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FULL PAPER

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New palladium (II) complexes containing phosphine-nitrogen ligands and their use as catalysts in aminocarbonylation reaction

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Aminocarbonylation of aryl halides, homogeneously catalysed by palladium, is an efficient method that can be employed for obtaining amides for pharmaceutical and synthetic applications.

In this work, palladium (II) complexes containing *P^N* ligands were studied as catalysts in the aminocarbonylation of iodobenzene in the presence of diethylamine. Two types of systems were used: a palladium (II) complex formed *in situ*; and one prepared prior to the catalytic reaction. In general, the palladium complexes studied achieved high conversions in an average reaction time of less than 2 hr, which is less than that for the standard system (Pd (II)/PPh_3) used. The pre-synthesized complexes were faster than their *in situ* counterparts, as the latter require an induction time to form the Pd/*P^N* species. The structure and electronic properties of the ligand *P^N* can influence both the activity and the selectivity of the reaction, stabilizing the acyl-palladium intermediates formed in a better manner.

KEYWORDS
amide synthesis, aminocarbonylation, aryl halide, palladium complex, phospho-nitrogen ligands

1 | INTRODUCTION

Palladium (II) catalysts have been used in the synthesis of amides since when Heck reported synthesis from aryl halides.[1–3] These aromatic amides can be used as synthesis blocks in the polymerization of products of pharmacological interest.[4–7] For example, 13α-steroid amide products that are pharmacologically significant have been synthesized using homogeneous palladium catalysts.[8,9]

For this reaction, palladium (II) catalysts formed *in situ* are currently used by reaction of a palladium (II) precursor and a ligand such as PPh_3. Palladium (II) complexes containing bidentate *P^P* ligands that have been studied as catalysts in aminocarbonylation show high activity but in a longer time compared with a standard catalyst Pd (II)/PPh_3, as the ligand stabilizes the Pd (0)/*P^P* species too much, hindering the oxidative addition of the substrate. Other bidentate ligands, such as the *P^N* ligands, combine the properties of phosphorus and

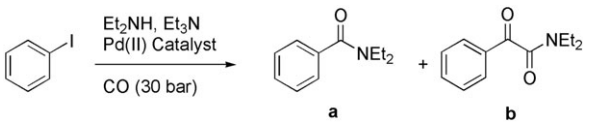
nitrogen to give the ligand potential hemilabile and bifunctional properties. These ligands have been successfully studied as part of catalytic systems where the properties of the ligand can influence both the activity and selectivity of the reaction. In this work, aminocarbonylation of aryl halides has been reported using new palladium (II) catalysts containing *P^N* ligands. The activity of the complexes used was compared with a Pd (II)/PPh_3 catalyst. All the catalysts that were studied reached 100% conversion and two major products were obtained: amide (**a**) and amide (**b**) (Scheme 1).

The results obtained show that the favoured product was amide (**b**), with the best results being obtained with the catalyst [Pd(L_1)Cl_2] (92% conversion with a 95% selectivity towards amide (**b**) after 2 hr), and that the electronic properties of the ligand can also influence both activity and chemoselectivity.

2 | RESULTS AND DISCUSSION

2.1 | Synthesis

For this study, new *P^N* ligands were prepared based on previous experiences (Figure 1).[10–12] In the case of ligand L_1 (Scheme 2), it was found that the usual excess of Et_3N used for its synthesis[10] could deprotonate the amine group of the precursor entirely, leading to the formation of a *bis*-diphenylphosphine (evidenced by the ^{31}P-NMR shift in 62.57 ppm).



SCHEME 1 Iodobenzene aminocarbonylation catalysed by palladium (II) complexes, which yield amides **a** and **b** as major products

This is attributed to the pKa of the substrate (pKa 2-picolineamine = 8.6),[13] which is lower than the standard for heterocyclic amines used as precursors (pKa ~ 13).[14] This double deprotonation led to a modification in the synthetic route using a stoichiometric amount of Et_3N for the synthesis of L_1.

After purification, single monocrystals from the oxide of L_1 ligand were obtained from the washing mixture and resolved via X-ray diffraction (Figure 2; Table 1). *P^N* ligands are known to be air-sensitive in solution, which

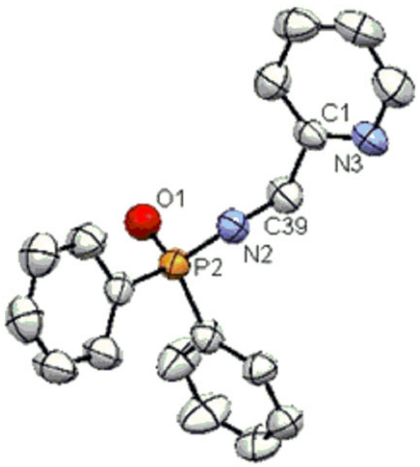


FIGURE 2 Molecular structure of the oxide of L_1 with ellipsoids drawn at 30% probability level. Hydrogen atoms and solvent molecules are omitted for clarity

