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Supplementary Information

Oxidative carbonylation of *N*-protected indoles by Rh(III)-zeolites

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1. Experimental details

A. Chemicals

All chemicals were used as received: CO (Air liquide, 99.97%), N_2 (Air liquide, 99.999%), O_2 (Air liquide, 99.999%), peracetic acid (Fisher scientific, 35 wt%), *t*-butylhydroperoxide (Thermo Fisher, 70%), *t*-butylperbenzoate (Thermo Fisher, 98%), *t*-butylperacetate (Acros organics, 50%), *t*-butylperoxy isopropyl carbonate (Acros organics, 75%), di-*t*-butylperoxide (Sigma-Aldrich, 98%), *t*-butylperoxy ethylhexylcarbonate (Sigma-Aldrich, 95%), $K_2S_2O_8$ (Sigma-Aldrich, 99%), $RhCl_3.3H_2O$ (Thermo Fisher, 38-45.5% Rh), $[Rh(COD)Cl]_2$ (Strem, 98%), chlorobenzene (Chemlab, 99%), cyclopentyl methyl ether (VWR, 99.9%), dichloromethane (Fisher scientific, 99%), mesitylene (Sigma-Aldrich, 97%), *N*-methylindole (Fisher scientific, 98%), *N*-methylindole-6-carboxylic acid methyl ester (Fluorochem, 98%), 6-chloro-*N*-methylindole (Ambeed, 98%), 5-bromo-*N*-methylindole (Fisher scientific, 97%), 1,2-dimethylindole (Merck, 99%), 4-methoxy-*N*-methylindole (Merck, 98%), 4-hydroxy-*N*-methylindole (Ambeed, 97%), *N*-acetylindole (Bio-connect, 97%), 2-phenyl-N-methylindole (Fisher, 99%), *N*-benzylindole (Fisher scientific, 97%), *N*-phenylindole (Fluorochem, 98%), *n*-decane (Carl Roth, 99%), tetradecane (TCI Europe, 99%), *n*-octanol (Acros organics, 99%), *t*-butanol (Sigma-Aldrich), *N*,*O*-bis(trimethylsilyl)trifluoroacetamide (BSTFA, Sigma-Aldrich, 99.0%)

B. Catalyst synthesis

The loading of the rhodium on the zeolite was achieved by an ion exchange of a zeolite (in either H^+ or NH_4^+ form) with a $RhCl_3$ precursor.[1] For example, 25.59 mg $RhCl_3.3H_2O$ is dissolved in 25 mL demineralized water and stirred at 80°C for 2h. Next, 1 g zeolite is added and stirred for 24h at 80°C. Afterwards, the mixture is filtered and washed thoroughly with demineralized water. Subsequently, the zeolite is dried under vacuum (80°C, 12h), yielding a Rh(III)-exchanged zeolite with 1 wt% Rh (in this example).

Table S1. Rh^{III}-catalyzed oxidative carbonylation of *N*-methylindole: overview used zeolites.

Topology	Sample code	Si/Al	Additional information
MFI	CBV 3024E	15	Zeolyst International, NH_4^+ form
MFI	CBV 5524G	25	Zeolyst International, NH_4^+ form
FAU	CBV 500	2.6	Zeolyst International, NH_4^+ form
FAU	CBV 712	6	Zeolyst International, NH_4^+ form
MWW	MCM-22	15	China catalyst, NH_4^+ form
*BEA	OF-BEA-1	4.6	As synthesized[2], NH_4^+ form
*BEA	CP814E	12.5	Zeolyst International, NH_4^+ form
*BEA	CP814C	19	Zeolyst International, NH_4^+ form
*BEA	Zeocat PB65H	32.5	Zeocat, H^+ form
*BEA	CZB 150	75	Clariant, H^+ form

C. Catalytic reaction

In a typical reaction, 50 mg Rh-Beta (1 wt% Rh) was added to a glass liner. Next, 2 mL solvent, acetic acid, *N*-methylindole (1 mmol), oxidant (1 mmol), *n*-decane (internal standard) and a magnetic stirring bar were added. Subsequently, the reactor was sealed and flushed 5 times with CO. Then, the reactor was pressurized with 5 bar CO and 5 bar N_2 and reaction was started (magnetically stirred at 500 rpm). After reaction, the reactor was cooled with water and ice. The catalyst was separated from the solution by centrifugation.

To determine conversion of *N*-methylindole and the yield of *N*-methylindole-3-carboxylic acid, the reaction mixture was first silylated to make the acids more volatile. Therefore, BSTFA was added to the reaction mixture and heated to 60°C for 1h. After silylation, product identification was done by gas chromatography coupled to mass spectrometry (GC-MS) with an Agilent 6890 GC, equipped with a HP-5ms column and a 5973 MSD mass spectrometer. Product quantification was done based on the effective carbon number[4] using a GC equipped with a CP Sil 8 CB column (60 m).

