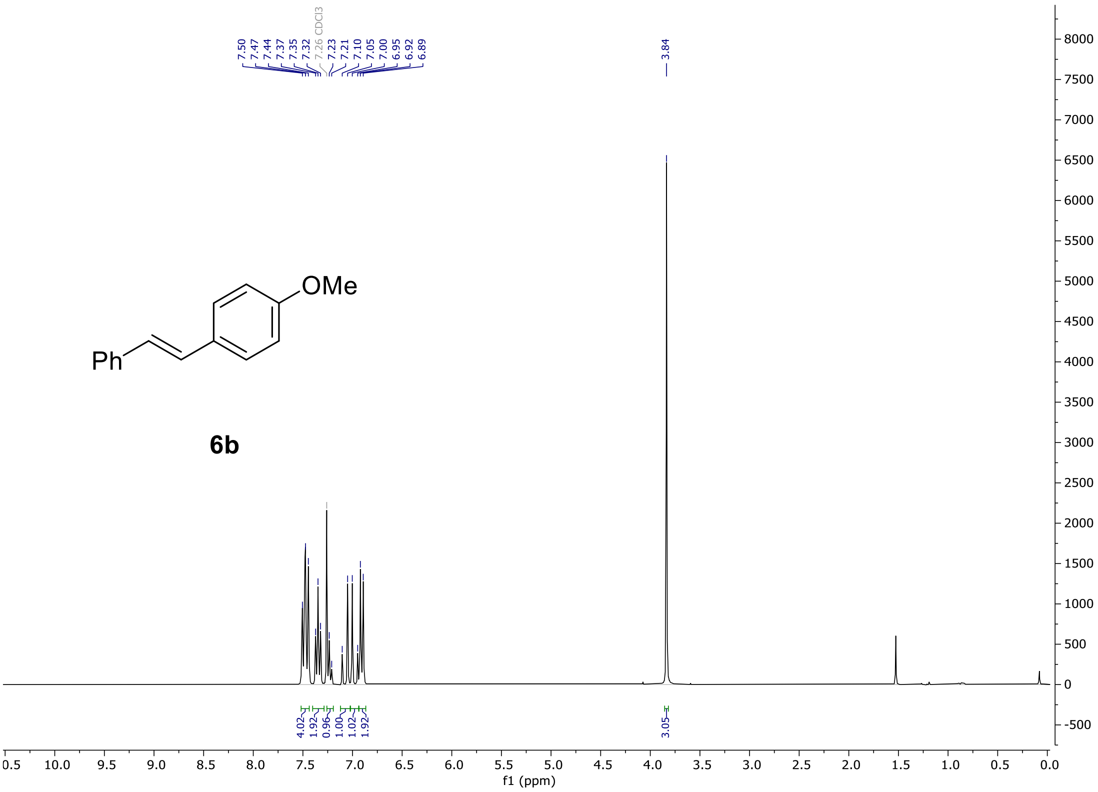


Figure 50. ^{1}H NMR spectra of product 6b.

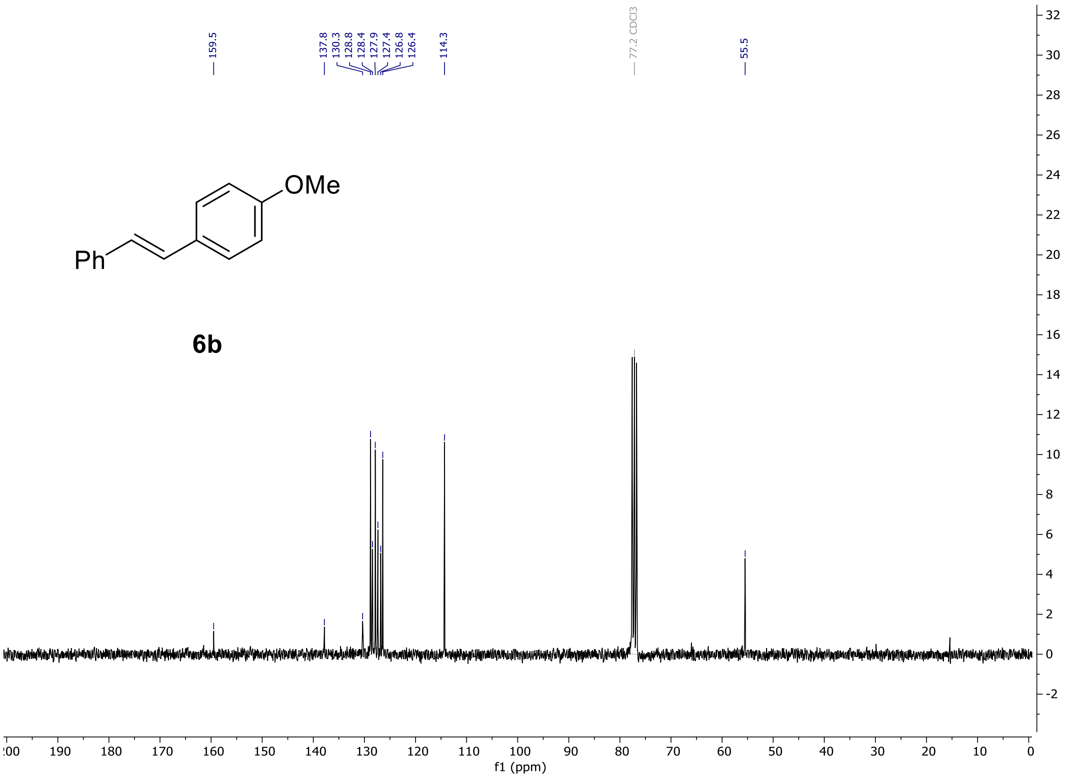


Figure 51. ^{13}C NMR spectra of product 6b.

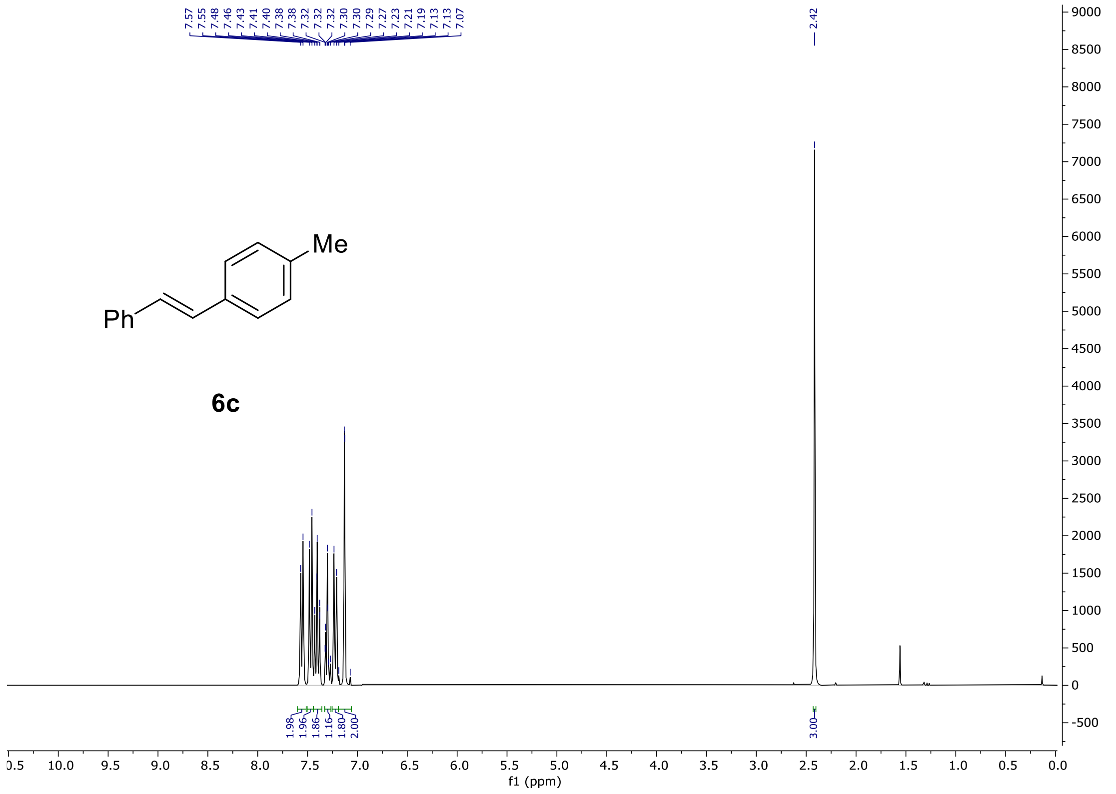


Figure 52. ^{1}H NMR spectra of product 6c.

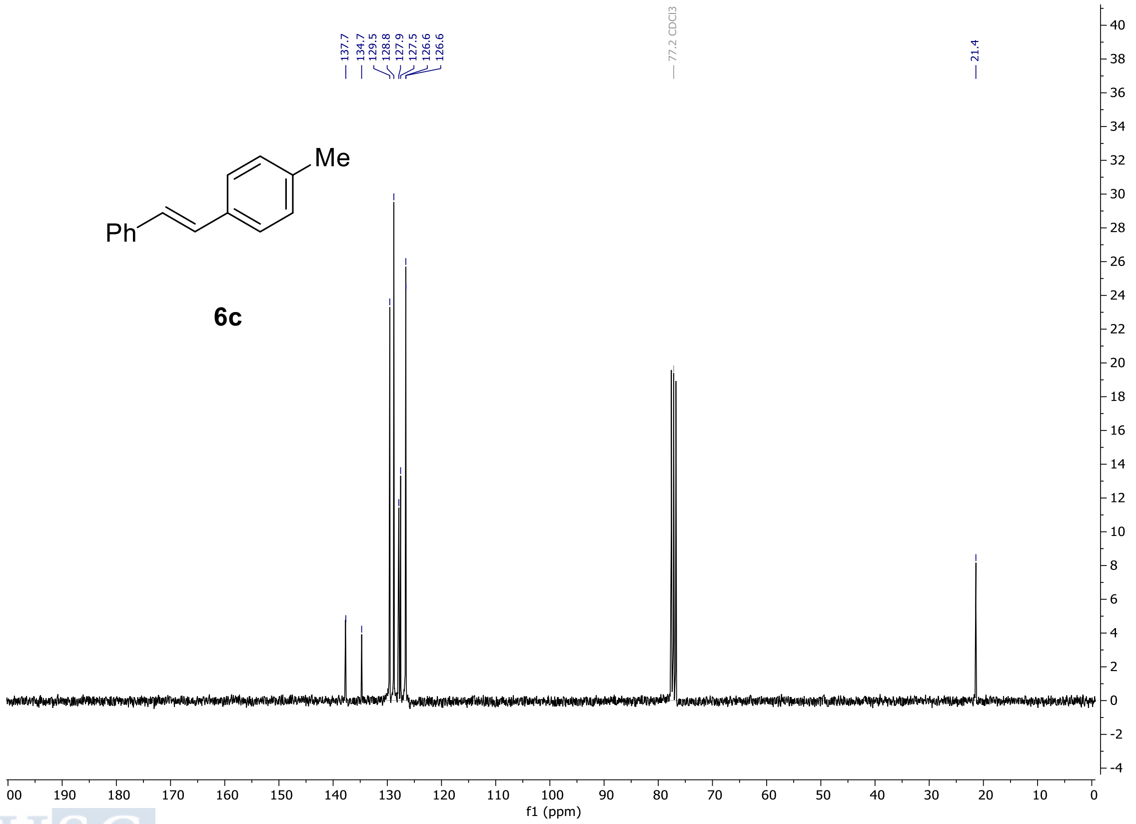


Figure 53. ^{13}C NMR spectra of product 6c.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

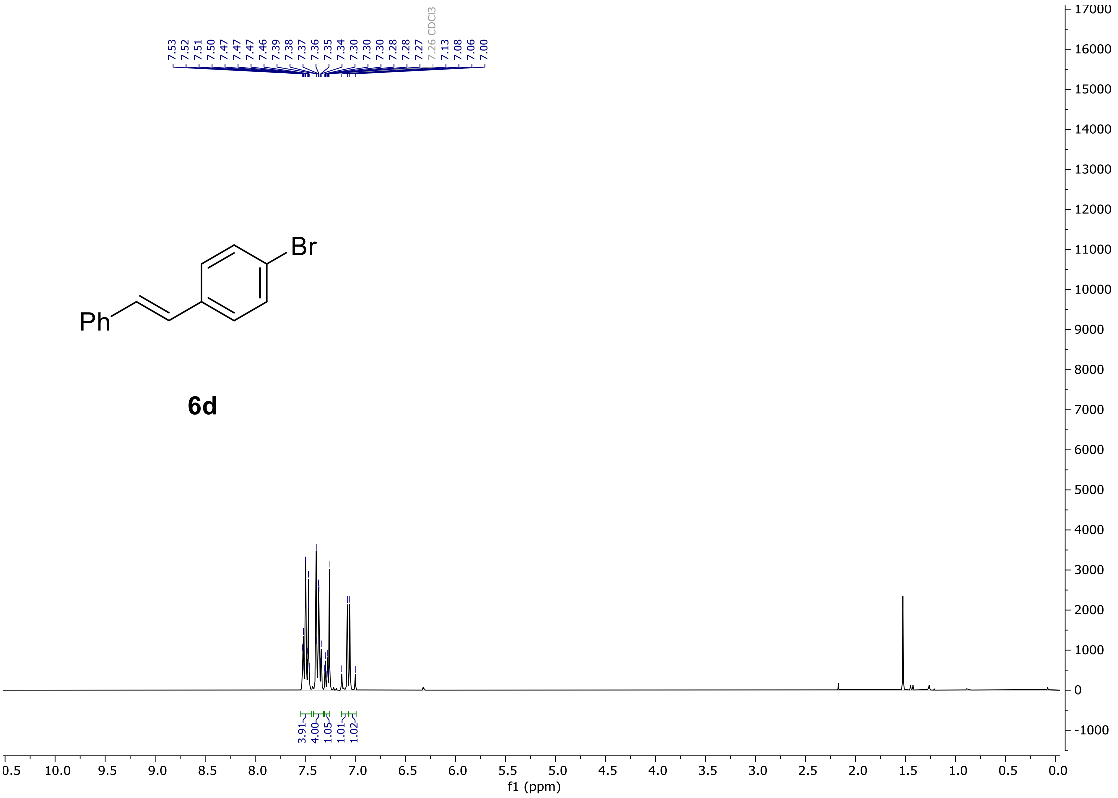


Figure 54. ^{1}H NMR spectra of product 6d.

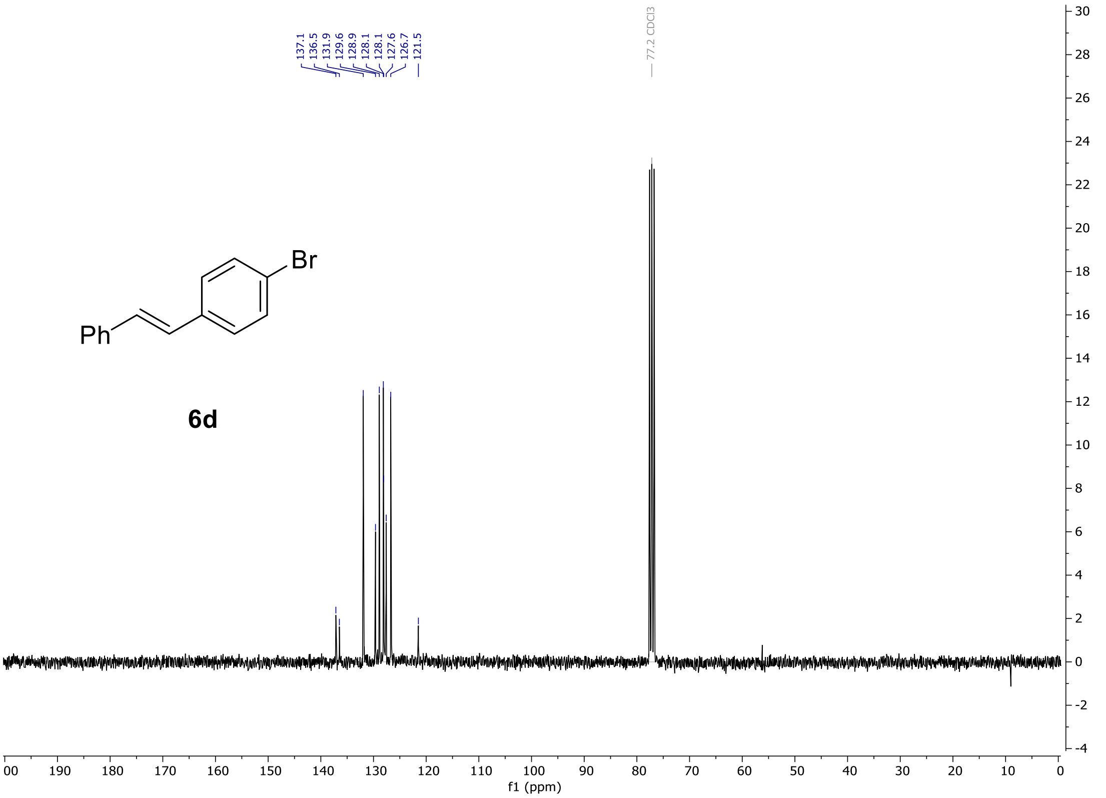


Figure 55. ^{13}C NMR spectra of product 6d.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

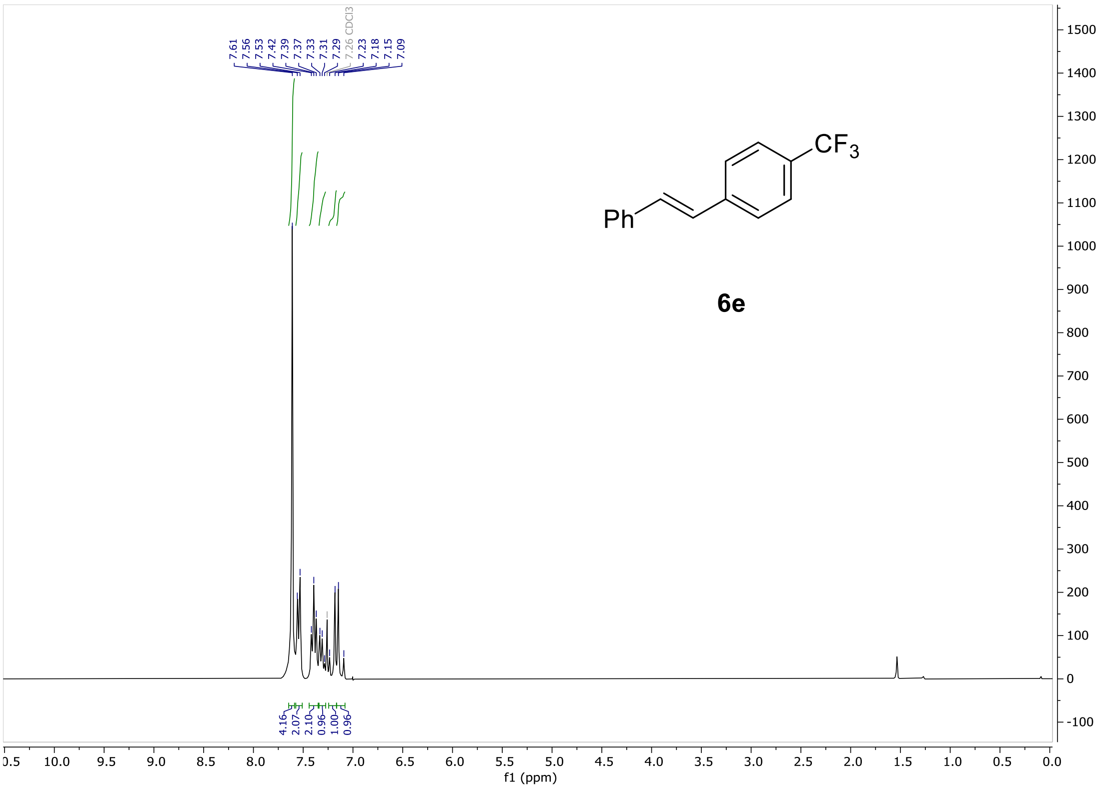


Figure 56. ^{1}H NMR spectra of product 6e.

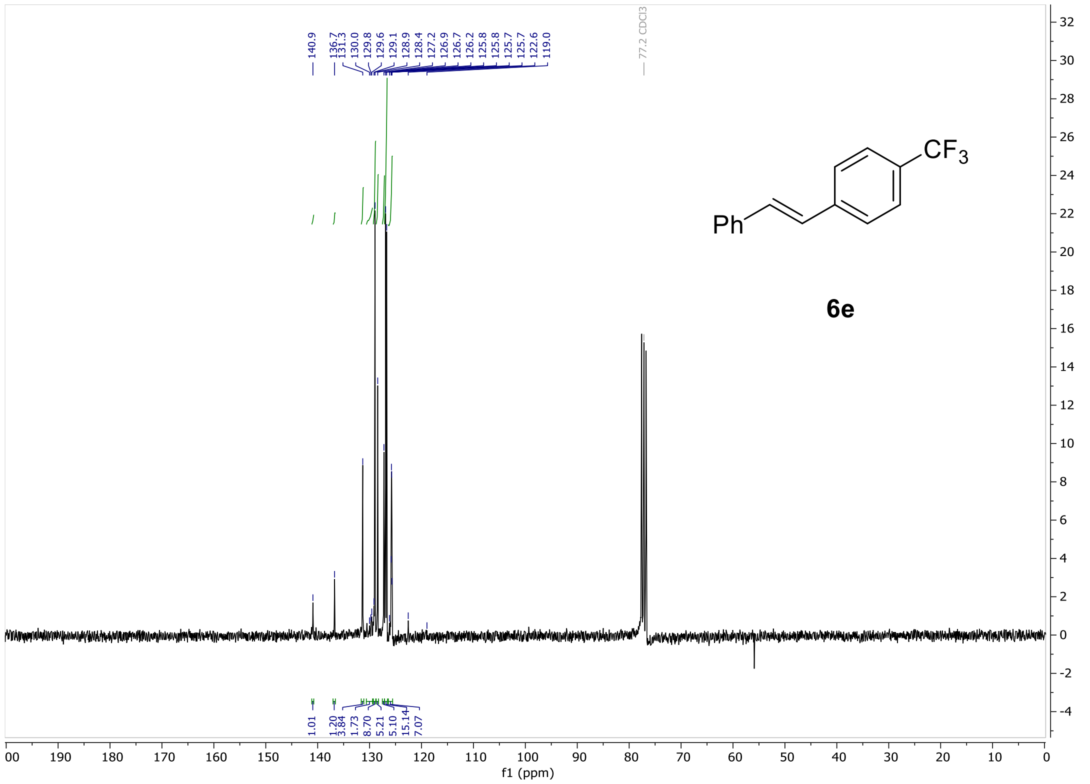


Figure 57. ^{13}C NMR spectra of product 6e.

