

醋酸锰引发的吲哚膦酰化反应

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摘要 吲哚膦酸酯是一类重要的化合物, 具有潜在的生理活性; 此外, 从它出发可以衍生出其他多种物质. 利用醋酸锰引发二烷基亚膦酸酯产生膦酸酯基自由基与吲哚发生选择性的反应, 成功合成了一系列吲哚膦酸酯衍生物, 该方法也适用于二苯氧膦. 该反应条件较温和、操作简单, 为 2-和 3-膦酰化吲哚的合成提供了一种有效的方法.

关键词 醋酸锰; 自由基反应; 吲哚; 膦酰化

Manganese Acetate-Mediated Phosphorylation of Indoles

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Abstract $\text{Mn}(\text{OAc})_3$ -mediated selective radical phosphorylation of indoles with dialkylphosphites or diphenylphosphine oxide in moderate to good yields is described. The reaction proceeds under mild conditions in air, no need to add extra additives, through a radical process involving phosphorus-centered radical generated from dialkylphosphites or diphenylphosphine oxide mediated by $\text{Mn}(\text{OAc})_3$, selectively added to 3-position of 2-substituted indoles or 2-position of 3-substituted indoles to form carbon radical intermediate, followed by oxidation with $\text{Mn}(\text{OAc})_3$ and deprotonation to afford products 2- or 3-phosphonyl indoles. This protocol provides an efficient and general method for the preparation of 2- and 3-phosphonyl indoles. The detailed investigation revealed that 1) the yields of *N*-methyl indoles were higher than NH unprotected analogues; 2) 2-Phenyl or 2-methyl indoles were unsuitable for the reaction with dialkylphosphites, but were suitable for the reaction with diphenyl phosphine oxide; 3) Indoles bearing electron-withdrawing groups such as F, Cl, Br on the phenyl ring were favored to the reaction. A representative procedure for this reaction is as follows: To a solution of substituted indoles **1** or **4** (1 mmol) and dialkylphosphites **2** (2 mmol) in HOAc (3 mL) heated with oil bath (50 °C), $\text{Mn}(\text{OAc})_3$ (3 mmol) was added in portions within 0.5 h, then, the mixture was allowed to stir further for 0.5 h. After removal of the most solvent under reduced pressure, 50 mL water was added to the residue and the mixture was extracted with EtOAc (20 mL $\times$ 3). The combined organic layers were dried over anhydrous Na_2SO_4 , filtered, concentrated under reduced pressure, and the residue was purified by flash silica-gel column chromatography (using mixture of petroleum ether/ethyl acetate as eluent from ratio of 20/1 to 1/2) to afford the desired 2- or 3-phosphonyl indoles **3** or **5**.

Keywords $\text{Mn}(\text{OAc})_3$; radical reaction; indole; phosphorylation

1 引言

三价锰是一种重要的单电子氧化剂, 它可以引发产生碳自由基及其他的杂原子自由基, 如磷、硫、氮等自由基, 这些自由基可以与不饱和体系发生分子内和分子间的各种加成反应、加成-消去反应、加成-成环串联等反应^[1,2]. 本文报道了醋酸锰引发产生的磷自由基与吲哚衍生物的反应.

吲哚衍生物广泛存在于自然界, 具有丰富的生理活性, 合成新的吲哚衍生物和开发已知吲哚衍生物的新合成方法一直受到科学家的关注^[3]. 在吲哚环上引入膦酰

基预计可以增强吲哚衍生物的活性或发现新的生物活性. 近年来的研究表明 3-膦酰化的吲哚具有抑制 HIV-1 病毒的作用^[4], 因此, 发展吲哚的新膦酰化方法具有学术研究价值和应用背景. 至今, 膦酰化吲哚的合成报道很少. 其中传统的合成方法是 Fischer 环化法, 用于合成 2-膦酰化吲哚^[5]; 近年来报道了钨催化的邻取代苯胺衍生物与二烷基亚膦酸酯、或与 1-烷基膦硫化物反应合成 2-膦酰化吲哚的方法^[6].

吲哚种类多, 易于得到, 所以吲哚环的直接膦酰化为膦酰化吲哚的合成提供了一种重要的新策略. 尽管近年来在吲哚的 C—H 直接官能化, 形成 C—C, C—O 和 C—B 键^[7]和(杂)芳烃的膦酰化方面取得了重要的进

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展^[8], 但通过吲哚的直接磷酰化合成磷酰化吲哚的报道很少, 文献仅报道了分别适用于 2-或 3-磷酰化吲哚的合成方法, 而同时适用于 2-和 3-磷酰化吲哚的合成方法则没有报道, 因此, 吲哚的直接 C—H 磷酰化仍然存在很大的挑战^[9]. 本文报道了醋酸锰引发二烷基亚磷酸酯产生的磷酸酯基自由基与吲哚 C—H 的反应, 成功合成了一系列吲哚-2-和吲哚-3-磷酸酯衍生物.

2 结果与讨论

根据本课题组前文的报道^[2k,2l,2v], 选择吲哚-2-甲酸甲酯与亚磷酸二甲酯的反应为模板, 对该反应进行了系统的条件筛选, 确定的最优化反应条件为: 吲哚-2-甲酸甲酯(**1a**, 1 mmol)、亚磷酸二甲酯(**2a**, 2 mmol)和醋酸锰(3 mmol)的醋酸(3 mL)溶液, 在 50 °C 时搅拌反应 1 h, 得到了 3-磷酰化吲哚-2-甲酸甲酯(**3a**) (表 1, Entry 1). 我们将此优化条件应用到其他的吲哚反应中(反应条件筛选的详细数据请参见 Supporting Information 中 Table S1).

2.1 底物拓展

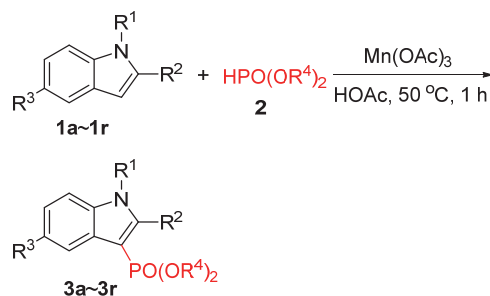
在优化的反应条件下, 对吲哚的适用范围进行了拓展. 首先考察了 2-取代吲哚的反应(表 1), 由表可见, 吲哚-2-甲酸甲酯(**1a**)的产率一般(表 1, Entry 1), 当 **1a** 的 NH 被甲基保护后, 产率明显提高(表 1, Entry 3). 但当吲哚的 2 位是苯基和甲基时, 反应复杂; 即使 NH 被甲基保护后, 反应也没有明显的改善(表 1, Entries 4~7). 随后, 探索了吲哚-2-甲酸甲酯衍生物苯环上取代基的电子效应对反应的影响, 发现当 5 位连有 F、Cl、Br 等吸电子基团时, 连有 F 和 Br 的底物产率明显提高(表 1, Entries 8, 12); 当底物中的 NH 被甲基保护后, 连有 F 和 Cl 的底物产率明显提高(表 1, Entries 9, 11). 当 5 位连有强吸电子基团 NO₂ 基时, 反应仅得到微量的产物 **3m**; 值得注意的是, 当 NH 被甲基保护后, 反应大大改善, 产物 **3n** 的产率达到了 55% (表 1, Entries 14, 15). 进一步的研究表明, 当吲哚-2-甲酸甲酯衍生物的苯环上连有给电子基团, 如甲基、甲氧基时, 反应产率与氢的情况类似; 不同的是当 NH 被甲基保护后, 反应没有明显的改善(表 1, Entries 16~19); 特别是连有 5-甲氧基时, 得到了吲哚-3-磷酰化产物 **3q**(磷酰化发生在吡咯环上)和吲哚-4-磷酰化产物 **3q'**(磷酰化发生在苯环上)的混合物(**3q/3q'**为 1/0.44), 而且二者难以分离. 其原因是当苯环上连有给电子基时增加了苯环的电子云密度, 由此增加了磷自由基进攻苯环的几率, 导致希望的产物(吡咯环磷酰化)产率有所下降.