D. Hot filtration test

In a hot filtration test, the reaction is interrupted at an intermediate stage (in this example after 2 h). At that point, the solid is separated from the hot liquid. New reactant is added to the solid. To the isolated liquid, fresh zeolite (not Rh-exchanged) is added to mimic the original conditions. Afterwards, both reactors are pressurized again with CO and the reaction proceeds. The hypothesis of heterogeneity is supported if the reaction proceeds with the recycled solid but no further reaction is observed in the clear liquid.

E. ICP-MS

In order to determine the Rh-content in solution, 0.5 mL of reaction mixture was diluted with 9.5 mL 1-octanol (taken as matrix). On this mixture, an elemental composition analysis was performed using an inductively coupled plasma mass spectrometer (Xseries ICP-MS by Thermo Fisher). The detection limit is 0.0005 µg/L. The obtained values for the samples were compared to a calibration curve, which allowed to quantify the amount of Rh in solution, and thus the amount of Rh leached from the support.

2. Optimization of reaction conditions

Table S2. Rh^{III}-catalyzed oxidative carbonylation of *N*-methylindole: parameter screening.

	oxidant[a]	**solvent**	**AcOH** (mmol)	**T** (°C)	**Conversion** (%)	**TON** (mol_{prod}/mol_{Rh})
1	O_2[b]	mesitylene	5	60	67	0
2	$K_2S_2O_8$	mesitylene	5	60	85	0
3	$K_2S_2O_8$[c]	toluene	0	110	100	0
4	dtbp	mesitylene	5	60	35	3
5	PAA	mesitylene	5	60	100	1
6	tbpa	mesitylene	5	60	54	38
7	tbhp	mesitylene	5	60	67	1
8	tbic	mesitylene	5	60	34	27
9	tbec	mesitylene	5	60	66	4
10	tbpb	mesitylene	5	60	40	72
11	tbpb	bromobenzene	5	60	25	20
12	tbpb	CPME	5	60	14	22
13	tbpb	*t*-butanol	5	60	4	8
14	tbpb	chlorobenzene	5	60	39	49
15	tbpb	DCM	5	60	8	3
16	tbpb	EtOAc	5	60	13	8
17	tbpb	heptane	5	60	14	5
18	tbpb	mesitylene	10	60	3	3
19	tbpb	mesitylene	7.5	60	13	24
20	tbpb	mesitylene	6.3	60	30	55
21	tbpb	mesitylene	3.8	60	20	36
22	tbpb	mesitylene	2.5	60	12	21
23	tbpb	mesitylene	1	60	10	15
24	tbpb	mesitylene	0.5	60	11	16
25	tbpb	mesitylene	5	40	5	2
26	tbpb	mesitylene	5	50	12	22
27	tbpb	mesitylene	5	70	51	91
28	tbpb	mesitylene	5	80	57	106
29	tbpb	mesitylene	5	90	60	84
30	tbpb	mesitylene	5	100	67	86
31	tbpb	mesitylene	5	110	56	58
32	tbpb	mesitylene	5	120	69	62

[a] abbreviations: AcOH, acetic acid; dtbp, di-*t*-butylperoxide; PAA, peracetic acid; tbpa, *t*-butyl peracetate; tbhp, *t*-butylhydroperoxide; tbic, *t*-butylperoxy isopropyl carbonate; tbec, *t*-butylperoxy ethylhexylcarbonate; tbpb, *t*-butylperbenzoate; CPME, cyclopentylmethylether; DCM, dichloromethane; EtOAc, ethyl acetate;

[b] general conditions: *N*-methylindole (1 mmol), 0.5 mol% Rh-exchanged Beta (Si/Al = 12.5; 1 wt% Rh; 0.5 mol% Rh with respect to *N*-methylindole), oxidant (1 mmol or 10 bar), AcOH in 2 mL solvent and 5 bar CO after 16h.

[c] literature reference: *N*-methylindole (1 mmol), *n*-butanol (5 eq), oxidant (2 eq) and 0.5 mol% Rh as $[Rh(COD)Cl]_2$ in 1 mL toluene and 1 bar CO for 24h.[15]