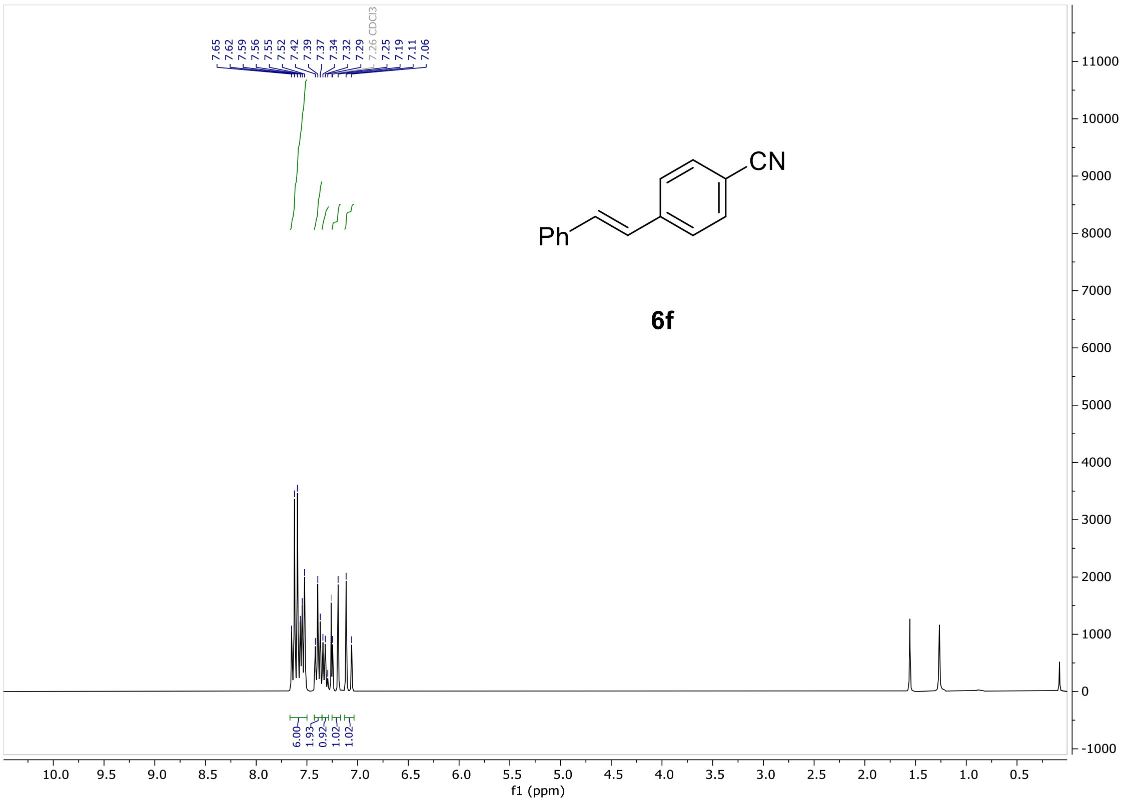


Figure 58. ^{1}H NMR spectra of product 6f.

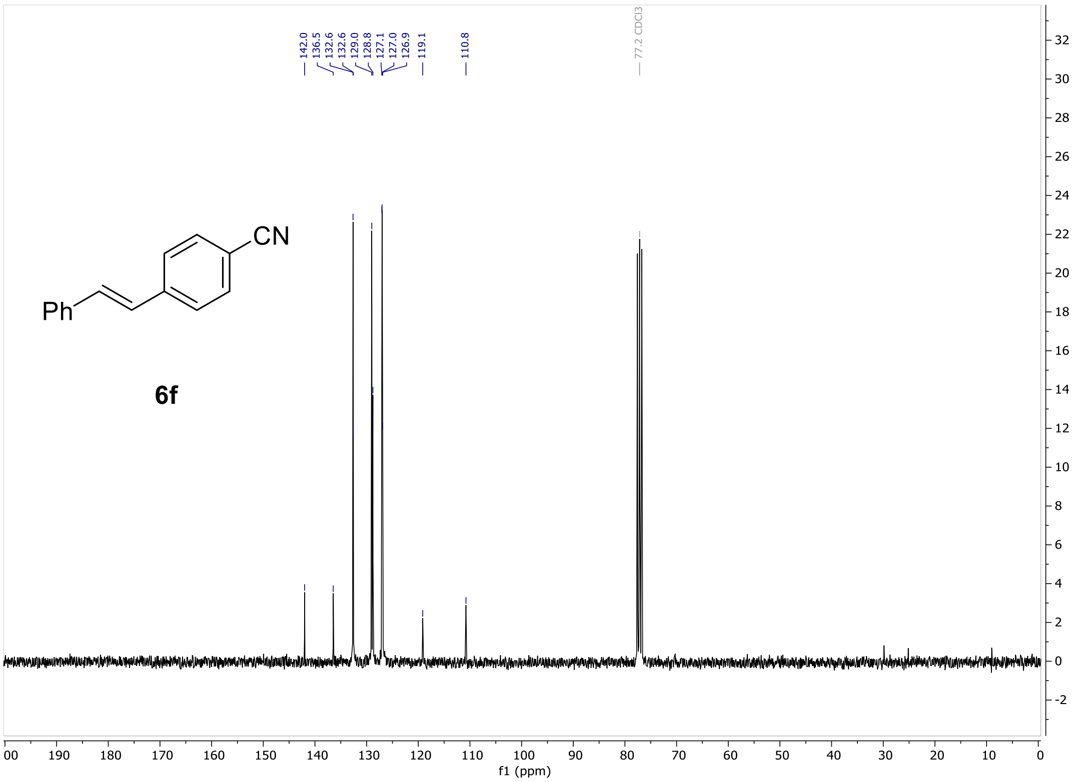


Figure 59. ^{13}C NMR spectra of product 6f.

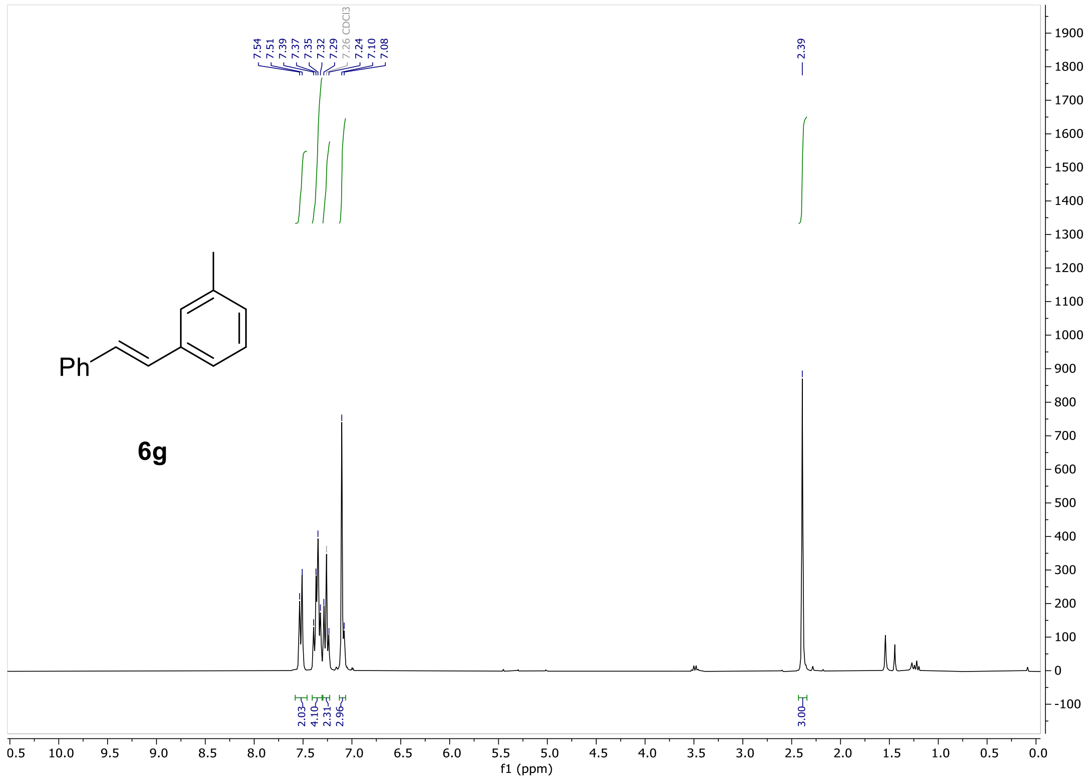


Figure 60. ^{1}H NMR spectra of product 6g.

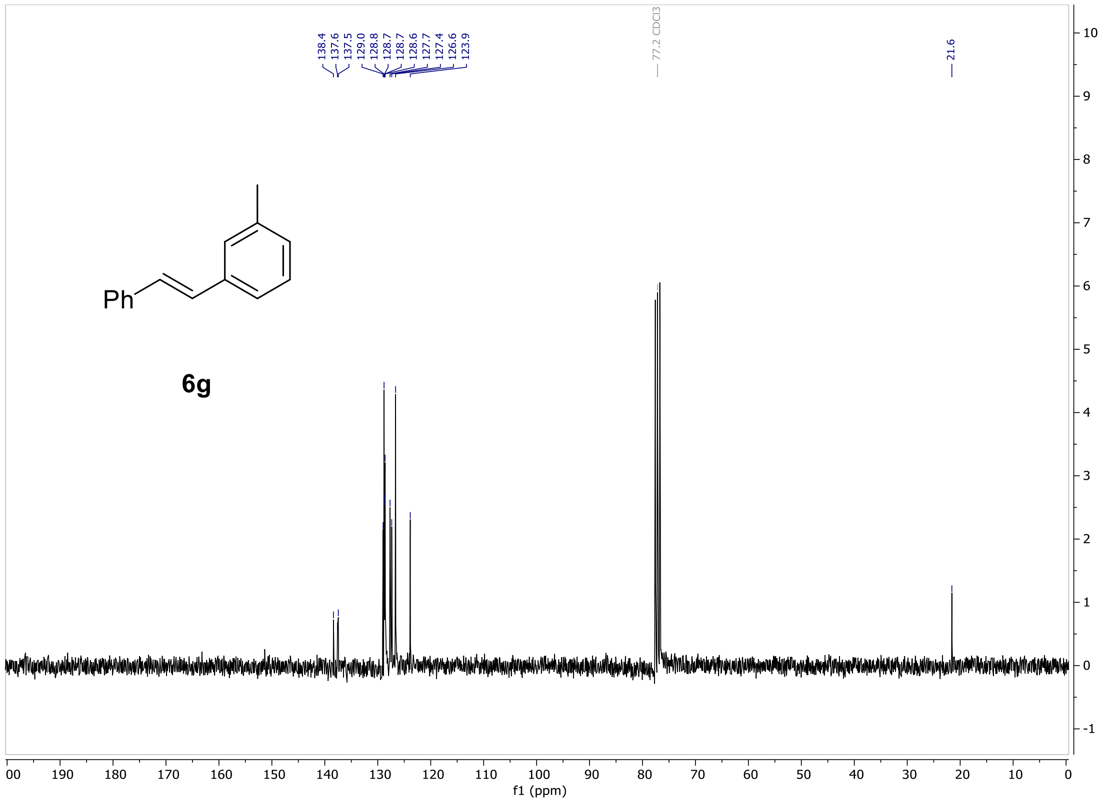


Figure 61. ^{13}C NMR spectra of product 6g.

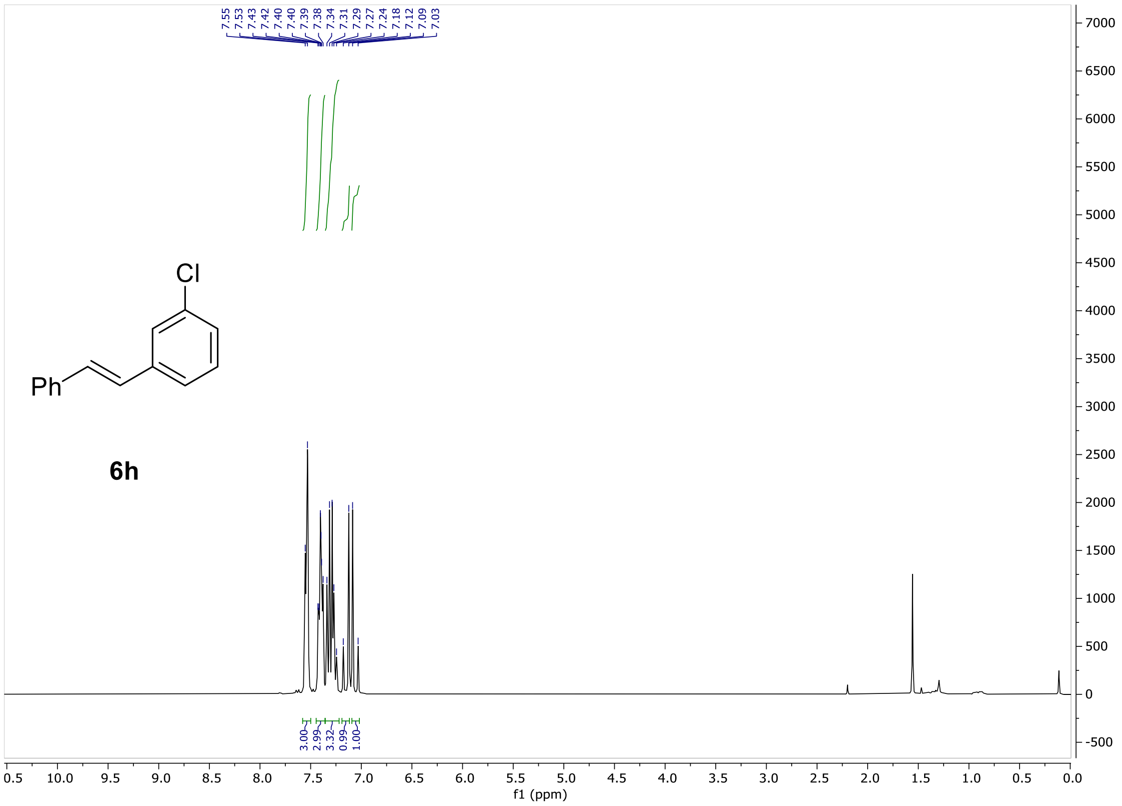


Figure 62. ^{1}H NMR spectra of product 6h.

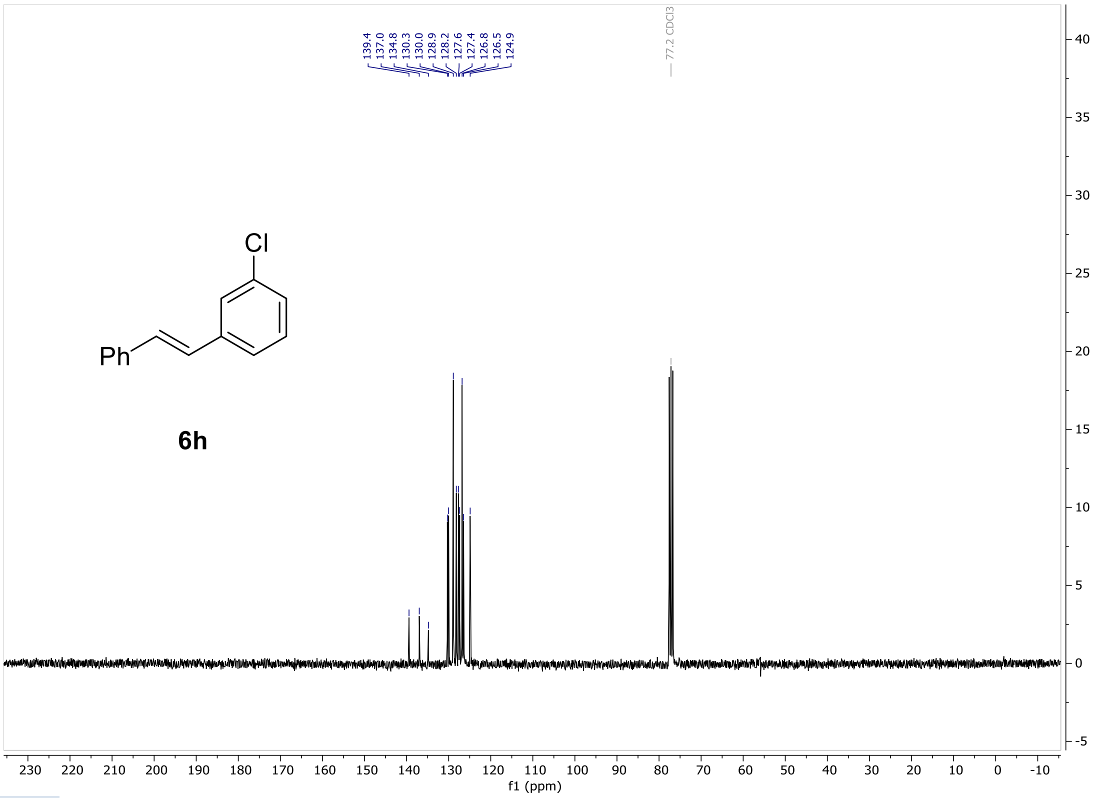


Figure 63. ^{13}C NMR spectra of product 6h.

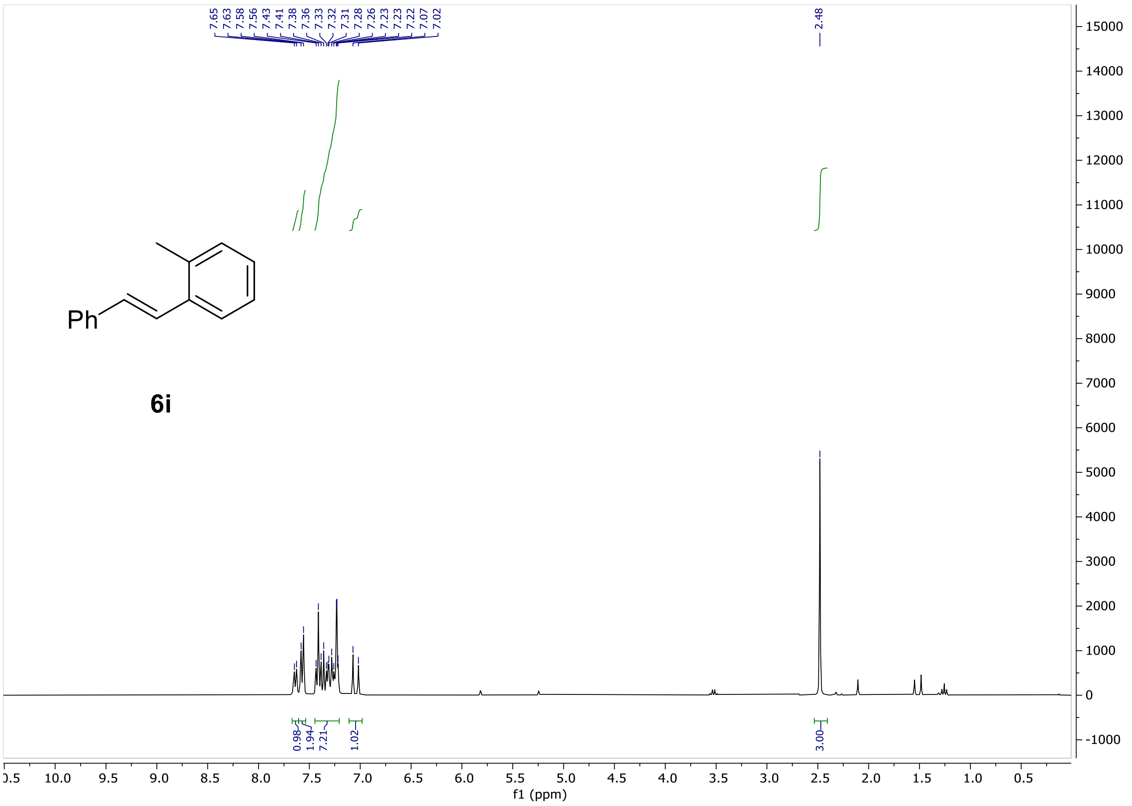


Figure 64. ^{1}H NMR spectra of product 6i.

