

Article

# Nickel-imidazolium low transition temperature mixtures with Lewis-acidic character

Mario Martos <sup>1</sup>, and Isidro M. Pastor <sup>1,\*</sup>

<sup>1</sup> Organic Chemistry Department and Institute of Organic Synthesis (ISO), University of Alicante, ctra. San Vicente del Raspeig s/n, 03690, San Vicente del Raspeig, Alicante, Spain

\* Correspondence: ipastor@ua.es; Tel.: (+34)965903728

## Supplementary Information

### Contents

Sustainability metrics.....	2
Differential Scanning Calorimetry traces.....	9
XPS analyses .....	12
NMR spectra .....	14
Miscellaneous images .....	26

## Sustainability metrics

### Equations and general considerations

The sustainability metrics used (E-factor, yield, stoichiometric factor, atom economy, Andraos' reaction mass efficiency, materials recovery parameter) were calculated with equations 1-6:

$$E\text{-factor} = \frac{\sum \text{Mass of components} - \text{Mass of product}}{\text{Mass of product}} \quad (S1)$$

$$Y = \frac{\text{Mass of product obtained}}{\text{Theoretical mass of product}} \cdot 100 \quad (S2)$$

$$AE = \frac{MW_{\text{Prod}}}{\sum (S_{\text{Reactants}} \cdot MW_{\text{Reactants}})} \cdot 100 \quad (S3)$$

$$SF = \frac{\text{Mass of product}}{\text{Mass of stoichiometric reagents}} \cdot 100 \quad (S4)$$

$$RME_{\text{Andraos}} = \frac{\text{Mass of product}}{\sum \text{Mass of components} - \sum \text{Mass recovered}} \cdot 100 \quad (S5)$$

$$MRP = \frac{1}{(1 + (\frac{\text{Mass of product}}{\sum \text{Mass of reagents}} \cdot 100) \cdot E_{\text{Aux}})} \cdot 100 \quad (S6)$$

The Y, AE, SF,  $RME_{\text{Andraos}}$  and MRP values were combined into a vector magnitude ratio (VMR) using equation 7:

$$VMR = \frac{1}{\sqrt{5}} \sqrt{(Y)^2 + (AE)^2 + (RME)^2 + \left(\frac{1}{SF}\right)^2 + (MRP)^2} \quad (S7)$$

The EcoScale score was obtained using the tool developed by the authors, available at <http://ecoscale.cheminfo.org/calculator> (last accessed July 24th 2023)

Some additional considerations and standard values applied to the calculations are compiled in Table S1.

**Table S1.** Standard values for the calculation of sustainability metrics on protocols with missing data.

Parameter	Value
Solvent recovery (reaction, work-up)	80% of the initial mass if not requiring fractional distillation
Water and saturated sodium chloride for work-up	Equal volume to the first fraction of organic solvent used
Work-up reported but not specified	3x10 mL/mmol of ethyl acetate and 10 mL/mmol of saturated sodium chloride
Drying agents	1/5 <sup>th</sup> of the total mass of organic solvent

## Full metrics of the comparison of Table 2

**Table S2.** Sustainability metrics for the synthesis of 1. Entries correlate with those of Table 2.

Entry	Yield	1/SF	AE	RME	MRP	E-factor	EcoScale
1	0.99	1	0.945	0.201	0.212	3.98	79
2	0.99	1	0.945	0.345	0.369	1.90	89
3	0.88	0.735	0.945	0.054	0.087	17.59	70
4	0.96	0.847	0.945	0.422	0.549	1.37	77
5	0.95	1	0.945	0.01	0.012	94.82	79
6	0.96	1	0.945	0.003	0.003	360.36	69

Purification by chromatography omitted for RME, MRP and E-factor in entries 3 to 6.

Actual Mass of Reagents	0,0817 g	Parameter	Actual	Ideal Limit
Stoichiometric Mass of Reagents	0,08 g	AE	0,945	1
Stoichiometric Factor	1,001097309	Rxn Yield	0,998	1
Materials Recovery Parameter	0,212926766	1/SF	0,999	1
		MRP	0,212926766	1
		RME	0,201	1
<i>Raw E-factor profile</i>				
E-kernel	0,05987595			
E-excess	0,001163011	VMR	0,771141135	
E-rxn solvent	0	(vector magnitude ratio)		
E-catalyst	0,064935065			
E-work-up	0			
E-purification	12,36363636			
	E-aux			
	12,43			
E-total	12,48961039			
<b>Corrected E-factor</b>	<b>3,983</b>			
Yield	99,8 %			
AE	94,5 %			
PMI	4,983			
RME (global)	20,1 %			

**Figure S1.** Sustainability metrics for the synthesis of 1 (Table 2, entry 1).

Reagents

☒ Link

	identifier*	name	MF*	MW	density	purity*	ml	g	mmoles	equiv.
1	<input type="text"/>	1,3-Diphenyl-2-propen-1-ol	C15H14O	210.27556		100%	0	0.052569	0.25	1
2	<input type="text"/>	Indole	C8H7N	117.15028	1.22	100%	0.024007	0.029288	0.25	1
3	<input type="text"/>	Nickel(II) chloride hexahydrate	Cl2Ni · 6H2O	237.68768		100%	0	0.0029	0.0122008847	0.0488035391
4	<input type="text"/>	mcmimCl	C7H11ClN2O2	190.6270		100%	0	0.0024	0.0125900318	0.0503601273

Products

identifier*	name	MF*	MW	g	mmoles	g theor.	yield
	Product 1	C23H19N	309.4	0.077	0.2488687782	0.07735	99.5475

Conditions

Reagents	Name	mmoles	eq.	Bp	Hazard	Price
	1,3-Diphenyl-2-propen-1-ol	3.24	1			
	Indole	3.24	1	253		
	Nickel(II) chloride hexahydrate	0.15	0.04			
	mcmimCl	0.16	0.05			

Yield

100

Price / availability

-8

Safety

-10

Technical setup

Possible items

Common set-up

Instruments for controlled addition of chemicals

Unconventional activation technique

Selected items

Common set-up

Temperature / time

Possible items

Heating, > 1h

Cooling, > 0°C

Cooling, < 0°C

Selected items

Heating, > 1h

Workup and purification

Possible items

Adding solvent

Simple filtration

Removal of solvent with bp < 150°C

Selected items

Adding solvent

Simple filtration

Removal of solvent with bp < 150°C

EcoScale

79

**Figure S2.** EcoScale for the synthesis of 1 (Table 2, entry 1).

Actual Mass of Reagents	1,65	g	Parameter	Actual	Ideal Limit
Stoichiometric Mass of Reagents	1,65	g	AE	0,945	1
Stoichiometric Factor	1,000619636		Rxn Yield	0,988	1
Materials Recovery Parameter	0,369127517		1/SF	0,999	1
<i>Raw E-factor profile</i>			MRP	0,369127517	1
E-kernel	0,070765086		RME	0,345	1
E-excess	0,000663485		VMR	0,790368533	
E-rxn solvent	0		(vector magnitude ratio)		
E-catalyst	0,071428571				
E-work-up	0				
E-purification	6,506493506				
E-aux	6,58				
E-total	6,649350649				
<b>Corrected E-factor</b>	<b>1,903</b>				
Yield	98,8	%			
AE	94,5	%			
PMI	2,903				
RME (global)	34,5	%			

Figure S3. Sustainability metrics for the synthesis of 1 (Table 2, entry 2).

Reagents										
Link	identifier*	name	MF*	MW	density	purity*	ml	g	mmoles	equiv.
1		1,3-Diphenyl-2-propen-1-ol	C15H14O	210.27556		100%	0	1.051378	5	1
2		Indole	C8H7N	117.15028	1.22	100%	0.480124	0.585751	5	1
3		bcmimCl	C7H9ClN2O4	220.61		100%	0	0.110305	0.5	0.1

Products							
identifier*	name	MF*	MW	g	mmoles	g theor	yield
	C23H19N	C23H19N	309.4120	1.54	4.9771825268	1.54706	99.5437

Conditions						
Reagents	Name	mmoles	eq.	Bp	Hazard	Price
	1,3-Diphenyl-2-propen-1-ol	3.24	1			
	Indole	3.24	1	253		
	bcmimCl	0.32	0.1			

Yield	100		
Price / availability		-8	
Safety		0	
Technical setup	Possible items Any additional special glassware (Inert) gas atmosphere Glove box	Selected items Common set-up	0
Temperature / time	Possible items Room temperature, < 1h Room temperature, < 24h Heating, < 1h	Selected items Heating, > 1h	-3
Workup and purification	Possible items Simple titration Removal of solvent with bp < 150°C Crystallization and filtration	Selected items Adding solvent Simple filtration Removal of solvent with bp < 150°C	0

EcoScale	
	89

Figure S4. EcoScale for the synthesis of 1 (Table 2, entry 2).

Actual Mass of Reagents	0,222	g	Parameter	Actual	Ideal Limit
Stoichiometric Mass of Reagents	0,16	g	AE	0,945	1
Stoichiometric Factor	1,357799942		Rxn Yield	0,887	1
Materials Recovery Parameter	0,087127159		1/SF	0,736	1
<i>Raw E-factor profile</i>			MRP	0,087127159	1
E-kernel	0,193429095		RME	0,054	1
E-excess	0,427008861		VMR	0,668150897	
E-rxn solvent	7,299270073		(vector magnitude ratio)		
E-catalyst	0,102189781				
E-work-up	46,80291971				
E-purification	0				
E-aux	54,20				
E-total	54,82481752				
Corrected E-factor	17,599				
Yield	88,7	%			
AE	94,5	%			
PMI	18,599				
RME (global)	5,4	%			

Figure S5. Sustainability metrics for the synthesis of 1 (Table 2, entry 3).

Reagents

☒ Link

	identifier*	name	MF*	MW	density	purity*	ml	g	mmoles	equiv.
1	<input type="text"/>	1,3-Diphenyl-2-propen-1-ol	C15H14O	210.2756		100%	0	0.105138	0.5000000000	1
2	<input type="text"/>	Indole	C8H7N	117.15028	1.22	100%	0.096025	0.11715	1.0000000000	2
3	<input type="text"/>	Iron(III) chloride hexahydrate	H12O6Cl3Fe	270.29768		100%	0	0.013515	0.0500000000	0.1
4	<input type="text"/>	Water	H2O	18.01528	1	100%	10	10	555.08435061	1110.1687012

Products

identifier\*

name

MF\*

MW

g

mmoles

g theor

yield

C23H19N

C23H19N

309.412

0.137

0.4427753286

0.154706

88.5551

Conditions

Reagents	Name	mmoles	eq.	Bp	Hazard	Price
	1,3-Diphenyl-2-propen-1-ol	3.64	1			
	Indole	7.29	2	253		
	Iron(III) chloride hexahydrate	0.36	0.1			
	Water	4051.71	1110.16			

Yield

-6

Price / availability

-8

Safety

0

Technical setup

Possible items

Any additional special glassware (Inert) gas atmosphere

Glove box

Selected items

Common set-up

Temperature / time

Possible items

Heating, > 1h

Cooling to 0°C

Cooling, < 0°C

Selected items

Heating, > 1h

Workup and purification

Possible items

Simple filtration

Removal of solvent with bp < 150°C

Crystallization and filtration

Selected items

Liquid - liquid extraction or washing

Classical chromatography

Removal of solvent with bp < 150°C

EcoScale

Figure S6. EcoScale for the synthesis of 1 (Table 2, entry 3).

Actual Mass of Reagents	0,193	g	Parameter	Actual	Ideal Limit
Stoichiometric Mass of Reagents	0,16	g	AE	0,945	1
Stoichiometric Factor	1,18042968		Rxn Yield	0,958	1
Materials Recovery Parameter	0,54985755		1/SF	0,847	1
<i>Raw E-factor profile</i>			MRP	0,54985755	1
E-kernel	0,104728284		RME	0,422	1
E-excess	0,19932577		VMR	0,77567565	
E-rxn solvent	5,391891892		(vector magnitude ratio)		
E-catalyst	0				
E-work-up	0				
E-purification	0				
E-aux	5,39				
E-total	5,695945946				
<b>Corrected E-factor</b>	<b>1,372</b>				
Yield	95,8	%			
AE	94,5	%			
PMI	2,372				
RME (global)	42,2	%			

Figure S7. Sustainability metrics for the synthesis of 1 (Table 2, entry 4).

Reagents										
Link	identifier*	name	MF*	MW	density	purity*	ml	g	mmoles	equiv.
1		1,3-Diphenyl-2-propen-1-ol	C15H14O	210.27566		100%	0	0.105138	0.5	1
2		Indole	C8H7N	117.15028	1.22	100%	0.072019	0.087863	0.75	1.5
3		1,1,1,3,3,3-Hexafluoro-2-propanol	C3H2F6O	168.038698	1.596	100%	0.5	0.798	4.7489061120	9.4978122241
Products										
	identifier*	name	MF*	MW	g	mmoles	g theor.	yield		
		C23H19N	C23H19N	309.421	0.148	0.4783127195	0.154711	95.6622		
Conditions										
Reagents										
Name	mmoles	eq.	Bp	Hazard	Price					
1,3-Diphenyl-2-propen-1-ol	3.37	1								
Indole	5.06	1.5	253							
1,1,1,3,3,3-Hexafluoro-2-propanol	32.08	9.49	59							
Yield	96									
Price / availability										-2
Safety										-8
Technical setup										0
Temperature / time										-3
Workup and purification										-10
EcoScale										77

Figure S8. EcoScale for the synthesis of 1 (Table 2, entry 4).

Actual Mass of Reagents	0,327	g	Parameter	Actual	Ideal Limit
Stoichiometric Mass of Reagents	0,33	g	AE	0,945	1
Stoichiometric Factor	1,000001309		Rxn Yield	0,951	1
Materials Recovery Parameter	0,011607476		1/SF	1,000	1
<i>Raw E-factor profile</i>			MRP	0,011607476	1
E-kernel	0,112243442		RME	0,010	1
E-excess	1,45585E-06		VMR	0,748124397	
E-rxn solvent	4,523809524		(vector magnitude ratio)		
E-catalyst	0,032312925				
E-work-up	90,15306122				
E-purification	0				
	E-aux	94,71			
E-total	94,82142857				
Corrected E-factor	94,821				
Yield	95,1	%			
AE	94,5	%			
PMI	95,821				
RME (global)	1,0	%			

Figure S9. Sustainability metrics for the synthesis of 1 (Table 2, entry 5).