TABLE 1 Selected bond lengths and angles for oxide of L_1

Bond	Bond length (Å)	Bond	Bond angle (°)
N2-P2	1.646(7)	P2-N2-C39	118.9(6)
N2-C39	1.429(11)	N2-P1-C13	103.5(3)
P2-O1	1.457(7)	N2-P2-O1	112.7(4)
P2-C13	1.799(8)	C13-P2-C31	108.7(4)
Pd-C31	1.806(8)		

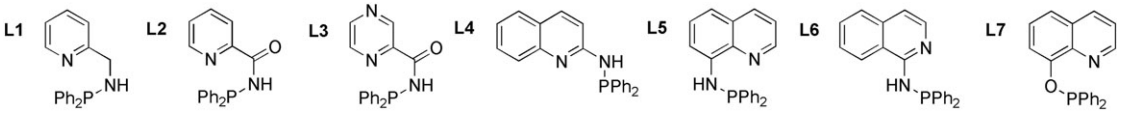
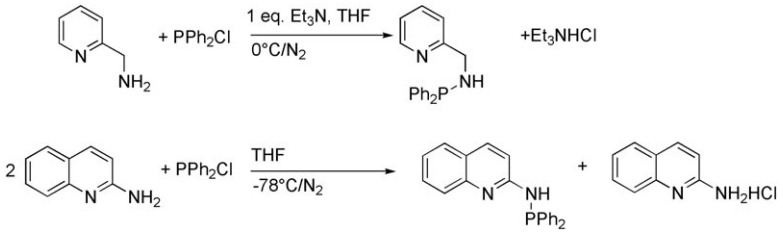


FIGURE 1 P, N-donor ligands used for aryl halide aminocarbonylation



SCHEME 2 Synthesis of phosphorus-nitrogen ligands

leads to oxidation of the phosphine group. The resolved structure shows that one diphenylphosphine group linked the amine moiety of the pyridine-derived substrate through nucleophilic substitution, which was the main goal. ^{31}P-NMR analysis confirmed that L_1 ligand has a non-oxidized diphenylphosphine group, showing a signal at 23.9 ppm, which is consistent with other *P^N* ligands, unlike its oxide that shows a higher shift at 42.2 ppm.

Regarding ligands L_4–L_6, Et_3N was not used for their synthesis because it forms a stable product with the substrate by avoiding nucleophilic substitution. Instead, a second equivalent of aminoquinoline was used to neutralize the formed HCl.[15] The L_7 ligand was prepared according to literature,[16] yielding a white product confirmed by ^{1}H- and ^{31}P-NMR.

Palladium (II) complexes containing *P^N* ligands were prepared according to the literature[9–12] using $PdCl_2$ as precursor. Palladium complexes based on Pd $(OAc)_2$ were also prepared with the aim of studying these complexes as catalysts, as the use of *in situ* palladium acetate systems is widely known.[12,17–19] Further, ^{31}P-NMR analysis yielded no signals of coordinated phosphine nor any signal at all, so no Pd(*P^N*)$(OAc)_2$ complexes were studied in this work.

All prepared complexes, with the exception of [Pd(L_7) Cl_2], are insoluble in most organic solvents; the presence of an oxygen atom in the structure of ligand L_7 is probably responsible for its better solubility in chloroform and dichloromethane. This allowed to obtain monocrystals of [Pd(L_7)Cl_2] (Figure 3; Table 2).

From the data obtained, it is confirmed that the *P^N* ligands coordinate in a bidentate manner with the palladium centre, forming a distorted planar square complex. The bite angle of the chelating ring formed by ligand L_7 is 86°, slightly greater than the bite angle of *P^N* ligands, which form a five-membered ring. The distance found between the palladium centre and a chloride ligand from another complex [Pd1-Cl21 = 3.9189(18) Å] may suggest the formation of a coordination dimer or polymer, which would explain the low solubility of almost all the palladium (II) complexes studied in this work (Figure 3, right). This interaction might be broken when one of these chlorides are substituted by dimethylformamide (DMF) or dimethylsulphoxide (DMSO), which can enter the coordination sphere of the metal when they are used as solvents.

TABLE 2 Selected bond lengths and angles for complex [Pd(L_7) Cl_2]

Bond	Bond length (Å)	Bond	Bond angle (°)
Pd1-Cl1	2.2827(15)	Cl1-Pd1-Cl2	89.69(5)
Pd1-Cl2	2.3799(15)	Cl1-Pd1-P1	91.61(5)
Pd1-P1	2.1738(14)	Cl1-Pd1-N1	175.35(10)
Pd1-N1	2.079(3)	Cl2-Pd1-P1	170.82(5)
Pd1-O2	1.613(3)	Cl2-Pd1-N1	92.93(10)
Pd1---Cl2	3.9189(18)	P1-Pd1-N1	86.40(10)
		P1-O2-Cqn	122.8(3)

2.2 | Catalytic studies

Catalytic results are summarized in Table 3. For this study, a Pd (II)/PPh_3 catalyst was used as reference (Table 3, entry 1), and two synthesis approaches were followed: forming the Pd (II)/*P^N* complex *in situ* (mixing the reactants in the reaction medium); and using a previously synthesized palladium (II) complex. Iodobenzene was used as a substrate as it is commonly used as a reference for these types of studies. On the other hand, the catalytic reaction was studied using palladium (II) acetate as precursor as *in situ* catalyst, while palladium