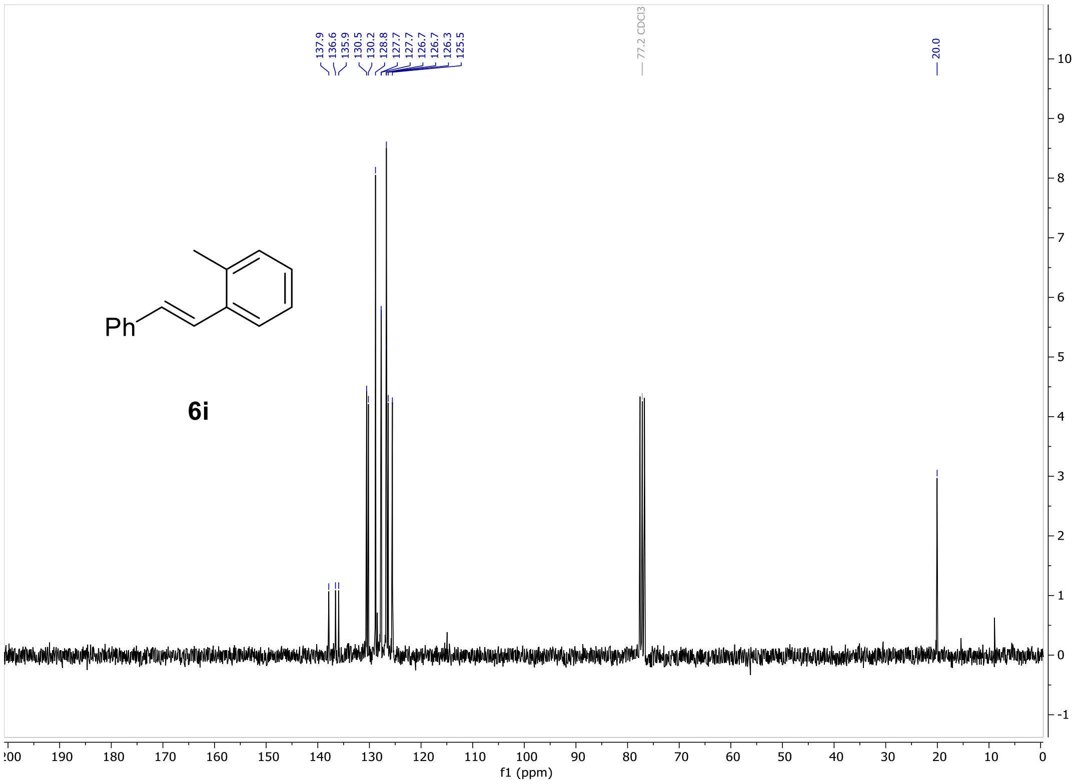


Figure 65. ^{13}C NMR spectra of product 6i.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

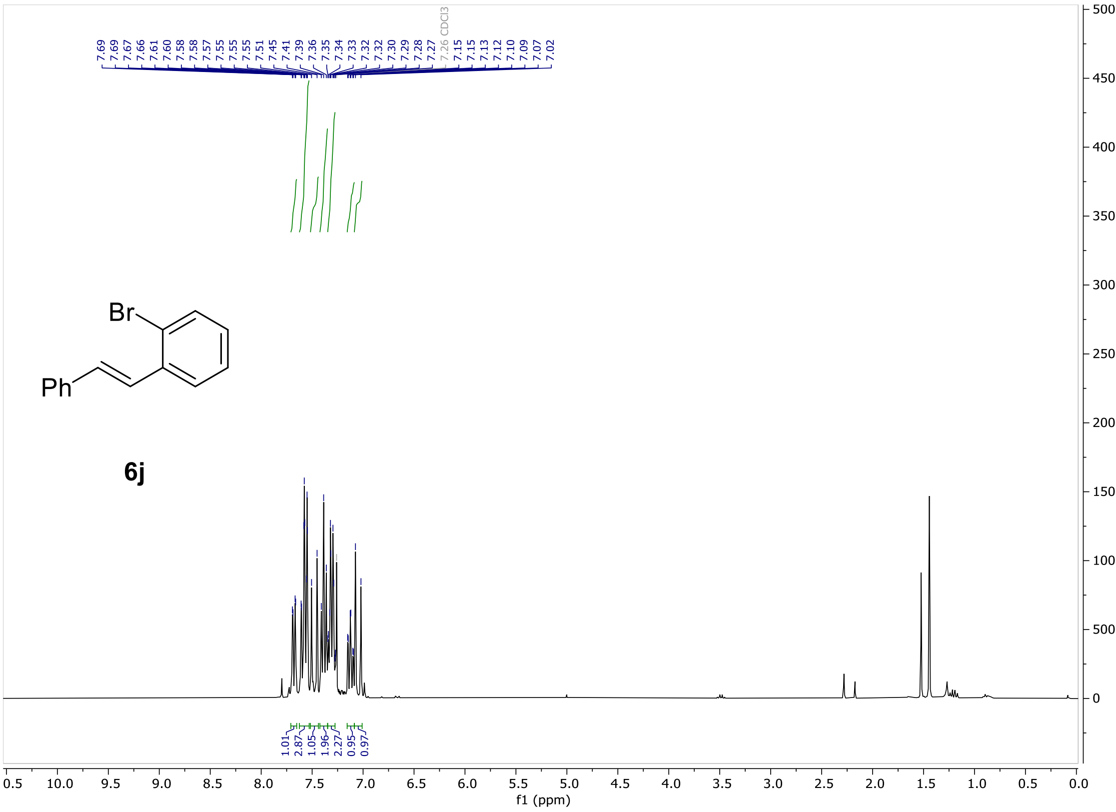


Figure 66. ^{1}H NMR spectra of product 6j.

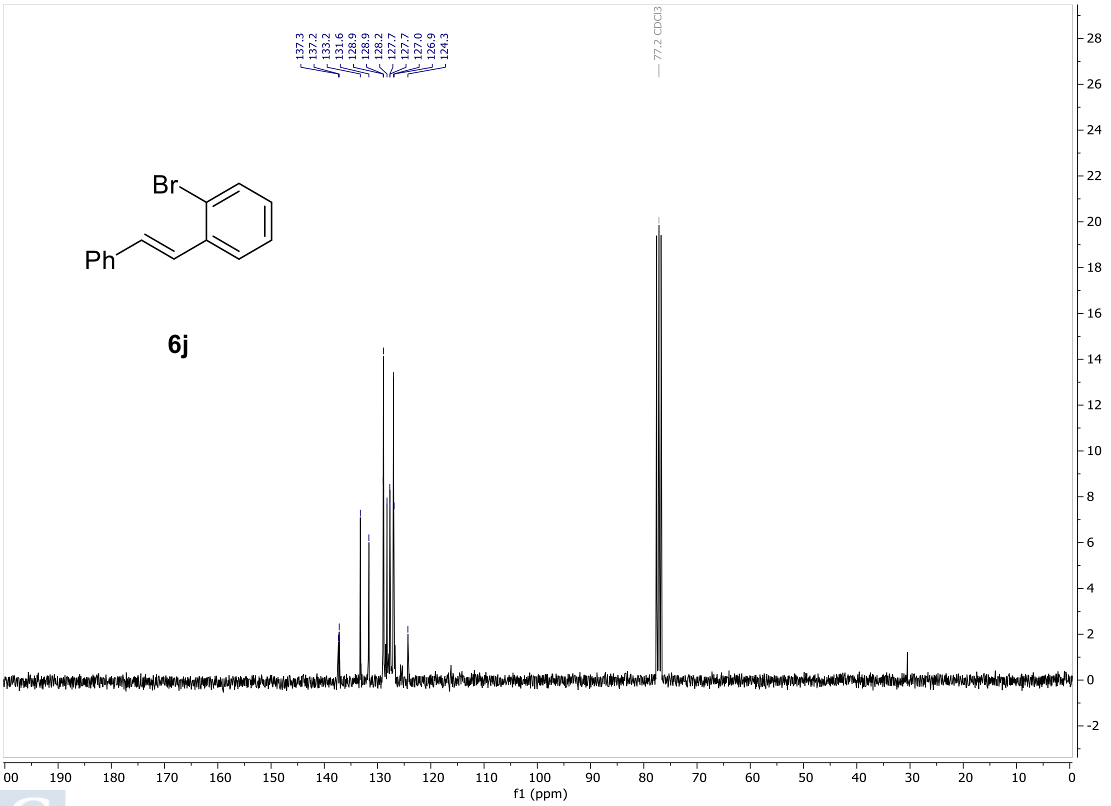


Figure 67. ^{13}C NMR spectra of product 6j.

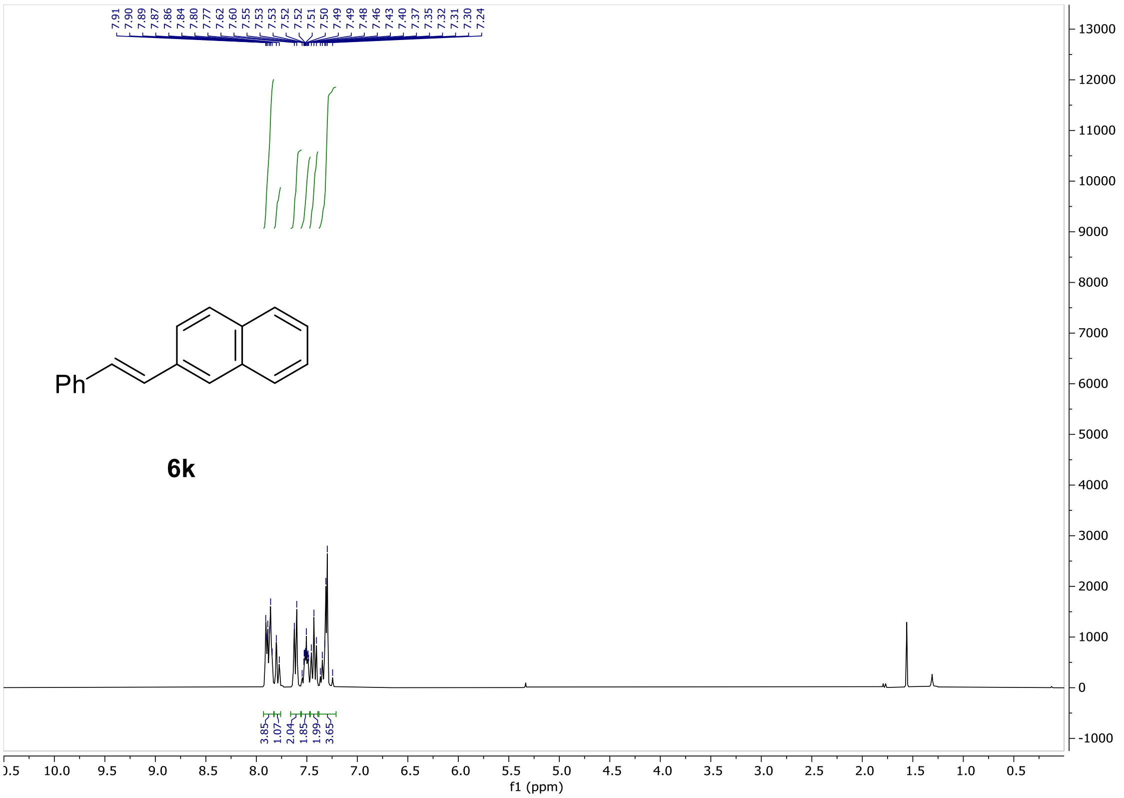


Figure 68. ^{1}H NMR spectra of product 6k.

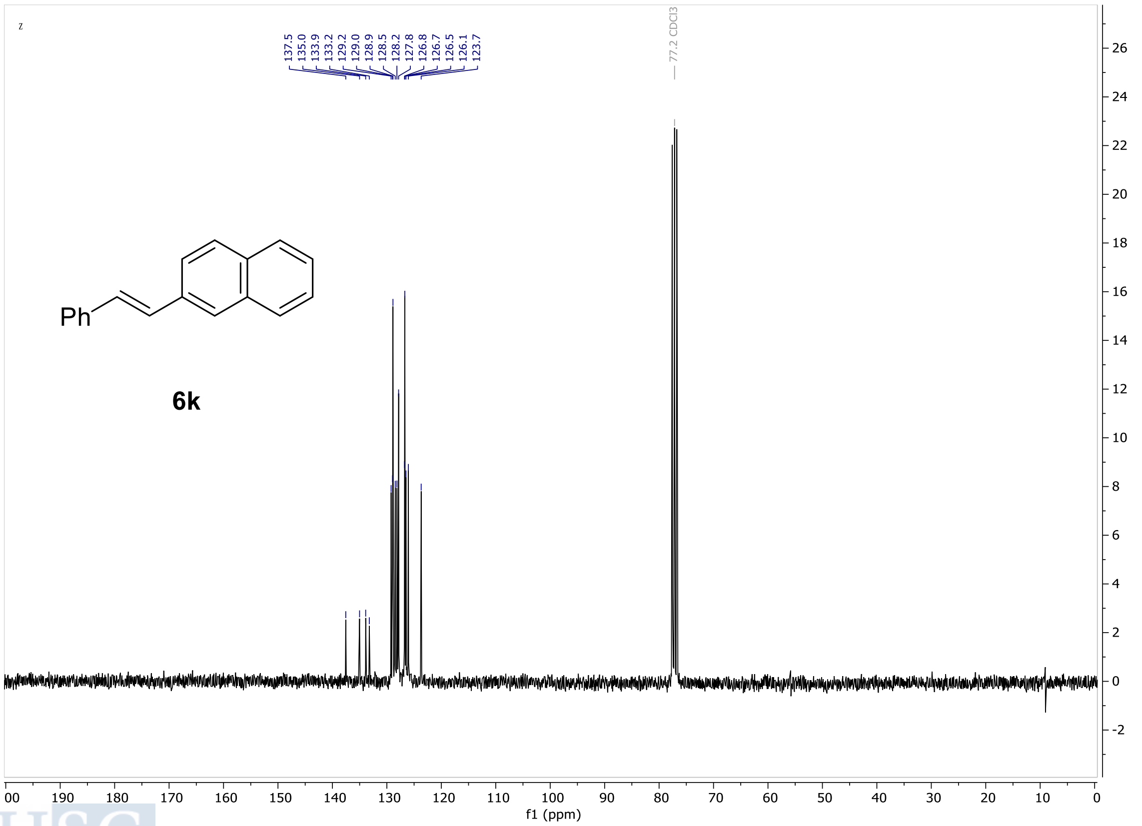


Figure 69. ^{13}C NMR spectra of product 6k.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

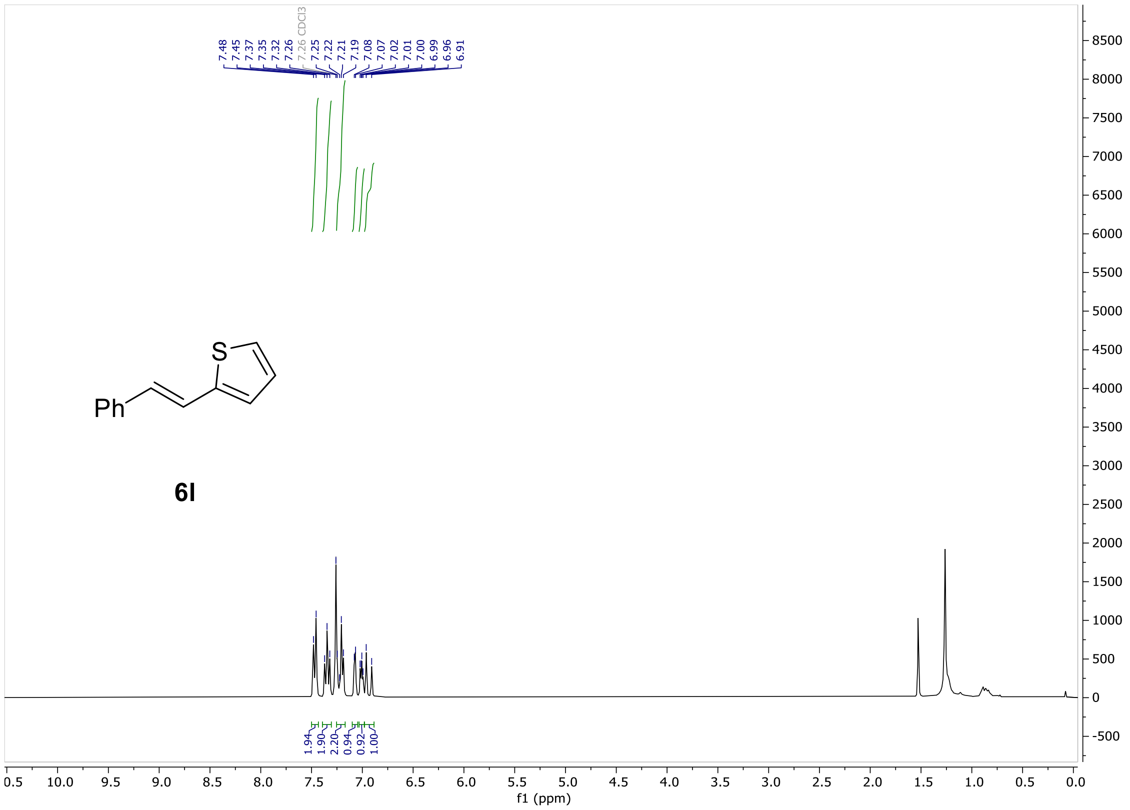


Figure 70. ^{1}H NMR spectra of product 6l.

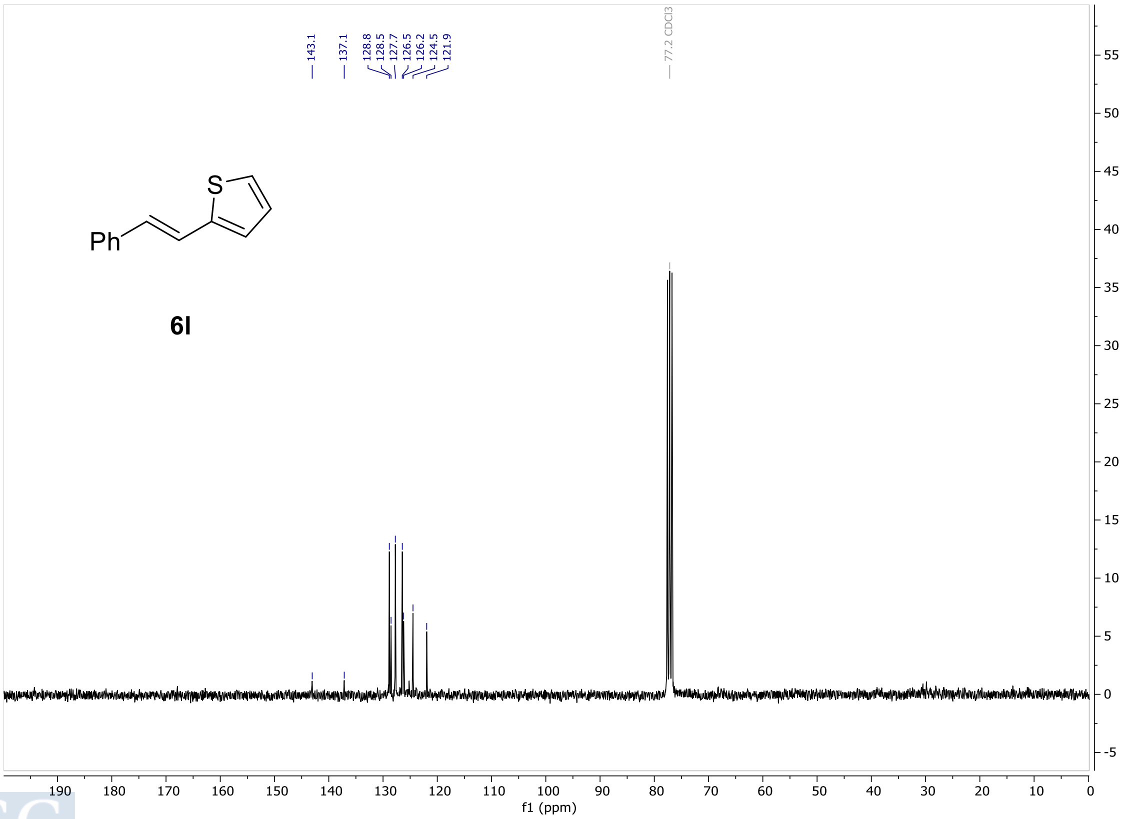


Figure 71. ^{13}C NMR spectra of product 6l.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

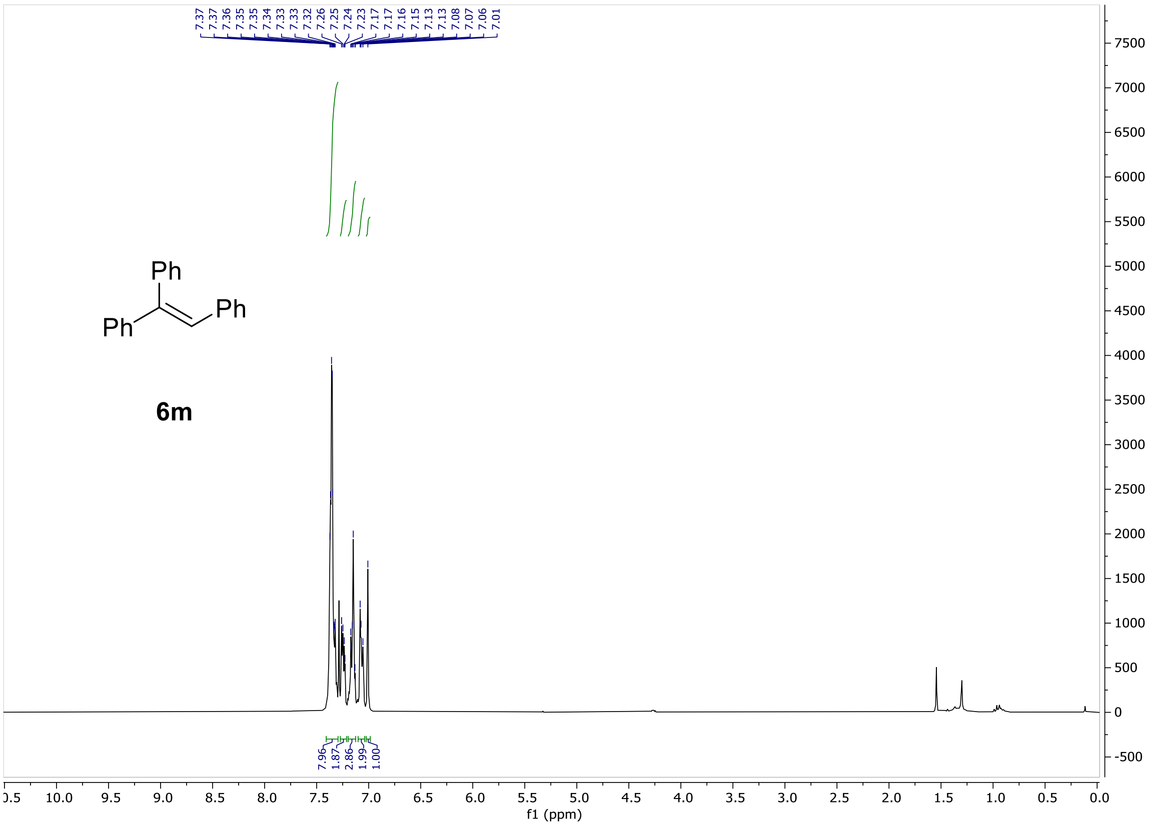


Figure 72. ^{1}H NMR spectra of product 6m.