Reagents

☒ Link

	identifier*	name	MF*	MW	density	purity*	ml	g	mmoles	equiv.	
1	<input type="text"/>	1,3-Diphenyl-2-propen-1-ol	C15H14O	210.27556		100%	0	0.210276	1	1	
2	<input type="text"/>	Indole	C8H7N	117.15028	1.22	100%	0.096025	0.11715	1	1	
3	<input type="text"/>	p-Toluenesulfonic acid monohydrate	C7H8O3S · H2O	190.214		100%	0	0.009511	0.05	0.05	
4	<input type="text"/>	Dichloromethane	CH2Cl2	84.93288	1.325	100%	1	1.325	15.600554225	15.600554225	

Products

identifier\*

name

MF\*

MW

g

mmoles

g theor

yield

C23H19N

C23H19N

309.412

0.294

0.9501893914

0.309412

95.0189

Conditions

Reagents

Name	mmoles	eq.	Bp	Hazard	Price
1,3-Diphenyl-2-propen-1-ol	3.4	1			
Indole	3.4	1	253		
p-Toluenesulfonic acid monohydrate	0.17	0.05			
Dichloromethane	53.06	15.6	39		

Yield

95

-2

Price / availability

-3

Safety

0

Technical setup

Possible items

Common set-up

Instruments for controlled addition of chemicals

Unconventional activation technique

Selected items

Common set-up

0

Temperature / time

Possible items

Heating, > 1h

Cooling to 0°C

Cooling, < 0°C

Selected items

Heating, > 1h

-3

Workup and purification

Possible items

None

Cooling to room temperature

Adding solvent

Selected items

Liquid - liquid extraction or washing

Classical chromatography

-13

EcoScale

79

Figure S10. EcoScale for the synthesis of 1 (Table 2, entry 5).

Actual Mass of Reagents	0,0327	g	Parameter	Actual	Ideal Limit
Stoichiometric Mass of Reagents	0,03	g	AE	0,945	1
Stoichiometric Factor	1,000001309		Rxn Yield	0,961	1
Materials Recovery Parameter	0,00304682		1/SF	1,000	1
<i>Raw E-factor profile</i>			MRP	0,00304682	1
E-kernel	0,10100866		RME	0,003	1
E-excess	1,44115E-06		VMR	0,750572138	
E-rxn solvent	8,417508418		(vector magnitude ratio)		
E-catalyst	0				
E-work-up	624,3703704				
E-purification	91,11111111				
E-aux	723,90				
E-total	724				
Corrected E-factor	360,364				
Yield	96,1	%			
AE	94,5	%			
PMI	361,364				
RME (global)	0,3	%			

Figure S11. Sustainability metrics for the synthesis of 1 (Table 2, entry 6).

Reagents										
Link	identifier*	name	MF*	MW	density	purity*	ml	g	mmoles	equiv.
1	+	1,3-Diphenyl-2-propen-1-ol	C15H14O	210.27556		100%	0	0.021028	0.1	1
2	+	Indole	C8H7N	117.15028	1.22	100%	0.009602	0.011715	0.1	1
3	+	DL-Lactic acid	C3H6O3	90.07884		100%	0	0.14	1.5541940815	15.541940815
4	+	Choline chloride	C5H14ClNO	139.62526		100%	0	0.11	0.7878230629	7.878230629

Products							
identifier*	name	MF*	MW	g	mmoles	g theor.	yield
	Product 1	C23H19N	309.4	0.0297	0.0959922430	0.03094	95.992200000

Conditions						
Reagents	Name	mmoles	eq.	Bp	Hazard	Price
	1,3-Diphenyl-2-propen-1-ol	3.36	1			
	Indole	3.36	1	253		
	DL-Lactic acid	52.32	15.54			
	Choline chloride	26.52	7.87			

Yield	96	-2
Price / availability		-13
Safety		0
Technical setup	Possible items Common set-up Instruments for controlled addition of chemicals Unconventional activation technique	Selected items Common set-up 0
Temperature / time	Possible items Heating, > 1h Cooling to 0°C Cooling, < 0°C	Selected items Heating, > 1h -3
Workup and purification	Possible items Sublimation Liquid - liquid extraction or washing Classical chromatography	Selected items Adding solvent Liquid - liquid extraction or washing Classical chromatography -13
EcoScale	69	

Figure S12. EcoScale for the synthesis of 1 (Table 2, entry 6).



## Differential Scanning Calorimetry traces

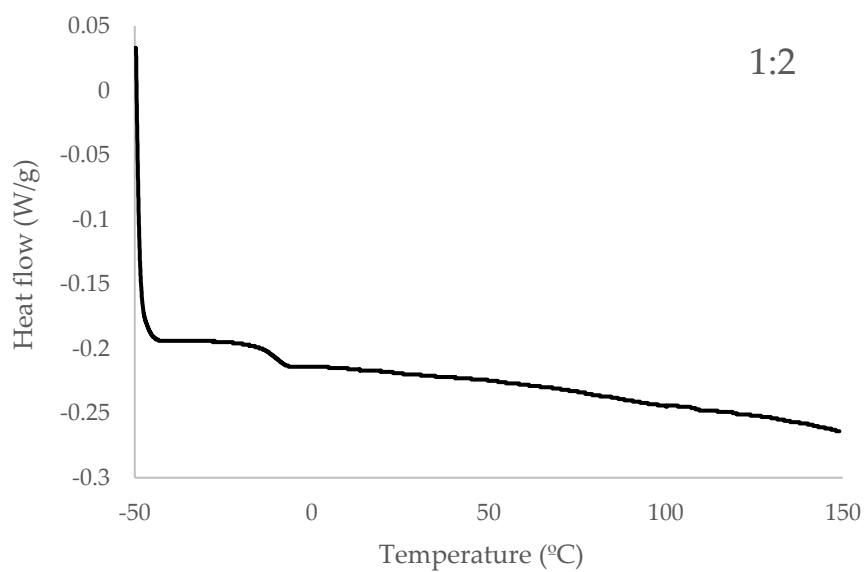


Figure S13. DSC trace of the 1:2 mcmimCl:NiCl<sub>2</sub> mixture (scanning rate 5 °C/min)

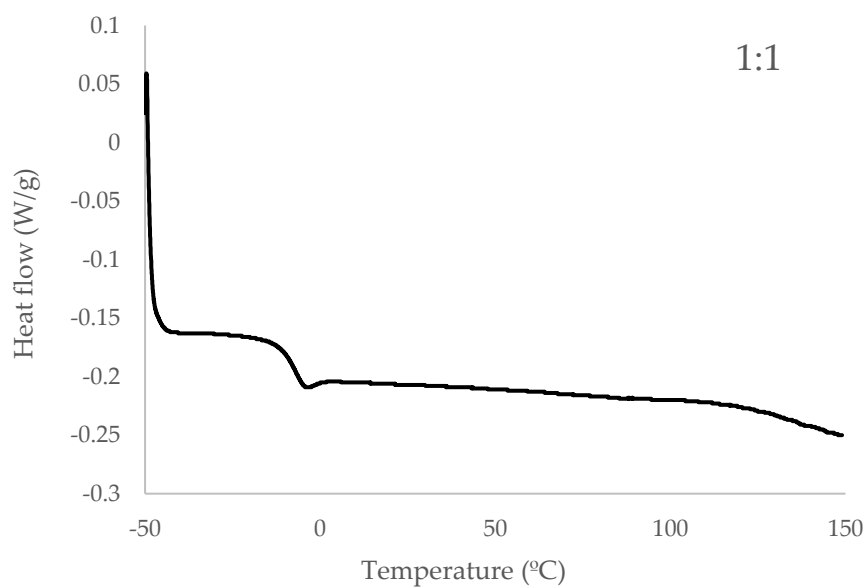


Figure S14. DSC trace of the 1:1 mcmimCl:NiCl<sub>2</sub> mixture (scanning rate 5 °C/min)

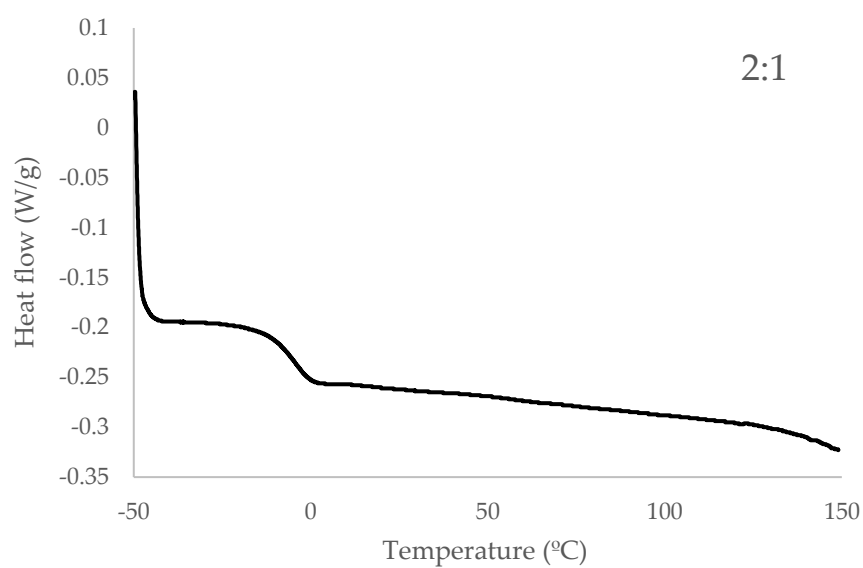


Figure S15. DSC trace of the 2:1 mcmimCl:NiCl<sub>2</sub> mixture (scanning rate 5 °C/min)

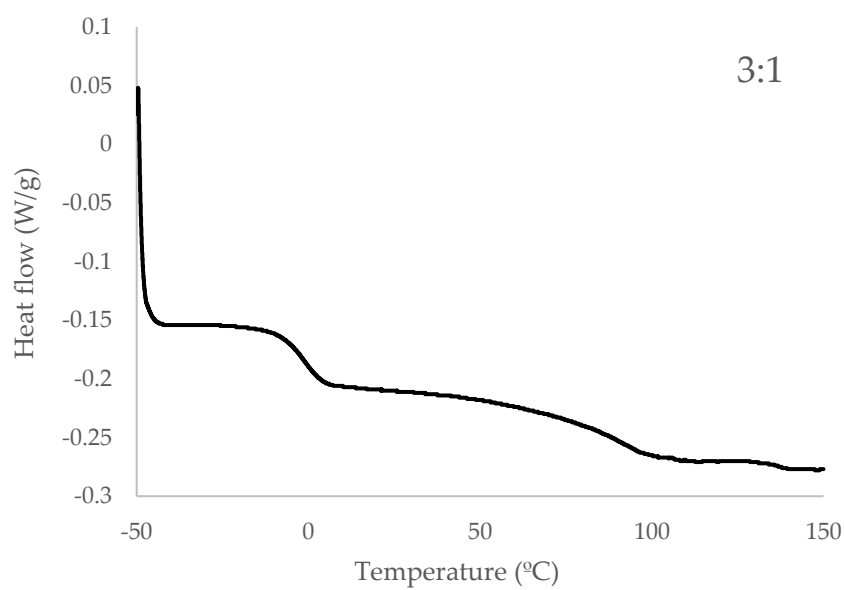


Figure S16. DSC trace of the 3:1 mcmimCl:NiCl<sub>2</sub> mixture (scanning rate 5 °C/min)

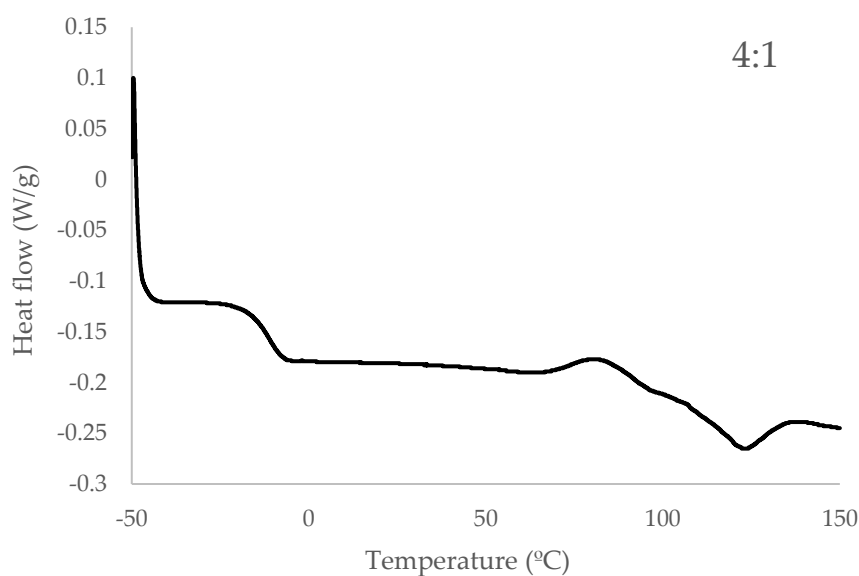


Figure S17. DSC trace of the 4:1 mcmimCl:NiCl<sub>2</sub> mixture (scanning rate 5 °C/min)

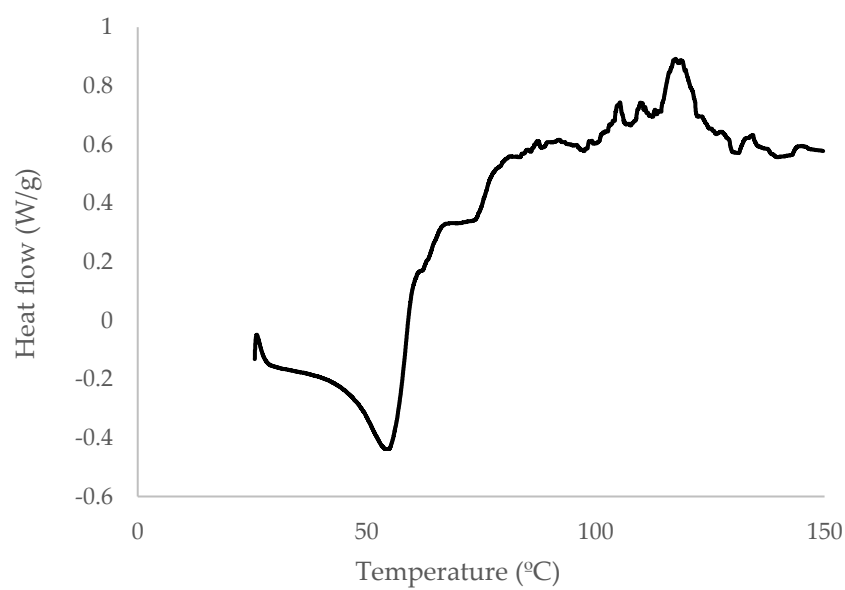


Figure S18. DSC trace of the 1:1 mcmimCl:NiCl<sub>2</sub>·6H<sub>2</sub>O mixture (scanning rate 5 °C/min)