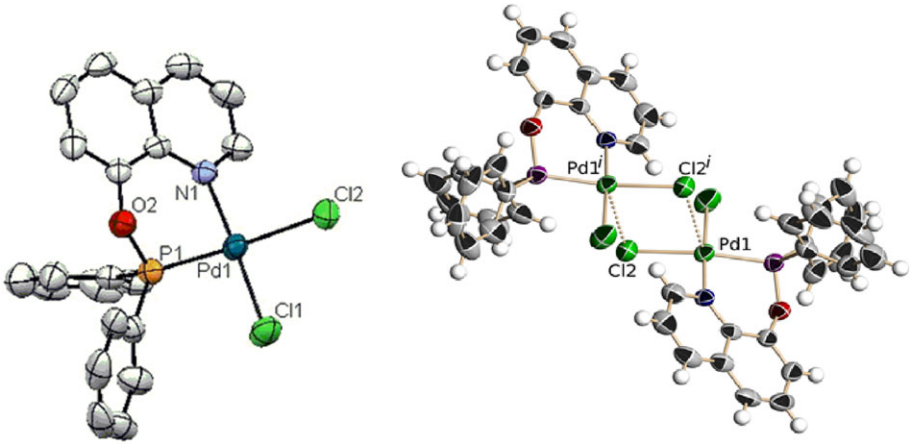


FIGURE 3 Molecular structure of complex Pd(L_7)Cl_2 with ellipsoids drawn at 30% probability level. Hydrogen atoms and solvent molecules are omitted for clarity

TABLE 3 Aryl halide aminocarbonylation with palladium (II) complexes

Entry	Catalyst	Conv. (%)	Time (hr)	k (hr^{-1})	a:b
1	Pd + PPh_3	96	4	0.76	29/71
2	Pd + L_1	92	2	1.15	5/95
3	Pd + L_2	98	3	0.63	40/60
4	Pd + L_3	96	3	1.02	39/61
5	Pd + L_4	97	2	1.63	14/86
6	Pd + L_5	98	2	1.62	16/84
7	Pd + L_6	93	3	0.91	14/86
8	Pd + L_7	96	3	1.08	25/75
9	[Pd(L_1)Cl_2]	91	2	1.33	5/95
10	[Pd(L_2)Cl_2]	97	4	0.84	32/68
11	[Pd(L_3)Cl_2]	99	3	1.52	28/72
12	[Pd(L_4)Cl_2]	97	2	1.65	34/66
13	[Pd(L_5)Cl_2]	99	3	1.54	40/60
14	[Pd(L_6)Cl_2]	94	2	1.32	14/86
15	[Pd(L_7)Cl_2]	96	2	1.62	34/66

Pd = Pd $(OAc)_2$ (0.075 mmol), L = 0.075 mmol, palladium catalyst (0.075 mmol), iodobenzene 7.5 mmol, Et_2NH 22.5 mmol, Et_3N 1.5 mL, DMF 10 mL, CO 30 bar, T 90°C. **a** = phenyl acetamide; **b** = oxo-phenyl acetamide.

complexes were synthesized from palladium (II) chloride. Nevertheless, when using $PdCl_2$ instead of Pd $(OAc)_2$, it behaves closely like the palladium acetate system, achieving 93% conversion after 4 hr of reaction and with a chemoselectivity towards amide (**b**) of 96%.

According to these results, all Pd (II) catalysts containing *P^N* ligands achieved near complete conversion after 3 hr of reaction on average, while reference Pd (II)/PPh3 catalyst required 4 hr to achieve the same conversion (Table 3, entry 1), which is consistent with results reported in literature.[12,17–19]

In all entries, Pd (II) catalysts remained in homogeneous phase in the course of the reaction; it seems that the *P^N* ligand forms a stable Pd (0) complex, avoiding the formation of palladium (0) (black) in the reductive carbon monoxide atmosphere.[20]

Overall, palladium (II) complexes synthesized prior to their study are faster catalysts than *in situ* systems containing the same *P^N* ligand, as evidenced by the calculated pseudo first-order kinetic rates (*k*, Table 3); however, these *k* rates can be only used as references as they were calculated only with a few points. These values suggest that *in situ* catalysts require an induction time in which the palladium (II)/*P^N* donor species is formed prior to its reduction to a palladium (0) complex.[20,21] This induction time is apparently neglected or eliminated by using the already formed Pd (II)/*P^N* species, leading directly to the formation of the corresponding Pd (0) complex, which is the active catalytic species for this reaction.

3 | INFLUENCE OF *P^N* LIGAND

In this work, several *P^N* ligands share the same general structure, which makes it interesting to study the electronic effects caused by the presence of different groups. For example, L_1 lacks the amide group that L_2 possesses, and L_3 has a pyrazine heterocycle instead of the pyridine cycle found in ligands L_1 and L_2. Pd (II) catalysts containing L_1 achieved higher reaction rates than palladium catalysts containing L_2, both *in situ* and pre-synthesized, as shown by the calculated *k* constant (Table 3, entries 2, 3, 9 and 10).