随后, 我们进一步考察了 3-取代吲哚的反应(表 2), 总体而言, 3-取代吲哚的磷酰化产率要比 2-取代吲哚的磷酰化产率略低, 这可能是由于吲哚衍生物 2 位的电子云密度比 3 位的低所致. 研究表明, 当吲哚的 3 位是酯基时, 二甲基亚磷酸酯(**2a**)与吲哚-3-甲酸甲酯(**4a**)可以

反应, 但产率较低(表 2, Entry 1); 但二异丙基亚磷酸酯与 **4a** 不反应(表 2, Entry 3), 可能是由于异丙基的位阻较大所致. 因此, 二烷基亚磷酸酯中烷基的结构会对反应产生明显的影响. 一般地, 当吲哚的 3 位连有吸电子基团, 如酯基、氰基和醛基时, 反应都能发生, 而且当底物中的 NH 被甲基保护后, 产率有明显提高(表 2, Entries 4, 6). 但当吲哚的 3 位是苯基和甲基时, 反应复杂, 即使 NH 被甲基保护后, 反应也没有明显的改善(表 2, Entries 9~12). 进一步的实验表明, 吲哚的 2 和 3 位均没有取代基时, 也仅得到复杂的混合物(表 2, Entries 13, 14).

表 1 2-取代吲哚与二烷基亚磷酸酯的反应^a

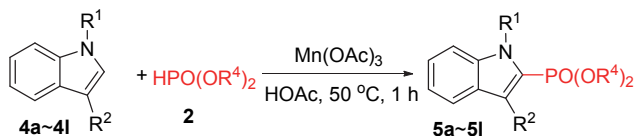
Table 1 Reactions of 2-substituted indoles (**1**) and dialkyl phosphites (**2**)



Entry	R ¹	R ²	R ³	R ⁴	3	Yield ^b /%
1	H	COOMe	H	Me	3a	42
2	H	COOMe	H	Et	3a'	55
3	Me	COOMe	H	Me	3b	69
4	H	Ph	H	Me	3c	Complex
5	Me	Ph	H	Me	3d	25
6	H	Me	H	Me	3e	Complex
7	Me	Me	H	Me	3f	Complex
8	H	COOEt	F	Me	3g	65
9	Me	COOEt	F	Me	3h	80
10	H	COOEt	Cl	Me	3i	41
11	Me	COOEt	Cl	Me	3j	57
12	H	COOEt	Br	Me	3k	62
13	Me	COOEt	Br	Me	3l	65
14	H	COOEt	NO ₂	Me	3m	trace
15	Me	COOEt	NO ₂	Me	3n	55
16	H	COOEt	Me	Me	3o	48
17	Me	COOEt	Me	Me	3p	52
18	H	COOEt	OMe	Me	3q+3q'	58 (1 : 0.44) ^c
19	Me	COOEt	OMe	Me	3r	47

^a Reaction conditions: **1** (1 mmol), **2** (2 mmol), Mn(OAc)₃ (3 mmol), HOAc (3 mL), 50 °C (oil bath) for 1 h. ^b Isolated yield. ^c **3q** is ethyl 3-(dimethoxyphosphoryl)-5-methoxy-1*H*-indole-2-carboxylate, **3q'** is ethyl 4-(dimethoxyphosphoryl)-5-methoxy-1*H*-indole-2-carboxylate, these two compounds can't be separated.

最后, 探索了二苯氧磷与吲哚-2-甲酸甲酯(**1a**)的反应, 结果比二甲基亚磷酸酯的反应好, 产率达到了 89% (表 3, Entry 1). 进一步的研究表明, **1a** 的 NH 是否被甲基保护对反应影响不大(表 3, Entries 1, 2); 当吲哚的苯

表2 3-取代吲哚与二烷基亚磷酸酯的反应^aTable 2 Reactions of 3-substituted indoles (**4**) and dialkyl phosphites (**2**)^a

Entry	R ¹	R ²	R ⁴	5	Yield ^b /%
1	H	COOMe	Me	5a	38
2	H	COOMe	Et	5a'	32
3	H	COOMe	<i>i</i> Pr	5a''	0
4	Me	COOMe	Me	5b	55
5	H	CN	Me	5c	25
6	Me	CN	Me	5d	62
7	H	CHO	Me	5e	51
8	Me	CHO	Me	5f	56
9	H	Ph	Me	5g	Complex
10	Me	Ph	Me	5h	Complex
11	H	Me	Me	5i	Complex
12	Me	Me	Me	5j	Complex
13	H	H	Me	—	Complex
14	Me	H	Me	—	Complex

^a Reaction conditions: **1** (1 mmol), **2** (2 mmol), Mn(OAc)₃ (3 mmol), HOAc (3 mL), 50 °C (oil bath) for 1 h. ^b Isolated yield.

环上连有甲基时仍然可以得到产率为 84% 的产物(表 3, Entry 5). 令人意外的是, 与二甲基亚磷酸酯的反应不同, 二苯氧磷与 2-苯基吲哚的反应选择性很高, 得到了 72% 产率的 3-磷酰化产物(表 3, Entry 3); 类似地, 反应中的 NH 不需要保护(表 3, Entry 4). 随后, 对 3-取代吲哚与二苯氧磷的反应进行了研究, 结果令人满意(产率为 51%~68%), 虽然比 2-取代吲哚略低. 值得一提的是, 3-苯基吲哚的反应也给出了 51% 产率的 2-磷酰化产物(表 3, Entry 9). 此外, 进一步探索了二(4-甲氧苯基)氧磷与 **1a** 的反应, 产率达到了 62% (表 3, Entry 11).