## XPS analyses

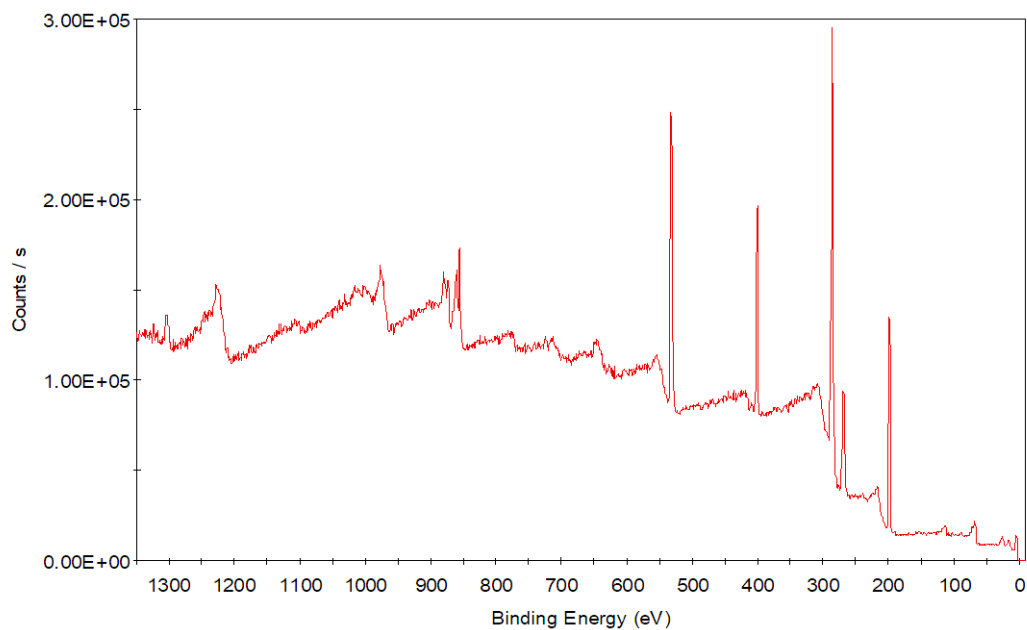


Figure S19. XPS survey of the 2:1 mcmimCl:NiCl<sub>2</sub> mixture

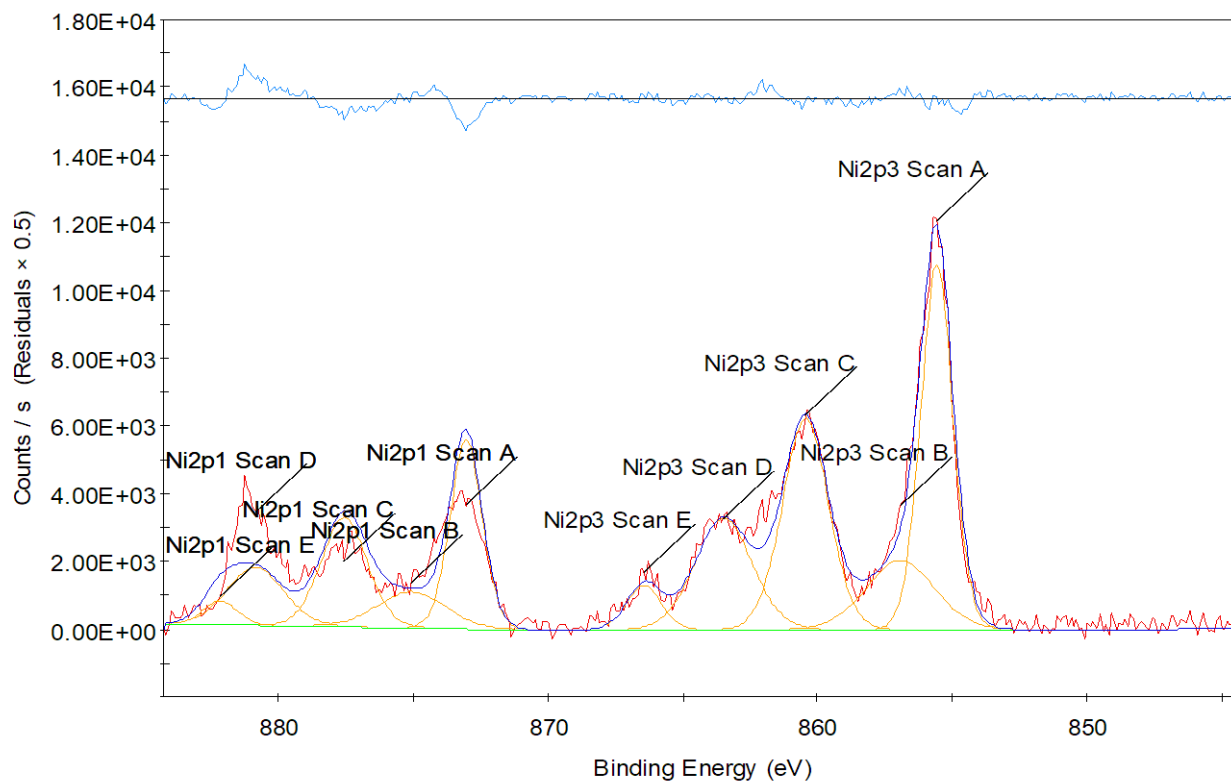


Figure S20. High resolution XPS Ni 2p scan of the 2:1 mcmimCl:NiCl<sub>2</sub> mixture

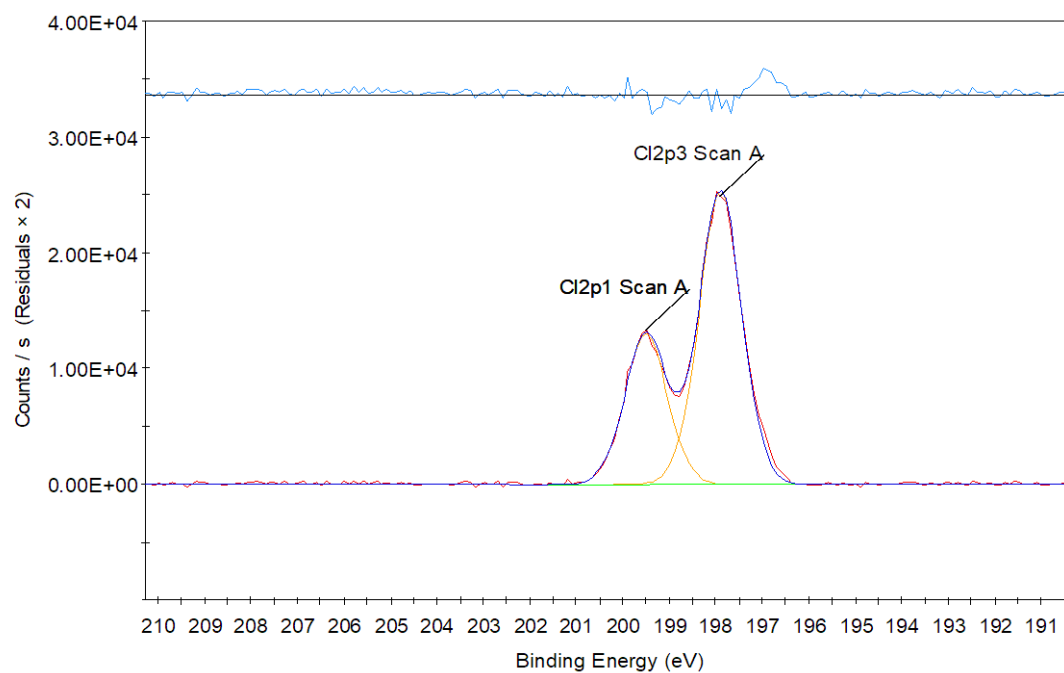


Figure S21. High resolution XPS Cl 2p scan of the 2:1 mcmimCl:NiCl<sub>2</sub> mixture

# NMR spectra

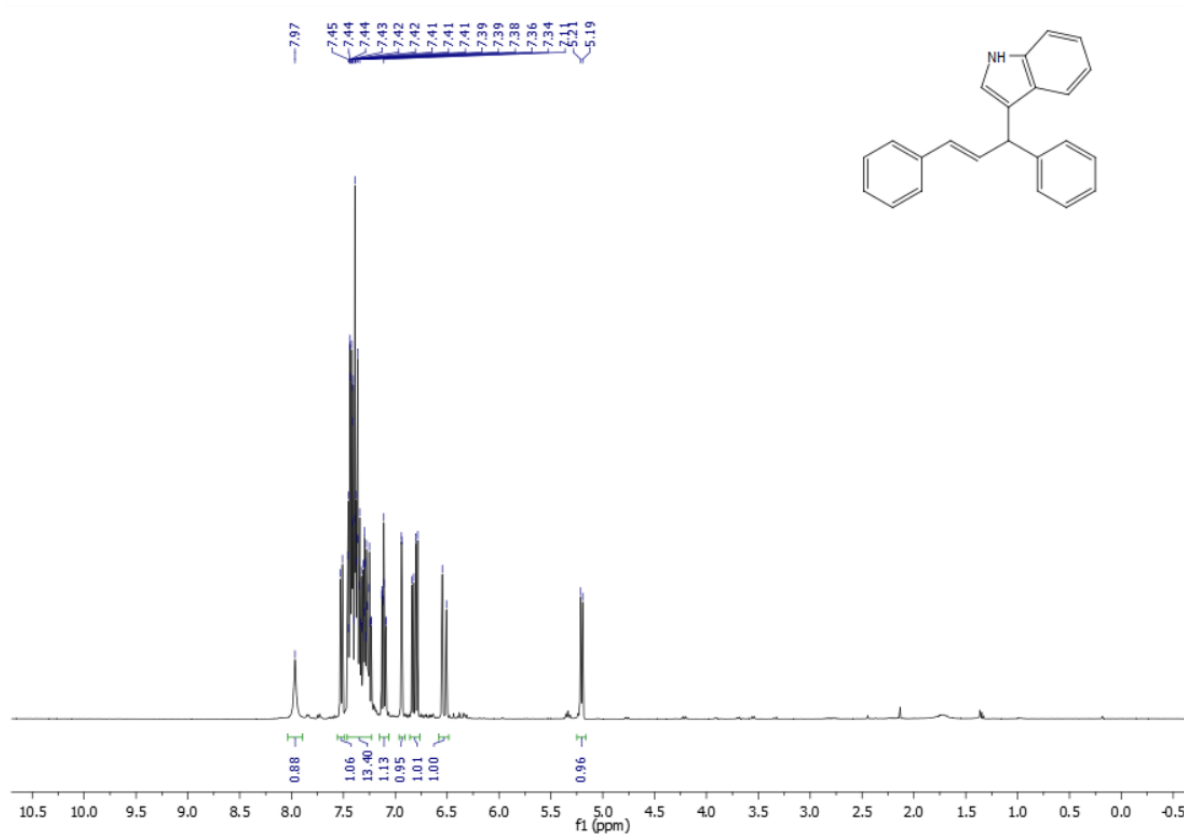


Figure S22. <sup>1</sup>H NMR spectrum of (E)-3-(1,3-diphenylallyl)-1H-indole (1)

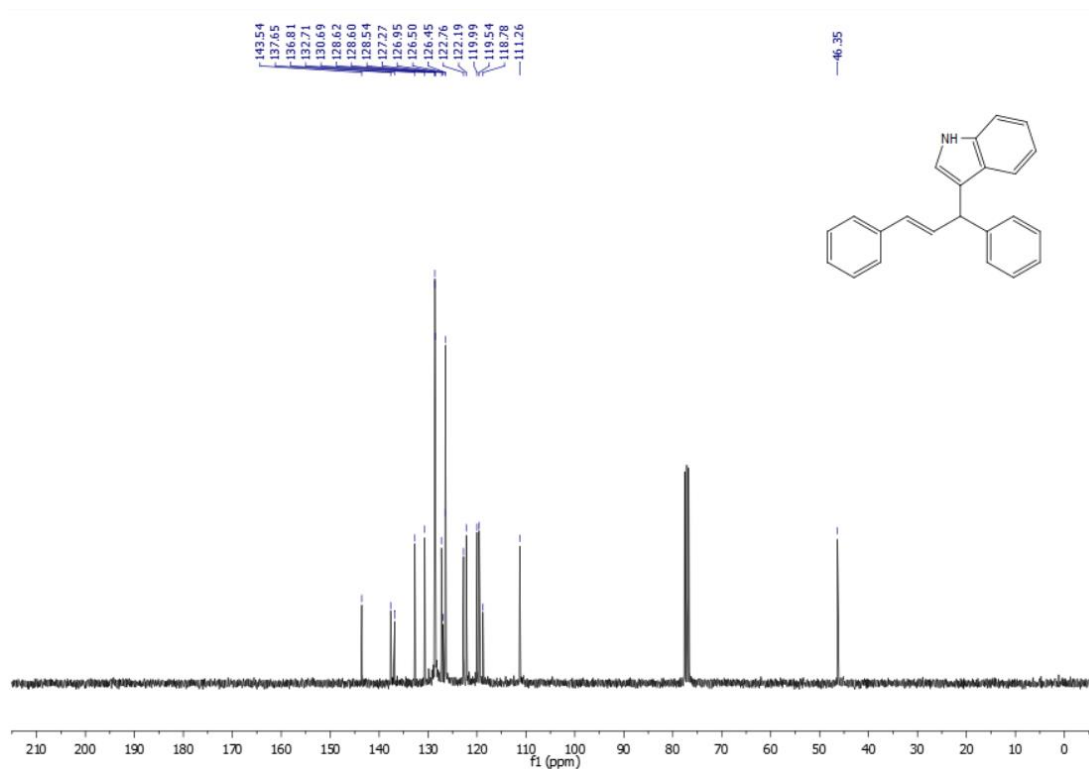


Figure S23. <sup>13</sup>C NMR spectrum of (E)-3-(1,3-diphenylallyl)-1H-indole (1)