It seems that the presence of an electron-withdrawing group in the structure of the ligand, such as an amide moiety, negatively affects the catalyst activity; *in situ* palladium (II) catalysts have a lower *k* constant compared with even the reference experiment using Pd/PPh_3 catalyst.

This drawback is overcome by adding a second nitrogen atom to the structure of the ligand as observed with catalysts containing L_3, which have similar *k* constants to Pd/L_1 catalysts (Table 3, entries 4 and 11), indicating that the pyrimidine group influences the reaction in the opposite direction of the effect of the amide group. Ligands *P^N* can stabilize early reaction states, such as the formation of the catalytic species of Pd (0), evidenced by the absence of black palladium (0). The presence of an additional electron-donating group improves the stability, while an electron-withdrawing group can hinder it.

The same effect can be observed in the chemoselectivity, where amide (**b**) constitutes almost the entire product that is formed when a catalyst containing L_1 is used; instead, using ligands L_2 and L_3 leads to a more even selectivity.

According to the mechanism proposed by Csók et al.[21] (Figure 4), chemoselectivity is defined as when the acyl palladium intermediary undergoes aminolysis [to produce amide (**a**)] or a second molecule of CO is coordinated, resulting in amide (**b**) (Figure 4). If the ligand *P^N* can better stabilize the intermediate, it will be more likely to enter a second molecule of CO, whereas the presence of an electron-withdrawing group in the ligand *P^N* stabilizes in a lesser way, relatively increasing the production of amide (**a**).

Both catalysts prepared *in situ* and those prepared prior to their use as catalysts show the same selectivity when compared with systems using the same ligand. This may be due to the fact that they form the same intermediary, resulting in the same proportion of products.

Palladium catalysts containing ligands L_4 and L_5 showed the highest conversion rate in this study,

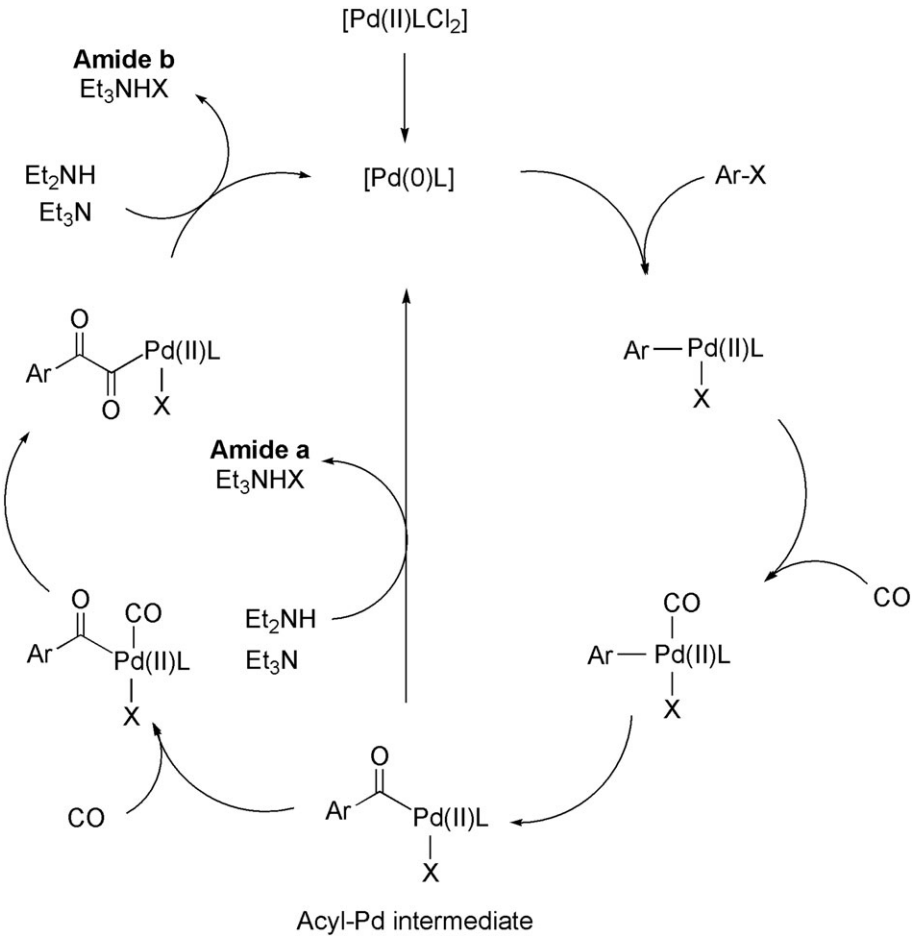


FIGURE 4 Mechanism of aminocarbonylation reaction

achieving almost complete conversions after 2 hr of reaction with both *in situ* and prior-synthesized methodologies (Table 3, entries 5, 6, 12 and 13). A more conjugated ligand could better stabilize the initial states of the reaction as compared with simpler ligands.