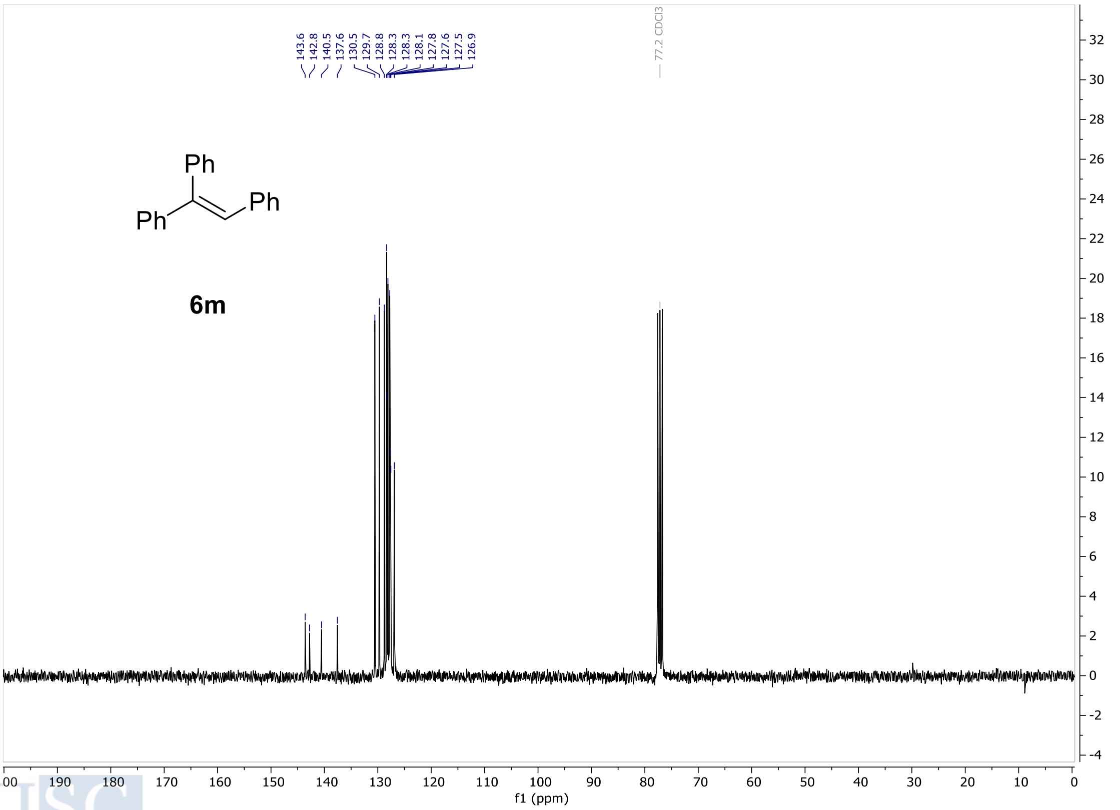


Figure 73. ^{13}C NMR spectra of product 6m.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

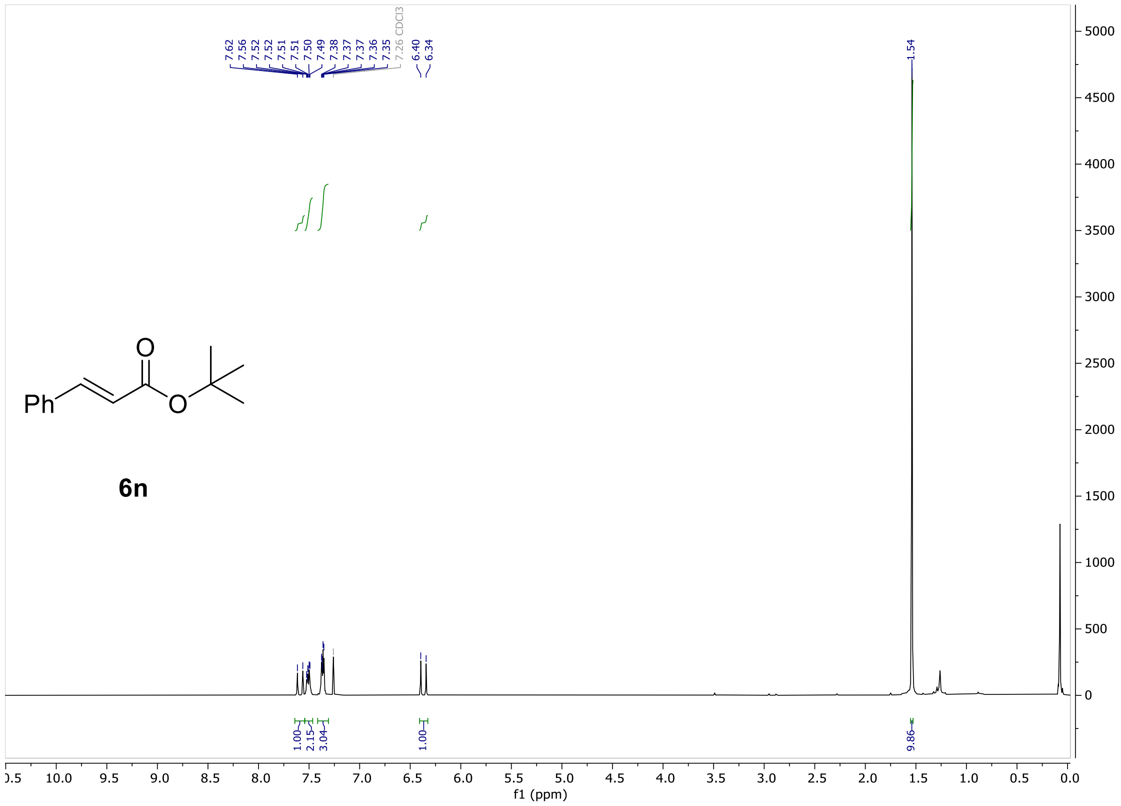


Figure 74. ^{1}**H NMR spectra of product 6n.**

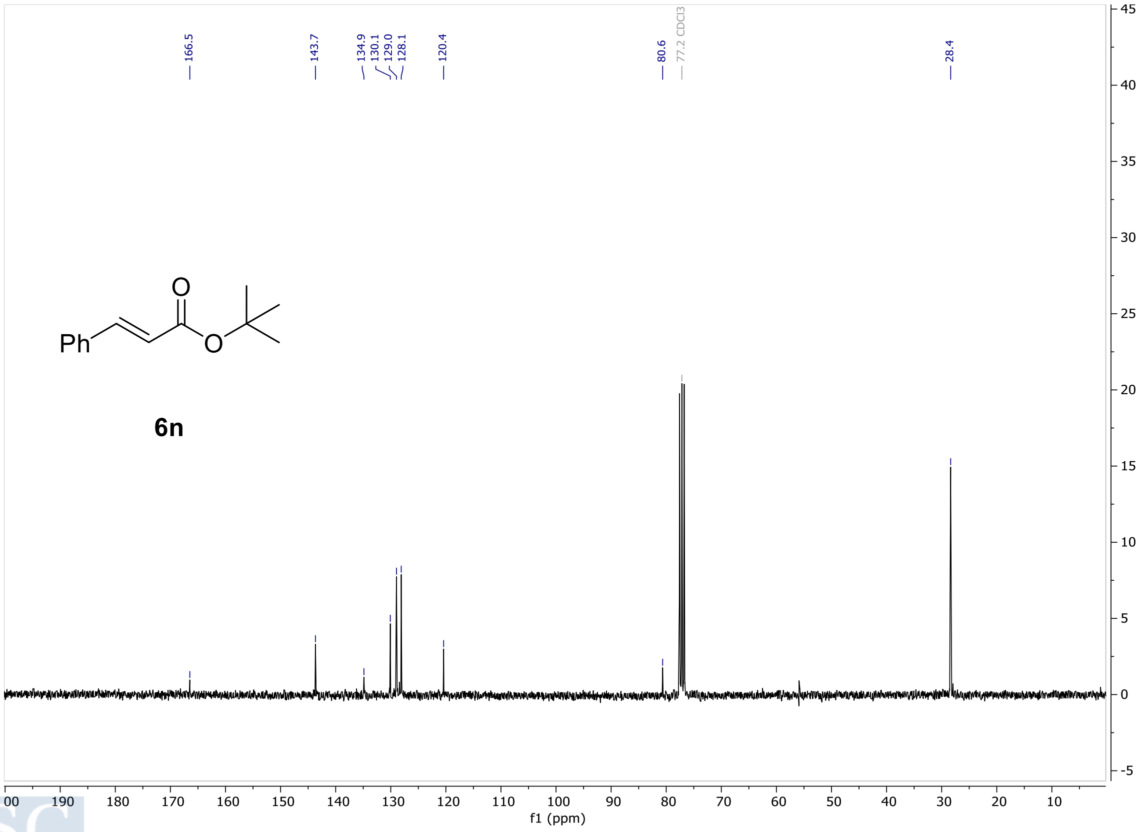


Figure 75. ^{13}**C NMR spectra of product 6n.**

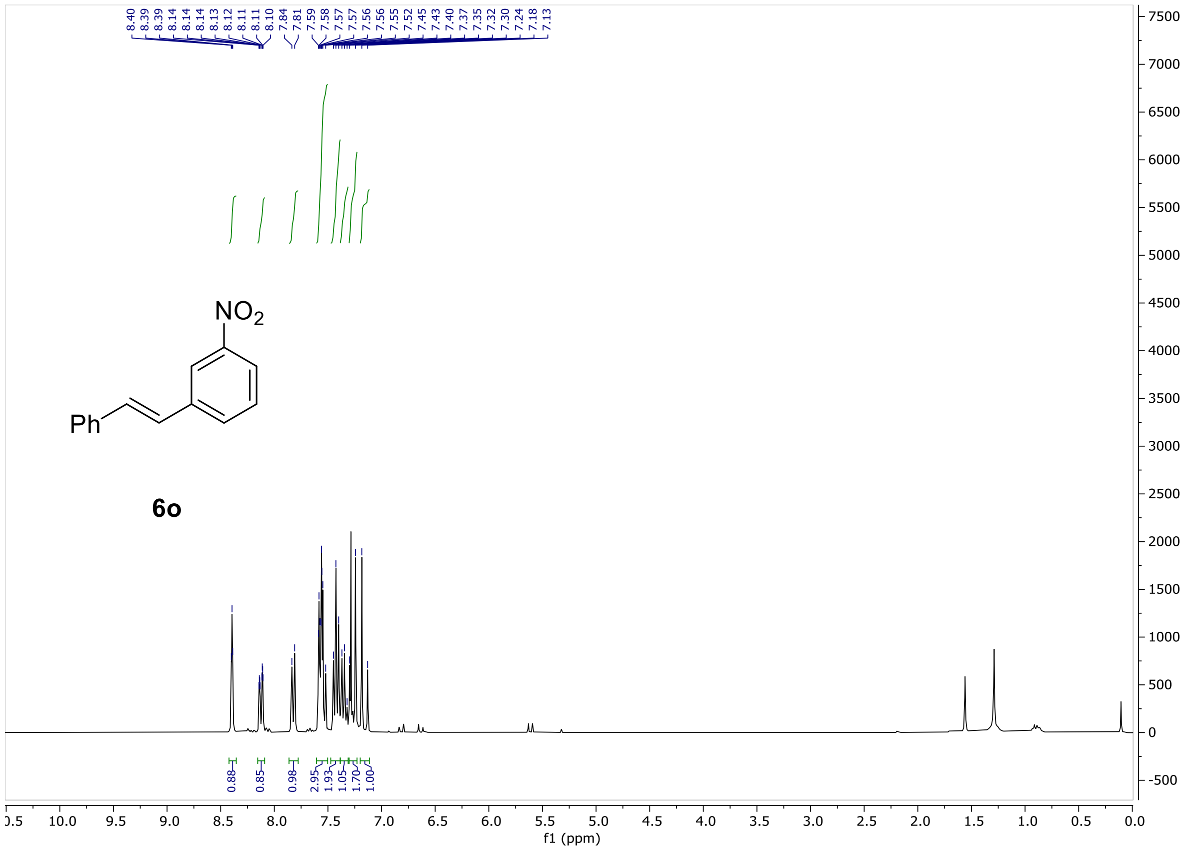
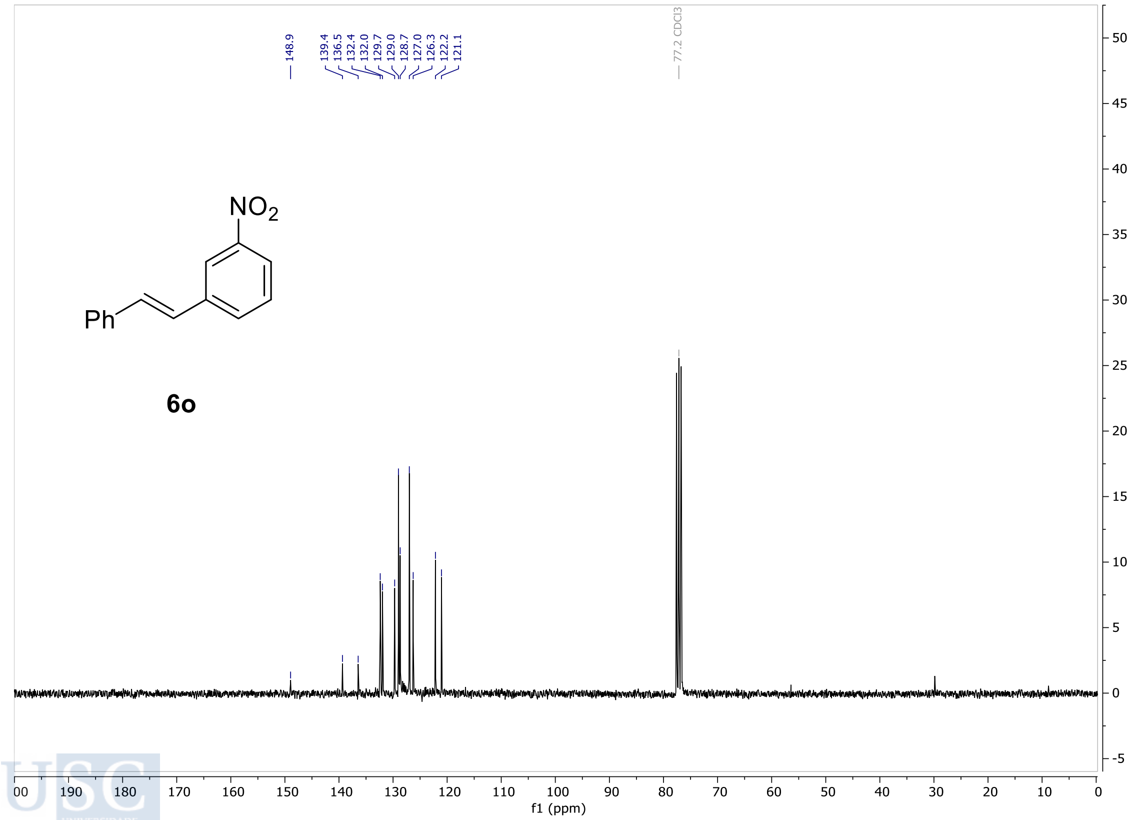


Figure 76. ^{1}H NMR spectra of product 6o.



USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

Figure 77. ^{13}C NMR spectra of product 6o.

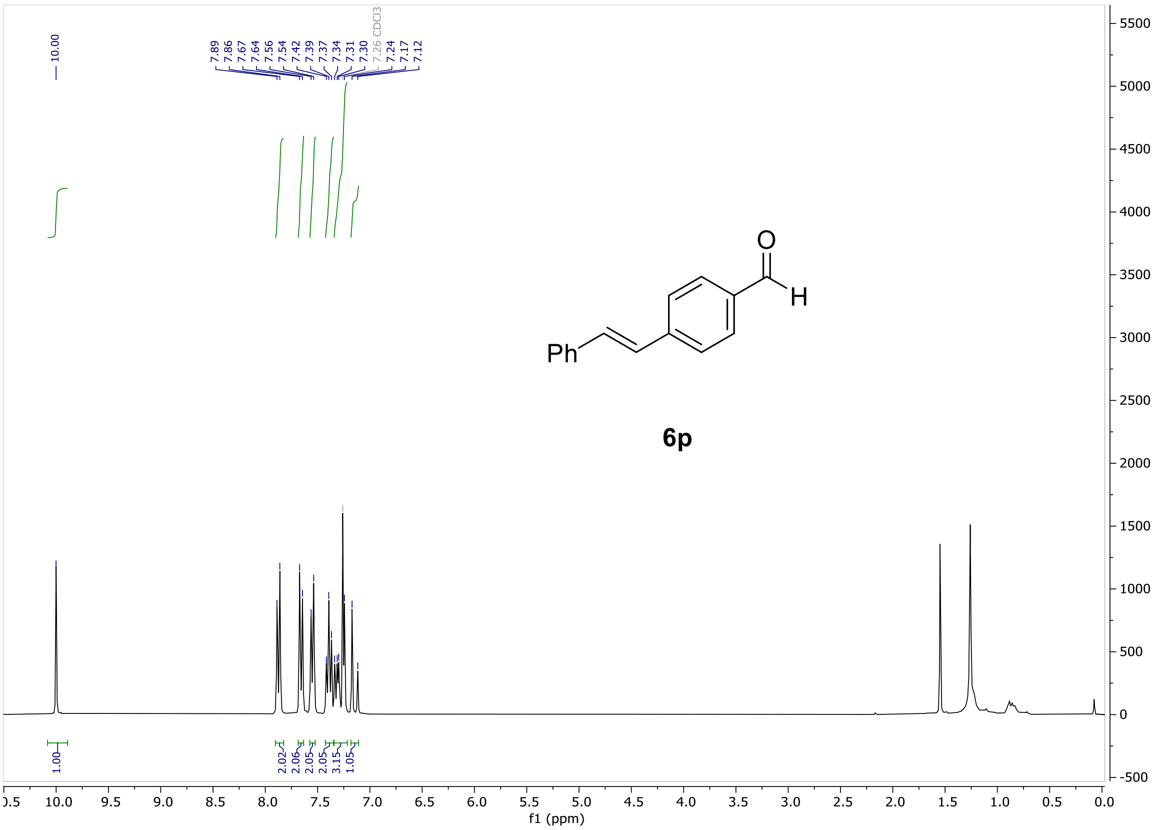


Figure 78. ^{1}H NMR spectra of product 6p.

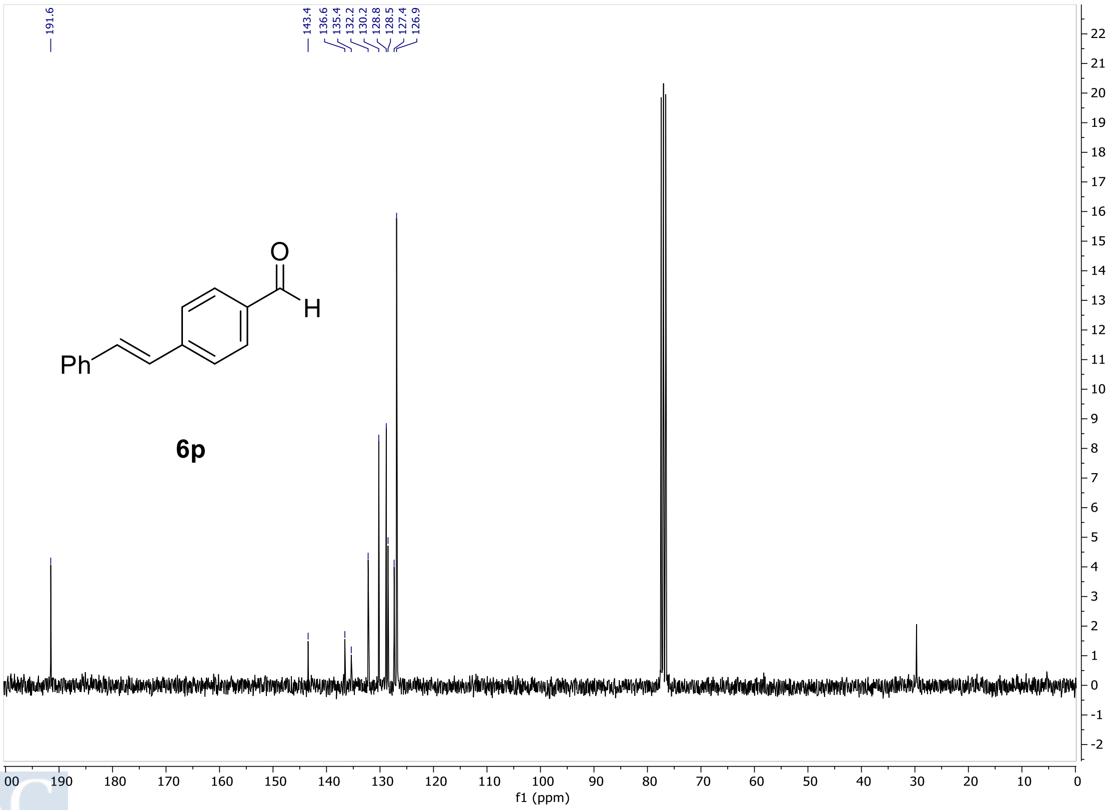


Figure 79. ^{13}C NMR spectra of product 6p.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

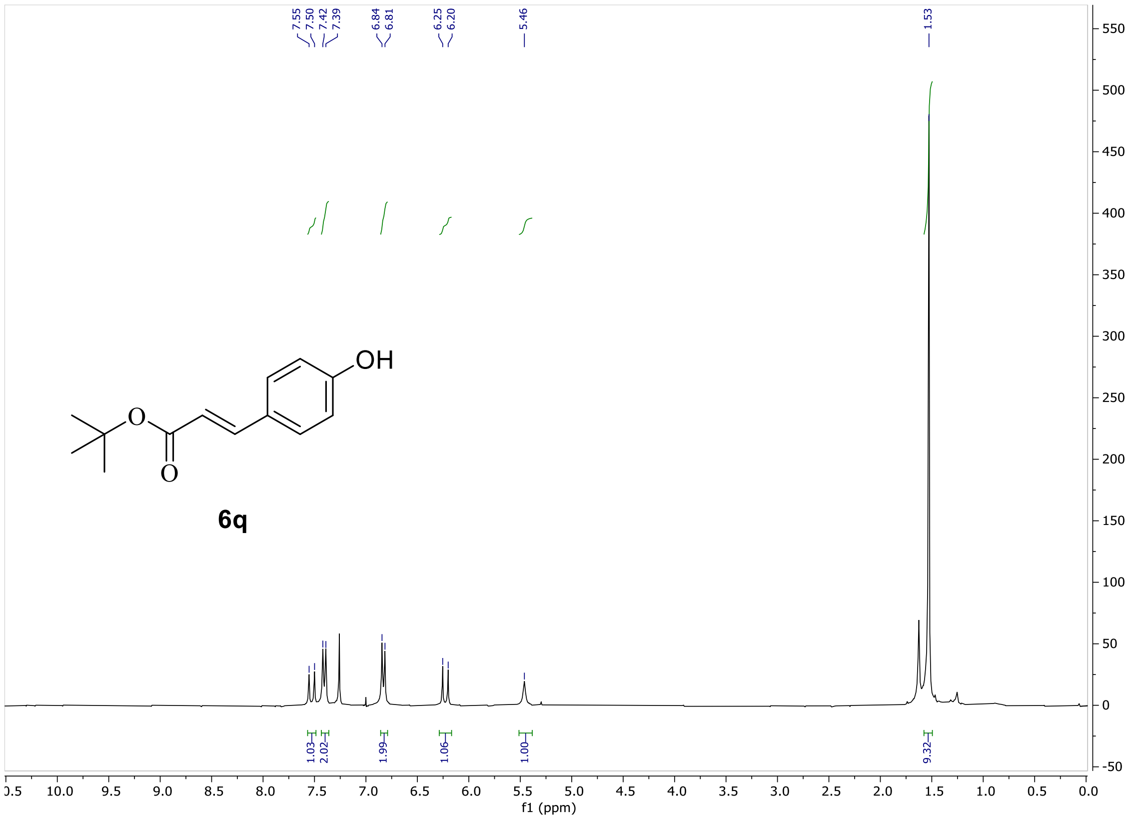


Figure 80. ¹H NMR spectra of product 6q.