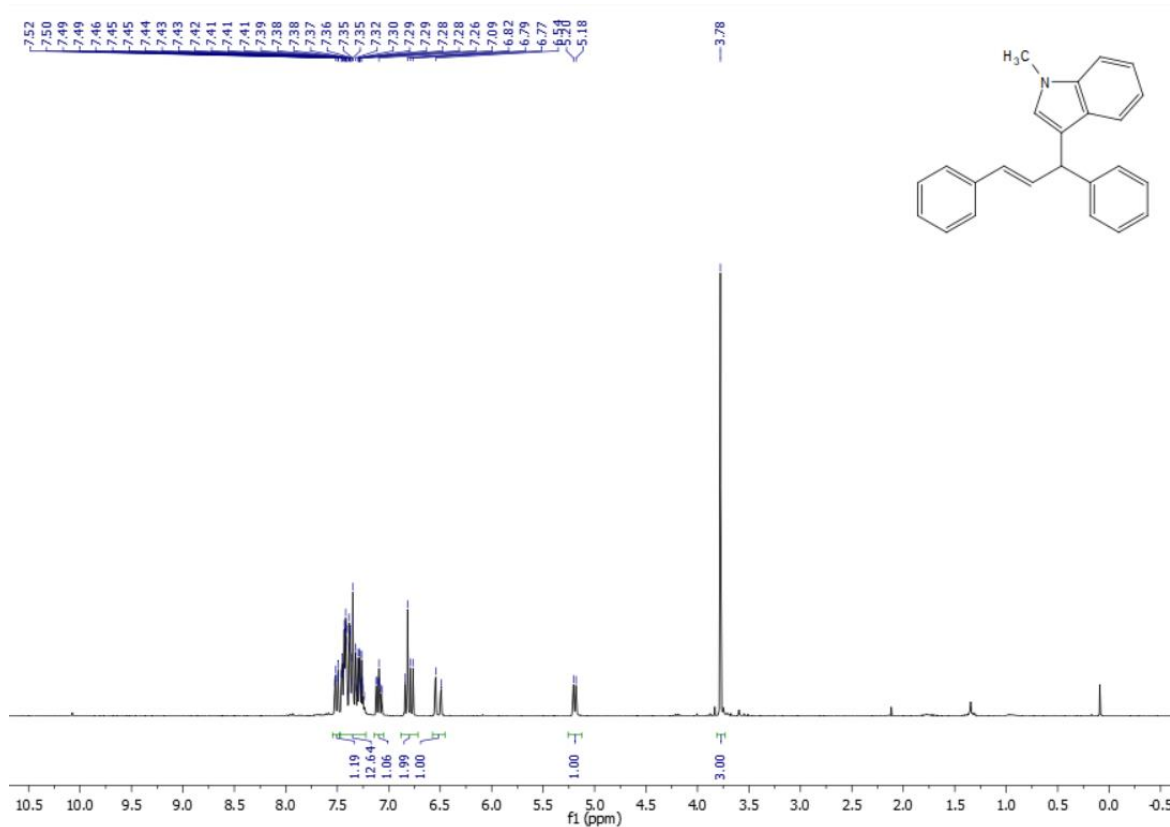


Figure S24. <sup>1</sup>H NMR spectrum of (E)-3-(1,3-diphenylallyl)-1-methyl-1H-indole (2)

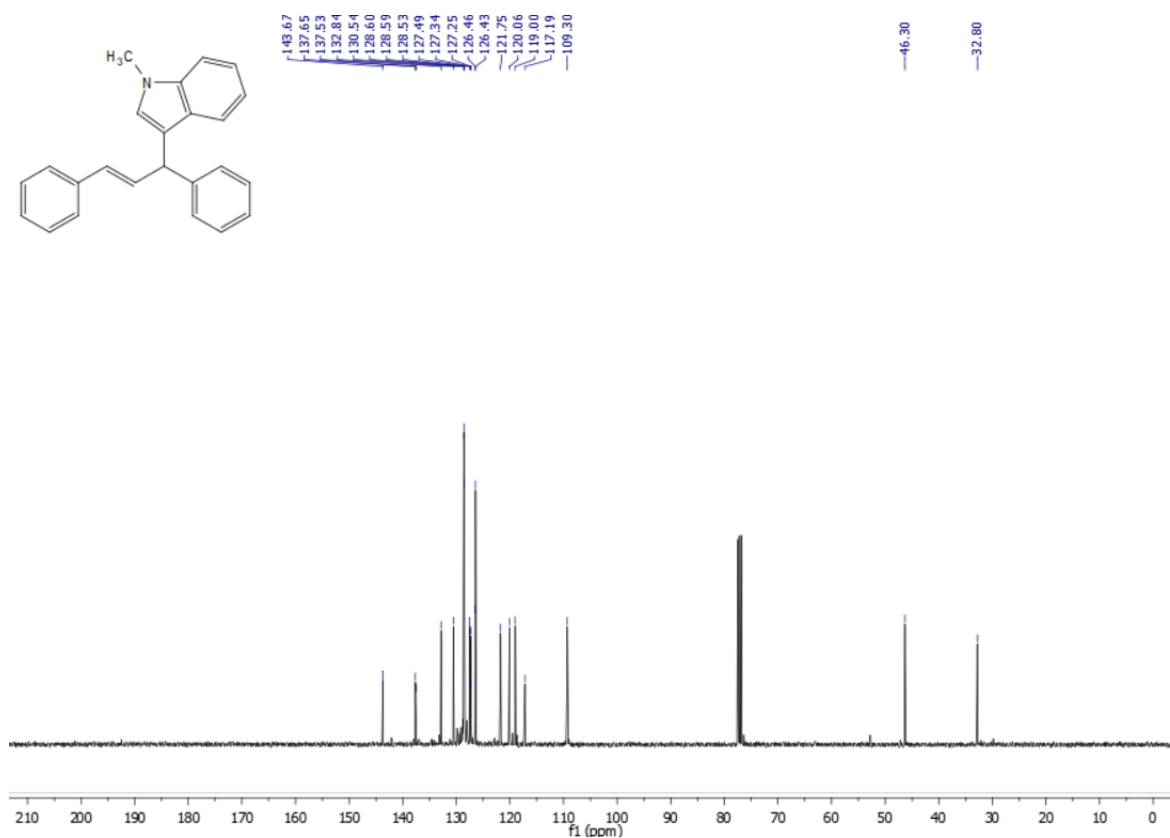


Figure S25. <sup>13</sup>C NMR spectrum of (E)-3-(1,3-diphenylallyl)-1-methyl-1H-indole (2)

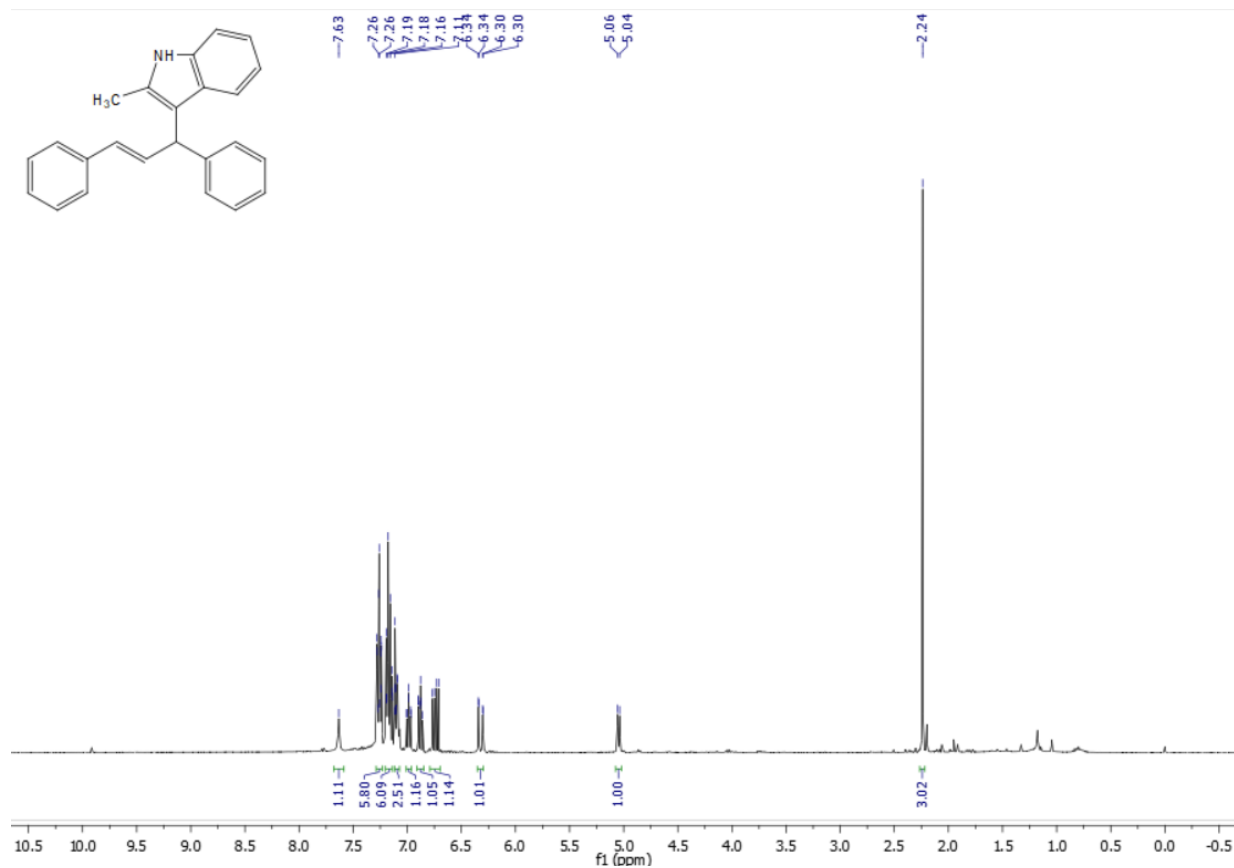


Figure S26. <sup>1</sup>H NMR spectrum of (E)-3-(1,3-diphenylallyl)-2-methyl-1H-indole (3)

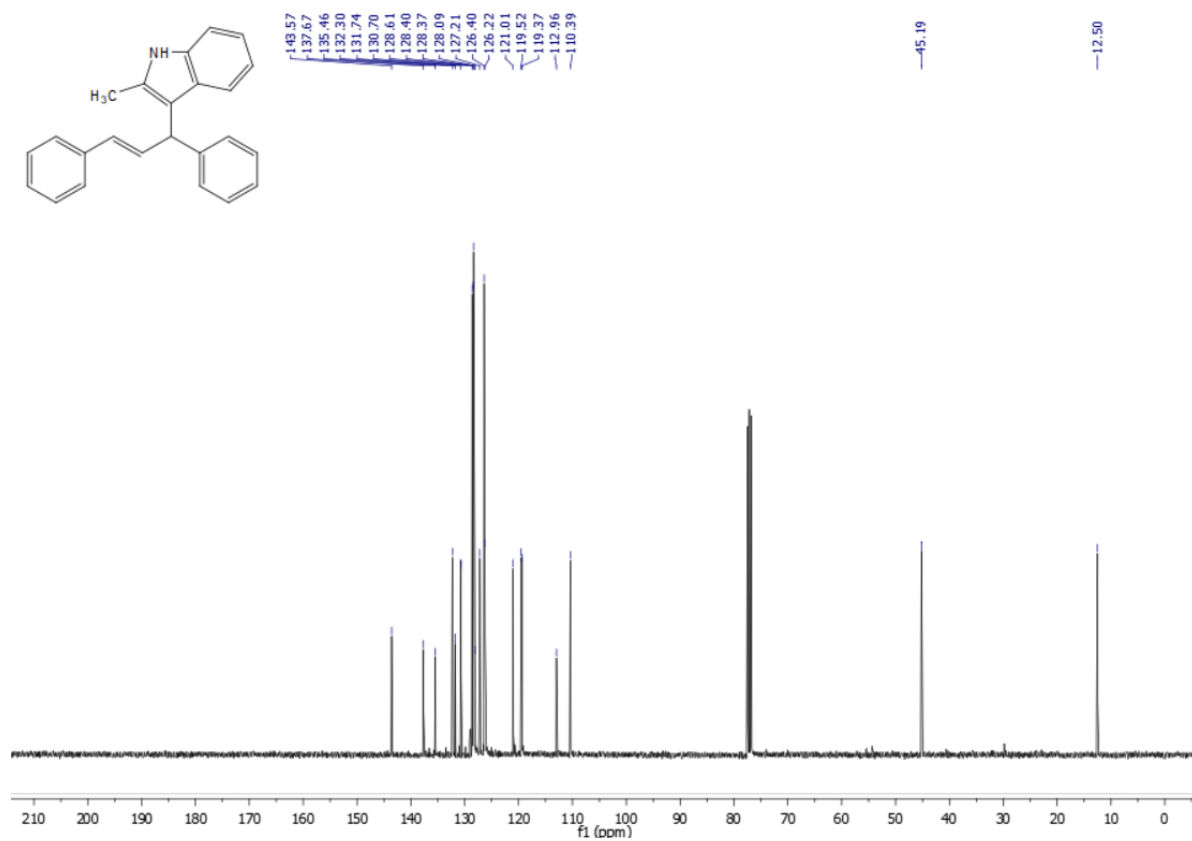


Figure S27. <sup>13</sup>C NMR spectrum of (E)-3-(1,3-diphenylallyl)-2-methyl-1H-indole (3)