2.2 可能的反应机理

基于文献报道和本课题组的工作^[2,10], 我们对该反应提出了一个可能的机理(图 1). 以二甲基亚磷酸酯和吲哚-2-甲酸甲酯的反应为例. 首先, 醋酸锰将二甲基

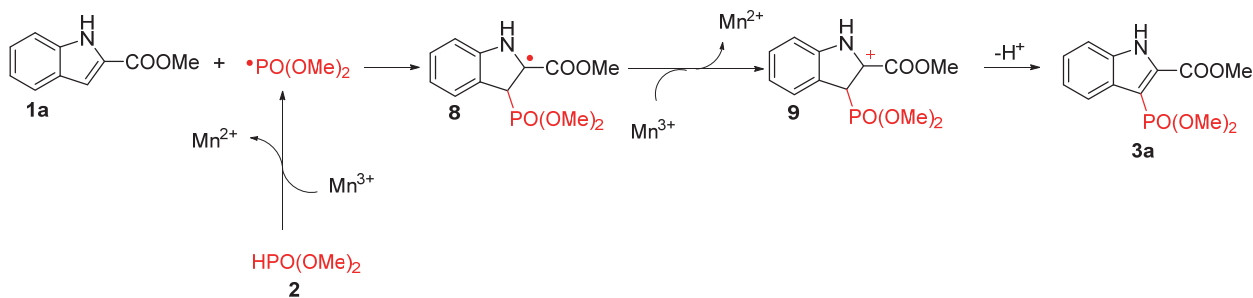
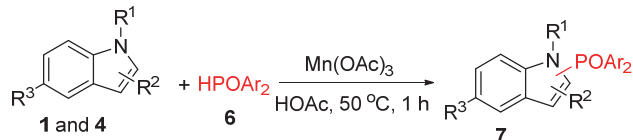


图1 可能的反应机理

Figure 1 Proposed mechanism

磷酸酯氧化为磷自由基, 随后该自由基选择性地加成到吲哚-2-甲酸甲酯的 3-位, 形成碳自由基中间体(**8**), **8** 被 Mn(III) 氧化为碳正离子中间体(**9**), 最后脱去质子得到目标产物 **3a**.

表3 2-/3-取代吲哚与二苯氧磷的反应^aTable 3 Reactions of 2- and 3-substituted indoles (**1** and **4**) with diphenylphosphine oxide (**6**)

Entry	R ¹	R ²	R ³	Ar	7	Yield ^b /%
1	H	2-COOMe	H	Ph	7a	89
2	Me	2-COOMe	H	Ph	7b	91
3	H	2-Ph	H	Ph	7c	72
4	Me	2-Ph	H	Ph	7d	68
5	H	2-COOEt	Me	Ph	7e	84
6	H	3-COOMe	H	Ph	7f	63
7	Me	3-COOMe	H	Ph	7g	65
8	H	3-CHO	H	Ph	7h	61
9	H	3-Ph	H	Ph	7i	51
10	H	3-CN	H	Ph	7j	68
11	H	2-COOMe	H	4-MeOC ₆ H ₄	7k	62

^a Reaction conditions: **1** and **4** (1 mmol), **6** (2 mmol), Mn(OAc)₃ (3 mmol), HOAc (3 mL), 50 °C (oil bath) for 1 h. ^b Isolated yield.

3 结论

本文发展了一种醋酸锰引发产生的磷自由基与吲哚 C—H 键反应生成吲哚磷酸酯的方法. 该反应经历了自由基过程, 首先二烷基亚磷酸酯在醋酸锰作用下生成磷自由基, 该自由基选择性地进攻 2-取代吲哚的 3-位或 3-取代吲哚的 2-位生成相应的中间体碳自由基, 碳自由基经氧化生成碳正离子、再失去质子得到产物 2-取代吲哚磷酸酯或 3-取代吲哚磷酸酯, 该方法也适用于二苯基氧磷的反应. 该方法反应条件温和, 在空气中进行, 操作方便简单, 为磷酰化吲哚衍生物的合成提供了一种有效的方法.

4 实验部分

吡啶磷酸酯的合成步骤: 在反应瓶中分别加入吡啶衍生物 (**1**, 1 mmol)、亚磷酸二烷基酯(**2**, 2 mmol)和醋酸 (3 mL). 反应物用油浴加热至 50 °C, 半小时内分批加入醋酸锰(3 mmol), 加完后再反应半小时. 反应结束后 (TLC 监测), 反应液在减压下浓缩除去溶剂, 然后向体系中加入 20 mL 水, 用乙酸乙酯萃取(20 mL×3), 合并有机层, 无水硫酸钠干燥. 萃取液经过滤、浓缩得粗产物, 再经柱层析 [*V*(石油醚): *V*(乙酸乙酯)=2:1] 得到产物.

Methyl 3-(dimethoxyphosphoryl)-1*H*-indole-2-carboxylate (**3a**) White solid (11.9 mg, 42% yield), m.p. 122~123 °C. ¹H NMR (400 MHz, DMSO-*d*₆) δ: 10.44 (s, 1H), 8.07~8.01 (m, 1H), 7.65~7.61 (m, 1H), 7.46~7.25 (m, 2H), 3.91 (s, 3H), 3.71 (d, *J*=11.3 Hz, 6H); ¹³C NMR (101 MHz, DMSO-*d*₆) δ: 161.5, 138.0 (d, *J*=7.1 Hz), 129.8 (d, *J*=6.8 Hz), 128.5, 128.3 (d, *J*=3.2 Hz), 127.9 (d, *J*=10.8 Hz), 121.1 (d, *J*=13.9 Hz), 109.0, 108.2 (d, *J*=3.6 Hz), 53.3 (d, *J*=5.4 Hz), 52.7. ³¹P NMR (162 MHz, DMSO-*d*₆) δ: 20.1. HRMS (ESI-TOF) *m/z*: [M+Na]⁺ Anal. calcd for C₁₂H₁₄PNaNO₅ 306.0507, found 306.0503.

Methyl 3-(diethoxyphosphoryl)-1*H*-indole-2-carboxylate (**3a'**) White solid (17.1 mg, 55% yield), m.p. 118~119 °C. ¹H NMR (400 MHz, DMSO-*d*₆) δ: 12.76 (d, *J*=2.6 Hz, 1H), 8.13 (d, *J*=8.3 Hz, 1H), 7.67~7.48 (m, 1H), 7.38~7.30 (m, 1H), 7.26~7.18 (m, 1H), 4.24~3.98 (m, 4H), 3.92 (s, 3H), 1.24 (t, *J*=7.1 Hz, 6H); ¹³C NMR (101 MHz, DMSO-*d*₆) δ: 161.1, 136.6 (d, *J*=15.4 Hz), 131.9 (d, *J*=20.5 Hz), 129.5 (d, *J*=12.2 Hz), 125.4, 123.0, 122.2, 113.4, 104.8 (d, *J*=21.2 Hz), 61.7 (d, *J*=5.4 Hz), 52.8, 16.6 (d, *J*=6.4 Hz). ³¹P NMR (162 MHz, CDCl₃) δ: 18.7. HRMS (ESI-TOF) *m/z*: [M+Na]⁺ Anal. calcd for C₁₄H₁₈PNaNO₅ 334.0820, found 334.0852.

Methyl 1-methyl-3-(dimethoxyphosphoryl)-1*H*-indole-2-carboxylate (**3b**) Yellow oil (103 mg, 69% yield). ¹H NMR (400 MHz, CDCl₃) δ: 8.09 (d, *J*=8.1 Hz, 1H), 7.48~7.37 (m, 2H), 7.33~7.29 (m, 1H), 4.04 (s, 3H), 3.98 (s, 3H), 3.81 (d, *J*=11.3 Hz, 6H); ¹³C NMR (101 MHz, CDCl₃) δ: 161.7, 137.5 (d, *J*=14.7 Hz), 134.9 (d, *J*=22.7 Hz), 127.5 (d, *J*=11.1 Hz), 124.6, 122.3, 122.2, 110.0, 52.4, 52.3 (d, *J*=5.1 Hz), 31.5. ³¹P NMR (162 MHz, CDCl₃) δ: 17.97. HRMS (ESI-TOF) *m/z*: [M+Na]⁺ Anal. calcd for C₁₃H₁₇NO₅P 298.0844, found 298.0853.