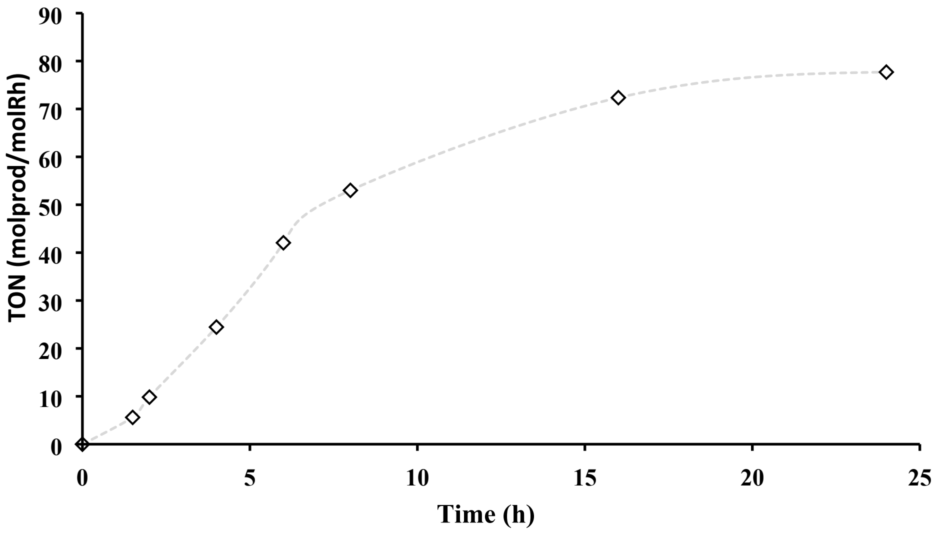


Fig. S1. Rh-catalyzed oxidative carbonylation of *N*-methylindole: time profile. Reaction conditions: 50 mg Rh-exchanged Beta (Si/Al = 12.5; 1 wt% Rh), *N*-methylindole (1 mmol), *t*-butyl perbenzoate (1 mmol), 5 mmol AcOH in 2 mL mesitylene and 5 bar CO at 60°C after x h.

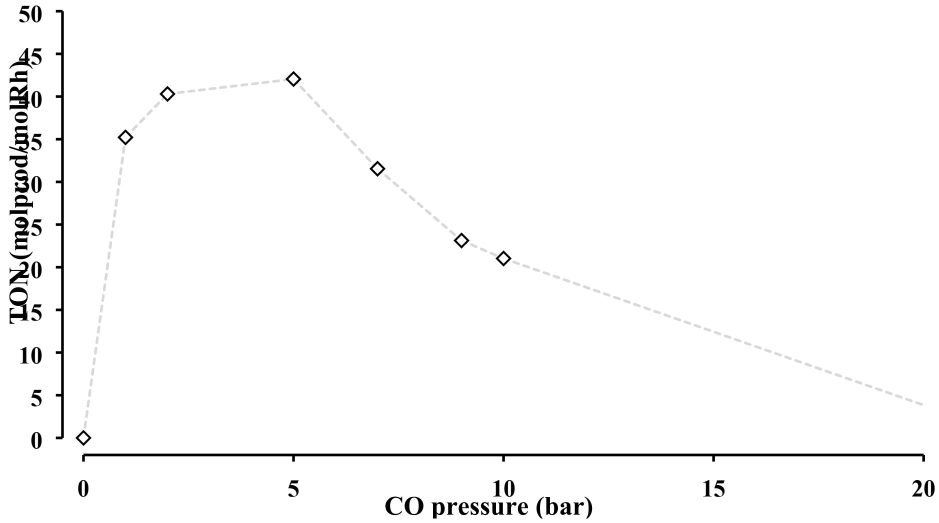


Fig. S2. Rh-catalyzed oxidative carbonylation of *N*-methylindole: CO pressure. Reaction conditions: 50 mg Rh-exchanged Beta (Si/Al = 12.5; 1 wt% Rh), *N*-methylindole (1 mmol), *t*-butyl perbenzoate (1 mmol), 5 mmol AcOH in 2 mL mesitylene and x bar CO at 60°C after 6 h.

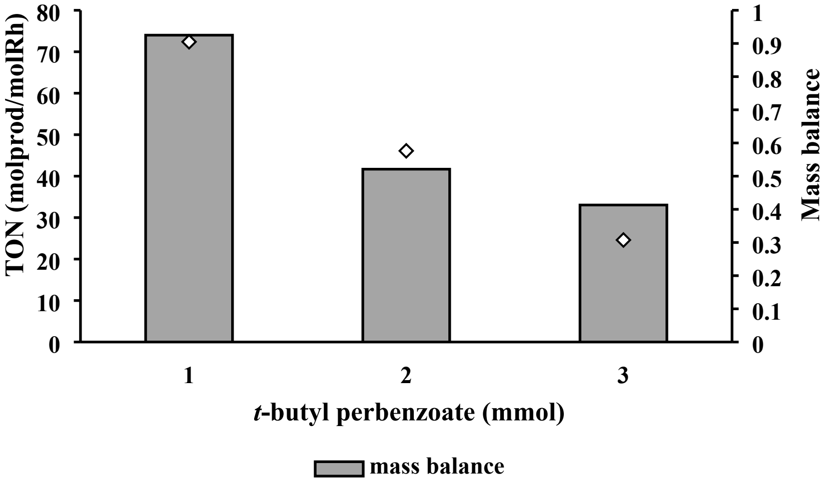


Fig. S3. Rh-catalyzed oxidative carbonylation of *N*-methylindole: CO pressure. Reaction conditions: 50 mg Rh-exchanged Beta (Si/Al = 12.5; 1 wt% Rh), *N*-methylindole (1 mmol), *t*-butylperbenzoate (x mmol), 5 mmol AcOH in 2 mL mesitylene and 5 bar CO at 60°C after 16 h.