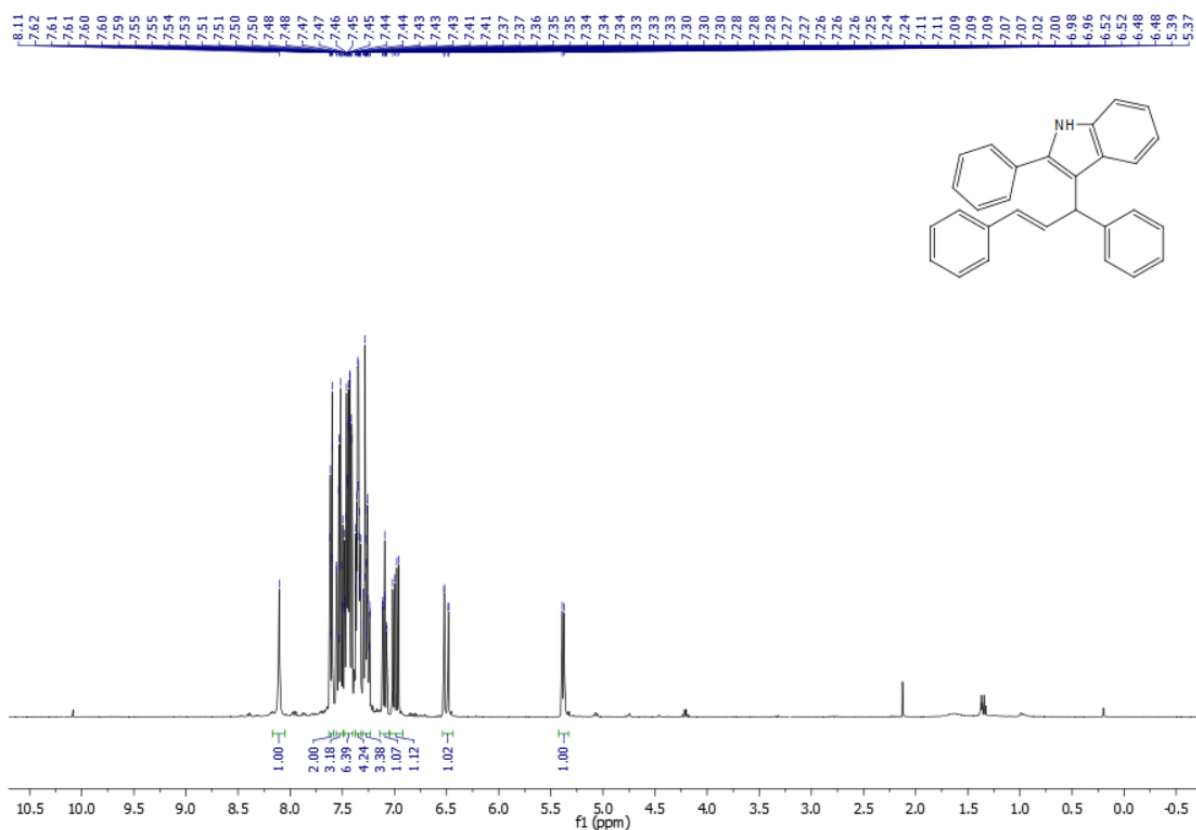


Figure S28. <sup>1</sup>H NMR spectrum of (E)-3-(1,3-diphenylallyl)-2-phenyl-1H-indole (4)

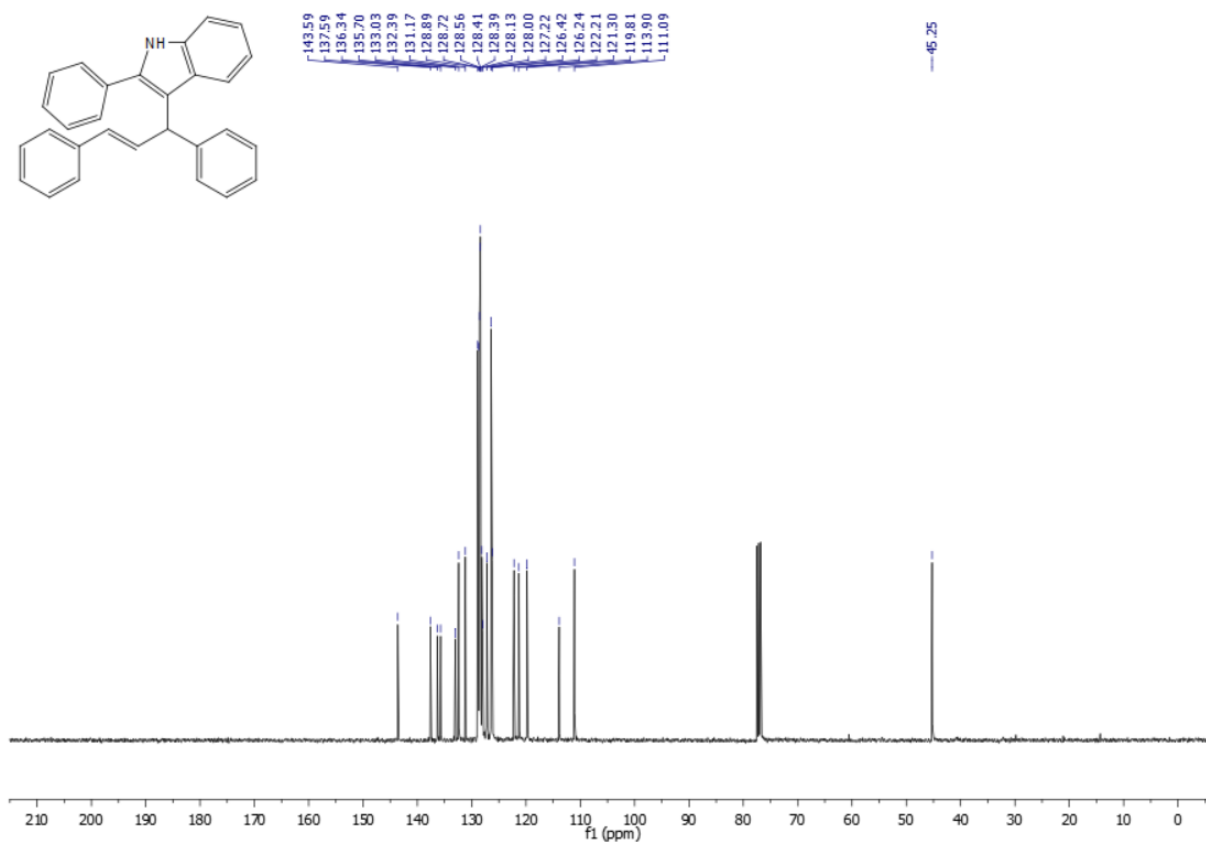
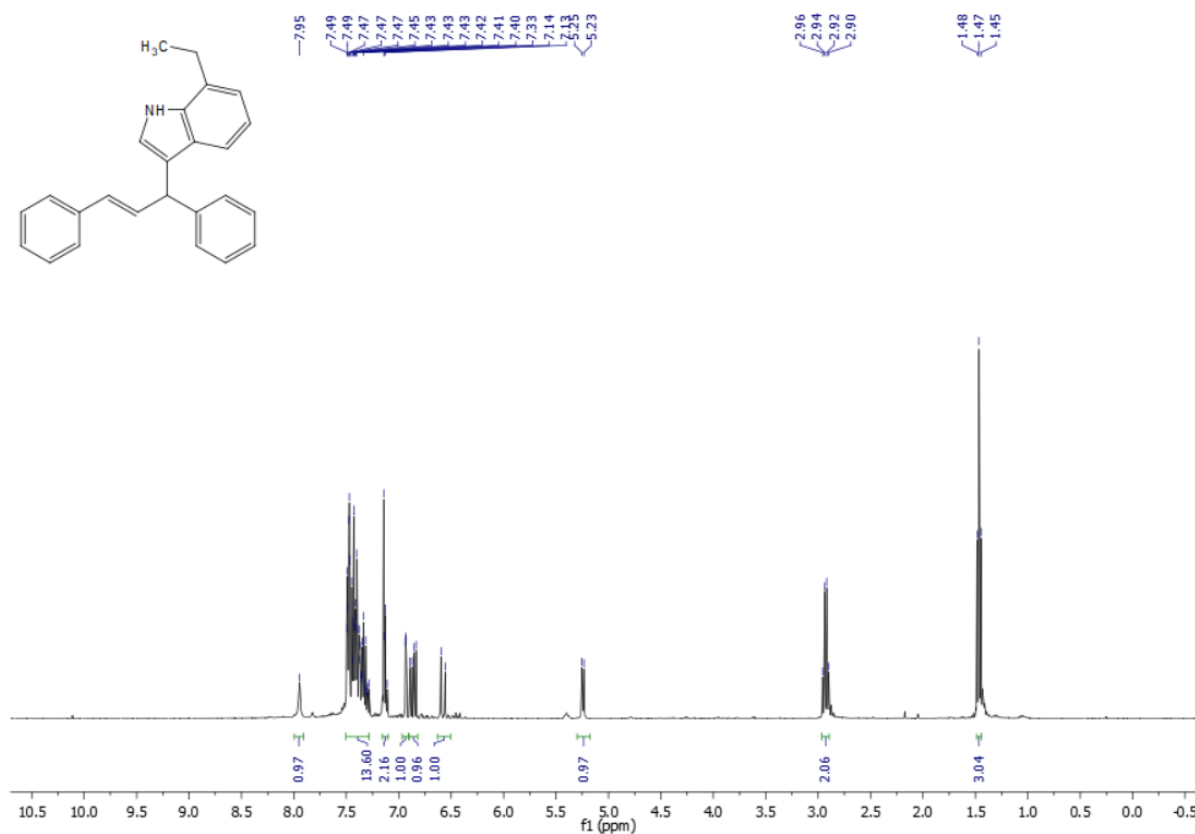


Figure S29. <sup>13</sup>C NMR spectrum of (E)-3-(1,3-diphenylallyl)-2-phenyl-1H-indole (4)



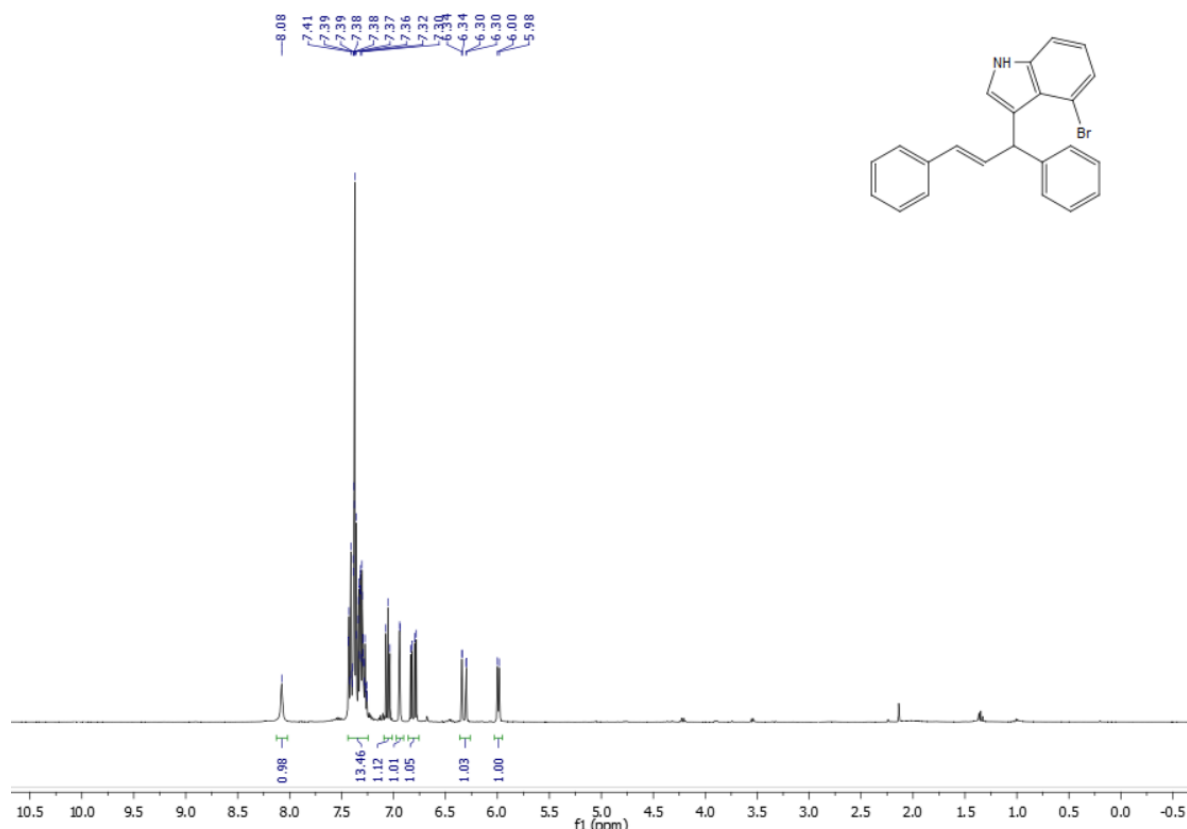


Figure S32. <sup>1</sup>H NMR spectrum of (E)-4-bromo-3-(1,3-diphenylallyl)-1H-indole (6)

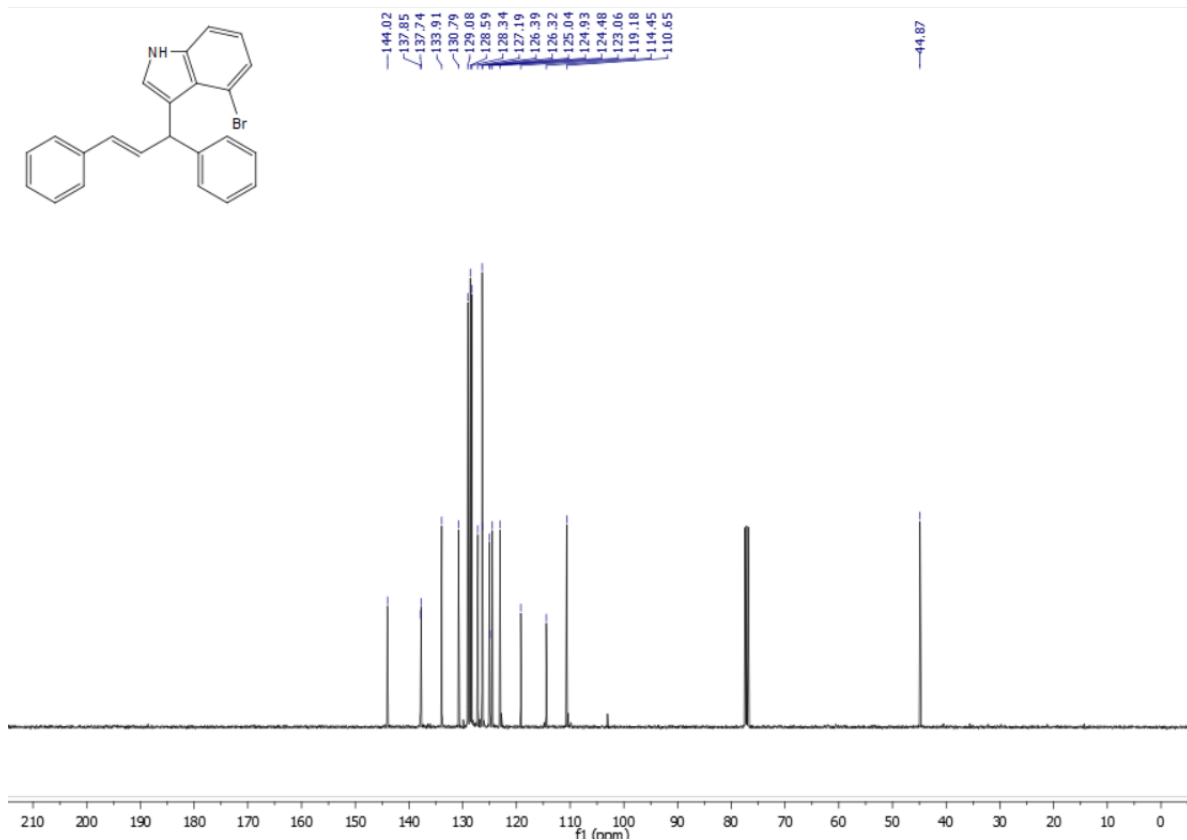


Figure S33. <sup>13</sup>C NMR spectrum of (E)-4-bromo-3-(1,3-diphenylallyl)-1H-indole (6)