Dimethyl (1-methyl-2-phenyl-1*H*-indol-3-yl)-phosphonate (**3d**) Yellow oil (79 mg, 25% yield). ¹H NMR (400 MHz, CDCl₃) δ: 8.06 (d, *J*=7.7 Hz, 1H), 7.52~7.45 (m, 5H), 7.40 (d, *J*=8.1 Hz, 1H), 7.37~7.32 (m, 1H), 7.31~7.26 (m, 1H), 3.60 (s, 6H), 3.57 (s, 3H);

¹³C NMR (101 MHz, CDCl₃) δ: 147.37 (d, *J*=24.2 Hz), 136.90 (d, *J*=14.4 Hz), 130.33, 130.04 (d, *J*=0.6 Hz), 128.79, 128.53 (d, *J*=12.7 Hz), 127.61, 122.46, 121.32, 120.98, 109.37, 97.19 (d, *J*=219.8 Hz), 51.55 (d, *J*=5.3 Hz), 30.60. ³¹P NMR (162 MHz, CDCl₃) δ: 19.69. HRMS (ESI-TOF) *m/z*: [M+H]⁺ Anal. calcd for C₁₇H₁₉NO₃P 316.1103, found 316.1088.

Ethyl 3-(dimethoxyphosphoryl)-5-fluoro-1*H*-indole-2-carboxylate (**3g**) Yellow oil (205 mg, 65% yield). ¹H NMR (400 MHz, CDCl₃) δ: 11.30 (s, 1H), 7.91 (dd, *J*=10.2, 2.4 Hz, 1H), 7.57~7.48 (m, 1H), 7.12~7.01 (m, 1H), 4.35 (q, *J*=7.1 Hz, 2H), 3.83 (d, *J*=11.6 Hz, 6H), 1.34 (t, *J*=7.1 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ: 159.58, 158.57 (d, *J*=238.0 Hz), 132.80 (d, *J*=20.7 Hz), 132.18 (d, *J*=15.2 Hz), 129.93 (t, *J*=11.4 Hz), 114.37 (d, *J*=27.1 Hz), 113.14 (d, *J*=9.6 Hz), 107.31 (d, *J*=25.4 Hz), 103.06 (d, *J*=217.5 Hz), 61.47, 52.26 (d, *J*=5.6 Hz), 13.52. ³¹P NMR (162 MHz, CDCl₃) δ: 17.83. HRMS (ESI-TOF) *m/z*: [M+H]⁺ Anal. calcd for C₁₃H₁₆FNO₅P 316.0750, found 316.0754.

Ethyl 3-(dimethoxyphosphoryl)-5-fluoro-1-methyl-1*H*-indole-2-carboxylate (**3h**) Yellow oil (263 mg, 80% yield). ¹H NMR (400 MHz, CDCl₃) δ: 7.79 (dd, *J*=9.8, 2.5 Hz, 1H), 7.37~7.31 (m, 1H), 7.17~7.08 (m, 1H), 4.47 (q, *J*=7.2 Hz, 2H), 3.94 (s, 3H), 3.77 (d, *J*=11.6 Hz, 6H), 1.45 (t, *J*=7.2 Hz, 3H); ¹³C NMR (101 MHz, CDCl₃) δ: 160.85, 158.68 (d, *J*=238.5 Hz), 136.15 (d, *J*=21.8 Hz), 133.98 (d, *J*=14.4 Hz), 128.15 (t, *J*=10.9 Hz), 113.45 (d, *J*=26.9 Hz), 110.97 (d, *J*=9.6 Hz), 107.09 (d, *J*=25.2 Hz), 101.71 (dd, *J*=217.0, 5.1 Hz), 61.89, 51.94 (d, *J*=5.3 Hz), 31.65, 13.34. ³¹P NMR (162 MHz, CDCl₃) δ: 17.48. HRMS (ESI-TOF) *m/z*: [M+H]⁺ Anal. calcd for C₁₄H₁₈FNO₅P 330.0907, found 330.0910.

Ethyl 5-chloro-3-(dimethoxyphosphoryl)-1*H*-indole-2-carboxylate (**3i**) Yellow oil (136 mg, 41% yield). ¹H NMR (400 MHz, CDCl₃) δ: 11.29 (s, 1H), 8.35 (s, 1H), 7.61 (d, *J*=8.7 Hz, 1H), 7.36 (d, *J*=10.3 Hz, 1H), 4.60~4.35 (m, 2H), 3.94 (d, *J*=11.5 Hz, 6H), 1.62~1.33 (m, 3H); ¹³C NMR (101 MHz, CDCl₃) δ: 159.55, 133.98 (d, *J*=15.2 Hz), 132.64 (d, *J*=20.8 Hz), 130.27 (d, *J*=11.8 Hz), 127.77, 125.68, 121.95, 113.29 (d, *J*=5.4 Hz), 102.61 (d, *J*=217.2 Hz), 61.55, 52.32 (d, *J*=5.5 Hz), 13.54. ³¹P NMR (162 MHz, CDCl₃) δ: 17.44. HRMS (ESI-TOF) *m/z*: [M+H]⁺ Anal. calcd for C₁₃H₁₆ClNO₅P 332.0455, found 332.0466.

Ethyl 5-chloro-3-(dimethoxyphosphoryl)-1-methyl-1*H*-indole-2-carboxylate (**3j**) Yellow oil (197 mg, 57% yield). ¹H NMR (400 MHz, CDCl₃) δ: 8.12 (s, 1H), 7.31 (s,

2H), 4.53~4.44 (m, 2H), 3.93 (d, $J=0.9$, 3H), 3.78 (dd, $J=11.6, 0.6$ Hz, 6H), 1.50~1.42 (m, 3H); ^{13}C NMR (101 MHz, CDCl_3) δ : 160.82, 136.07 (d, $J=22.0$ Hz), 135.72 (d, $J=14.3$ Hz), 128.50 (d, $J=10.9$ Hz), 127.86, 124.95, 121.60, 111.06, 101.41 (d, $J=216.7$ Hz), 61.96, 52.00 (d, $J=5.3$ Hz), 31.62, 13.36. ^{31}P NMR (162 MHz, CDCl_3) δ : 17.12. HRMS (ESI-TOF) m/z : $[\text{M}+\text{H}]^+$ Anal. calcd for $\text{C}_{14}\text{H}_{18}\text{ClNO}_5\text{P}$ 346.0611, found 346.0610.

Ethyl 5-bromo-3-(dimethoxyphosphoryl)-1*H*-indole-2-carboxylate (**3k**) Yellow oil (233 mg, 62% yield). ^1H NMR (400 MHz, CDCl_3) δ : 10.78 (s, 1H), 8.43 (s, 1H), 7.43 (d, $J=9.4$ Hz, 2H), 4.38 (q, $J=7.1$ Hz, 2H), 3.83 (d, $J=11.6$ Hz, 6H), 1.37 (t, $J=7.1$ Hz, 3H); ^{13}C NMR (101 MHz, CDCl_3) δ : 159.52, 134.07 (d, $J=15.1$ Hz), 132.33 (d, $J=20.6$ Hz), 130.91 (d, $J=11.9$ Hz), 128.31, 125.24, 115.53, 113.45, 102.81 (d, $J=216.9$ Hz), 61.61, 52.31 (d, $J=5.6$ Hz), 13.56. ^{31}P NMR (162 MHz, CDCl_3) δ : 17.34. HRMS (ESI-TOF) m/z : $[\text{M}+\text{H}]^+$ Anal. calcd for $\text{C}_{13}\text{H}_{16}\text{BrNO}_5\text{P}$ 375.9949, found 375.9960.