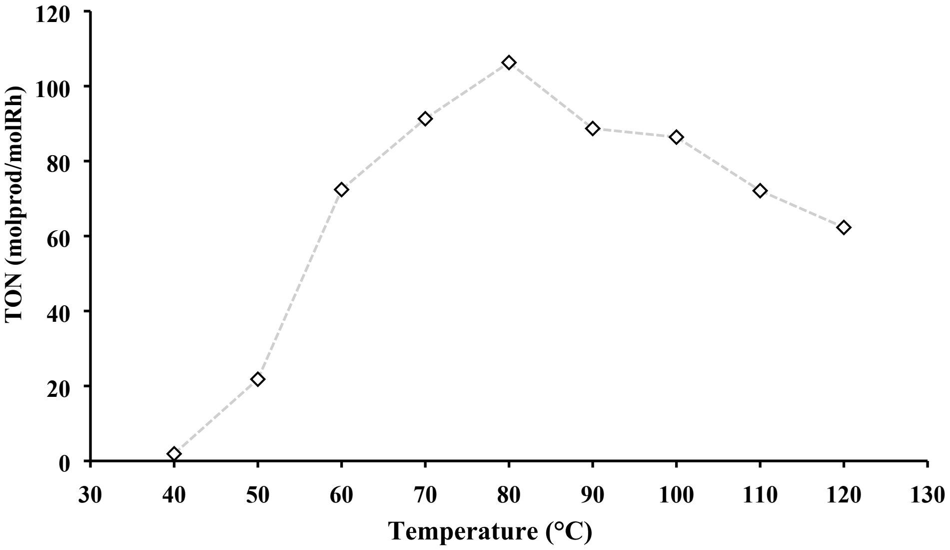


Fig. S4. Rh-catalyzed oxidative carbonylation of *N*-methylindole: CO pressure. Reaction conditions: 50 mg Rh-exchanged Beta (Si/Al = 12.5; 1 wt% Rh), *N*-methylindole (1 mmol), *t*-butylperbenzoate (1 mmol), 5 mmol AcOH in 2 mL mesitylene and 5 bar CO at x°C after 16 h.

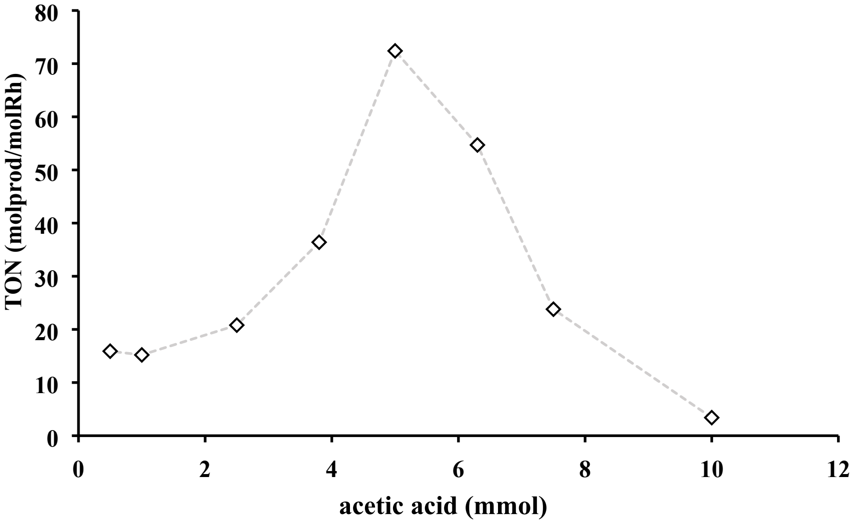


Fig. S5. Rh-catalyzed oxidative carbonylation of *N*-methylindole: CO pressure. Reaction conditions: 50 mg Rh-exchanged Beta (Si/Al = 12.5; 1 wt% Rh), *N*-methylindole (1 mmol), *t*-butylperbenzoate (1 mmol), x mmol AcOH in 2 mL mesitylene and 5 bar CO at 60°C after 16 h.