It is worth noting that ligand L_4 forms a five-member chelating ring with the metallic centre, while L_5 forms a six-member chelating one, which slightly increases the bite angle according to what can be observed with $[Pd(L_7)Cl_2]$. However, catalysts containing ligands L_4 and L_5 achieve the same activity and selectivity, which implies that the change is less important than the electronic and steric properties of the ligand. The steric effect can be observed with the *in situ* catalyst Pd + L_6, which shows a longer induction time compared with Pd + L_4, whereas the corresponding previously formed complex does not show greater differences with respect to $[Pd(L_4)Cl_2]$, considering that both ligands form the same coordination ring.

Meanwhile, the *in situ* generated catalyst Pd + L_7 exhibits similar behaviour for catalysts containing L_2 with a lower *k* constant. The presence of an electron-withdrawing atom in the structure of the ligand lowers the potential stabilization of the palladium (0) species, which leads to a longer induction time. In contrast, $[Pd(L_7)Cl_2]$ shows no signs of this effect, as both activity and chemoselectivity are close to palladium complexes, containing quinoline amine-derived ligands.

4 | EFFECT OF THE AUXILIARY LIGAND AND LOW CO PRESSURE IN THE AMINOCARBONYLATION REACTION

Several carbonylation reactions can only be carried out in the presence of an auxiliary ligand, usually PPh_3, even when working with *P^N* heterobidentated ligands.[22] This ligand is oxidized in the formation of the catalytic palladium (0) species, reducing it, and avoiding the formation of metallic palladium (0). To establish the necessity of an auxiliary ligand in this study, three catalytic systems were selected and an equivalent of PPh_3 (0.075 mmol) was added *in situ*. Results are resumed in Table 4.

TABLE 4 Aminocarbonylation using PPh_3 as auxiliary ligand

Entry	Catalyst	Aux. ligand	Time (hr)	Conv. (%)	TOF (hr^{-1})	a:b
1	Pd + L_3	PPh_3	3	90	30	29/71
2	Pd + L_3	–	3	96	32	39/61
3	Pd + L_5	PPh_3	3	98	33	25/75
4	Pd + L_5	–	2	98	49	16/84
5	[Pd(L_7)Cl_2]	PPh_3	2	90	45	34:66
6	[Pd(L_7)Cl_2]	–	2	96	48	36:64

Pd = Pd $(OAc)_2$ (0.075 mmol), L = 0.075 mmol, palladium catalyst (0.075 mmol), iodobenzene 7.5 mmol, Et_2NH 22.5 mmol, Et_3N 1.5 mL, DMF 10 mL, CO 30 bar, T 90°C. **a** = phenyl acetamide; **b** = oxo-phenyl acetamide.

All the studied systems achieved high conversions after 3 hr of reaction. However, when an additional equivalent of PPh_3 is added to *in situ* catalysts (Table 4, entries 1 and 3), there is a slight change in the activity and chemoselectivity; for example, the catalytic system containing $L_5 + PPh_3$ took longer to achieve the same conversion compared with the same system without the auxiliary ligand. In both *in situ* entries, chemoselectivity is similar to the observed when a standard Pd/PPh_3 catalyst is used. On the other hand, when the same auxiliary ligand is added to a palladium complex (Table 4, entries 5 and 6), no significant changes are observed.

These results suggest that, for this study, the reduction step of the catalytic species does not need an auxiliary ligand that could act as a reducing agent. Instead, when PPh_3 is added to *in situ* catalysts, it acts competitively with *P^N* ligands in the induction step, yielding a Pd (0)/PPh_3 active species. This is verified when a Pd (II) complex is used as catalyst, as the coordinate species is already formed; the same ligand competition was reported in octene hydrosterification carried by palladium (II) catalysts.[23] It also suggests that the reduction process might be carried out by the highly reductive CO atmosphere, where the *P^N* ligand is useful to stabilize the catalytic intermediate species.[20]

Catalytic experiments resumed in Table 3 were carried out at high CO pressure with the goal to compare with previously reported works.[7–9,17–20] In all entries, amide (**b**) is the favoured product. To establish what the influence of the CO pressure is in this behaviour, two *in situ* systems using ligands L_3 and L_4 (both with high activities and chemoselectivities at high CO pressure) were studied at the minimum pressure allowed by the reactors (approximately 5 bar). Catalytic results are resumed in Table 5.

In both low-pressure experiments, activities were lower than their higher-pressure counterparts. This can be attributed to a slower reduction step, in which the palladium (II) species is reduced by the CO atmosphere;[20] a lower CO availability leads to a slower reduction process. There is a change in the chemoselectivity in both cases, in which more amide (**a**) is produced. This is expected as a high CO pressure would force the insertion of a second monoxide molecule into the catalytic cycle. However, this change is notorious in the case of Pd + L_4, yielding amide (**a**) in a 4:1 ratio. On the other hand, catalyst containing L_3 achieved an **a**/**b** ratio more closely balanced. These results imply that structural differences in the P^N ligand could affect which pathway will follow the catalytic cycle. A more conjugated ligand, such as L_4, will stabilize acyl-palladium intermediates better under high-pressure conditions, whereas a *P^N* ligand with a minor conjugation will stabilize at lower or higher CO pressure at the same level.