Ethyl 5-bromo-3-(dimethoxyphosphoryl)-1-methyl-1*H*-indole-2-carboxylate (**3l**) Yellow oil (253 mg, 65% yield). ^1H NMR (400 MHz, CDCl_3) δ : 8.29 (d, $J=1.7$ Hz, 1H), 7.45 (dd, $J=8.8, 1.8$ Hz, 1H), 7.27 (dd, $J=8.9, 2.0$ Hz, 1H), 4.48 (q, $J=7.1$ Hz, 2H), 3.93 (s, 3H), 3.78 (d, $J=11.6$ Hz, 6H), 1.47 (t, $J=7.2$ Hz, 3H); ^{13}C NMR (101 MHz, CDCl_3) δ : 160.82, 136.00 (d, $J=14.2$ Hz), 135.93 (d, $J=21.8$ Hz), 129.10 (d, $J=11.0$ Hz), 127.51, 124.73, 115.54 (d, $J=1.0$ Hz), 111.41, 101.37 (d, $J=216.6$ Hz), 61.99, 52.02 (d, $J=5.2$ Hz), 31.60, 13.37. ^{31}P NMR (162 MHz, CDCl_3) δ : 17.06. HRMS (ESI-TOF) m/z : $[\text{M}+\text{H}]^+$ Anal. calcd for $\text{C}_{14}\text{H}_{18}\text{BrNO}_5\text{P}$ 390.0106, found 390.0120.

Ethyl 3-(dimethoxyphosphoryl)-1-methyl-5-nitro-1*H*-indole-2-carboxylate (**3n**) Yellow oil (188 mg, 55% yield). ^1H NMR (400 MHz, CDCl_3) δ : 9.02 (d, $J=1.9$ Hz, 1H), 8.20 (dd, $J=5.0, 4.2$ Hz, 1H), 7.47 (dd, $J=9.2, 1.8$ Hz, 1H), 4.47 (q, $J=7.1$ Hz, 2H), 3.99 (s, 3H), 3.79 (d, $J=11.6$ Hz, 6H), 1.44 (t, $J=7.1$ Hz, 3H); ^{13}C NMR (101 MHz, CDCl_3) δ : 160.38, 143.20, 139.81 (d, $J=13.6$ Hz), 138.28 (d, $J=21.3$ Hz), 126.75 (d, $J=10.5$ Hz), 119.64, 119.54, 110.39, 104.82 (d, $J=216.7$ Hz), 62.39, 52.25 (d, $J=5.4$ Hz), 32.03, 13.37. ^{31}P NMR (162 MHz, CDCl_3) δ : 15.48. HRMS (ESI-TOF) m/z : $[\text{M}+\text{H}]^+$ Anal. calcd for $\text{C}_{14}\text{H}_{18}\text{N}_2\text{O}_7\text{P}$ 357.0852, found 357.0855.

Ethyl 3-(dimethoxyphosphoryl)-5-methyl-1*H*-indole-2-carboxylate (**3o**) Yellow oil (118 mg, 48% yield). ^1H NMR (400 MHz, CDCl_3) δ : 9.45 (s, 1H), 7.78 (d, $J=1.4$ Hz, 1H), 7.56~7.50 (m, 1H), 7.20 (dd, $J=8.5, 4.8$ Hz, 1H), 4.41 (q, $J=7.1$ Hz, 2H), 3.77 (d, $J=11.3$ Hz, 6H), 2.70 (d, $J=2.0$ Hz, 3H), 1.40 (t, $J=7.1$ Hz, 3H); ^{13}C NMR

(101 MHz, CDCl_3) δ : 161.7, 136.7 (d, $J=10.2$ Hz), 134.8 (d, $J=16.5$ Hz), 129.5, 129.3, 129.2, 128.6, 128.4, 128.1, 126.8, 121.3, 117.5, 115.9 (d, $J=3.5$ Hz), 115.7, 111.1, 109.3, 107.6, 60.7, 60.5, 51.7 (d, $J=5.2$ Hz), 21.1 (d, $J=3.9$ Hz), 20.9, 13.9. ^{31}P NMR (162 MHz, CDCl_3) δ : 18.26. HRMS (ESI-TOF) m/z : $[\text{M}+\text{H}]^+$ Anal. calcd for $\text{C}_{14}\text{H}_{19}\text{NO}_5\text{P}$ 312.1001, found 312.1008.

Ethyl 3-(dimethoxyphosphoryl)-1,5-dimethyl-1*H*-indole-2-carboxylate (**3p**) Yellow oil (169 mg, 52% yield). ^1H NMR (400 MHz, CDCl_3) δ : 7.95 (s, 1H), 7.34~7.30 (m, 1H), 7.29~7.16 (m, 1H), 4.50 (q, $J=7.2$ Hz, 2H), 3.96 (s, 3H), 3.80 (d, $J=11.5$ Hz, 6H), 2.50 (s, 3H), 1.49 (t, $J=7.2$ Hz, 3H); ^{13}C NMR (101 MHz, CDCl_3) δ : 161.34, 135.90 (d, $J=14.7$ Hz), 134.96 (d, $J=22.3$ Hz), 131.61, 127.97 (d, $J=11.4$ Hz), 126.32, 121.64, 109.53 (d, $J=1.0$ Hz), 100.89 (d, $J=215.7$ Hz), 61.72, 51.91 (d, $J=5.1$ Hz), 31.41, 21.09, 13.40. ^{31}P NMR (162 MHz, CDCl_3) δ : 18.41. HRMS (ESI-TOF) m/z : $[\text{M}+\text{H}]^+$ Anal. calcd for $\text{C}_{15}\text{H}_{21}\text{NO}_5\text{P}$ 326.1157, found 326.1169.

Ethyl 3-(dimethoxyphosphoryl)-5-methoxy-1-methyl-1*H*-indole-2-carboxylate (**3r**) Yellow oil (160 mg, 47% yield). ^1H NMR (400 MHz, CDCl_3) δ : 7.56 (d, $J=2.4$ Hz, 1H), 7.26~7.20 (m, 1H), 7.02~6.95 (m, 1H), 4.41 (q, $J=7.1$ Hz, 2H), 3.88 (s, 3H), 3.83 (s, 3H), 3.72 (d, $J=11.6$ Hz, 6H), 1.40 (t, $J=7.2$ Hz, 3H); ^{13}C NMR (101 MHz, CDCl_3) δ : 161.09, 155.51, 134.58 (d, $J=22.0$ Hz), 132.72 (d, $J=14.8$ Hz), 128.60 (d, $J=11.3$ Hz), 115.92, 110.75 (d, $J=0.9$ Hz), 102.50, 100.88 (d, $J=216.0$ Hz), 61.61, 55.14, 51.89 (d, $J=5.2$ Hz), 31.57, 13.36. ^{31}P NMR (162 MHz, CDCl_3) δ : 18.52. HRMS (ESI-TOF) m/z : $[\text{M}+\text{H}]^+$ Anal. calcd for $\text{C}_{15}\text{H}_{21}\text{NO}_6\text{P}$ 342.1106, found 342.1093.