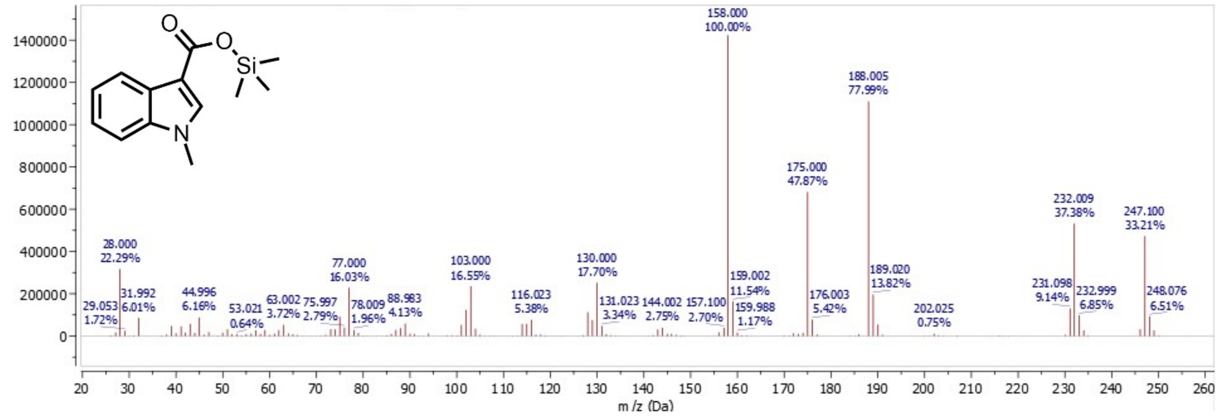
Table S3 Rh leaching after reaction and the effect of post treatments (evacuating CO + 2 h at 60°C, optional addition of 25 eq oxidant). Reaction conditions: 50 mg Rh-exchanged Beta (Si/Al = 19; 1 wt% Rh), *N*-methylindole (1 mmol), *t*-butylperbenzoate (1 mmol), 5 mmol AcOH in 2 mL mesitylene and 5 bar CO at 60°C after 16 h.

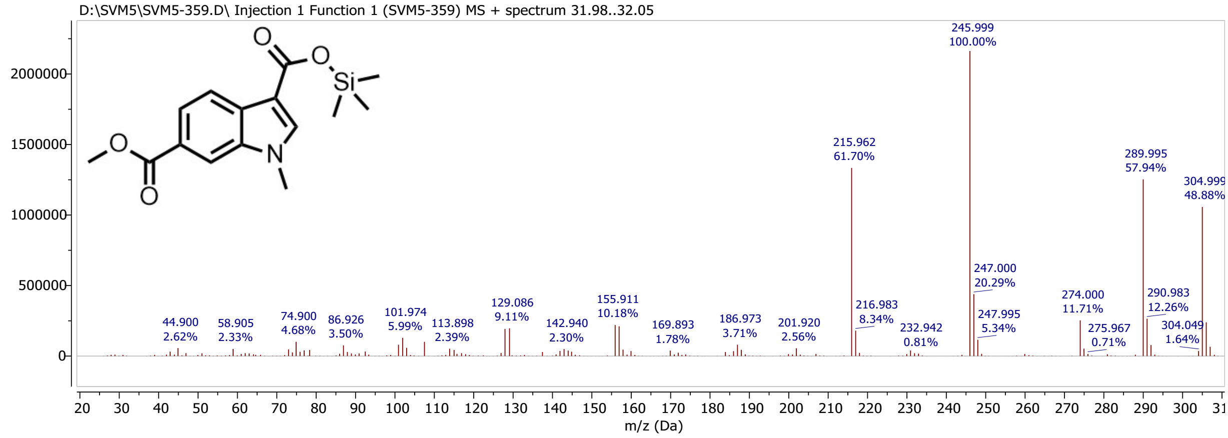
Entry	Rh leaching (%)
After reaction	75
No oxidant	68
Oxidant	9

3. Product identification

For the substrate scope shown in Fig. 6, reactions were performed using 50 mg Rh-exchanged Beta (Si/Al = 12.5; 1 wt% Rh) in 2 mL mesitylene with 5 mmol AcOH, 1 mmol *t*-butylperbenzoate, 0.2 mmol substrate and 50 µL *n*-decane (internal standard) at 80°C for 24 h. After reaction, the obtained mixture was silylated for GC-analysis. Quantification of the product was done based on the effective carbon number.[4]