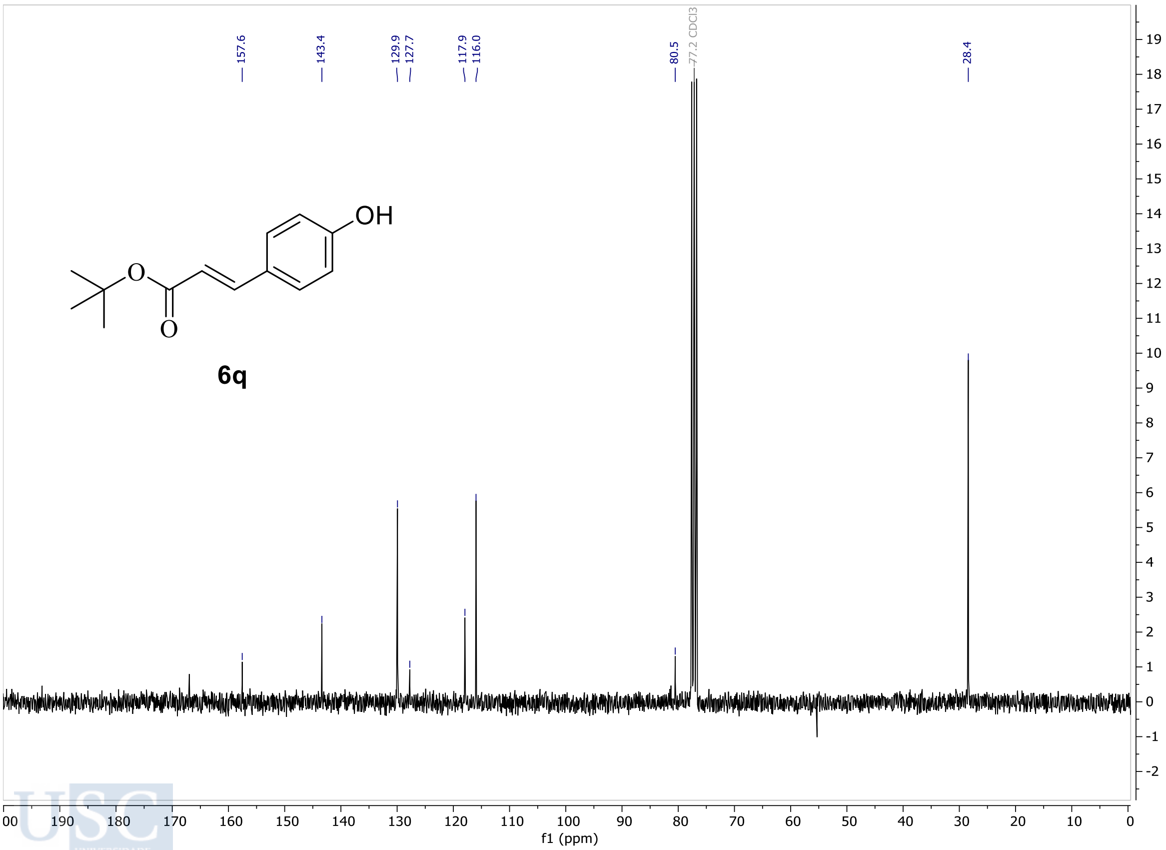


Figure 81. ¹³C NMR spectra of product 6q.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

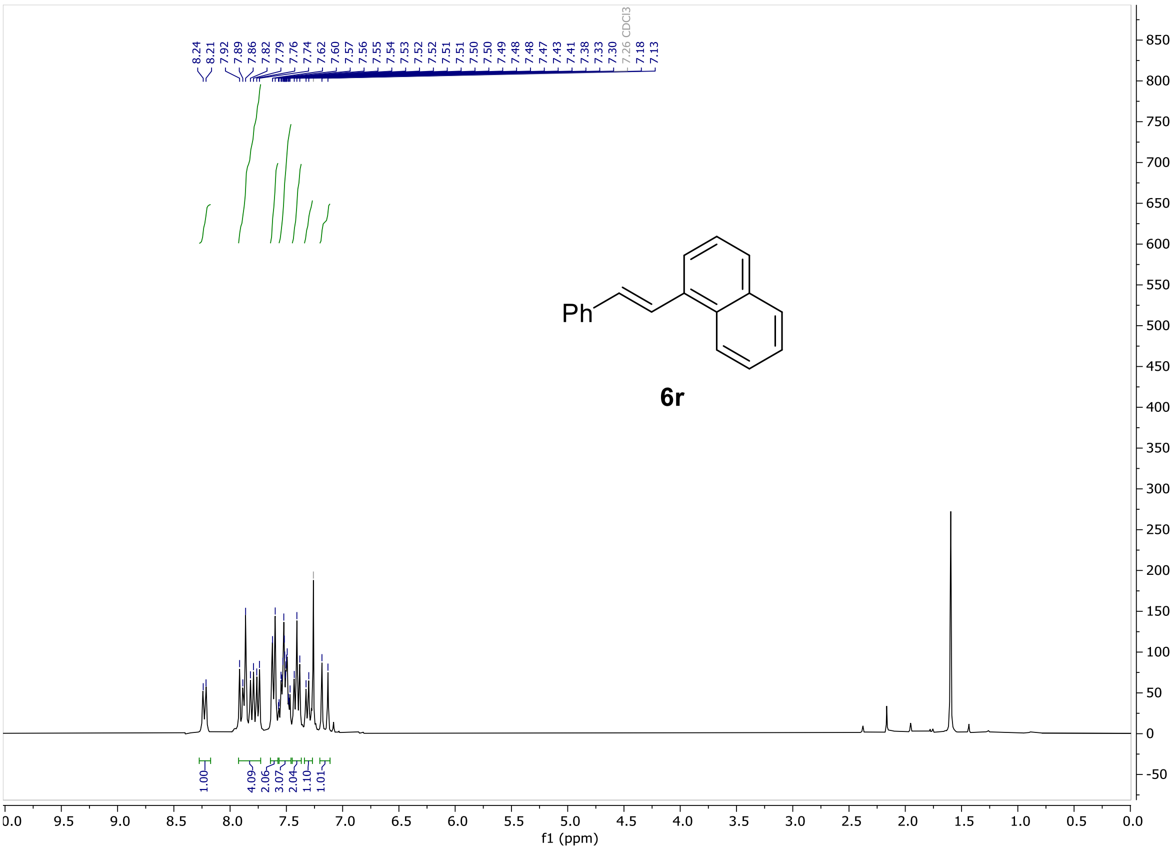


Figure 82. **^{1}H NMR spectra of product 6r.**

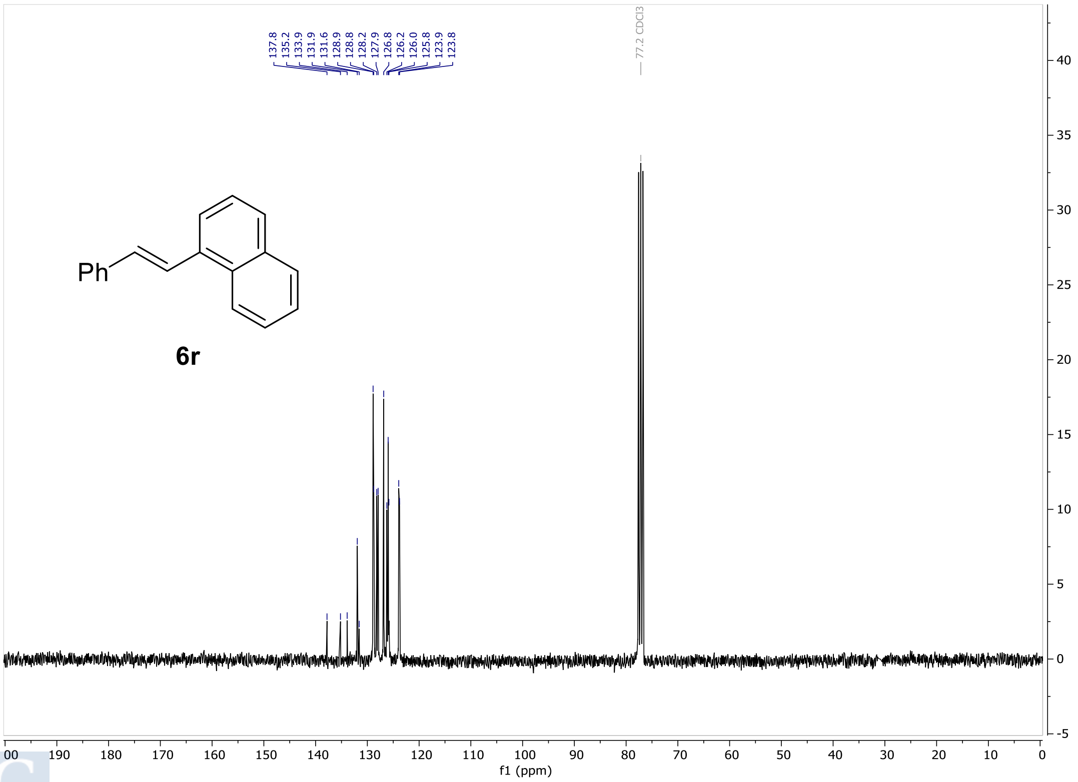


Figure 83. **^{13}C NMR spectra of product 6r.**


USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

9. BIBLIOGRAPHY

1. Hagen, J. Economic Importance of Catalysts. In Industrial Catalysis, A Practical Approach; Hagen, J., Ed.; Wiley: 2015; Chapter 17, pp 459-462.
2. a) Kashmi, A. S. K. *Chem. Rev.* **2007**, *107*, 3180-3211. b) Witzel, S.; Kashmi, A. S. K.; Xie, J. *Chem. Rev.* **2021**, *121*, 8868-8925. c) Hendrich, C. M.; Sekine, K.; Koshikawa, T.; Tanaka, K.; Kashmi, A. S. K. *Chem. Rev.* **2021**, *121*, 9113-9163.
3. a) Yin, L.; Liebscher, J. *Chem. Rev.* **2007**, 107, 133-173. b) Biffis, A.; Centorno, P.; Del Zotto, A.; Zecca, M. *Chem. Rev.* **2018**, *118*, 2249-2295. c) Sarkar, S.; Cheung, K. P. S.; Gevorgyan, V. *Angew. Chem. Int. Ed.* **2024**, *63*, e202311972.
4. a) Takeuchi, R.; Kezuka, S. *Synthesis* **2006**, *20*, 3349-3366. b) Cheng, Q.; Tu, H.-F.; Zheng, C.; Qu,J.-P.; Helmchen, G.; You, S.-L. *Chem. Rev.* **2019**, *119*, 1855-1969. c) Chauhan, D.; Prasad P.; Sasmal, P. K. *Coord. Chem. Rev.* **2024**, *520*, 216139.
5. a) Fang, G.; Bi, X. *Chem. Soc. Rev.* **2015**, *44*, 8124-8173. b) Labinger, J. A. *Chem. Rev.* **2017**, *117*, 8483-8496. c) Gunanathan, C.; Milstein, D. *Chem. Rev.* **2014**, *114*, 12024-12087.
6. Egorova, K. S.; Ananikov, V. *Organometallics* **2017**, *36*, 4071−4090.
7. a) Shamzhy, M.; Opanasenko, M.; Concepción, P.; Martínez, A. *Chem. Soc. Rev.* **2019**, *48*, 1095-1149. b) Li, Y.; Yu, J. *Nature Revisions Materials* **2021**, *6*, 1156-1174. c) Zhang, Q.; Gao, S.; Yu, J. Chem. Rev. 2023, 123, 6039-6106.
8. Yu. X.; Williams, C. T. *Catal. Sci. Technol*. **2022**, *12*, 5765-5794.
9. *Chem. Soc. Rev.* **2010**, *39*, 4541-5072.
10. a) Zhang, W.; Zheng, B.; Shi, W.; Chen, X.; Xu, Z.; Li, S.; Chi, Y. R.; Yang, Y.; Lu, J.; Huang, W.; Huo, F. *Adv. Mater.* **2018**, *30*, 1800643. b) Genna, D. T.; Pfund, L. Y.; Samblanet, D. C.; Wong-Foy, A. G.; Matzger, A. J.; Sanford, M. S. *ACS Catal.* **2016**, *6*, 3569-3574. c) Bauer, G.; Ongari, D.; Xi, X.; Tiana, D.; Smit, B.; Ranocchiari, M. *J. Am. Chem. Soc*. **2017**, *139*, 18166-18169. d) Liu, L.; Zhou, T. Y.; Telfer, S. G. *J. Am. Chem. Soc.* **2017**, *139*, 13936-13943.
11. Deng, H.; Doonan, C. J.; Furukawa, H.; Ferreira, R. B.; Towne, J.; Knobler, C. B.; Wang, B.; Yaghi, O. M. *Science* **2010**, *327*, 846-850.
12. Li, H.; Eddaoudi, M.; O'Keeffe, M.; Yaghi, O. M. *Nature* **1999,** *402*, 276-279.
13. Fujita, M.; Kwon, Y. J.; Washizu, S.; Ogura, K. *J. Am. Chem. Soc.* **1994**, *116*, 1151-1152.
14. Chen, B.; Eddaoudi, M.; Reineke, T. M.; Kampf, J. W.; O'Keeffe, M.; Yaghi, O. M.; *J. Am. Chem. Soc.* **2000**, *122*, 11559-11560.
15. Chui, S. S.-Y.; Lo, S. M.-F.; Charmant, J. P. H.; Orpen, A. G.; Williams, I. D. *Science* **1999**, *283*, 1148-1150.
16. Schlichte, K.; Kratzke, T.; Kaskel, S. *Microporous Mesoporous Mater.* **2004**, *73*, 81-88.
17. Gómez-Lor, B.; Gutiérrez-Puebla, E.; Iglesias, M.; Monge, M. A.; Ruiz-Valero, C.; Snejko, N. *Chem. Mater*. **2005**, *17*, 2568-2573.

USC UNIVERSIDADE DE SANTIAGO DE COMPOSTELA

18. Navarro, J.A.R.; Barea, E.; Salas, J.M.; Masciocchi, N.; Galli, S.; Sironi, A.; Ania, C.O.; Parra, J.B. *Inorg. Chem.* **2006**, *45*, 2397-2399.
19. Llabrés i Xamena, F. X.; Abad, A.; Corma, A.; Garcia, H. *J. Catal*. **2007**, *250*, 294-298.
20. Canioni, R.; Roch-Marchal, C.; Sécheresse, F.; Horcajada, P.; Serre, C.; Hardi-Dan, M.; Férey, G.; Grenèche, J.-M.; Lefebvre, F.; Chang, J.-S.; Hwang, Y.-K.; Lebedev, O.; Turner, S.; Van Tendeloo, G. *J. Mater. Chem.* **2011**, *21*, 1226-1233.
21. Wang, H.; Rassu, P.; Wang, X.; Li, H.; Wang, X.; Wang, X.; Feng, X.; Yin, A.; Li, P.; Jin, X.; Chen, S.L.; Ma, X.; Wang. B. *Angew. Chem. Int. Ed.* **2018**, *57*, 16416-16420.
22. Liu, L.; Telfer, S. G. *J. Am. Chem. Soc.* **2015**, *137*, 3901-3909.
23. Liu, L.; Zhou, T. Y.; Telfer, S. G *J. Am. Chem. Soc.* **2017**, *139*, 13936-13943.
24. Xie, M.-H.; Yang, X.-L.; Wu, C.-D.; *Chem. Commun.* **2011**, *47*, 5521-5523.
25. Burgess, S. A.; Kassie, A.; Baranowski, S. A.; Fritzsching, K. J.; Schmidt-Rohr, K.; Brown, C. M.; Wade, C. R. *J. Am. Chem. Soc.* **2016**, *138*, 1780-1783.
26. Cavka, J. H.; Jakobsen, S.; Olsbye, U.; Guillou, N.; Lamberti,C.; Bordiga, S.; Lillerud, K. P. *J. Am. Chem. Soc.* **2008**, *130*, 13850-13851.
27. Tu, B.; Pang, Q.; Xu, H.; Li, X.; Wang, Y.; Ma, Z.; Weng, L.; Li, Q. *J. Am. Chem. Soc.* **2017**, *139*, 7998-8007.
28. Sawano, T.; Lin, Z.; Boures, D.; An, B.; Wang, C.; Lin, W. *J. Am. Chem. Soc.* **2016**, *138*, 9783-9786.
29. a) Boller, T. M.; Murphy, J. M.; Hapke, M.; Ishiyama, T.; Miyaura, N.; Hartwig, J. F. *J. Am. Chem. Soc.* **2005**, *127*, 14263-14278. b) Manna, K.; Zhang, T.; Lin, W. *J. Am. Chem. Soc.* **2014**, *136*, 6566-6569. c) Manna, K.; Zhang, T.; Greene, F. X.; Lin, W. *J. Am. Chem. Soc.* **2015**, *137*, 2665-2673.
30. a) Kong, G.-Q.; Xu, X.; Zou, C.; Wu, C.-D. *Chem. Commun.* **2011**, 47, 11005-11007. b) Kong, G.-Q.; Ou, S.; Zou, C.; Wu, C.-D. *J. Am. Chem. Soc.* **2012**, *134*, 19851-19857.
31. a) Thacker, N. C.; Lin, Z.; Zhang, T.; Gilhula, J. C.; Abney, C. W.; Lin. *J. Am. Chem. Soc.* 2016, *138*, 3501-3509. b) Manna, K.; Zhang, T.; Carboni, M.; Abney, C. W.; Lin, W. *J. Am. Chem. Soc.* **2014**, *136*, 13182-13185.
32. Manna, K.; Zhang, T.; Lin, W. *J. Am. Chem. Soc.* **2014**, *136*, 6566-6569.
33. Grigoropoulos, A.; McKay, A. I.; Katsoulidis, A. P.; Davies, R. P.; Haynes, A.; Brammer, L.; Xiao, J.; Weller, A. S.; Rosseinsky, M. J. *Angew. Chem. Int. Ed.* **2018**, *57*, 4532-4537.
34. Crabtree, R. *Acc. Chem. Res.* **1979**, *12*, 331-337.
35. Akiyama, G.; Matsuda, R.; Sato, H.; Takata, M.; Kitagawa, S. *Adv. Mater.* **2011**, *23*, 3294-3297.
36. a) Cook, A. K.; Schimler, S. D.; Matzger, A. J; Sanford, M. S. *Science* **2016**, *351*, 1421-1424. b) Smith, K. T.; Berritt, S.; González-Moreiras, M.; Ahn, S.; Smith, M. R.; Baik, M.-H.; Mindiola, D. J. *Science* **2016**, *351*, 1424-1427.
37. Zhang, X., Huang, Z., Ferrandon, M.; Yang, D.; Robison, L.; Li, P.; Wang, T. C.; Delferro, M.; Farha, O. M. *Nat Catal* **2018**, *1*, 356-362.
38. Feng, X.; Song, Y.; Lin, W. *Trends in Chemistry* **2020**, *2*, 965-979.
39. a) Planas, N.; Mondloch, J. E.; Tussupbayev, S.; Borycz, J.; Gagliardi, L.; Hupp, J. T.; Farha, O. K.; Cramer, C. J. *J. Phys. Chem. Lett.* **2014**, *5*, 3716-3723. b) Nguyen, H. G. T.; Schweitzer, N. M.; Chang, C.-Y.; Drake, T.L.; So, M. C.; Stair, P. C.; Farha, O. K.; Hupp, J. T.; Nguyen, S. T. *ACS Catal.* **2014**, *4*, 2496-2500. c) Manna, K.; Ji, P.;

Greene, F. X.; Lin, W. *J. Am. Chem. Soc.* **2016**, *138*, 7488-7491. d) Ji, P.; Manna, K.; Lin, Z.; Urban, A.; Greene, F. X.; Lan, G.; Lin, W. *J. Am. Chem. Soc.* **2016**, *138*, 12234-12242. e) An, B.; Li, Z.; Song, Y.; Zhang, J.; Zeng, L.; Wang, C.; Lin, W. *Nat. Catal* **2019**, *2*, 709-717.