Methyl 2-(dimethoxyphosphoryl)-1*H*-indole-3-carboxylate (**5a**) White solid (10.7 mg, 38% yield), m.p. 130~131 °C. ^1H NMR (400 MHz, $\text{DMSO}-d_6$) δ : 12.34 (s, 1H), 8.07 (d, $J=8.1$ Hz, 1H), 7.61 (d, $J=8.2$ Hz, 1H), 7.41~7.22 (m, 2H), 3.87 (s, 3H), 3.79 (d, $J=11.6$ Hz, 6H); ^{13}C NMR (101 MHz, $\text{DMSO}-d_6$) δ : 164.2, 137.3 (d, $J=12.9$ Hz), 129.4 (d, $J=214.1$ Hz), 126.7 (d, $J=12.7$ Hz), 125.0, 122.9, 122.1, 113.7, 112.7 (d, $J=15.2$ Hz), 53.8 (d, $J=5.8$ Hz), 51.8. ^{31}P NMR (162 MHz, $\text{DMSO}-d_6$) δ : 9.8. HRMS (ESI-TOF) m/z : $[\text{M}+\text{Na}]^+$ Anal. calcd for $\text{C}_{12}\text{H}_{14}\text{PNaO}_5$ 306.0507, found 306.0513.

Methyl 2-(diethoxyphosphoryl)-1*H*-indole-3-carboxylate (**5a'**) White solid (9.9 mg, 32% yield), m.p. 127~128 °C. ^1H NMR (400 MHz, CDCl_3) δ : 10.59 (s, 1H), 8.25 (d, $J=8.0$ Hz, 1H), 7.58 (d, $J=8.1$ Hz, 1H), 7.36 (m, 2H), 4.24 (m, 4H), 3.99 (s, 3H), 1.36 (t, $J=7.0$ Hz, 6H); ^{13}C NMR (101 MHz, CDCl_3) δ : 164.4, 125.0, 122.7 (d, $J=7.6$ Hz), 112.5, 63.5, 51.3, 16.3. ^{31}P NMR (162

MHz, CDCl₃) δ : 7.6. HRMS (ESI-TOF) m/z : [M+Na]⁺ Anal. calcd for C₁₄H₁₈PNaNO₅ 334.0820, found 334.0852.

Methyl 2-(dimethoxyphosphoryl)-1-methyl-1*H*-indole-3-carboxylate (**5b**) Yellow oil (253 mg, 65% yield). ¹H NMR (400 MHz, CDCl₃) δ : 8.07 (d, J =8.1 Hz, 1H), 7.47~7.36 (m, 2H), 7.29 (t, J =7.4 Hz, 1H), 4.15 (s, 3H), 3.97 (s, 3H), 3.85 (d, J =11.7 Hz, 6H); ¹³C NMR (101 MHz, CDCl₃) δ : 164.19, 138.62 (d, J =13.0 Hz), 127.17 (d, J =213.4 Hz), 125.34 (d, J =12.7 Hz), 124.80, 122.02, 121.94, 115.99 (d, J =14.6 Hz), 110.05 (d, J =1.9 Hz), 52.94 (d, J =5.7 Hz), 51.25, 32.54. ³¹P NMR (162 MHz, CDCl₃) δ : 10.16. HRMS (ESI-TOF) m/z : [M+Na]⁺ Anal. calcd for C₁₃H₁₆NNaO₅P 320.0664, found 320.0649.

Dimethyl (3-cyano-1*H*-indol-2-yl)phosphonate (**5c**) Yellow oil (63 mg, 25% yield). ¹H NMR (400 MHz, CDCl₃) δ : 12.31 (s, 1H), 7.82 (d, J =8.1 Hz, 1H), 7.66 (d, J =8.3 Hz, 1H), 7.44 (t, J =7.6 Hz, 1H), 7.34 (t, J =7.5 Hz, 1H), 3.97 (d, J =11.6 Hz, 6H); ¹³C NMR (101 MHz, CDCl₃) δ : 136.96 (d, J =13.2 Hz), 128.98 (d, J =216.0 Hz), 127.62 (d, J =11.5 Hz), 125.72, 122.68, 119.72, 114.22, 113.03, 92.82 (d, J =12.9 Hz), 53.75 (d, J =5.6 Hz). ³¹P NMR (162 MHz, CDCl₃) δ : 7.74. HRMS (ESI-TOF) m/z : [M+H]⁺ Anal. calcd for C₁₁H₁₂N₂O₃P 251.0586, found 251.0575.

Dimethyl (3-cyano-1-methyl-1*H*-indol-2-yl)phosphonate (**5d**) Yellow oil (164 mg, 62% yield). ¹H NMR (400 MHz, CDCl₃) δ : 7.75 (d, J =8.1 Hz, 1H), 7.44~7.38 (m, 2H), 7.34~7.27 (m, 1H), 4.03 (s, 3H), 3.90 (d, J =11.5 Hz, 6H); ¹³C NMR (101 MHz, CDCl₃) δ : 138.17 (d, J =12.2 Hz), 131.38 (d, J =214.1 Hz), 127.00 (d, J =11.8 Hz), 125.81, 122.62, 119.96, 114.05, 110.54 (d, J =1.9 Hz), 94.23 (d, J =12.8 Hz), 53.41 (d, J =6.0 Hz), 32.37. ³¹P NMR (162 MHz, CDCl₃) δ : 6.94. HRMS (ESI-TOF) m/z : [M+H]⁺ Anal. calcd for C₁₂H₁₄N₂O₃P 265.0742, found 265.0752.

Dimethyl (3-formyl-1*H*-indol-2-yl)phosphonate (**5e**) Yellow oil (129 mg, 51% yield). ¹H NMR (400 MHz, CDCl₃) δ : 11.98 (s, 1H), 10.37 (s, 1H), 8.44 (d, J =8.0 Hz, 1H), 7.65 (d, J =8.1 Hz, 1H), 7.42 (t, J =7.5 Hz, 1H), 7.36 (t, J =7.5 Hz, 1H), 3.90 (d, J =11.7 Hz, 6H); ¹³C NMR (101 MHz, CDCl₃) δ : 185.77, 137.45 (d, J =13.3 Hz), 130.39 (d, J =211.3 Hz), 125.59, 125.13 (d, J =13.0 Hz), 123.50, 122.56, 122.33 (d, J =16.0 Hz), 112.18, 53.18 (d, J =5.2 Hz). ³¹P NMR (162 MHz, CDCl₃) δ : 10.68. HRMS (ESI-TOF) m/z : [M+H]⁺ Anal. calcd for C₁₁H₁₃NO₄P 254.0582, found 254.0574.

Dimethyl (3-formyl-1-methyl-1*H*-indol-2-yl)phosphonate (**5f**) Yellow oil (150 mg, 56% yield). ¹H NMR

(400 MHz, CDCl₃) δ : 10.63 (s, 1H), 8.47 (d, J =8.0 Hz, 1H), 7.42~7.36 (m, 2H), 7.34~7.27 (m, 1H), 3.98 (s, 3H), 3.83 (d, J =11.6 Hz, 6H); ¹³C NMR (101 MHz, CDCl₃) δ : 188.43, 138.89 (d, J =12.2 Hz), 131.40 (d, J =208.4 Hz), 125.67, 124.66 (d, J =19.0 Hz), 124.38 (d, J =13.9 Hz), 123.36, 123.05, 109.76 (d, J =1.6 Hz), 52.73 (d, J =5.3 Hz), 31.99. ³¹P NMR (162 MHz, CDCl₃) δ : 9.64. HRMS (ESI-TOF) m/z : [M+H]⁺ Anal. calcd for C₁₁H₁₃NO₄P 268.0739, found 268.0741.