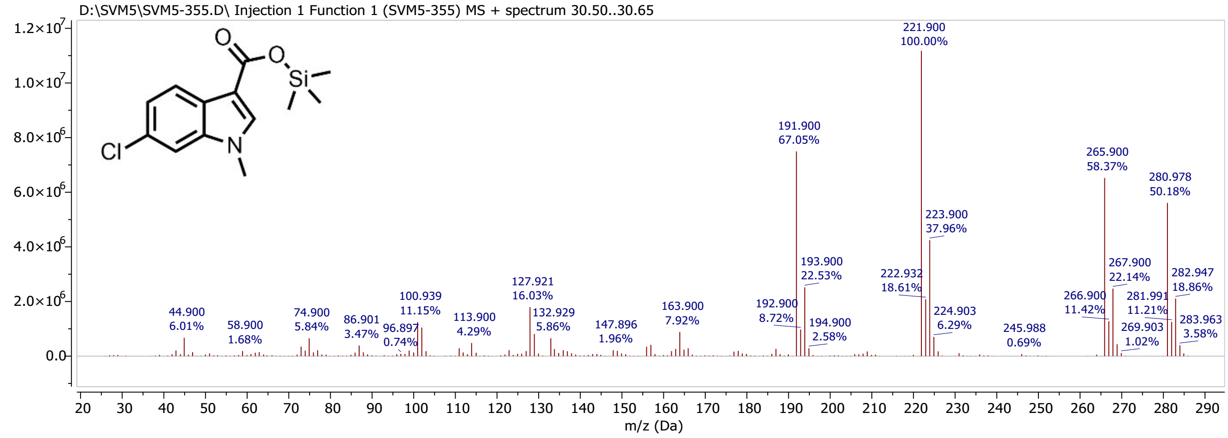
A. *N*-methylindole



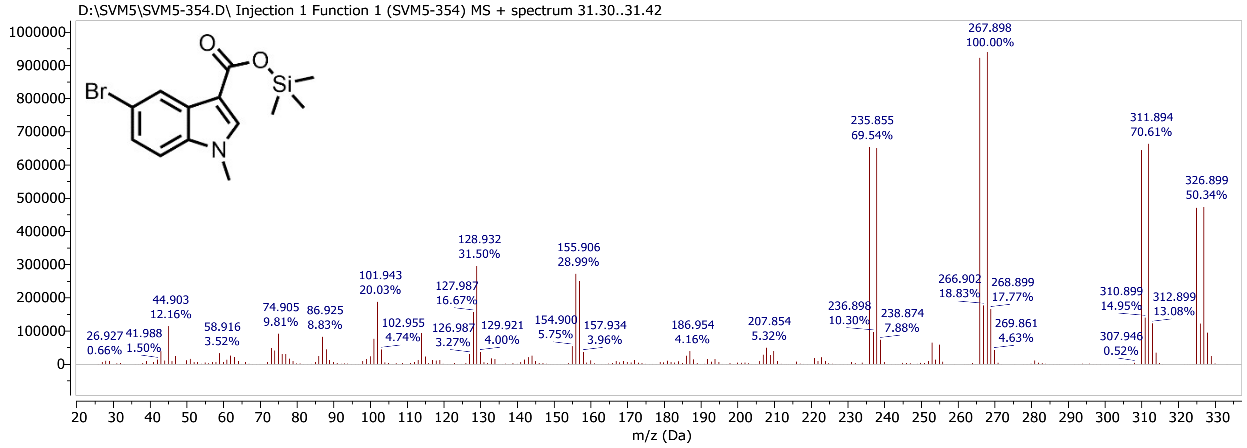


B. *N*-methylindole-6-methylester

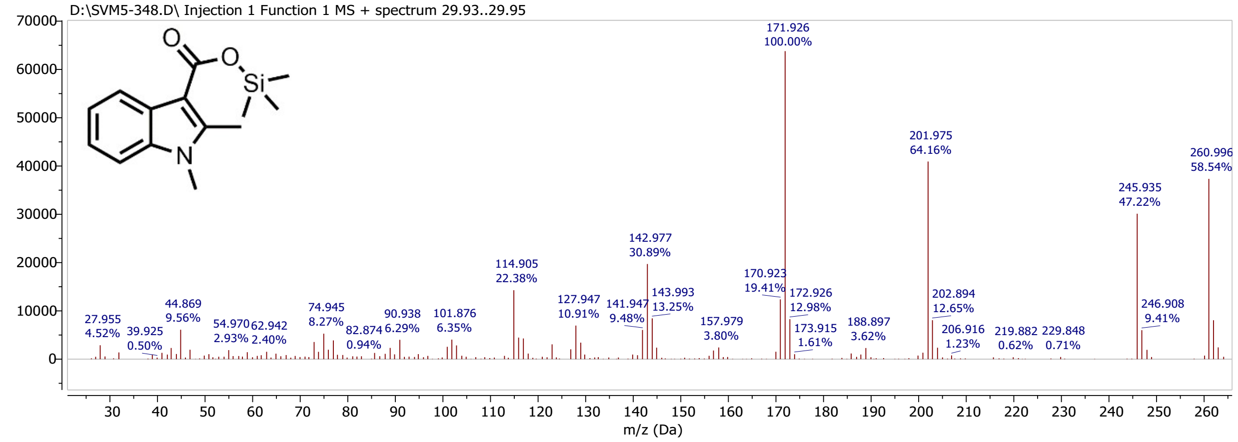
C. 6-chloro-*N*-methylindole