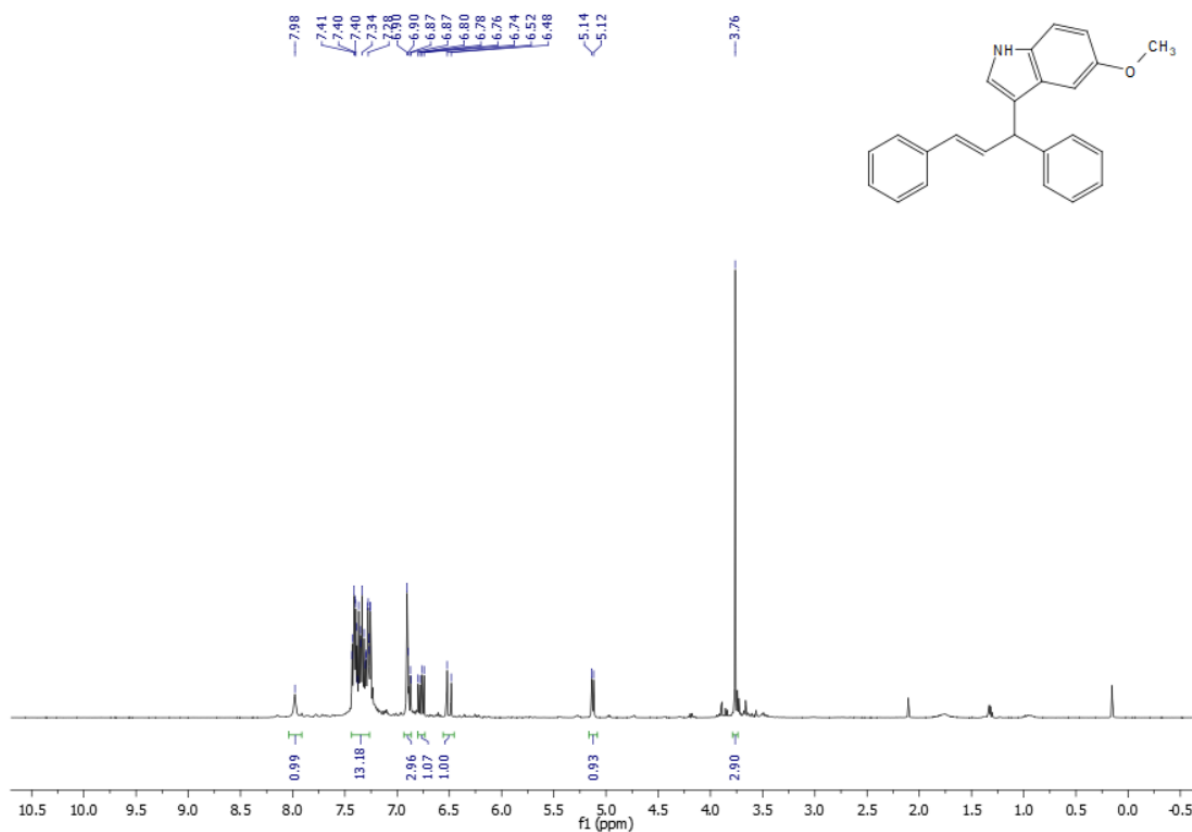


Figure S34. <sup>1</sup>H NMR spectrum of (E)-3-(1,3-diphenylallyl)-5-methoxy-1H-indole (7)

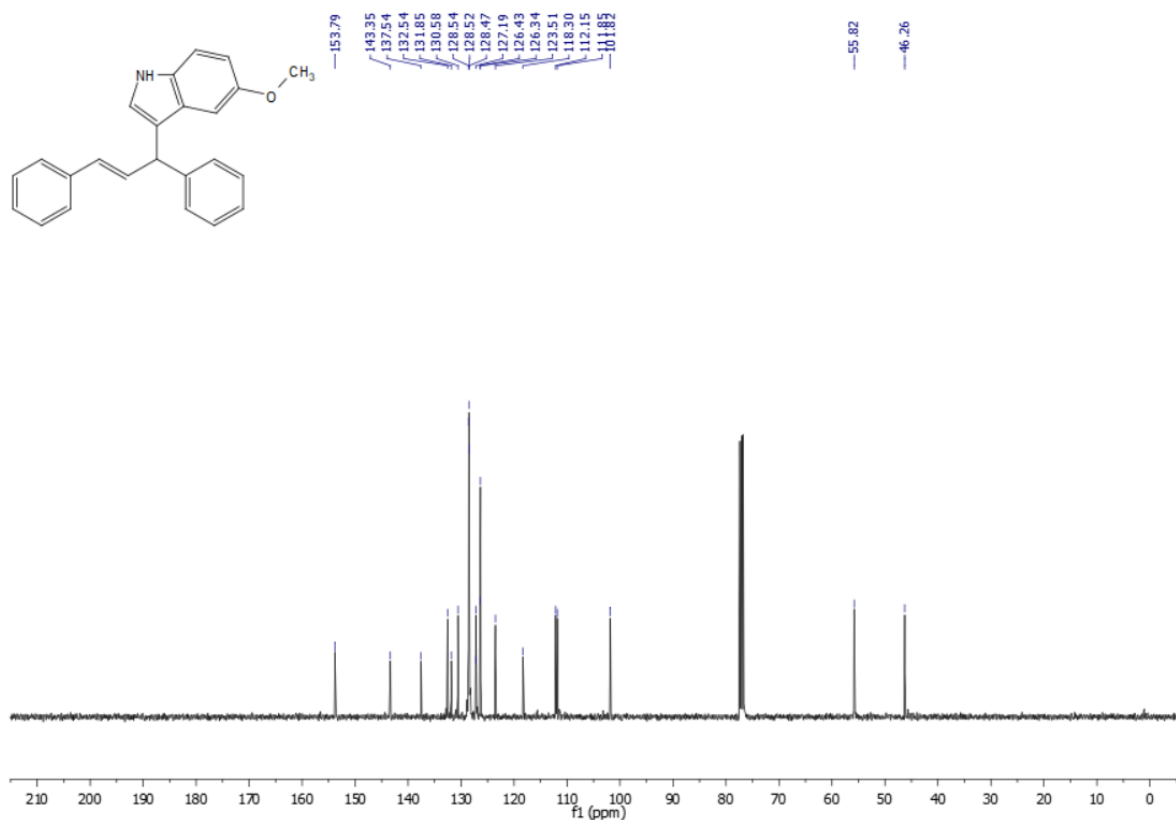


Figure S35. <sup>13</sup>C NMR spectrum of (E)-3-(1,3-diphenylallyl)-5-methoxy-1H-indole (7)

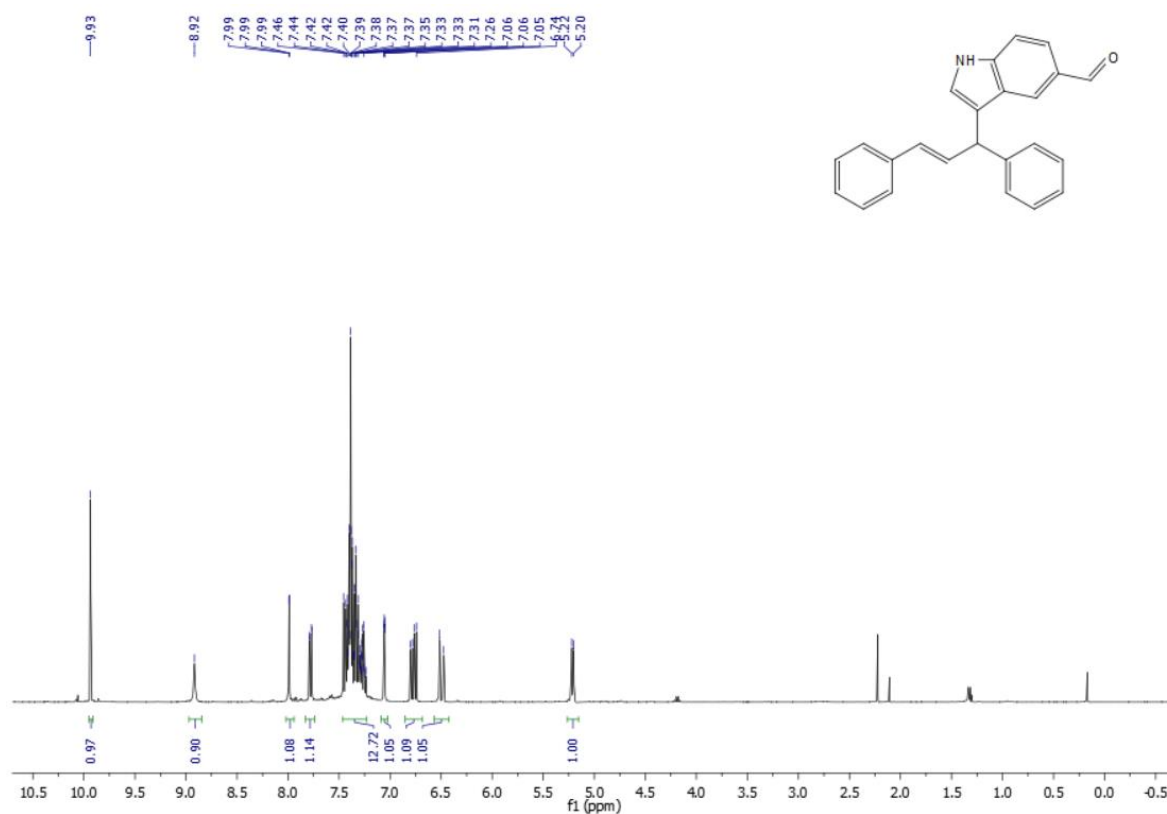


Figure S36. <sup>1</sup>H NMR spectrum of (E)-3-(1,3-diphenylallyl)-5-formyl-1H-indole (8)

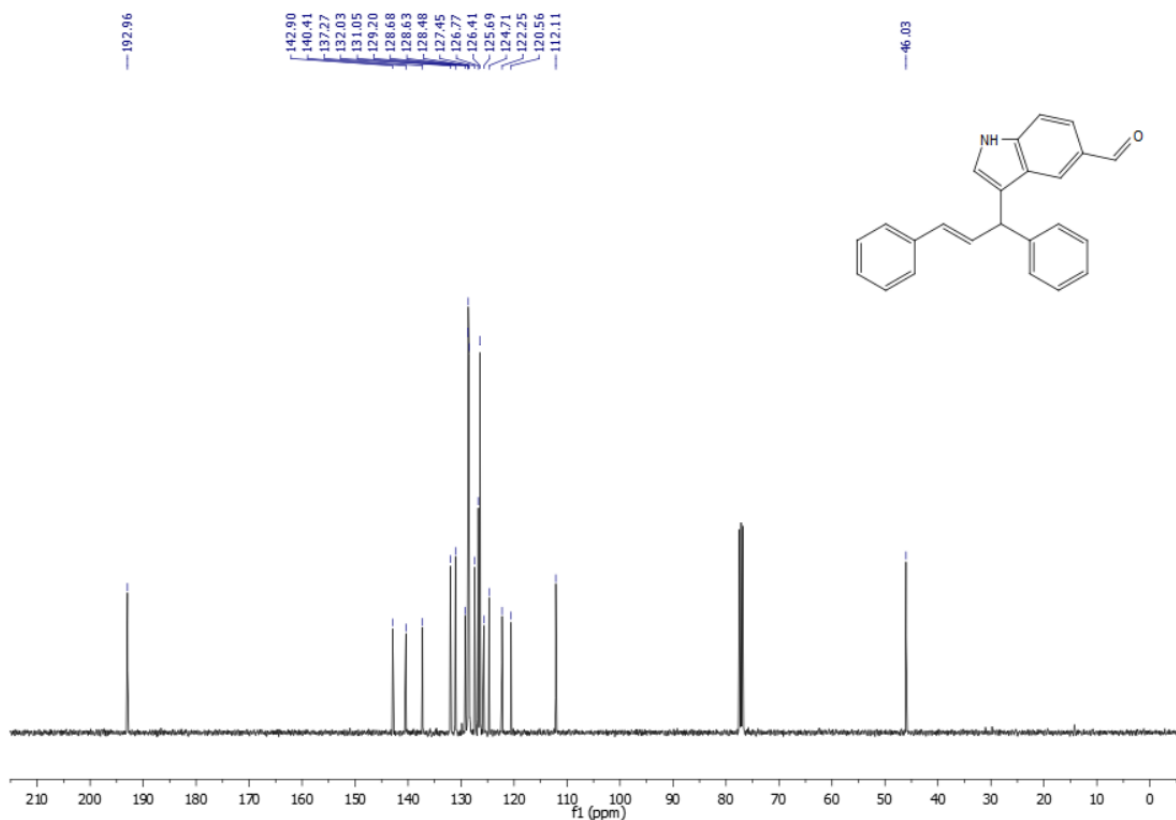


Figure S37. <sup>13</sup>C NMR spectrum of (E)-3-(1,3-diphenylallyl)-5-formyl-1H-indole (8)