40. Mondloch, J. E.; Bury, W.; Fairen-Jimenez, D.; Kwon, S.; DeMarco, E. J.; Weston, M. H.; Sarjeant, A. A.; Nguyen, S. T.; Stair, P.C.; Snurr, R. Q.; Farha, O. K.; Hupp, J. T. *J. Am. Chem. Soc.* **2013**, *135*, 10294-10297.
41. Li, Z.; Schweitzer, N.M.; League, A.B.; Bernales, V.; Peters, A.W.; Getsoian, A.B.; Wang, T.C.; Miller, J.T.; Vjunov, A.; Fulton, J.L.; Lercher, J.A.; Cramer, C.J.; Gagliardi, L.; Hupp, J. T.; Farha, O.K. *J. Am. Chem. Soc.* **2016**, *138*, 1977-1982.
42. Khoo, R. S. H.; Fiankor, C.; Yang, S.; Hu, W.; Yang, C.; Lu, J.; Morton, M. D.; Zhang, X.; Liu, Y.; Huang, J.; Zhang, J. *J. Am. Chem. Soc.* **2023**, *145*, 24052-24060.
43. Yang, Q.; Xu, Q.; Jiang, H.-J. *Chem. Soc. Rev.* **2017**, *46*, 4774-4808.
44. Gao, S.; Zhao, N.; Shu, M.; Che, S. *Appl. Catal. A* **2010**, *388*, 196-201.
    Cirujano, F. G.; Llabrés i Xamena, F. X.; Corma, A. *Dalton Trans.* **2012**, *41*, 4249-4254.
45. Ferey, G.; Mellot-Draznieks, C.; Serre, C.; Millange, F.; Dutour, J.; Surble, S.; Margiolaki, I. *Science* **2005**, *309*, 2040-2042.
46. Li, X.; Goh, T. W.; Li, L.; Xiao, C.; Guo, Z.; Zeng, X. C.; Huang, W. *ACS Catal.* **2016**, *6*, 3461-3468.
47. Cavka, J. H.; Jakobsen, S.; Olsbye, U.; Guillou, N.; Lamberti, C.; Bordiga, S.; Lillerud, K. P. *J. Am. Chem. Soc.* **2008**, *130*, 13850-13851.
48. Tsuji, J.; Takahashi, H.; Morikawa, M. *Tetrahedron Lett*. **1965**, *6*, 4387-4388.
49. Atkins, K.; Walker, W.; Manyik, R. *Tetrahedron Lett*. **1970**, *11*, 3821-3824.
50. Takahashi, K.; Miyaki, A.; Hata, G. *Bull. Chem. Soc. Jpn*. **1972**, *45*, 230-236.
51. Trost, B. M.; Fullerton. T. J. *J. Am. Chem. Soc.* **1973**, *95*, 292-294.
52. Trost, B. M.; Van Vranken, D. L. *Chem. Rev*. **1996**, *96*, 395-422.
53. Trost, B. M.; Verhoeven, T. R. *J. Am. Chem. Soc.* **1976**, *98*, 630-632.
54. a) Minami, I.; Shimizu, I.; Tsuji, J. *J. Organomet. Chem.* **1985**, *296*, 269-280. b) Trost, B. M.; Spagnol, M. D. *J. Chem. Soc., Perkin Trans. 1* **1995**, 2083-2097. c) Gomez-Bengoa, E.; Heron, N. M.; Didiuk, M. T.; Luchaco, C. A.; Hoveyda, A. H. *J. Am. Chem. Soc.* **1998**, *120*, 7649-7650.
55. a) Kondo, T.; Ono, H.; Satake, N.; Mitsudo, T.; Watanabe, Y. *Organometallics* **1995**, *14*, 1945-1953. b) Zhang, S.; Mitsudo, T.; Kondo, T.; Watanabe, Y. J. *Organomet. Chem*. **1993**, *450*, 197-207.
56. a) Takeuchi, R.; Kashio, M. *J. Am. Chem. Soc*. **1998**, *120*, 8647-8655. b) Graening, T.; Hartwig, J. F. *J. Am. Chem. Soc.* **2005**, *127*, 17192-17193.
57. a) Wang, ZJ.; Zheng, S.; Romero, E.; Matsui, J. K.; Molander, G. A. *Org. Lett.* **2019**, 21, 6543-6547. b) Martínez-Balart, P.; Tóth, B. L.; Velasco-Rubio, A.; Fañanás-Mastral, M. *Org. Lett.* **2022**, *24*, 6874-6879.
58. Ibrahem, I.; Córdova, A. *Angew. Chem. Int. Ed.*, **2006**, *45*, 1952-1956.
59. a) Crawley, M. L.; Trost, B. M. *Chem. Rev*. **2003**, *103*, 82921-2944. b) Pàmies, O.; Margalef, J.; Cañellas, S.; James, J.; Judge, E.; Guiry, P. J.; Moberg, C.; Bäckvall, J.-E.; Pfaltz, A.; Pericàs, M. A.; Diéguez, M. *Chem. Rev*. **2021**, *121*, 4373-4505.
60. a) Trost, B. M. *Acc. Chem. Res*. **1980**, *13*, 385-393. b) Van Vranken, D. L.; Trost, B. M. *Chem. Rev*. **1996**, *96*, 395-422.
61. a) Moineau, C.; Bolitt, V., Sinou, D. *J. Org. Chem.* **1998**, *63*, 582-591. b) Rosales, V.; Zambrano, J. L.; Demuth, M. *J. Org. Chem.* **2002**, *67*, 1167-1170. b) Volla,

C. M. R.; Dubbaka, S. R.; Vogel, P. *Tetrahedron* **2009**, *65*, 504-511. d) Negishi, E.; Fang, L. in Handbook of Organopalladium Chemistry for Organic Synthesis, ed. E. Negishi, Wiley, New York, 2002, vol. 1, ch. III.2.9. e) Mao, J.; Zhang, J.; Jiang, H.; Bellomo, A.; Zhang, M.; Walsh, P. J. *Angew. Chem., Int. Ed.* **2016**, *55*, 2526-2530. f) Zhang, J.; Stanciu, C.; Wang, B.; Hussain, M. M.; Da, C.-S.; Carroll, P. J.; Dreher, S. D.; Walsh, P. J. *J. Am. Chem. Soc*. **2011**, *133*, 20552-20560. g) Chaves-Pouso, A.; Rivera-Chao, E.; Fañanas-Mastral, M. *ACS Catal.* **2023**, *13*, 12656-12664.

62. Miyaura, N.; Yamada, K.; Suginome, H.; Suzuki, A. *J. Am. Chem. Soc*. **1985**, *107*, 972-980.

63. Moreno-Manas, M.; Pajuelo, F.; Pleixats, R. *J. Org. Chem.* **1995**, *60*, 8, 2396-2397.

64. a) Botella, L.; Nájera, C. *J. Organomet. Chem.* **2002**, 663, 46-57. b) Singh, R.; Viciu, M. S.; Kramareva, N.; Navarro, O.; Nolan, S. P. *Org. Lett*. **2005**, *7*, 1829-1832. c) Alacid, E.; Nájera, C. *Org. Lett*. **2008**, *10*, 5011-5014. d) Ghosh, R.; Adarsh, N. N.; Sarkar, A. *J. Org. Chem*. **2010**, *75*, 5320-5322. e) Lipshutz, B. H.; Ghorai, S.; Abela, A. R.; Moser, R.; Nishikata, T.; Duplais, C.; Krasovskiy, A.; Gaston, R. D.; Gadwood, R. C. *J. Org. Chem*. **2011**, *76*, 4379-4391.

65. Endo, K.; Ohkubo, T.; Ishioka, T.; Shibata, T. *J. Org. Chem*. **2012**, *77*, 4826-4831.

66. Kaneda, K.; Uchiyama, T.; Terasawa, M.; Imanaka, T.; Teranishi, S. *Chem. Lett.* **1976**, 449-452.

67. Bergbreiter, D. E.; Weatherford, D. A. *J. Org. Chem.* **1989**, *54*, 2726-2730.

68. a) Song, C. E.; Yang, J. W.; Roh, E. J.; Lee, S.; Ahn, J. H.; Han, H. *Angew. Chem. Int. Ed*. **2002**, *41*, 3852-3854. b) Kim, S.; Kim, G.; *J. Ind. Eng. Chem.* **2006**, *12*, 643-647. c) Swennenhuis, B. H. G.; Chen, R.; van Leeuwen, P. W. N. M.; de Vries, J. G.; Kamer, P. C. J. *Eur. J. Org. Chem*. **2009**, 5796-5803. c) Wagh, Y. S.; Tambade, P. J.; Sawant, D. N.; Bhanage, B. M. *Eur. J. Org. Chem.* **2010**, 5071-5076. d) Wagh, Y. S.; Sawant, D. N.; Dhake, K. P.; Deshmukh, K. M.; Bhanage, B. M. *Tetrahedron Lett*. **2011**, *52*, 5676-5679.

69. a) Danjo, H.; Tanaka, D.; Hayashi, T.; Uozumi, Y. *Tetrahedron* **1999**, *55*, 14341-14352. b) Uozumi, Y.; Shibatomi, K. *J. Am. Chem. Soc.* **2001**, *123*, 2919-2920. c) Uozumi, Y.; Tanaka, H.; Shibatomi, K. *Org. Lett.* **2004**, *6*, 281-283. d) Uozumi, Y.; Kimura, M.; *Tetrahedron: Asymmetry* **2006**, *17*, 161-166. e) Kobayashi, Y.; Tanaka, D.; Danjo, H.; Uozumi, Y. *Adv. Synth. Catal.* **2006**, *348*, 1561-1566. f) Uozumi, Y.; Suzuka, T.; Kawade, R.; Takenaka, H. *Synlett* **2006**, 2109-2113. g) Uozumi, Y.; Suzuka, T. *J. Org. Chem.* **2006**, *71*, 8644-8646. h) Uozumi, Y. *Pure Appl. Chem.* **2007**, *79*, 1481-1489. i) Uozumi, Y.; Takenaka, H.; Suzuka, T. *Synlett* **2008**, 1557-1561. j) Uozumi, Y.; Suzuka, T. *Synthesis* **2008**, 1960-1964. k) Sarkar, S. M.; Y. Uozumi, Y.; Yamada, M. A. *Angew. Chem. Int. Ed.* **2011**, *50*, 9437-9441. l) Yamada, Y. M. A.; Sarkar, S. M.; Uozumi, Y. *J. Am. Chem. Soc*. **2012**, *134*, 3190-3198.

70. Uozumi, Y.; Danjo, H.; Hayashi, T. *Tetrahedron Lett*. **1997**, *38*, 3557-3560.

71. Uozumi, Y.; Danjo, H.; Hayashi, T. *J. Org. Chem.* **1999**, *64*, 3384-3388.

72. Yamada, Y. M. A.; Watanabe, T.; Torii, K.; Uozumi. Y. *Chem. Commun*. **2009**, 5594-5596.

73. Suzuka, T.; Takayama, N.; Unten, M.; Onda, K.; Ogihara, K. *Trans. Mater. Res. Soc. Jpn*. **2019**, *44*, 41-44.

74. Sandee, A. J.; Dimitrijevic, D.; van Haaren, R. J.; Reek, J. N. H.; Kamer, P. C. J.; van Leeuwen, P. W. N. M. *J. Mol. Catal. A* **2002**, 309-317.

75. Son, S. U.; Park, K. H.; Chung, Y. K. *J. Am. Chem. Soc.* **2002**, *124*, 6838-6839.
76. Park, K. H.; Son, S. U.; Chung, Y. K. *Org. Lett.*, **2002**, *4*, 4361-4363.
77. Mitsudome, T.; Nose, K.; Mori, K.; Mizugaki, T.; Ebitani, K.; Jitsukawa, K.; Kaneda, K. *Angew. Chem. Int. Ed.* **2007**, *46*, 3288-3290.
78. Okumura, K.; Sato, K.; Kamioka, K.; Koga, Y. *Microporous Mesoporous Mater.* **2019**, *288*, 109571.
79. a) Dickschat, A. T.; Behrends, F.; Surmiak, S.; Weiß, M.; Eckert, H.; Studer, A. *Chem. Commun.* **2013**, *49*, 2195-2197. b) Noda, H.; Motokura, K.; Miyaji, A.; Baba, T. *Angew. Chem. Int. Ed.* **2012**, *51*, 8017-8020. c) Noda, H.; Motokura, K.; Miyaji, A.; Baba, T. *Adv. Synth. Catal.* **2013**, *355*, 973-980. d) Motokura, K.; Saitoh, K.; Noda, H.; Chun, W.; Miyaji, A.; Yamaguchi, S.; Baba, T. *Catal. Sci. Technol.* **2016**, *6*, 5380-5388. e) Motokura, K.; Saitoh, K.; Noda, H.; Uemura, Y.; Chun, W.; Miyaji, A.; Yamaguchi, S.; Baba, T. *ChemCatChem* **2016**, *8*, 331-335. f) Motokura, K.; Ikeda, M.; Nambo, M.; Chun, W.; Nakajima, K.; Tanaka, S. *ChemCatChem* **2017**, *9*, 2924-2929. g) Motokura, K.; Ikeda, M.; Kim, M.; Nakajima, K.; Kawashima, S.; Nambo, M.; Chun, W.; Tanaka, S. *ChemCatChem* **2018**, *10*, 4536-4544. h) Motokura, K.; Kawashima, S.; Nambo, M.; Manaka, Y.; Chun, W.-J. *ChemCatChem* **2020**, *12*, 2783-2791.
80. a) Cai, M.; Huang, Y.; Zhao, H.; Zhang, R. *J. Organomet. Chem.* **2004**, *689*, 2436-2440. b) Zhao, H.; Cai, M. *Chin. J. Chem.* **2006**, *24*, 1669-1673.
81. a) Motokura, K.; Ikeda, M.; Kim, M.; Nakajima, K.; Kawashima, S.; Nambo, M.; Chun, W.-J.; Tanaka, S. *ChemCatChem* **2018**, *10*, 4536-4544. b) Ding, S.; Manaka, Y.; Nambo, m.; Chun, W-J.; Tomita, I.; Motokura, K. *Catal. Sci. Technol.* **2023**, *13*, 3047-3059.
82. Zhao, Q.; Zhu, Y.; Sun, Z.; Li, Y.; Zhang, G.; Zhang, F.; Fan, X. *J. Mater. Chem. A* **2015**, *3*, 2609-2616.
83. Liu, J.; Huo, X.; Li, T.; Yang, Z.; Xi, P.; Wang, Z.; Wang, B. *Chem. Eur. J.* **2014**, *20*, 11549-11555.
84. Nasir Baig, R. B.; Varma, R. S. *Ind. Eng. Chem. Res.* **2014**, *53*, 18625-18629.
85. Touzani, R.; Alper, H. *J. Mol. Catal. A* **2005**, *227*, 197-207.
86. Sharma, V.; R. Saha, D. De; Chattaraj, P. K.; Bharadwaj. P. K. *ACS Appl. Mater. Interfaces* **2020**, *12*, 8539-8546.
87. Heck, R. F.; Nolley, Jr., J. P. *J. Org. Chem.* **1972**, *37*, 2320-2322.
88. Mizoroki, T.; Mori, K.; Ozaki, A. *Bull. Chem. SOC. Jpn.* **1972**, *44*, 581-581.
89. a) Prashad, M. *Top. Organmet. Chem.* **2004**, *6*, 181-203. b) Nicolaou, K. C.; Bulger P. G.; Sarlah, D. *Angew. Chem., Int. Ed.* **2005**, *44*, 4442-4489. c) Kobetic R.; Biliskov, N.; *Kem. Ind.* **2007**, *56*, 391-402. d) Tietze, L. F.; Kinzel, T. *Pure Appl. Chem.* **2007**, *79*, 629-650.
90. a) Heck, R. F. *J. Am. Chem. Soc.* **1968**, *90*, 5518-5526. b) Heck, R. F. *J. Am. Chem. Soc.* **1968**, *90*, 5538-5542. c) Heck, R. F. *J. Am. Chem. Soc.* **1968**, *91*, 6707-6714.
91. a) Trost, B. M.; Burgess, K. *J. Chem. Soc., Chem. Commun.* **1985**, 1084-1086. b) Larock, R. C.; Stinn, D. E.; Mann-Yan, K. *Tetrahedron Lett.* **1990**, 31, 17-20.
92. a) Yoshida, J.-i.; Tamao, K.; Yamamoto, H.; Kakui, T.; Uchida, T.; Kumada, M. *Organometallics* **1982**, *1*, 542-549. b) Hirabayashi, K.; Nishihara, Y.; Mori, A.; Hiyama, T. *Tetrahedron Lett.* **1998**, *39*, 7893-7896.
93. a) Tamaru, Y.; Hojo, M.; Kawamura, S.-i.; Yoshida, Z.-i. *J. Org. Chem.* **1986**, *51*, 4089-4090. b) Hirabayashi, K.; Ando, J.-i.; Nishihara, Y.; Mori, A.; Hiyama, T.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

Synlett 1999, **1999**, 99-101. c) Parrish, J. P.; Jung, Y. C.; Shin, S. I.; Jung, K. W. *J. Org. Chem.* **2002**, *67*, 7127-7130.

94. a) Inoue, A.; Shinokubo, H.; Oshima, K. *J. Am. Chem. Soc.* **2003**, *125*, 1484-1485. b) Hwang, L. K.; Na, Y.; Lee, J.; Do, Y.; Chang, S. *Angew. Chem. Int. Ed.* **2005**, *44*, 6166-6169.

95. a) Kjonaas, R. A. *J. Org. Chem.* **1986**, *51*, 3708-3710. b) Moiseev, D. V.; Gushchin, A. V.; Shavirin, A. S.; Kursky, Y. A.; Dodonov, V. A. *J. Organomet. Chem.* **2003**, *667*, 176-184. c) Hirabayashi, K.; Nara, Y.; Shimizu, T.; Kamigata, N. *Chem. Lett.* **2004**, *33*, 1280-1281. d) Malysheva, Y. B.; Gushchin, A. V.; Mei, Y.; Lu, Y.; Ballauff, M.; Proch, S.; Kempe, R. *Eur. J. Inorg. Chem.* **2008**, *3*, 379-383.

96. Dieck, H. A.; Heck, R. F. *J. Org. Chem.* **1975**, *40*, 1083-1090.

97. Cho, C. S.; Uemura, S.; *J. Organomet. Chem.* **1994**, *465*, 85-92.

98. a) Du, X.; Suguro, M.; Hirabayashi, K.; Mori, A.; Nishikata, T.; Hagiwara, N.; Kawata, K.; Okeda, T.; Wang, H. F.; Fugami, K.; Kosugi, M. *Org. Lett.* **2001**, *3*, 3313-3316.

99. Parrish, J. P.; Jung, Y. C.; Shin, S. I.; Jung K. W. *J. Org. Chem.* **2002**, *67*, 7127-7130.

100. a) Yoo, K. S.; Yoon, C. H.; Mishra, R. K.; Jung, Y. C.; Yi, S. W.; Jung, K. W. *J. Am. Chem. Soc.* **2006**, *128*, 16384-16393. b) Crowley, J. D.; Hänni, K. D.; Lee, A.-L.; Leigh, D. A. *J. Am. Chem. Soc.* **2007**, *129*, 12092-12093. c) Delcamp, J.H.; Gormisky, P. E.; White, M. C. *J. Am. Chem. Soc.* **2013**, *135*, 8460−8463.

101. a) Jung, Y. C.; Mishra, R. K.; Yoon, C. H.; Jung, K. W. *Org. Lett.* **2003**, *5*, 2231-2234. b) Andappan, M. M. S.; Nilsson, P.; Larhed, M. *Chem. Commun.* **2004**, 218-219. c) Andappan, M. M. S.; Nilsson, P.; von Schenck, H.; Larhed, M. *J. Org. Chem.* **2004**, *69*, 5212-5218. d) Akiyama, K.; Wakabayashi, K.; Mikami, K. *Adv. Synth. Catal.* **2005**, *347*, 1569-1575.

102. a) Enquist, P.-A.; Lindh, J.; Nilsson, P.; Larhed, M. *Green Chem.* **2006**, *8*, 338-343. b) Lindh, J.; Enquist, P.-A.; Pilotti, Å.; Nilsson, P.; Larhed, M. *J. Org. Chem.* **2007**, *72*, 7957-7962.

103. Yamaguchi, K.; Kondo, H.; Yamaguchi, J.; Itami, K. *Chem. Sci***.** **2013**, *4*, 3753-3757.

104. Zhou, Y. B.; Wang, Y. Q.; Ning, L. C.; Ding, Z. C.; Wang, W. L.; Ding, C. K.; Li, R. H.; Chen, J. J.; Lu, X.; Ding, Y. J.; Zhan, Z. P. *J. Am. Chem. Soc.* **2017**, *139*, 3966-3969.

105. Li, R. H.; Ding, Z. C.; Li, C. Y.; Chen, J. J.; Zhou, Y. B.; An, X. M.; Ding, Y. J.; Zhan, Z. P. *Org. Lett.* **2017**, *19*, 4432-4435.

106. Li, W. H.; Li, C. Y.; Xiong, H. Y.; Liu, Y.; Huang, W. Y.; Ji, G. J.; Jiang, Z.; Tang, H. T.; Pan, Y. M.; Ding, Y. J. *Angew. Chem. Int. Ed.* **2019**, *58*, 2448-2453.

107. Han, J.; Sun, X.; Wang, X.; Wang, Q.; Hou, S.; Song, X.; Wei, Y.; Wang, R.; Ji, W. *Org. Lett.* **2020**, *22*, 1480-1484.

108. Chevreau, H.; Permyakova, A.; Nouar, F.; Fabry, P.; Livage, C.; Ragon, F.; Garcia-Marquez, A.; Devic, T.; Steunou, N.; Serre, C.; Horcajada, P. *CrystEngComm* **2016**, *18*, 4094-4101.

109. Smidt, J.; Hafner, W.; Jira, R.; Sedlmeier, J.; Sieber, R.; Kojer, H.; Rttinger, R. *Angew. Chem.* **1959**, *71*, 176-182

110. Rivera-Chao, E.; Mitxelena, M.; Varela, J. A.; Fañanás-Mastral, M. *Angew. Chem. Int. Ed.* **2019**, *58*, 18230-18234.

111. Amatore, C.; Le Duc, G.; Jutand, A. *Chem. Eur. J.* **2013**, *19*, 10082-10093.

112. Lee, J.-E.; Kwon, J.; Yun, J. *Chem. Commun.* **2008**, 733-734.

113. Yang, W.; Chen C.; Chan, K. S. *Dalton Trans.* **2018**, *47*, 12879-12883.

114. Lin, Q.; Hu, B.; Xu, X.; Dong, S.; Liu, X.; Feng, X.; *Chem. Sci*. **2020**, *11*, 3068-3073.
115. Liu, X.; Liu, S.; Wang, Q.; Zhou, G.; Yao, L.; Ouyang, Q.; Jiang, R.; Lan Y.; Chen, W. *Org. Lett*. **2020**, *22*, 3149-3154.
116. Guduguntla, S.; Hornillos, V.; Tessier, R.; Fañanas-Mastral, M.; Feringa, B. L. *Org. Lett*. **2016**, *18*, 252-255.
117. He, J.; Jia, Z.; Tan, H.; Luo, X.; Qiu, D.; Shi, J.; Xu, H.; Li, Y. *Angew. Chem. Int. Ed*. **2019**, *58*, 18513-18518.
118. Gao, S.; Niggemann, M.; *Adv. Synth. Catal.* **2019**, *361*, 1549-1553
119. Hill, E. A.; Engel, M. R. *J. Org. Chem*. **1971**, *36*, 1356-1360.
120. Kumar, R.; Sharma, A.; Sharma, N.; Kumar, V.; Sinha, A. K. *Eur. J. Org. Chem*. **2008**, *33*, 5577-5582.
121. Zhu, N.; Zhao, J.; Bao, H.; *Chem. Sci.* **2017**, *8*, 2081-2085.
122. Yu, X.; Zhao, H.; Li, P.; Koh, M. J. *J. Am. Chem. Soc*. **2020**, *142*, 18223-18230.
123. Zhang, R. K.; Chen, K.; Huang, X.; Wohlschlager, L.; Renata, H.; Arnold, F. H. *Nature* **2019**, *565*, 67-72.
124. Yasunori, Y.; Shingo, T.; Norio, M.; *Chem. Lett.* **2006**, *35*, 704-705.
125. Endo, K.; Ohkubo, T.; Ishioka, T.; Shibata, T.; *J. Org. Chem.* **2012**, *77*, 4826-4831.
126. Zhang, Z.-Q.; Zhang, B.; Lu, X.; Liu, J.-H.; Lu, X.-Y.; Xiao, B.; Fu, Y. *Org. Lett.* **2016**, *18*, 952-955.
127. Wang, Y.; Shao, Z.; Zhang, K.; Liu, Q. *Angew. Chem. Int. Ed*. **2018**, *57*, 15143-15147.
128. Yang, B.; Wang, Z.-X. *J. Org. Chem.* **2017**, *82*, 4542-4549.
129. Tsukamoto, H.; Uchiyama, T.; Suzuki, T.; Kondo, Y. *Org. Biomol. Chem.* **2008**, *6*, 3005- 3013.
130. Lee, Y.; Shabbir, S.; Lee, S.; Ahn, H.; Rhee, H. *Green Chem*. **2015**, *17*, 3579-3583.
131. Qiu, J.; Zhang, R.; *Org. Biomol. Chem*. **2013**, *11*, 6008-6012.
132. Lipshutz, B. H.; Ghorai, S.; Abela, A. R.; Moser, R.; Nishikata, T.; Duplais, C.; Krasovskiy, A.; Gaston, R. D.; Gadwood, R. C. *J. Org. Chem*. **2011**, *76*, 4379-4391.
133. Alacid, E.; Nájera, C. *J. Org. Chem*. **2009**, *74*, 2321-2327.
134. Dai, M.; Liang, B.; Wang, C.; Chen, J.; Yang, Z. *Org. Lett*. **2004**, *6*, 221-224
135. Iwasaki, T.; Miyata, Y.; Akimoto, R.; Fujii, Y.; Kuniyasu, H.; Kambe. *J. Am. Chem. Soc*. **2014**, *136*, 9260-9263.
136. Aydin, J.; Larsson, J. M.; Selander, N.; Szabó, K. J. *Org. Lett*. **2009**, *11*, 2852-2854.
137. Selvakumar, K.; Zapf, A.; Beller, M. *Org. Lett*. **2002**, *4*, 3031-3033.
138. Khalafi-Nezhad, A.; Panahi, F. *ACS Sustainable Chem. Eng.* **2014**, *2*, 1177-1186.
139. Zhang, J.-Q.; Cao, J.; Li, W.; Li, S.-M.; Li, Y.-K.; Wang, J.-T.; Tang, L. *New J. Chem*. **2017**, *41*, 437-441.
140. Tanaka, S.; Mori, A. *Eur. J. Org. Chem*. **2014**, *2014*, 1167-1171.
141. Krasovkskiy, A. L.; Haley, S.; Voigtritter, K.; Lipshutz, B. H. *Org. Lett*. **2014**, *16*, 4066-4069.
142. Mennecke, K.; Kirschning, A. *Beilstein J. Org. Chem*. **2009,** 5, No. 21.
143. Cahiez, G.; Moyeux, A.; Poizat, M. *Chem. Commun*. **2014**, 50, 8982-8984
144. Zhou, X.; Luo, J.; Liu, J.; Peng, S.; Deng, G.-J. *Org. Lett.* **2011**, 13, 1432-1435.