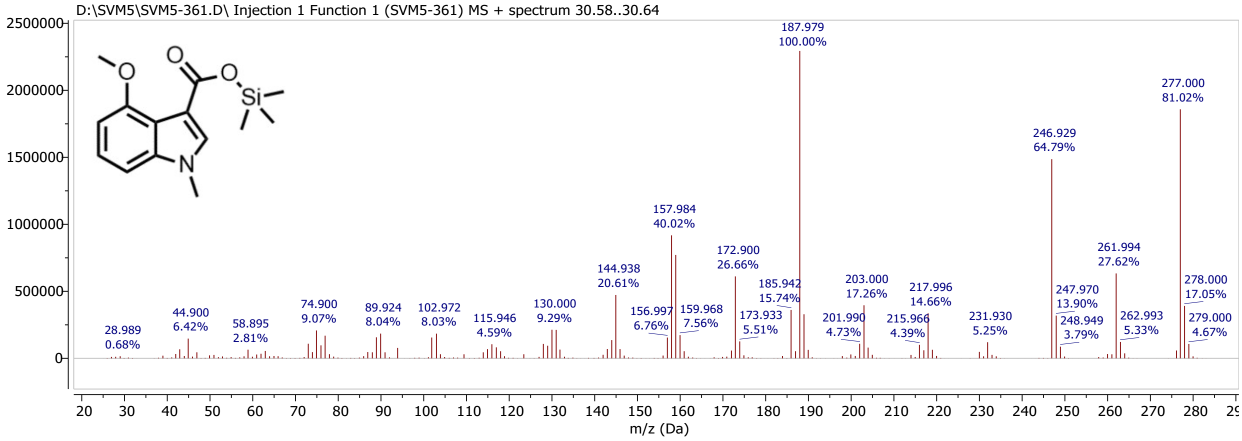


D. 5-bromo-*N*-methylindole



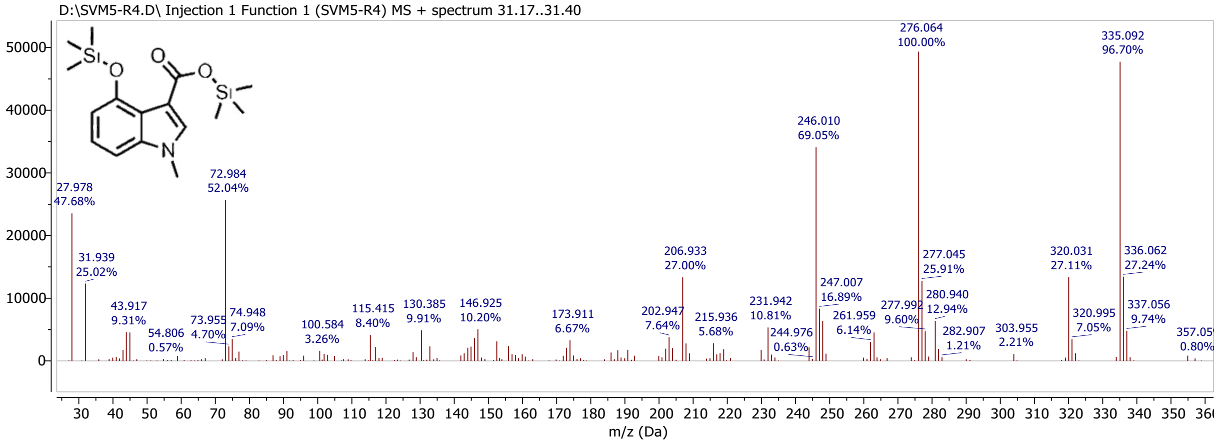
E. 1,2-dimethylindole



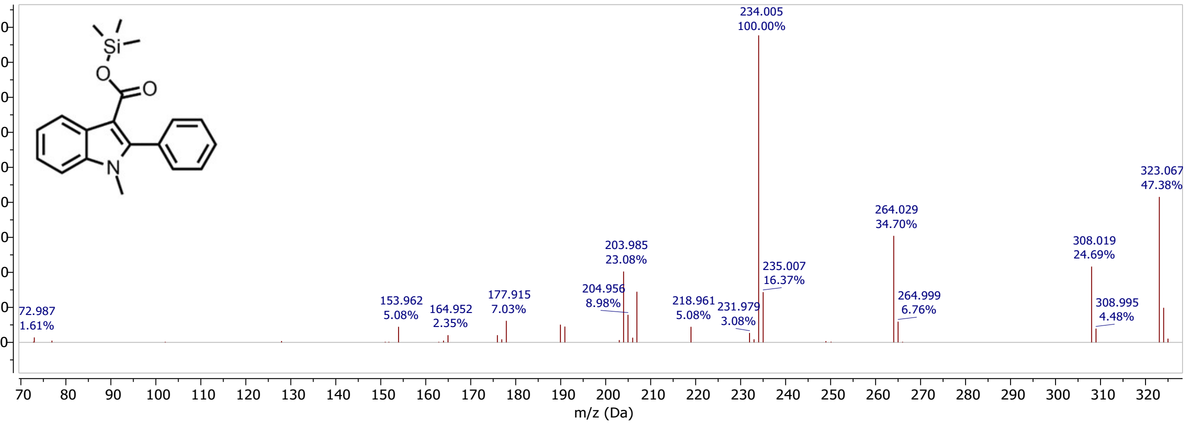


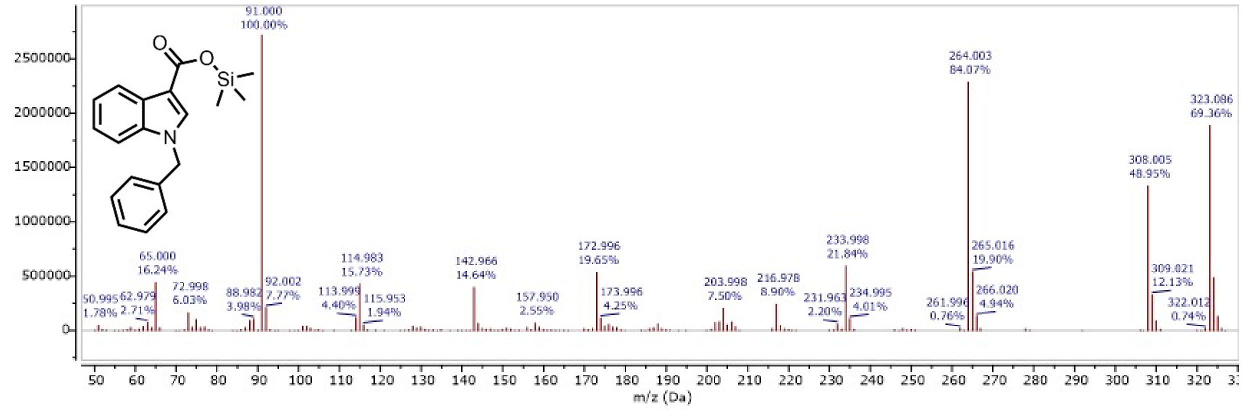