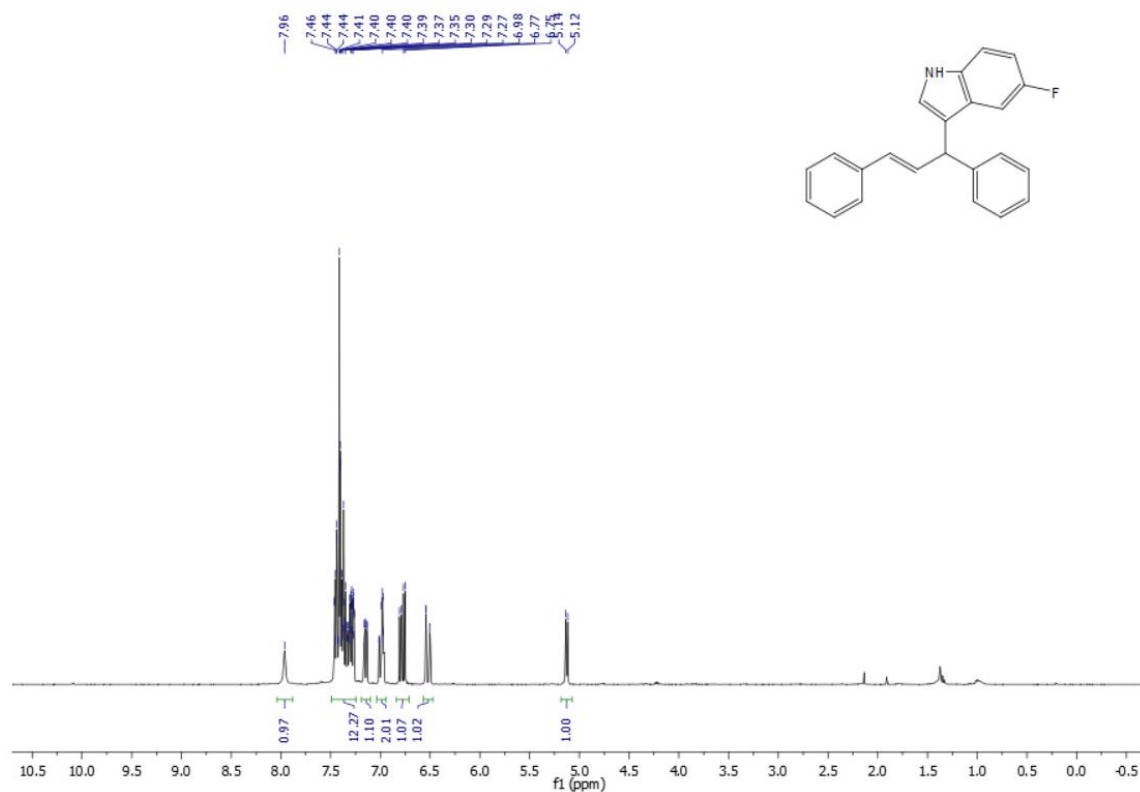


Figure S38. <sup>1</sup>H NMR spectrum of (E)-3-(1,3-diphenylallyl)-5-fluoro-1H-indole (9)

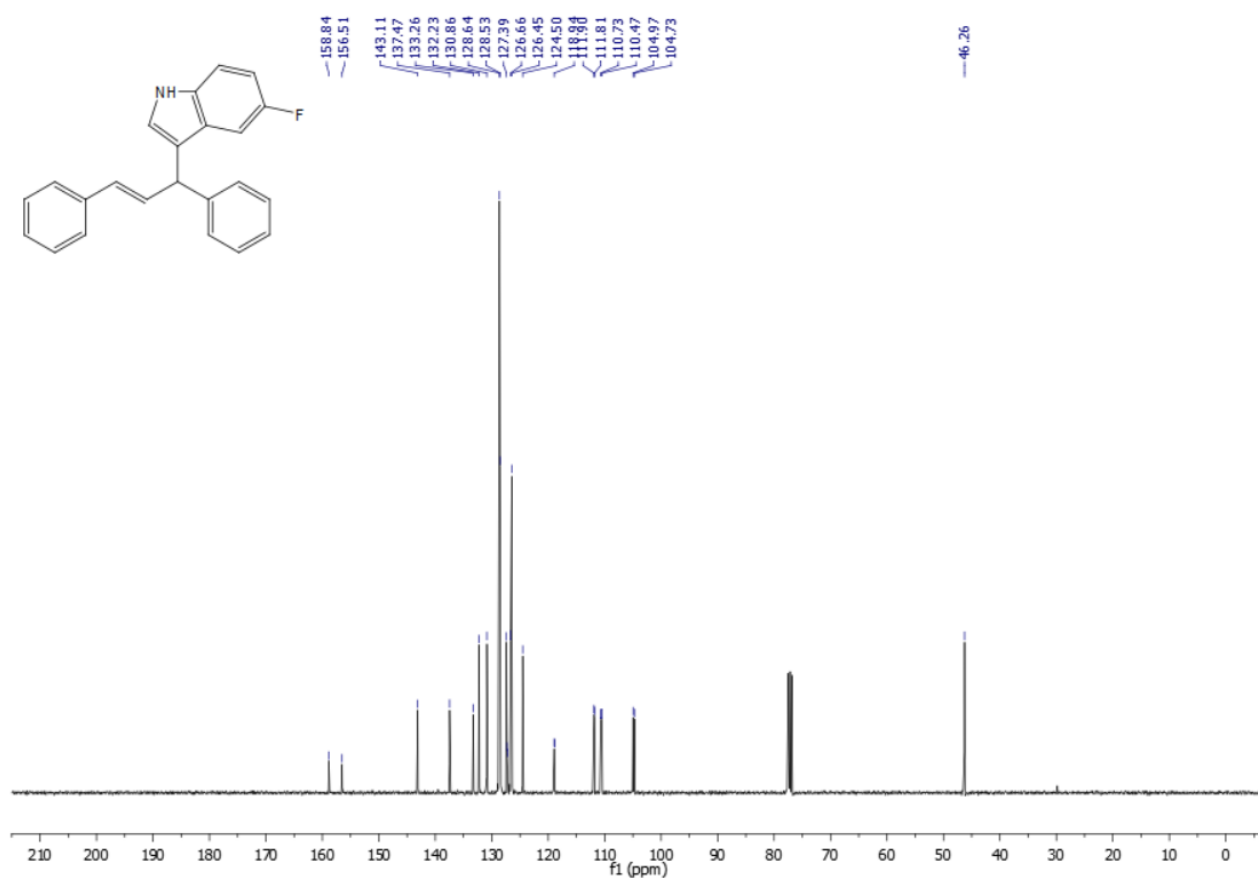


Figure S39. <sup>13</sup>C NMR spectrum of (E)-3-(1,3-diphenylallyl)-5-fluoro-1H-indole (9)

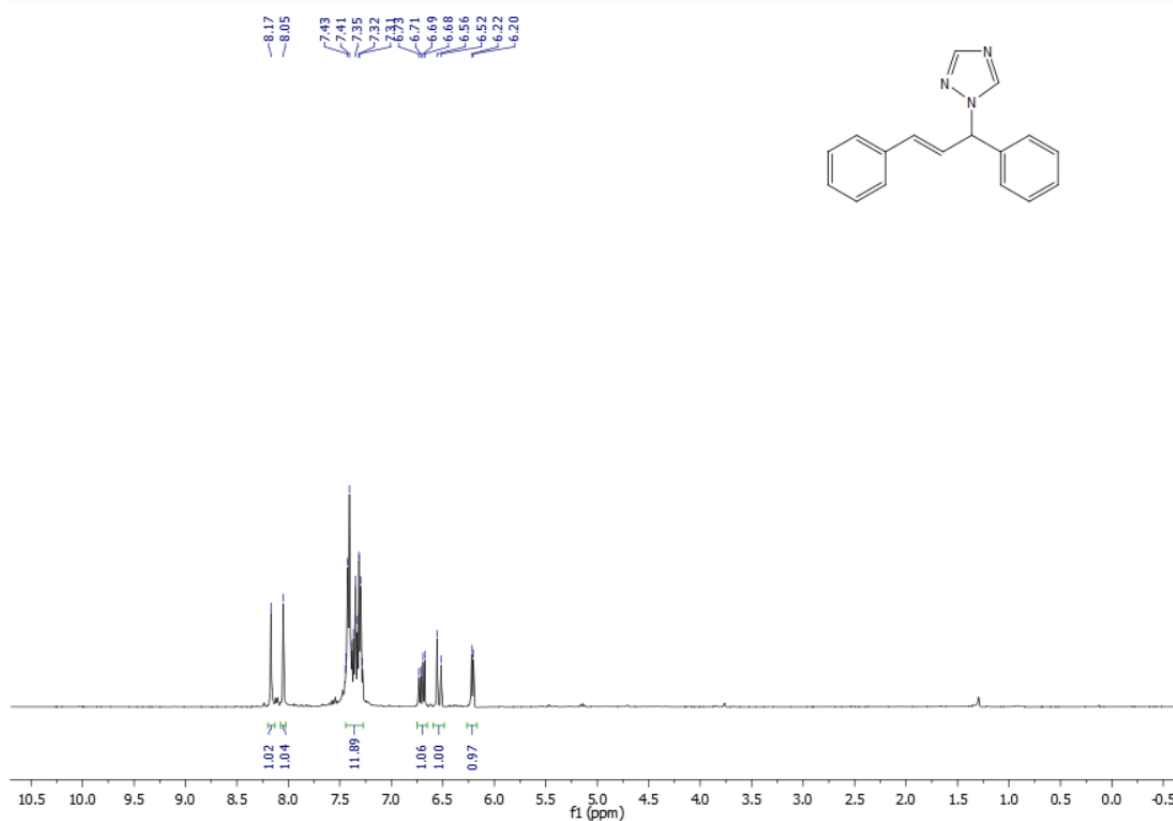


Figure S40. <sup>1</sup>H NMR spectrum of (E)-1-(1,3-diphenylallyl)-1,2,4-triazole (10)

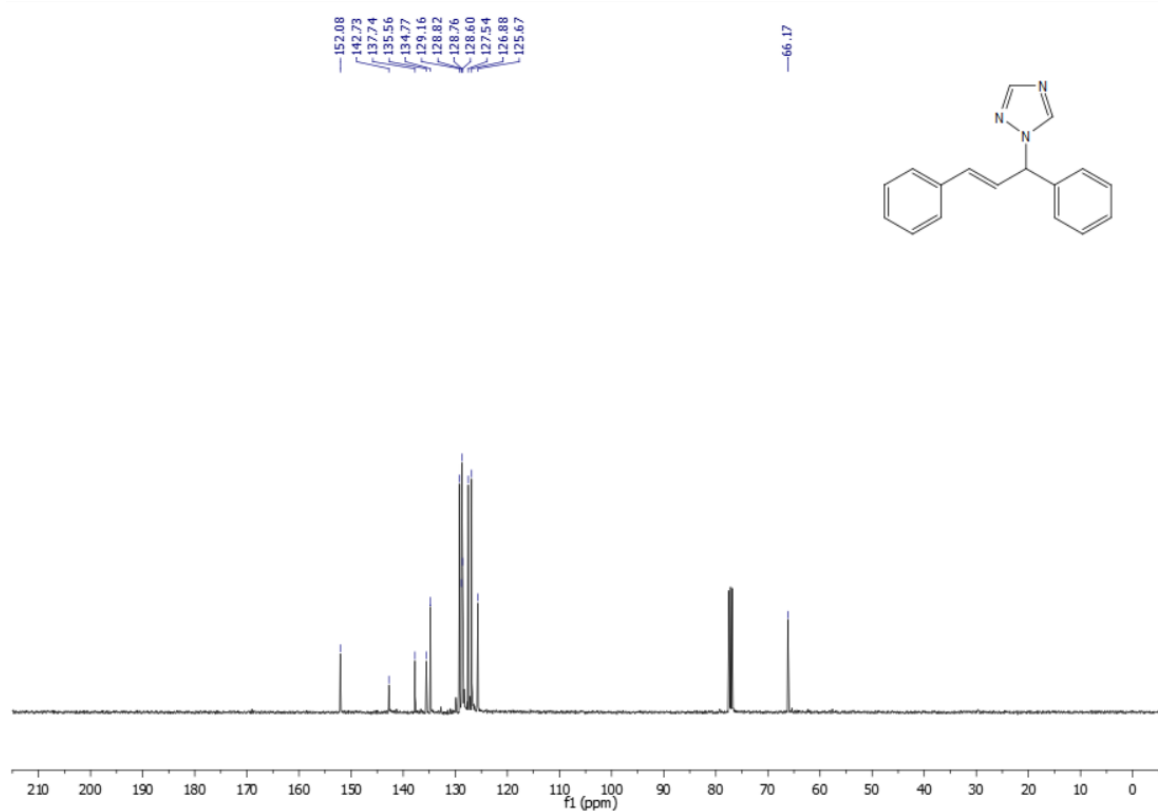


Figure S41. <sup>13</sup>C NMR spectrum of (E)-1-(1,3-diphenylallyl)-1,2,4-triazole (10)