TABLE 5 Low CO pressure studies with selected *in situ* Pd/*P^N* catalysts

Entry	Catalyst	CO pressure (bar)	Time (hr)	Conv. (%)	a:b
1	Pd + L_3	5	3	44	57/43
2	Pd + L_3	30	3	96	39/61
3	Pd + L_4	5	3	60	72/28
4	Pd + L_4	30	2	97	16/84

Pd = Pd $(OAc)_2$ (0.075 mmol), L = 0.075 mmol, palladium catalyst (0.075 mmol), iodobenzene 7.5 mmol, Et_2NH 22.5 mmol, Et_3N 1.5 mL, DMF 10 mL, T 90°C. **a** = phenyl acetamide; **b** = oxo-phenyl acetamide.

Aminocarbonylation reactions have been studied by several authors in order to obtain carboimines, amidoimidazopyridine and 2-ynamides.[23–25] The reaction has been catalysed using palladium complexes containing phosphine and diphosphine ligands. The catalysts studied showed high conversions; however, the time reaction was in the range of 5–12 hr. The advantage of palladium complexes containing phosphorus-nitrogen ligands reported here is that the catalysts show high conversions in a short reaction time (1 hr). Palladium complexes containing *P^N* heterobidentate ligands show advantages in aminocarbonylation reactions, where the ligand (by combining the hard and soft properties of the nitrogen and phosphorus atoms) favours the coordination effect on the metal during the catalytic reaction. These effects could favour the formation of the catalytic intermediate in the aminocarbonylation reaction.

5 | CONCLUSIONS

The palladium (II)/*P^N* complexes studied in this work are active catalysts in the aminocarbonylation of iodobenzene, and are usually faster than the reference

catalyst Pd (II)/PPh_3. The performance of the catalysts can be improved by using a more conjugated *P^N* ligand or more electron-donating fractions. Complexes prepared prior to their use as catalysts are faster than their *in situ* counterparts, as the ligand is already coordinated with the metal centre, reducing the induction time to form the palladium (0) species. The main factor of the chemoselectivity is the CO pressure; however, the ligand can mildly influence the selectivity by better stabilizing the intermediate that leads to the formation of amide (**b**). The use of ligand *P^N* also prevents the formation of black palladium, which is not catalytically active. The optimal Pd (II) catalyst found in this study is the complex $[Pd(L_1)Cl_2]$, which gives a 91% conversion in only 2 hr of reaction, and a chemoselectivity of 95% for the oxo-phenyl acetamide [or amide (**b**)] product.

6 | EXPERIMENTAL

All synthesis and procedures described in this work were carried out in an N_2 atmosphere using Schlenk techniques. Organic solvents (analysis grade) and substrates (synthesis grade) were supplied from Merck or Sigma-Aldrich, and dried before using if required. The NMR data were obtained using a Bruker 300 MHz spectrometer, and all measures were carried out at 298 K. Elemental analysis for the ligands and palladium complexes was conducted using a Thermo Scientific Flash 2000 Organic Elemental Analyzer coupled with an Agilent Technologies 6890 gas chromatograph. The X-ray diffraction studies were carried out using a Bruker-AXS Smart Apex II area-detector diffractometer, and the structures were resolved using direct methods and refined using the SHELXL software package. The GC analysis was performed on a Hewlett-Packard 5890 series II chromatograph equipped with a flame ionization detector (FID) and a Supelco Equity-1 column.

6.1 | Synthesis of L_1

A mixture of 2-picolineamine (1.5 g, 14 mmol) and Et_3N (1 eq.) in dry tetrahydrofuran (THF; 10 mL) was cooled down to 0°C. Then, a solution of PPh_2Cl (2.5 mL, 14 mmol) in THF (5 mL) was added drop-wise, and the resulting mixture was stirred overnight at room temperature. The solution was then filtered, and the solvent was removed under vacuum to yield a yellow oil. The ligand was precipitated using a $CHCl_3$/hexane mixture, yielding a white powder. Single crystals from the oxide of L_1 were obtained from the hexane phase, which were resolved using X-ray diffraction. Yield: 40% (white solid). ^{1}H-NMR (300 MHz, $CDCl_3$): 8.55 (d, $J = 4.6$ Hz, 1H, Py), 8.02–7.88 (m, 4H, Ph), 7.65 (td, $J = 7.7$, 1.7 Hz, 1H, Py), 7.57–7.39 (m, 6H, Ph), 7.27 (d, $J = 8.1$ Hz, 1H, Py), 7.20 (dd, $J = 7.1$, 5.2 Hz, 1H, Py), 4.44–4.22 (m, 2H, CH_2), 2.06 (s, 1H, NH).^{31}P-NMR (101 MHz, $CDCl_3$): 23.9 (s, 1P). IR (KBr, λ cm^{-1}): 3437, 1586 (NH); 3049, 744 (CH); 2915, 1433 (CH_2); 1072 (C-N); 859 (P-N). Crystallographic data for $C_{18}H_{17}N_2OP$ ($M = 38.54$ g mol^{-1}): monoclinic, space group $P2_1/c$ (no.14), $a = 11.304(2)$ Å, $b = 14.843(3)$ Å, $c = 10.553(2)$ Å, $\beta = 116.385(10)°$, $V = 1586.3(6)$ Å^3, $Z = 32$, $T = $ N/A K, μ (Mo Kα) = 0.176 mm^{-1}, D_{calc} = 1.2909 g cm^{-3}, 16 952 reflections measured (4.02° ≤ 2Θ 52°), 3113 unique ($R_{int} = 0.1333$, $R_{sigma} = 0.1161$), which were used in all calculations. The final R_1 was 0.1703 [$I \geq 2u(I)$] and wR_2 was 0.4943 (all data). Elemental analysis for $C_{17}H_{15}N_2P$ calcd (found): C: 73.37 (72.99); H: 5.43 (5.44); N: 10.07 (10.52).