F. 4-methoxy-*N*-methylindole

G. 4-hydroxy-*N*-methylindole



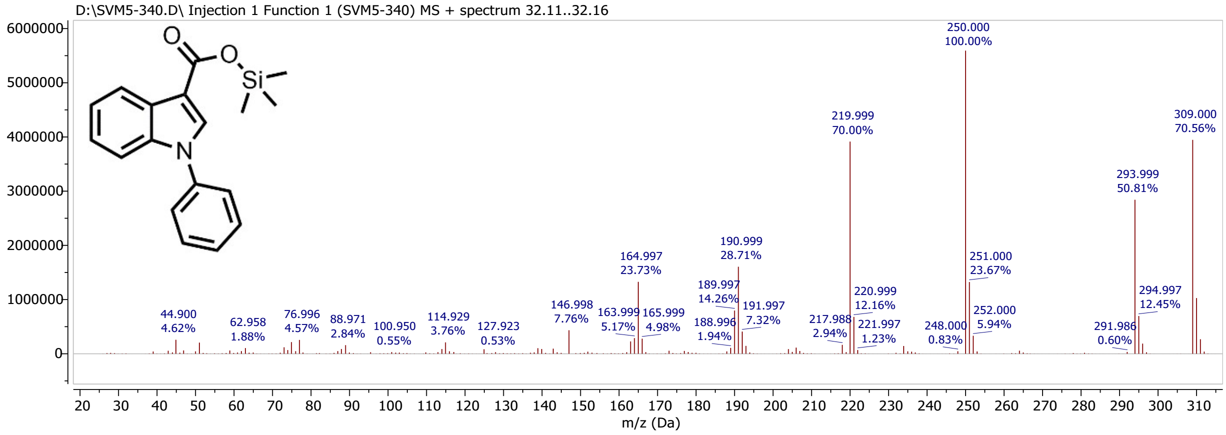
H. 2-phenyl-*N*-methylindole





I. *N*-benzylindole

J. *N*-phenylindole



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