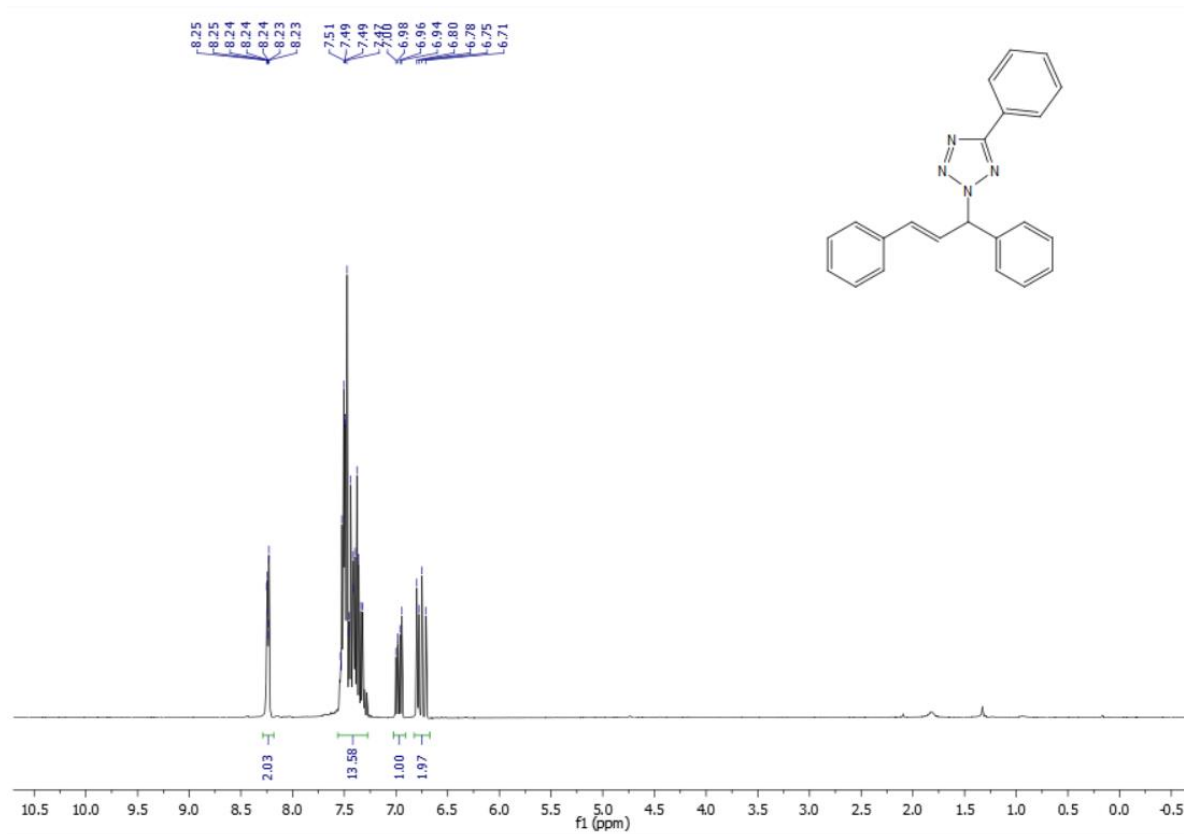


Figure S42. <sup>1</sup>H NMR spectrum of (E)-2-(1,3-diphenylallyl)-5-phenyl-2H-tetrazole (11)

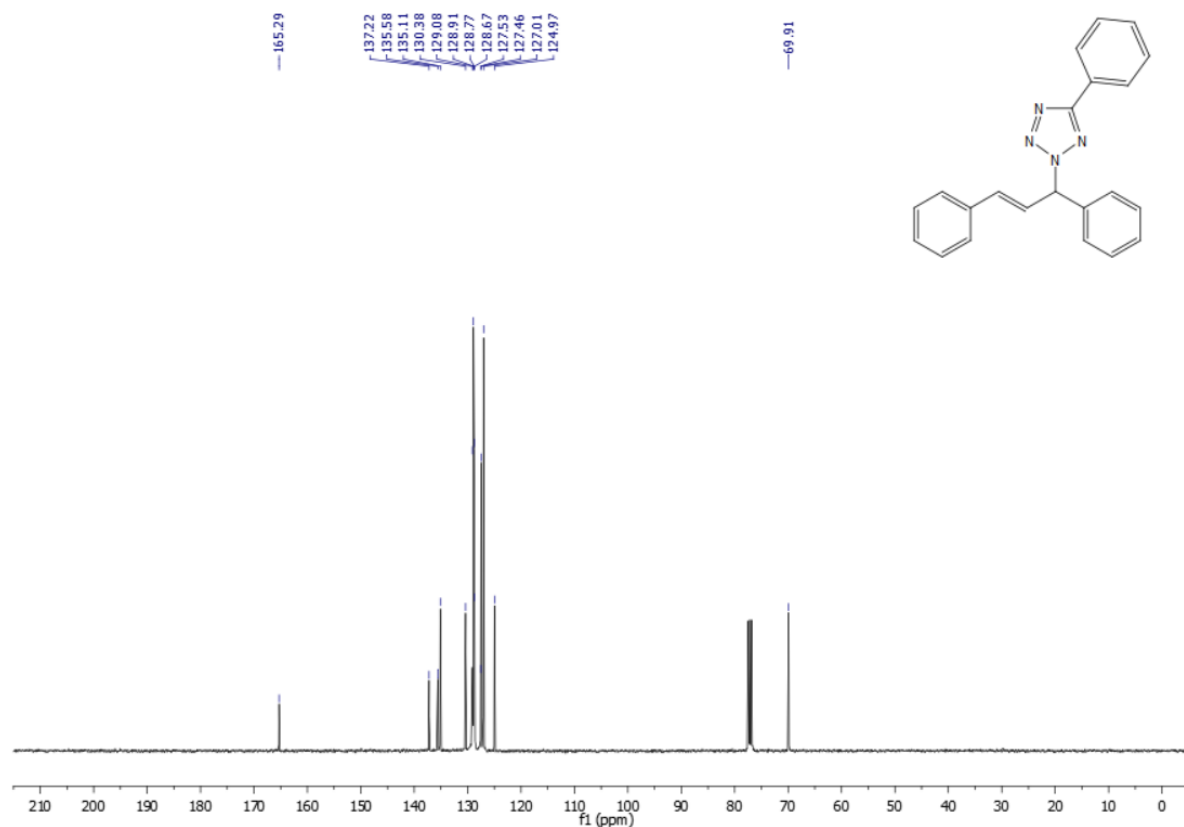


Figure S43. <sup>13</sup>C NMR spectrum of (E)-2-(1,3-diphenylallyl)-5-phenyl-2H-tetrazole (11)



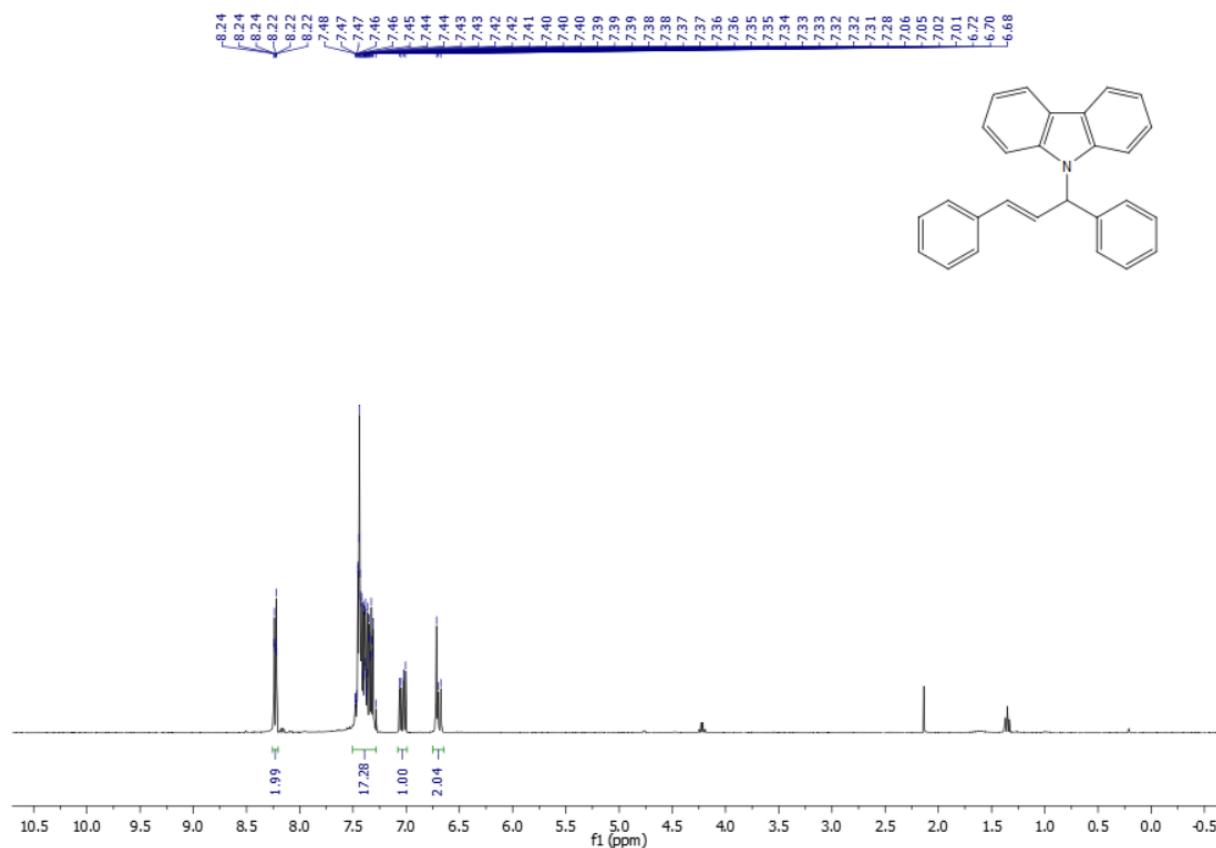


Figure S44. <sup>1</sup>H NMR spectrum of (E)-9-(1,3-diphenylallyl)-9H-carbazole (12)

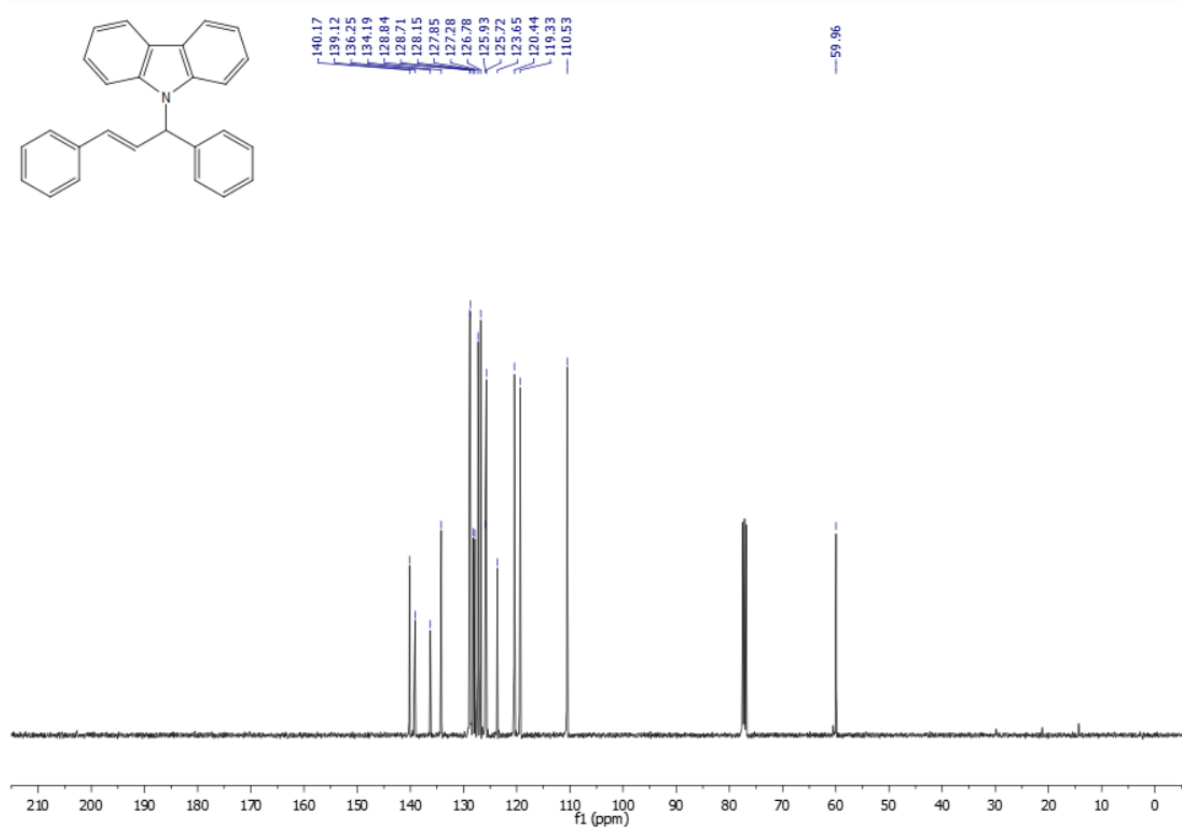


Figure S45. <sup>13</sup>C NMR spectrum of (E)-9-(1,3-diphenylallyl)-9H-carbazole (12)

Miscellaneous images

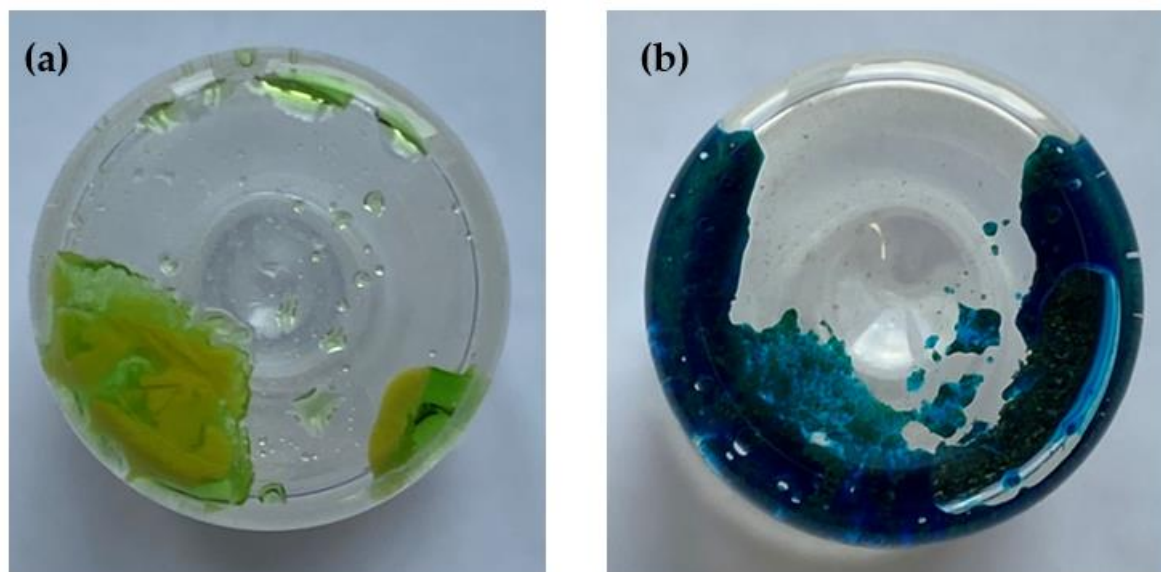


Figure S46. 1:1 mcmimCl:NiCl<sub>2</sub>·6H<sub>2</sub>O mixture (a) cooled down for 5 minutes after preparation (b) heated up again until development of condensation