145. Huang, M.-H.; Liang, L.-C. *Organometallics* **2004**, *23*, 2813-2816.
146. Szewczyk, S. M.; Zhao, Y.; Sakai, H. A.; Dube, P.; Newhouse, T. R. *Tetrahedron* **2018,** *74*, 3293-3300.
147. Alacid, E.; Nájera, C. *J. Org. Chem.* **2009**, *74*, 8191-8195.

APPENDIX A.I: LIST OF PUBLICATIONS AND CONTRIBUTION STATEMENT

Data compiled from Web of Science (Clarivate Analytics) on December 25th, 2024.

Miguel-Casañ, E.;[a] Darawsheh, M. D.;[a] Fariña-Torres, V.;[b] Vitórica-Yrezábal, I. J.;[c] Andres-Garcia, E.;[a] Fañanás-Mastral, M.;[b] Mínguez Espallargas, G.[a] Chem. Sci. **2023**, *14*, 179-185.

Impact factor (2023): 7.6

Journal Ranking (2023): Chemistry, multidisciplinary, Q1

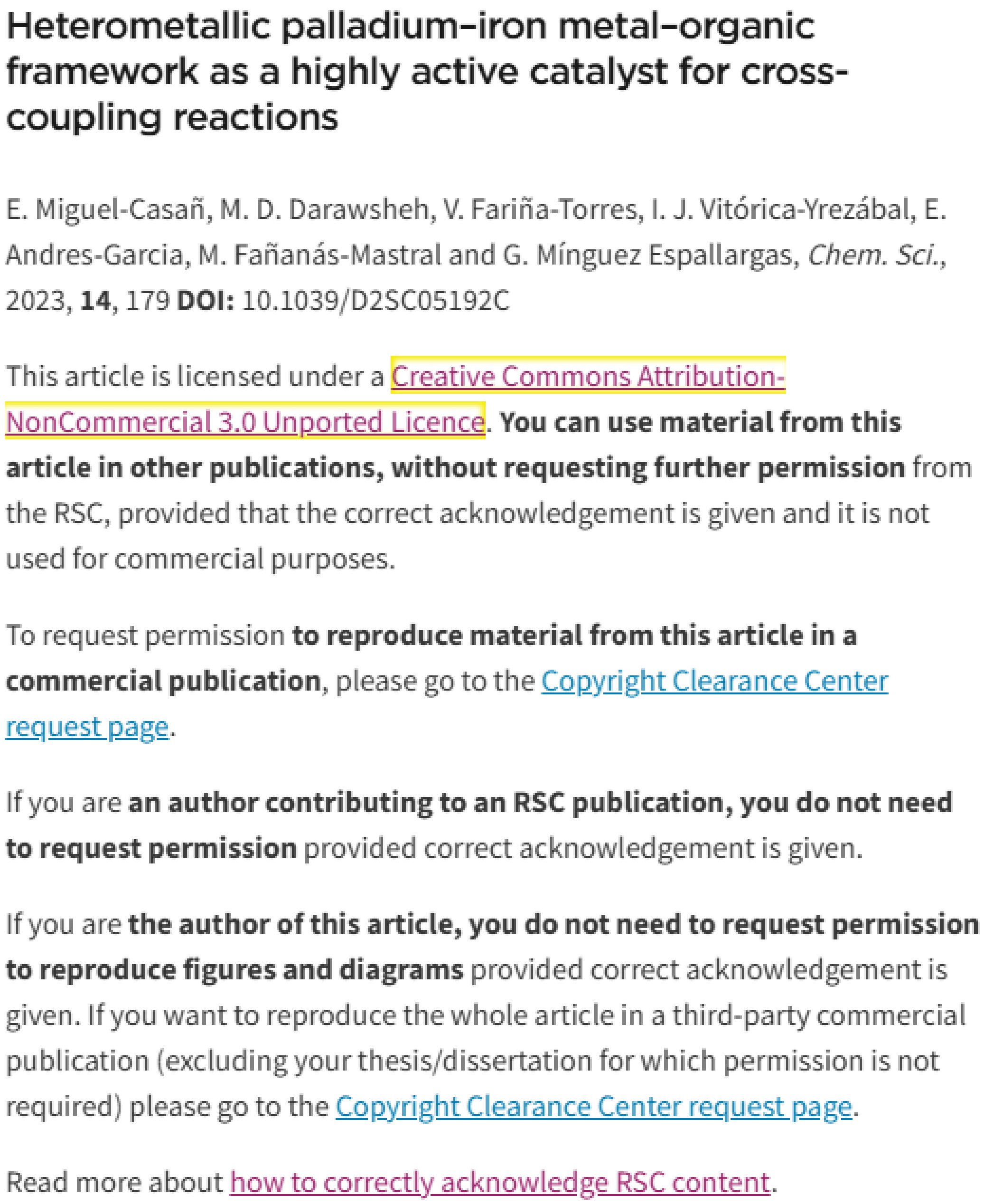
Contribution statement: I carried out all the catalytic studies, including the optimization of the reaction, comparative with other catalysts, scope and limitations of the reaction and stability studies excluding the x-ray powder diffraction technique and EDX study. All authors contributed with critical feedback and helped to shape the final version of the manuscript and the supporting information.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

APPENDIX A.II: PERMISSIONS TO REPRODUCE ARTICLE

Permission associated with section 6.1.:

Miguel-Casañ, E.;[a] Darawsheh, M. D.;[a] Fariña-Torres, V.;[b] Vitórica-Yrezábal, I. J.;[c] Andres-Garcia, E.;[a] Fañanás-Mastral, M.;[b] Mínguez Espallargas, G.[a] Chem. Sci. **2023**, *14*, 179-185. **DOI:** 10.1039/D2SC05192C



Heterometallic palladium–iron metal–organic framework as a highly active catalyst for cross-coupling reactions

E. Miguel-Casañ, M. D. Darawsheh, V. Fariña-Torres, I. J. Vitórica-Yrezábal, E. Andres-Garcia, M. Fañanás-Mastral and G. Mínguez Espallargas, *Chem. Sci.*, 2023, **14**, 179 **DOI:** 10.1039/D2SC05192C

This article is licensed under a Creative Commons Attribution-NonCommercial 3.0 Unported Licence. **You can use material from this article in other publications, without requesting further permission** from the RSC, provided that the correct acknowledgement is given and it is not used for commercial purposes.

To request permission **to reproduce material from this article in a commercial publication**, please go to the Copyright Clearance Center request page.

If you are **an author contributing to an RSC publication, you do not need to request permission** provided correct acknowledgement is given.

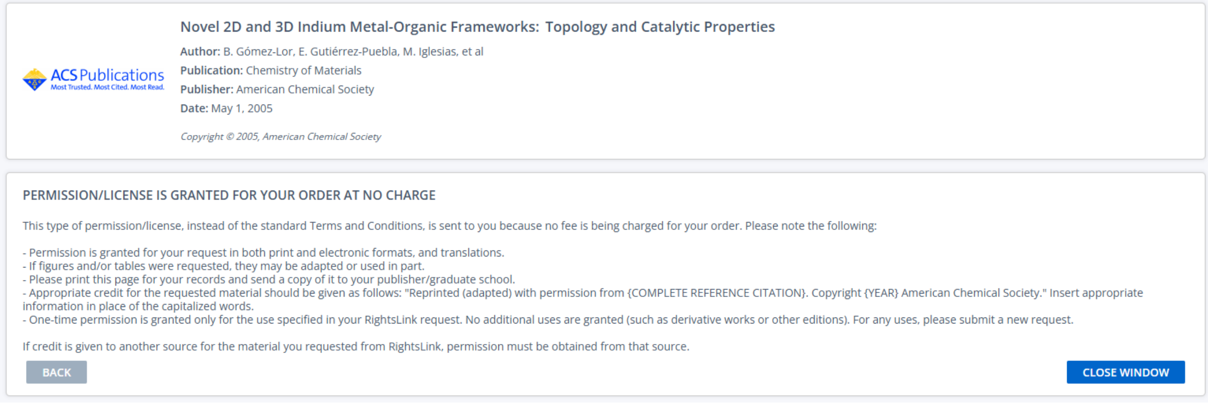
If you are **the author of this article, you do not need to request permission to reproduce figures and diagrams** provided correct acknowledgement is given. If you want to reproduce the whole article in a third-party commercial publication (excluding your thesis/dissertation for which permission is not required) please go to the Copyright Clearance Center request page.

Read more about how to correctly acknowledge RSC content.


USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

APPENDIX A.III: PERMISSIONS TO PUBLISH IMAGES, TABLES AND FIGURES

Scheme 8. a):



Novel 2D and 3D Indium Metal-Organic Frameworks: Topology and Catalytic Properties

Author: B. Gómez-Lor, E. Gutiérrez-Puebla, M. Iglesias, et al

Publication: Chemistry of Materials

Publisher: American Chemical Society

Date: May 1, 2005

Copyright © 2005, American Chemical Society

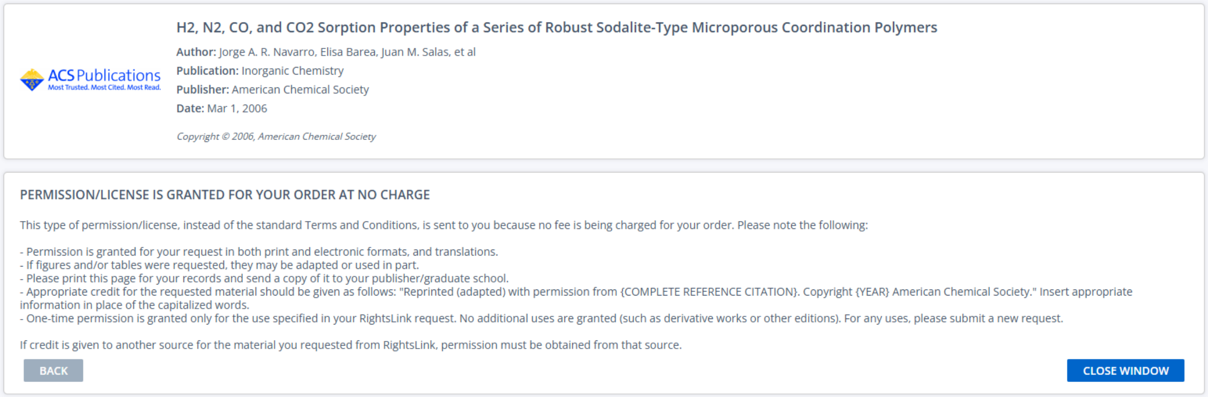
PERMISSION/LICENSE IS GRANTED FOR YOUR ORDER AT NO CHARGE

This type of permission/license, instead of the standard Terms and Conditions, is sent to you because no fee is being charged for your order. Please note the following:

- Permission is granted for your request in both print and electronic formats, and translations.
- If figures and/or tables were requested, they may be adapted or used in part.
- Please print this page for your records and send a copy of it to your publisher/graduate school.
- Appropriate credit for the requested material should be given as follows: "Reprinted (adapted) with permission from {COMPLETE REFERENCE CITATION}. Copyright {YEAR} American Chemical Society." Insert appropriate information in place of the capitalized words.
- One-time permission is granted only for the use specified in your RightsLink request. No additional uses are granted (such as derivative works or other editions). For any uses, please submit a new request.

If credit is given to another source for the material you requested from RightsLink, permission must be obtained from that source.

Scheme 9. a):



H2, N2, CO, and CO2 Sorption Properties of a Series of Robust Sodalite-Type Microporous Coordination Polymers

Author: Jorge A. R. Navarro, Elisa Barea, Juan M. Salas, et al

Publication: Inorganic Chemistry

Publisher: American Chemical Society

Date: Mar 1, 2006

Copyright © 2006, American Chemical Society

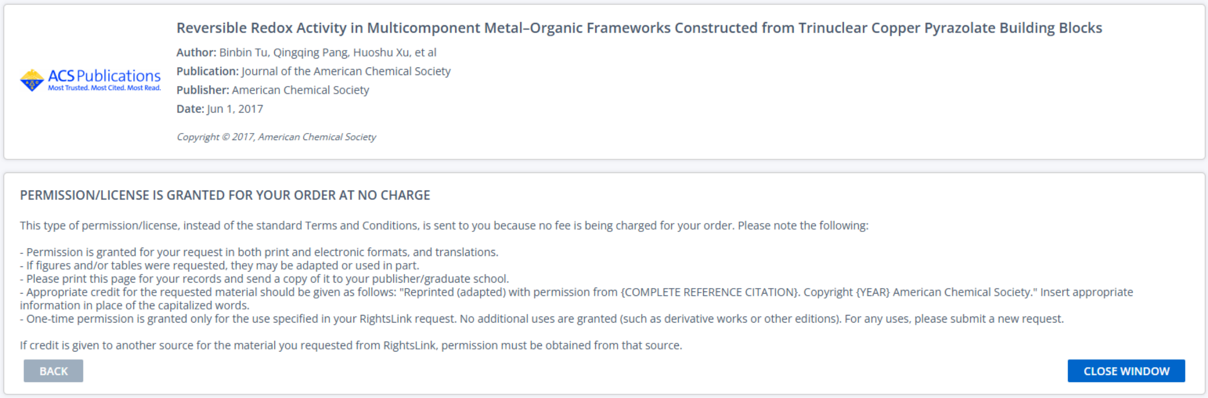
PERMISSION/LICENSE IS GRANTED FOR YOUR ORDER AT NO CHARGE

This type of permission/license, instead of the standard Terms and Conditions, is sent to you because no fee is being charged for your order. Please note the following:

- Permission is granted for your request in both print and electronic formats, and translations.
- If figures and/or tables were requested, they may be adapted or used in part.
- Please print this page for your records and send a copy of it to your publisher/graduate school.
- Appropriate credit for the requested material should be given as follows: "Reprinted (adapted) with permission from {COMPLETE REFERENCE CITATION}. Copyright {YEAR} American Chemical Society." Insert appropriate information in place of the capitalized words.
- One-time permission is granted only for the use specified in your RightsLink request. No additional uses are granted (such as derivative works or other editions). For any uses, please submit a new request.

If credit is given to another source for the material you requested from RightsLink, permission must be obtained from that source.

Scheme 10. a):



Reversible Redox Activity in Multicomponent Metal–Organic Frameworks Constructed from Trinuclear Copper Pyrazolate Building Blocks

Author: Binbin Tu, Qingqing Pang, Huoshu Xu, et al

Publication: Journal of the American Chemical Society

Publisher: American Chemical Society

Date: Jun 1, 2017

Copyright © 2017, American Chemical Society

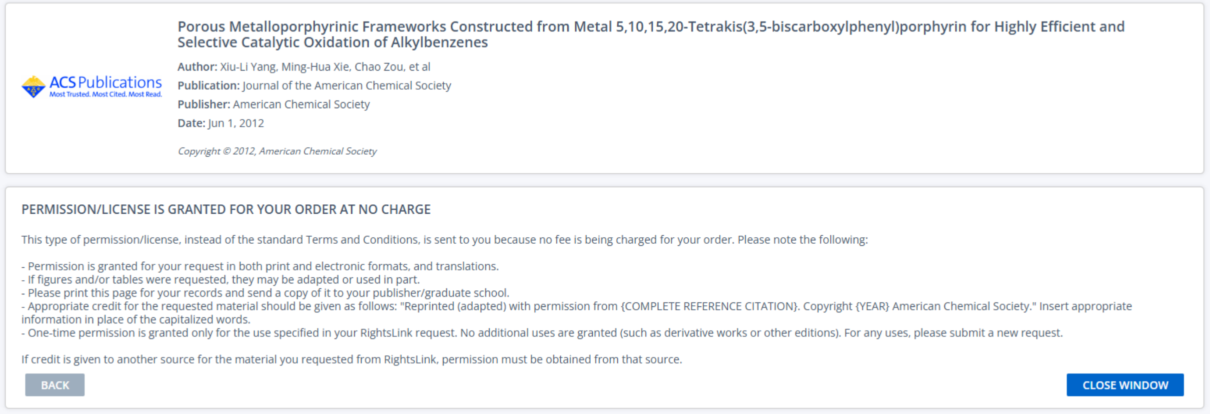
PERMISSION/LICENSE IS GRANTED FOR YOUR ORDER AT NO CHARGE

This type of permission/license, instead of the standard Terms and Conditions, is sent to you because no fee is being charged for your order. Please note the following:

- Permission is granted for your request in both print and electronic formats, and translations.
- If figures and/or tables were requested, they may be adapted or used in part.
- Please print this page for your records and send a copy of it to your publisher/graduate school.
- Appropriate credit for the requested material should be given as follows: "Reprinted (adapted) with permission from {COMPLETE REFERENCE CITATION}. Copyright {YEAR} American Chemical Society." Insert appropriate information in place of the capitalized words.
- One-time permission is granted only for the use specified in your RightsLink request. No additional uses are granted (such as derivative works or other editions). For any uses, please submit a new request.

If credit is given to another source for the material you requested from RightsLink, permission must be obtained from that source.

Scheme 11. a):



Porous Metalloporphyrinic Frameworks Constructed from Metal 5,10,15,20-Tetrakis(3,5-biscarboxylphenyl)porphyrin for Highly Efficient and Selective Catalytic Oxidation of Alkylbenzenes

Author: Xiu-Li Yang, Ming-Hua Xie, Chao Zou, et al
Publication: Journal of the American Chemical Society
Publisher: American Chemical Society
Date: Jun 1, 2012

Copyright © 2012, American Chemical Society

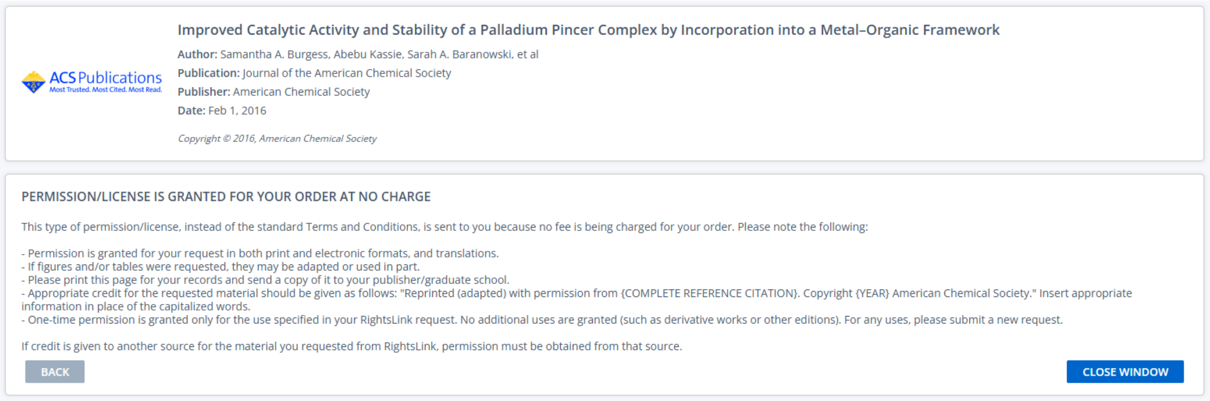
PERMISSION/LICENSE IS GRANTED FOR YOUR ORDER AT NO CHARGE

This type of permission/license, instead of the standard Terms and Conditions, is sent to you because no fee is being charged for your order. Please note the following:

- Permission is granted for your request in both print and electronic formats, and translations.
- If figures and/or tables were requested, they may be adapted or used in part.
- Please print this page for your records and send a copy of it to your publisher/graduate school.
- Appropriate credit for the requested material should be given as follows: "Reprinted (adapted) with permission from {COMPLETE REFERENCE CITATION}. Copyright {YEAR} American Chemical Society." Insert appropriate information in place of the capitalized words.
- One-time permission is granted only for the use specified in your RightsLink request. No additional uses are granted (such as derivative works or other editions). For any uses, please submit a new request.

If credit is given to another source for the material you requested from RightsLink, permission must be obtained from that source.