Methyl 3-(diphenylphosphoryl)-1*H*-indole-2-carboxylate (**7a**) White solid (315 mg, 83% yield), m.p. 215~216 °C. ¹H NMR (400 MHz, CDCl₃) δ : 9.95 (s, 1H), 7.90~7.75 (m, 4H), 7.60~7.40 (m, 7H), 7.35~7.25 (m, 1H), 7.21 (d, J =8.3 Hz, 1H), 7.10~6.96 (m, 1H), 3.39 (s, 3H); ¹³C NMR (101 MHz, DMSO-*d*₆) δ : 161.0, 137.1 (d, J =11.6 Hz), 135.6 (d, J =108.7 Hz), 132.1 (d, J =15.5 Hz), 131.8 (d, J =2.5 Hz), 131.3 (d, J =10.1 Hz), 130.3 (d, J =8.8 Hz), 128.9 (d, J =12.2 Hz), 125.3, 123.0, 121.8, 113.5, 108.4 (d, J =118.5 Hz), 52.0. ³¹P NMR (162 MHz, CDCl₃) δ : 22.3. MS (ESI-TOF) m/z : [M+H]⁺ Anal. calcd for C₂₂H₁₉PNO₃ 376.1, found 376.1.

Methyl 3-(diphenylphosphoryl)-1-methyl-1*H*-indole-2-carboxylate (**7b**) White solid (320 mg, 84% yield), m.p. 175~176 °C. ¹H NMR (400 MHz, DMSO-*d*₆) δ : 7.75~7.65 (m, 5H), 7.62~7.57 (m, 2H), 7.55~7.45 (m, 4H), 7.40~7.30 (m, 1H), 7.18 (d, J =8.2 Hz, 1H), 7.08~7.00 (m, 1H), 3.93 (s, 3H), 3.20 (s, 3H); ¹³C NMR (101 MHz, DMSO-*d*₆) δ : 161.9, 138.2 (d, J =10.6 Hz), 135.64 (d, J =16.2 Hz), 135.63, 134.5, 132.0 (d, J =2.7 Hz), 131.3 (d, J =10.1 Hz), 129.0 (d, J =12.1 Hz), 128.4 (d, J =8.7 Hz), 124.9, 124.9, 122.2 (d, J =20.7 Hz), 112.0, 107.0 (d, J =120.2 Hz), 52.3, 32.2. ³¹P NMR (162 MHz, DMSO-*d*₆) δ : 18.7. MS (ESI-TOF) m/z : [M+H]⁺ Anal. calcd for C₂₃H₂₁PNO₃ 390.1, found 390.1.

Diphenyl (2-phenyl-1*H*-indol-3-yl) phosphine oxide (**7c**) Yellow solid (287 mg, 73% yield), m.p. 237~238 °C. ¹H NMR (400 MHz, DMSO-*d*₆) δ : 12.27 (s, 1H), 7.67~7.58 (m, 4H), 7.56~7.47 (m, 3H), 7.45~7.37 (m, 2H), 7.38~7.28 (m, 4H), 7.25~7.08 (m, 4H), 6.82 (t, J =7.6 Hz, 1H), 6.49 (d, J =8.1 Hz, 1H); ¹³C NMR (101 MHz, DMSO-*d*₆) δ : 147.2 (d, J =17.3 Hz), 137.0 (d, J =11.5 Hz), 135.6 (d, J =105.8 Hz), 132.0, 131.9, 131.6 (d, J =9.7 Hz), 130.2, 130.1 (d, J =2.9 Hz), 128.9, 128.7 (d, J =11.8 Hz), 128.0, 125.7, 122.6, 120.7, 112.4, 101.1 (d, J =124.9 Hz). ³¹P NMR (162 MHz, DMSO-*d*₆) δ : 16.6. MS (ESI-TOF) m/z : [M+H]⁺ Anal. calcd for C₂₆H₂₁PNO 394.1, found 394.1.

Diphenyl (1-methyl-2-phenyl-1*H*-indol-3-yl)

phosphine oxide (**7d**) Yellow solid (167 mg, 72% yield), m.p. 213~214 °C. ^1H NMR (400 MHz, DMSO- d_6) δ : 7.70~7.48 (m, 5H), 7.42~7.39 (m, 2H), 7.34~7.09 (m, 10H), 6.98~6.93 (m, 2H), 3.53 (s, 3H); ^{13}C NMR (101 MHz, DMSO- d_6) δ : 147.9 (d, $J=18.4$ Hz), 137.7 (d, $J=10.7$ Hz), 135.3 (d, $J=106.0$ Hz), 131.6 (d, $J=9.8$ Hz), 131.5 (d, $J=2.6$ Hz), 131.1, 130.5, 129.2 (d, $J=9.8$ Hz), 129.0, 128.7, 128.6, 128.1, 122.8, 121.1 (d, $J=13.9$ Hz), 111.3, 102.5 (d, $J=126.1$ Hz), 31.4. ^{31}P NMR (162 MHz, DMSO- d_6) δ : 17.3. HRMS (ESI-TOF) m/z : $[\text{M} + \text{H}]^+$ Anal. calcd for $\text{C}_{27}\text{H}_{23}\text{PNO}$ 408.1517, found 408.1528.

Ethyl 3-(diphenylphosphoryl)-5-methyl-1*H*-indole-2-carboxylate (**7e**) Green solid (278 mg, 79% yield), m.p. 196~197 °C. ^1H NMR (400 MHz, DMSO- d_6) δ : 12.69 (s, 1H), 7.73~7.62 (m, 4H), 7.59~7.55 (m, 2H), 7.54~7.43 (m, 5H), 7.15~7.10 (m, 2H), 3.81 (q, $J=7.1$ Hz, 2H), 2.20 (s, 3H), 0.89 (t, $J=7.1$ Hz, 3H); ^{13}C NMR (101 MHz, DMSO- d_6) δ : 160.6, 135.8 (d, $J=109.1$ Hz), 135.4 (d, $J=11.6$ Hz), 132.2 (d, $J=15.6$ Hz), 131.8 (d, $J=2.4$ Hz), 131.4 (d, $J=10.1$ Hz), 130.7 (d, $J=8.8$ Hz), 130.5, 128.8 (d, $J=12.1$ Hz), 127.1, 122.3, 113.1, 107.2 (d, $J=118.9$ Hz), 61.3, 21.8, 14.0. ^{31}P NMR (162 MHz, DMSO- d_6) δ : 21.3. HRMS (ESI-TOF) m/z : $[\text{M} + \text{H}]^+$ Anal. calcd for $\text{C}_{24}\text{H}_{23}\text{PNO}_3$ 404.1416, found 404.1425.