6.2 | Synthesis of L_2 and L_3

Ligands L_2 and L_3 were synthesized by procedures described in the literature[10–12] using 2-picolineamide as the substrate for L_2 and pyrazine carboxamide for L_3.

L_2 (white solid); yield: 47%. ^{1}H-NMR (300 MHz, $CDCl_3$): δ 8.66 (d, $J = 8.7$ Hz, 1H, OH), 8.55 (d, $J = 8.5$ Hz, 1H, Py), 8.26 (d, $J = 8.2$ Hz, 1H, Py), 7.89–7.83 (m, 1H, Py), 7.54–7.37 (m, 10H, 2 Ph), 7.11 (s, 1H, NH). ^{31}P-NMR (101 MHz, $CDCl_3$): δ 23.69 (s, 1P). IR (KBr, λ cm^{-1}): 3300, 1452 (N-H); 3059, 698 (C-H); 1692 (C=O); 1412 (C-N); 817 (P-N). Elemental analysis for $C_{18}H_{15}N_2OP$ calcd (found): C: 70.58 (70.80); H: 4.94 (5.13); N: 9.15 (9.18).

L_3 (white yellow solid); yield: 62%. ^{1}H-NMR (300 MHz, $CDCl_3$): δ 9.46 (d, $J = 9.5$ Hz, 1H, Pyz), 8.78 (d, $J = 8.8$ Hz, 1H, Pyz), 8.53 (m, 1H, Pyz), 8.33 (d, $J = 8.3$ Hz, 1H, OH), 7.53–7.38 (m, 10H, 2 Ph), 5.78 (s, 1H, NH). ^{31}P-NMR (101 MHz, $CDCl_3$): δ 22.95 (s, 1P). IR (KBr, λ cm^{-1}): 3238, 1452 (N-H); 3054, 698 (C-H); 1667 (C=O); 1131 (C-N); 810 (P-N). Elemental analysis for $C_{17}H_{14}N_3OP$ calcd (found): C: 66.45 (65.71); H: 4.59 (4.44); N: 13.67 (13.62).

6.3 | Synthesis of L_4–L_6

Quinoline amine precursor (1 g, 7 mmol, L_4: quinoline-2-amine; L_5: 8-aminoquinoline; L_6: 1-aminoisoquinoline) in THF (10 mL) was cooled down to −78°C, and then a solution of PPh_2Cl (3.5 mmol) in THF (5 mL) was added drop-wise. The mixture was allowed to warm up to room temperature and stirred overnight. The solution was then filtered. The solvent evaporated under vacuum, and the product was precipitated from a mixture of CH_2Cl_2/diethyl ether, yielding a white powder for L_4 and L_6,

and an orange one for L_5. Aminoquinoline hydrochloride was obtained as a byproduct, which can be recovered using a $NaHCO_3/H_2O$ solution.

L_4 (white solid); yield: 79%. ^{1}H-NMR (250 MHz, $CDCl_3$): δ 8.01 (d, $J = 9.1$ Hz, 1H, Qn), 7.97–7.88 (m, 1H, Qn), 7.83 (d, $J = 9.5$ Hz, 1H, Qn), 7.79–7.68 (m, 1H, Qn), 7.70–7.62 (m, 1H, Qn), 7.62 (d, $J = 7.2$ Hz, 1H, Qn), 7.45–7.29 (m, 10H, 2 Ph), 6.27 (s, 1H, NH). ^{31}P-NMR (101 MHz, $CDCl_3$): δ 23.21 (s). Elemental analysis for $C_{21}H_{17}N_2P$ calcd (found): C: 76.36 (74.93); H: 5.22 (5.20); N: 8.53 (8.45).