Scheme 12. a):



Improved Catalytic Activity and Stability of a Palladium Pincer Complex by Incorporation into a Metal–Organic Framework

Author: Samantha A. Burgess, Abebu Kassie, Sarah A. Baranowski, et al
Publication: Journal of the American Chemical Society
Publisher: American Chemical Society
Date: Feb 1, 2016

Copyright © 2016, American Chemical Society

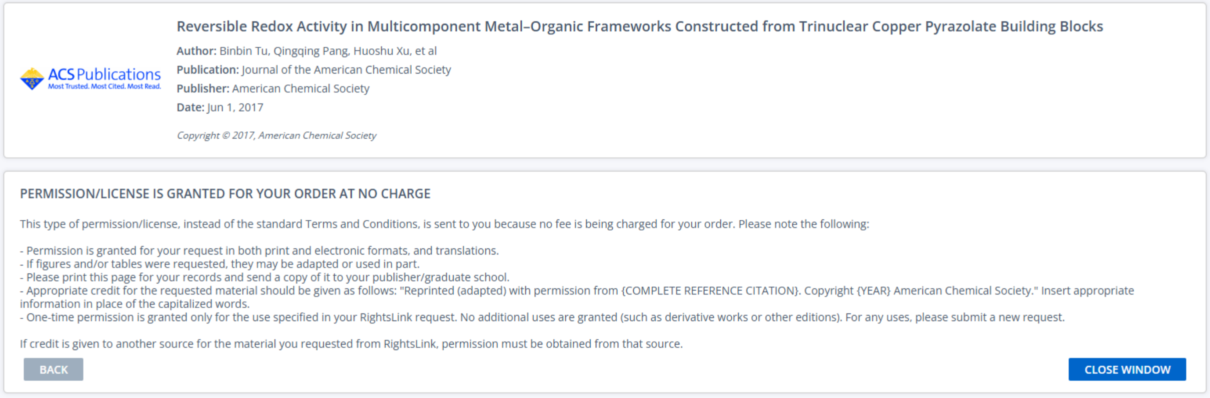
PERMISSION/LICENSE IS GRANTED FOR YOUR ORDER AT NO CHARGE

This type of permission/license, instead of the standard Terms and Conditions, is sent to you because no fee is being charged for your order. Please note the following:

- Permission is granted for your request in both print and electronic formats, and translations.
- If figures and/or tables were requested, they may be adapted or used in part.
- Please print this page for your records and send a copy of it to your publisher/graduate school.
- Appropriate credit for the requested material should be given as follows: "Reprinted (adapted) with permission from {COMPLETE REFERENCE CITATION}. Copyright {YEAR} American Chemical Society." Insert appropriate information in place of the capitalized words.
- One-time permission is granted only for the use specified in your RightsLink request. No additional uses are granted (such as derivative works or other editions). For any uses, please submit a new request.

If credit is given to another source for the material you requested from RightsLink, permission must be obtained from that source.

Scheme 13. a):



Reversible Redox Activity in Multicomponent Metal–Organic Frameworks Constructed from Trinuclear Copper Pyrazolate Building Blocks

Author: Binbin Tu, Qingqing Pang, Huoshu Xu, et al
Publication: Journal of the American Chemical Society
Publisher: American Chemical Society
Date: Jun 1, 2017

Copyright © 2017, American Chemical Society

PERMISSION/LICENSE IS GRANTED FOR YOUR ORDER AT NO CHARGE

This type of permission/license, instead of the standard Terms and Conditions, is sent to you because no fee is being charged for your order. Please note the following:

- Permission is granted for your request in both print and electronic formats, and translations.
- If figures and/or tables were requested, they may be adapted or used in part.
- Please print this page for your records and send a copy of it to your publisher/graduate school.
- Appropriate credit for the requested material should be given as follows: "Reprinted (adapted) with permission from {COMPLETE REFERENCE CITATION}. Copyright {YEAR} American Chemical Society." Insert appropriate information in place of the capitalized words.
- One-time permission is granted only for the use specified in your RightsLink request. No additional uses are granted (such as derivative works or other editions). For any uses, please submit a new request.

If credit is given to another source for the material you requested from RightsLink, permission must be obtained from that source.

Scheme 14. a):

Postsynthetic Metalation of Bipyridyl-Containing Metal–Organic Frameworks for Highly Efficient Catalytic Organic Transformations

Author: Kuntal Manna, Teng Zhang, Wenbin Lin
Publication: Journal of the American Chemical Society
Publisher: American Chemical Society
Date: May 1, 2014

Copyright © 2014, American Chemical Society

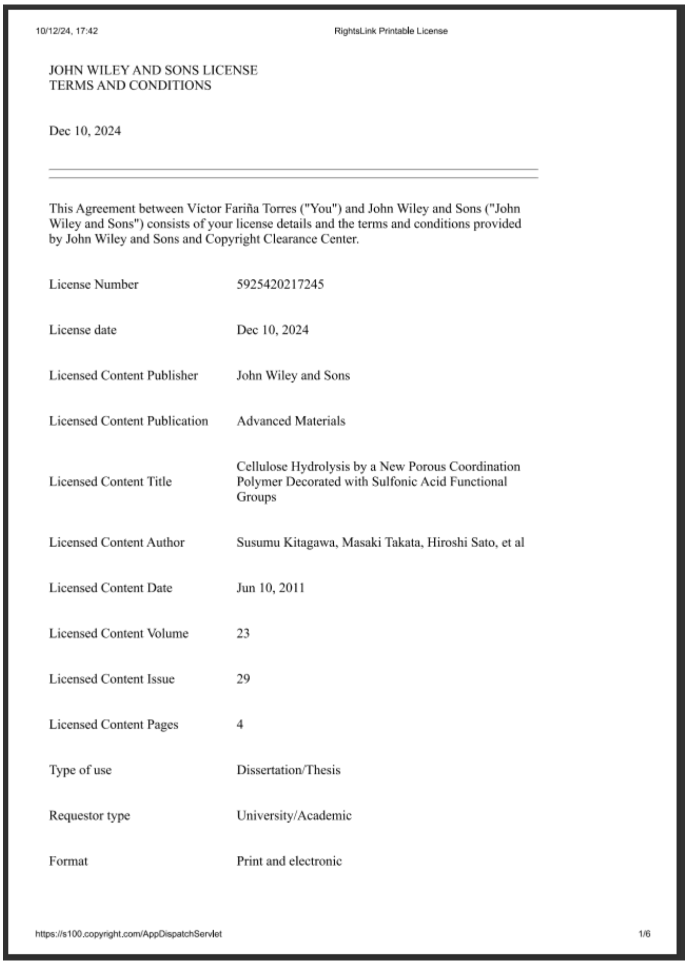
PERMISSION/LICENSE IS GRANTED FOR YOUR ORDER AT NO CHARGE

This type of permission/license, instead of the standard Terms and Conditions, is sent to you because no fee is being charged for your order. Please note the following:

- Permission is granted for your request in both print and electronic formats, and translations.
- If figures and/or tables were requested, they may be adapted or used in part.
- Please print this page for your records and send a copy of it to your publisher/graduate school.
- Appropriate credit for the requested material should be given as follows: "Reprinted (adapted) with permission from {COMPLETE REFERENCE CITATION}. Copyright {YEAR} American Chemical Society." Insert appropriate information in place of the capitalized words.
- One-time permission is granted only for the use specified in your RightsLink request. No additional uses are granted (such as derivative works or other editions). For any uses, please submit a new request.

If credit is given to another source for the material you requested from RightsLink, permission must be obtained from that source.

Scheme 15. a):



10/12/24, 17:42 RightsLink Printable License

JOHN WILEY AND SONS LICENSE
TERMS AND CONDITIONS

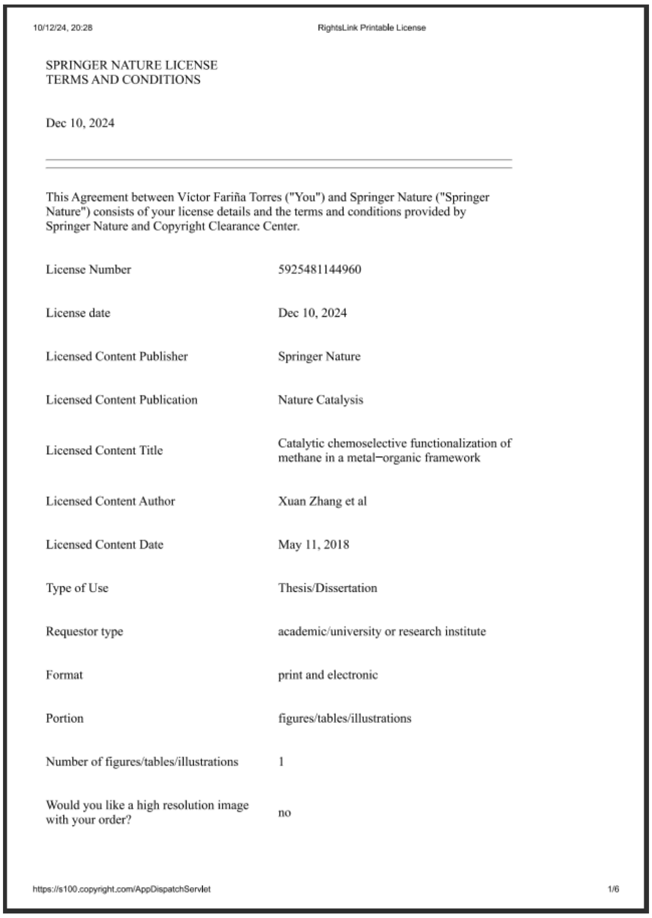
Dec 10, 2024

This Agreement between Victor Fariña Torres ("You") and John Wiley and Sons ("John Wiley and Sons") consists of your license details and the terms and conditions provided by John Wiley and Sons and Copyright Clearance Center.

License Number	5925420217245
License date	Dec 10, 2024
Licensed Content Publisher	John Wiley and Sons
Licensed Content Publication	Advanced Materials
Licensed Content Title	Cellulose Hydrolysis by a New Porous Coordination Polymer Decorated with Sulfonic Acid Functional Groups
Licensed Content Author	Susumu Kitagawa, Masaki Takata, Hiroshi Sato, et al
Licensed Content Date	Jun 10, 2011
Licensed Content Volume	23
Licensed Content Issue	29
Licensed Content Pages	4
Type of use	Dissertation/Thesis
Requestor type	University/Academic
Format	Print and electronic

https://s100.copyright.com/AppDispatchServlet 1/6

Scheme 16. a):



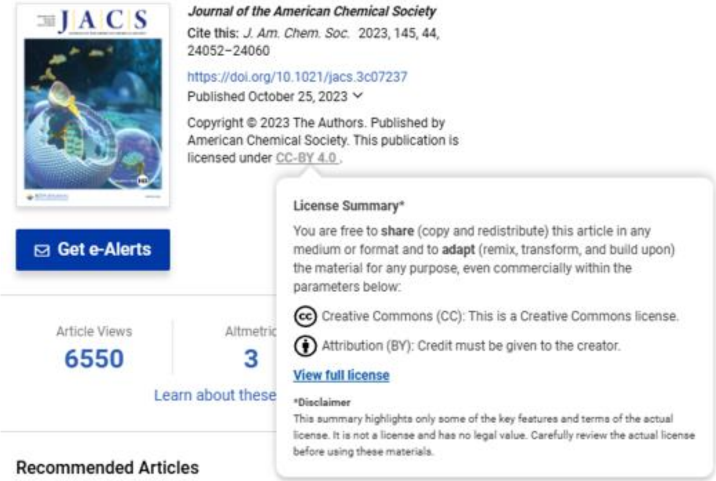
SPRINGER NATURE LICENSE
TERMS AND CONDITIONS

Dec 10, 2024

This Agreement between Victor Fariña Torres ("You") and Springer Nature ("Springer Nature") consists of your license details and the terms and conditions provided by Springer Nature and Copyright Clearance Center.

License Number	5925481144960
License date	Dec 10, 2024
Licensed Content Publisher	Springer Nature
Licensed Content Publication	Nature Catalysis
Licensed Content Title	Catalytic chemoselective functionalization of methane in a metal−organic framework
Licensed Content Author	Xuan Zhang et al
Licensed Content Date	May 11, 2018
Type of Use	Thesis/Dissertation
Requestor type	academic/university or research institute
Format	print and electronic
Portion	figures/tables/illustrations
Number of figures/tables/illustrations	1
Would you like a high resolution image with your order?	no

Scheme 17. a):



Journal of the American Chemical Society

Cite this: *J. Am. Chem. Soc.* 2023, 145, 44, 24052−24060

https://doi.org/10.1021/jacs.3c07237

Published October 25, 2023

Copyright © 2023 The Authors. Published by American Chemical Society. This publication is licensed under CC-BY 4.0 .

Article Views 6550

Altmetric 3

Learn about these

Recommended Articles

License Summary*

You are free to **share** (copy and redistribute) this article in any medium or format and to **adapt** (remix, transform, and build upon) the material for any purpose, even commercially within the parameters below:

Ⓒ Creative Commons (CC): This is a Creative Commons license.

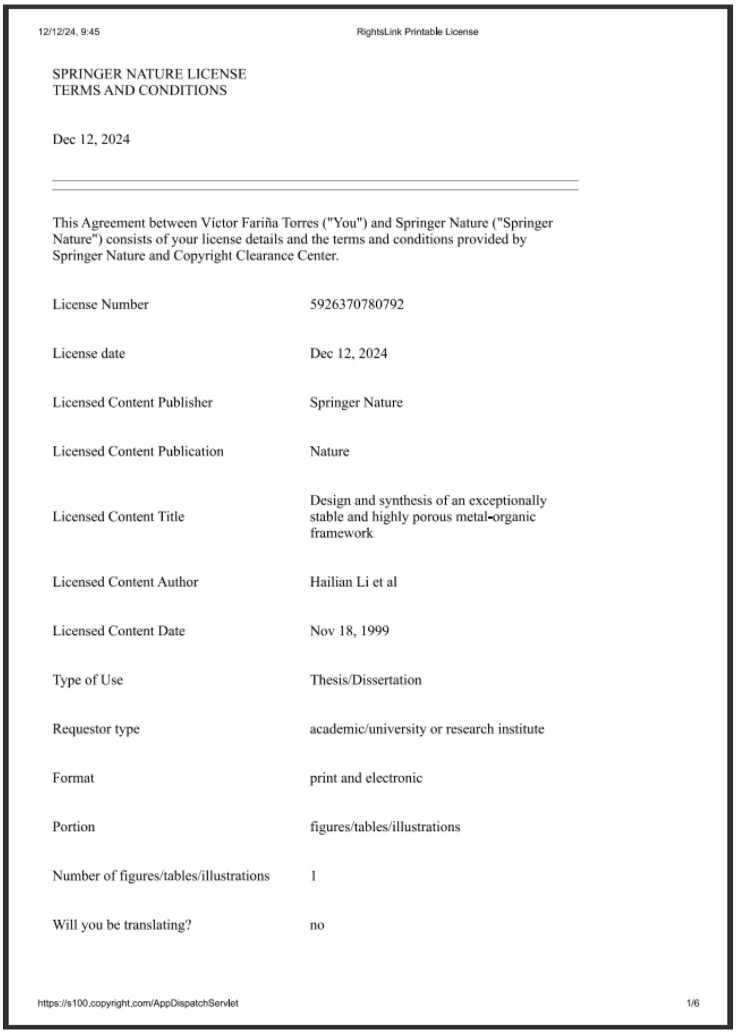
ⓘ Attribution (BY): Credit must be given to the creator.

View full license

*Disclaimer

This summary highlights only some of the key features and terms of the actual license. It is not a license and has no legal value. Carefully review the actual license before using these materials.

Scheme 18. a):



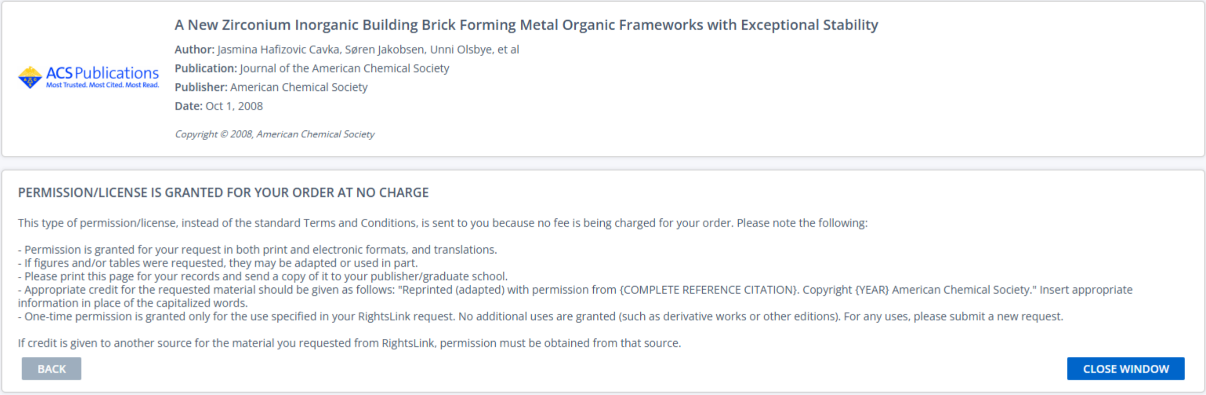
SPRINGER NATURE LICENSE
TERMS AND CONDITIONS

Dec 12, 2024

This Agreement between Victor Fariña Torres ("You") and Springer Nature ("Springer Nature") consists of your license details and the terms and conditions provided by Springer Nature and Copyright Clearance Center.

License Number	5926370780792
License date	Dec 12, 2024
Licensed Content Publisher	Springer Nature
Licensed Content Publication	Nature
Licensed Content Title	Design and synthesis of an exceptionally stable and highly porous metal-organic framework
Licensed Content Author	Hailian Li et al
Licensed Content Date	Nov 18, 1999
Type of Use	Thesis/Dissertation
Requestor type	academic/university or research institute
Format	print and electronic
Portion	figures/tables/illustrations
Number of figures/tables/illustrations	1
Will you be translating?	no

Scheme 20. a):



A New Zirconium Inorganic Building Brick Forming Metal Organic Frameworks with Exceptional Stability

Author: Jasmina Hafizovic Cavka, Søren Jakobsen, Unni Olsbye, et al
Publication: Journal of the American Chemical Society
Publisher: American Chemical Society
Date: Oct 1, 2008

Copyright © 2008, American Chemical Society

PERMISSION/LICENSE IS GRANTED FOR YOUR ORDER AT NO CHARGE

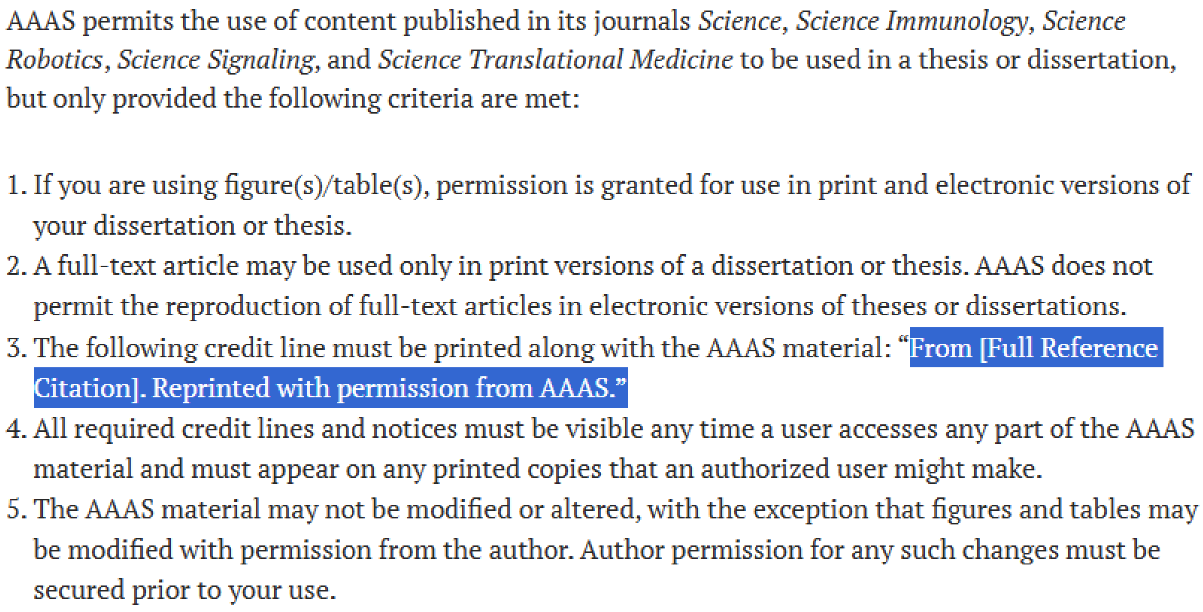
This type of permission/license, instead of the standard Terms and Conditions, is sent to you because no fee is being charged for your order. Please note the following:

- Permission is granted for your request in both print and electronic formats, and translations.
- If figures and/or tables were requested, they may be adapted or used in part.
- Please print this page for your records and send a copy of it to your publisher/graduate school.
- Appropriate credit for the requested material should be given as follows: "Reprinted (adapted) with permission from {COMPLETE REFERENCE CITATION}. Copyright {YEAR} American Chemical Society." Insert appropriate information in place of the capitalized words.
- One-time permission is granted only for the use specified in your RightsLink request. No additional uses are granted (such as derivative works or other editions). For any uses, please submit a new request.

If credit is given to another source for the material you requested from RightsLink, permission must be obtained from that source.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

Scheme 7. a) and Scheme 19. a):



AAAS permits the use of content published in its journals *Science*, *Science Immunology*, *Science Robotics*, *Science Signaling*, and *Science Translational Medicine* to be used in a thesis or dissertation, but only provided the following criteria are met:

1. If you are using figure(s)/table(s), permission is granted for use in print and electronic versions of your dissertation or thesis.
2. A full-text article may be used only in print versions of a dissertation or thesis. AAAS does not permit the reproduction of full-text articles in electronic versions of theses or dissertations.
3. The following credit line must be printed along with the AAAS material: "From [Full Reference Citation]. Reprinted with permission from AAAS."
4. All required credit lines and notices must be visible any time a user accesses any part of the AAAS material and must appear on any printed copies that an authorized user might make.
5. The AAAS material may not be modified or altered, with the exception that figures and tables may be modified with permission from the author. Author permission for any such changes must be secured prior to your use.

USC
UNIVERSIDADE
DE SANTIAGO
DE COMPOSTELA

CAMPUS VIDA
CAMPUS DE EXCELENCIA INTERNACIONAL

Catalysis is a powerful tool for the synthesis of a wide variety of compounds. A catalyst allows to increase the rate in which a chemical reaction reaches the equilibrium without being consumed in the process.

Common transformations have been typically carried out under homogeneous catalysis. However, the catalyst is difficult to recover after the reaction. In this context the development of new recyclable heterogeneous catalysts is of high value.

On this field, MOFs have emerged as powerful catalysts that can combine the advantages of both homogeneous and heterogeneous catalysts.

This thesis presents the principal results obtained in the investigation of the applications of a novel bimetallic framework based on iron clusters and a palladium metalloligand in different palladium catalyzed reactions.