Methyl 2-(diphenylphosphoryl)-1*H*-indole-3-carboxylate (**7f**) White solid (191 mg, 51% yield), m.p. 214~215 °C. ^1H NMR (400 MHz, CDCl_3) δ : 11.90 (s, 1H), 8.24~8.16 (m, 1H), 7.93~7.85 (m, 4H), 7.60~7.57 (m, 2H), 7.47~7.50 (m, 5H), 7.36~7.20 (m, 2H), 3.55 (s, 3H); ^{13}C NMR (101 MHz, DMSO- d_6) δ : 164.0, 138.0 (d, $J=9.7$ Hz), 134.5 (d, $J=110.6$ Hz), 132.9, 132.6 (d, $J=2.7$ Hz), 131.7 (d, $J=10.6$ Hz), 129.0 (d, $J=12.7$ Hz), 127.5 (d, $J=8.3$ Hz), 124.8, 122.9, 121.9, 114.0, 112.4 (d, $J=10.0$ Hz), 50.9. ^{31}P NMR (162 MHz, CDCl_3) δ : 26.2. HRMS (ESI-TOF) m/z : $[\text{M} + \text{H}]^+$ Anal. calcd for $\text{C}_{22}\text{H}_{19}\text{PNO}_3$ 376.1103, found 376.1105.

Methyl 2-(diphenylphosphoryl)-1-methyl-1*H*-indole-3-carboxylate (**7g**) White solid (214 mg, 55% yield), m.p. 181~182 °C. ^1H NMR (400 MHz, DMSO- d_6) δ : 7.89 (d, $J=8.1$ Hz, 1H), 7.81~7.69 (m, 4H), 7.69~7.61 (m, 3H), 7.59~7.54 (m, 4H), 7.43 (t, $J=7.4$ Hz, 1H), 7.30 (t, $J=7.3$ Hz, 1H), 4.03 (s, 3H), 3.11 (s, 3H); ^{13}C NMR (101 MHz, DMSO- d_6) δ : 164.1, 139.6 (d, $J=8.0$ Hz), 133.6, 132.63 (d, $J=2.7$ Hz), 132.57 (d, $J=107.0$ Hz), 132.5, 131.5 (d, $J=10.5$ Hz), 129.2 (d, $J=12.7$ Hz), 125.7 (d, $J=9.1$ Hz), 125.5, 122.2 (d, $J=127.2$ Hz), 115.9 (d, $J=11.7$ Hz), 111.7, 51.4, 33.7. ^{31}P NMR (162 MHz, CDCl_3) δ : 22.3. HRMS (ESI-TOF) m/z : $[\text{M} + \text{H}]^+$ Anal.

calcd for $\text{C}_{23}\text{H}_{21}\text{PNO}_3$ 390.1259, found 390.1284.

2-(Diphenylphosphoryl)-1*H*-indole-3-carbaldehyde (**7h**) Yellow solid (245 mg, 68% yield), m.p. 263~264 °C. ^1H NMR (400 MHz, DMSO- d_6) δ : 12.40 (s, 1H), 10.33 (s, 1H), 8.23 (d, $J=7.9$ Hz, 1H), 7.81~7.69 (m, 6H), 7.66~7.61 (m, 4H), 7.58 (d, $J=8.1$ Hz, 1H), 7.40~7.25 (m, 2H); ^{13}C NMR (101 MHz, DMSO- d_6) δ : 187.5, 138.7 (d, $J=43.3$ Hz), 138.2 (d, $J=54.6$ Hz), 133.5 (d, $J=2.7$ Hz), 132.6, 132.0 (d, $J=10.7$ Hz), 131.5, 129.6 (d, $J=12.5$ Hz), 125.8, 125.6 (d, $J=8.6$ Hz), 124.3 (d, $J=11.2$ Hz), 123.1 (d, $J=147.5$ Hz), 113.6. ^{31}P NMR (162 MHz, DMSO- d_6) δ : 19.4. HRMS (ESI-TOF) m/z : $[\text{M} + \text{H}]^+$ Anal. calcd for $\text{C}_{21}\text{H}_{16}\text{PNaNO}_2$ 368.0816, found 368.0847.

Diphenyl (3-phenyl-1*H*-indol-2-yl) phosphine oxide (**7i**) Yellow solid (208 mg, 51% yield), m.p. 219~220 °C. ^1H NMR (400 MHz, DMSO- d_6) δ : 11.39 (s, 1H), 7.62~7.42 (m, 8H), 7.40~7.38 (m, 4H), 7.34~7.24 (m, 3H), 7.20~7.05 (m, 4H); ^{13}C NMR (101 MHz, DMSO- d_6) δ : 138.3 (d, $J=9.9$ Hz), 133.8 (d, $J=11.5$ Hz), 132.6, 132.3 (d, $J=2.6$ Hz), 131.8 (d, $J=10.1$ Hz), 130.6, 129.5 (d, $J=12.5$ Hz), 128.9 (d, $J=12.2$ Hz), 128.1, 127.6 (d, $J=10.8$ Hz), 127.0, 126.7 (d, $J=13.1$ Hz), 125.9, 124.7 (d, $J=4.0$ Hz), 120.6 (d, $J=53.2$ Hz), 113.2. ^{31}P NMR (162 MHz, DMSO- d_6) δ : 17.3. HRMS (ESI-TOF) m/z : $[\text{M} + \text{H}]^+$ Anal. calcd for $\text{C}_{26}\text{H}_{21}\text{PNO}$ 394.1361, found 394.1379.

2-(Diphenylphosphoryl)-1*H*-indole-3-carbonitrile (**7j**) White solid (209 mg, 61% yield), m.p. 229~230 °C. ^1H NMR (400 MHz, DMSO- d_6) δ : 12.92 (s, 1H), 7.79~7.67 (m, 7H), 7.66~7.60 (m, 5H), 7.44~7.40 (m, 1H), 7.36~7.29 (m, 1H); ^{13}C NMR (101 MHz, DMSO- d_6) δ : 137.7 (d, $J=6.6$ Hz), 136.6, 133.6 (d, $J=2.7$ Hz), 132.0 (d, $J=10.7$ Hz), 131.1 (d, $J=109.4$ Hz), 129.6 (d, $J=12.6$ Hz), 128.6 (d, $J=8.0$ Hz), 126.1, 123.3, 119.6, 114.7, 114.2, 92.7 (d, $J=10.7$ Hz). ^{31}P NMR (162 MHz, DMSO- d_6) δ : 17.5. HRMS (ESI-TOF) m/z : $[\text{M} + \text{H}]^+$ Anal. calcd for $\text{C}_{21}\text{H}_{16}\text{PN}_2\text{O}$ 343.1000, found 343.1013.

Methyl 3-(bis(4-methoxyphenyl)phosphoryl)-1*H*-indole-2-carboxylate (**7k**) Yellow oil (270 mg, 62% yield). ^1H NMR (400 MHz, CDCl_3) δ : 11.39 (s, 1H), 7.86~7.59 (m, 4H), 7.47 (s, 1H), 7.27~7.11 (m, 2H), 7.02~6.90 (m, 5H), 3.83 (s, 6H), 3.30 (s, 3H); ^{13}C NMR (101 MHz, CDCl_3) δ : 162.1, 136.6, 133.4, 132.0, 130.2, 126.7, 125.6, 125.1, 123.0, 121.8, 113.9, 113.8, 112.8, 55.3, 51.8. ^{31}P NMR (162 MHz, CDCl_3) δ : 23.2. HRMS (ESI-TOF) m/z : $[\text{M} + \text{H}]^+$ Anal. calcd for $\text{C}_{24}\text{H}_{23}\text{PNO}_5$ 436.1314, found 436.1327.

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