L_5 (orange solid); yield: 31%. ^{1}H-NMR (300 MHz, $CDCl_3$): δ 8.67 (dd, $J = 4.2$–1.6 Hz, 1H, Qn), 7.97 (dd, $J = 8.3$–1.6 Hz, 1H, Qn), 7.60 (m, $J = 17.2$, 16.0, 10.4, 4.4 Hz, 1H, Qn), 7.48–7.32 (m, 1H, Qn), 7.34–7.13 (m, 10H, 2 Ph), 7.06 (d, $J = 8.1$ Hz, 1H, Qn), 6.84 (d, $J = 8.6$ Hz, 1H, Qn), 4.73 (s, 1H, NH). ^{31}P-NMR (101 MHz, $CDCl_3$): δ 22.67 (s). IR (KBr, λ cm^{-1}): 3306, 1481 (N-H); 1123, 721 (P-N). Elemental analysis for $C_{21}H_{17}N_2P$ calcd (found): C: 76.82 (74.93); H: 5.22 (5.15); N: 8.53 (8.65).

L_6 (white yellow solid); yield: 41%. ^{1}H-NMR (300 MHz, $CDCl_3$): δ 7.87 (dd, $J = 15.1$–7.1 Hz, 3H, Qn), 7.74–7.55 (m, 10H, 2 Ph), 7.46 (t, $J = 7$ Hz, 1H, Qn), 7.38 (dd, $J = 4.3$, 2.3 Hz, 1H, Qn), 7.27 (s, 1H, NH), 7.00 (d). ^{31}P-NMR (101 MHz, $CDCl_3$): δ 22.88 (s). IR (KBr, λ cm^{-1}): 3485, 1504 (N-H); 793, 701 (P-N). Elemental analysis for $C_{21}H_{17}N_2P$ calcd (found): C: 76.82 (75.93); H: 5.22 (5.20); N: 8.53 (8.25).

6.4 | Synthesis of L_7

Ligand L_7 was synthesized by procedures described in the literature,[16] yielding a white powder. Yield: 47%. ^{1}H-NMR (300 MHz, $CDCl_3$): δ 8.95–8.90 (m, 1H, Qn), 8.78 (d, $J = 4.2$ Hz, 1H, QN), 8.17 (d, $J = 1.5$ Hz, 1H, Qn), 8.14 (d, $J = 1.6$ Hz, 1H, Qn), 8.11 (d, $J = 1.7$ Hz, 1H, Qn), 7.63–7.53 (m, 1H), 7.54–7.31 (m, 10H, Ph). ^{31}P-NMR (121 MHz, $CDCl_3$): δ 116.89 (s). Elemental analysis for $C_{21}H_{16}NOP$ calcd (found): C: 76.59 (77.03); H: 4.90 (4.80); N: 4.25 (4.45).

6.5 | Synthesis of $[Pd(L)Cl_2]$ complexes ($L = L_1$–L_7)

Pd (II) complexes containing *P^N* ligands were synthesized by procedures described in the literature,[10–12] using $PdCl_2$ (500 mg, 2.8 mmol) as the precursor. Single crystals for X-ray diffraction studies were obtained from $[Pd(L_7)Cl_2]$.

$[Pd(L_1)Cl_2]$ (yellow solid); yield: 74%. ^{1}H-NMR (300 MHz, DMSO-d_6): δ 7.96 (d, $J = 8$ Hz, 1H, Py), 7.90–7.59 (m, 10H, 2 Ph), 7.42–7.36 (dt, $J = 7{,}4$, 7.4 Hz, 1H, Py), 7.04–7.00 (dd, $J = 7.0$–7.0 Hz, 1H, Py), 6.57 (d, $J = 6.6$ Hz, 1H, Py), 5.76 (s, 1H, NH), 4.49 (t, JH-H = 4.5 Hz, 2H, CH_2). ^{31}P-NMR (101 MHz, DMSO-d_6): δ 31.95 (s, 1P). IR (KBr, λ cm^{-1}): 3436, 1438 (N-H); 3078, 692 (C-H); 965, 730 (P-N). Elemental analysis for $C_{19}H_{19}Cl_2N_2PPd$ calcd (found): C: 46.03 (45.03); H: 3.65 (3.80); N: 5.96 (4.95).

$[Pd(L_2)Cl_2]$ (yellow green solid); yield: 37%. ^{1}H-NMR (300 MHz, DMSO-d_6): δ 8.85 (d, $J = 8.8$ Hz, 1H, NH), 8.64 (d, $J = 8.63$ Hz, 1H, Py), 8.14 (s, 1H, Py), 8.00 (s, 1H, Py), 8.04 (dt, $J = 8.0$–8.0 Hz, 1H, Py), 7.87–7.39 (m, 10H, 2 Ph). ^{31}P-NMR (101 MHz, DMSO-d_6): δ 78.84 (s, 1P). IR (KBr, λ cm^{-1}): 3232, 1446 (N-H); 3056, 746 (C-H); 1695 (C=O); 1392 (C-N); 1101 (P-N). Elemental analysis for $C_{18}H_{15}Cl_2N_2OPPd$ calcd (found): C: 44.70 (45.01); H: 3.13 (2.90); N: 5.79 (5.15).

$[Pd(L_3)Cl_2]$ (yellow solid); yield: 81%. ^{1}H-NMR (300 MHz, DMSO-d_6): δ 10.55 (s, 1H, OH); 9.19–8.62 (m, 2H, Pyz); 8.27 (s, 1H, Pyz); 8.05–7.40 (m, 10H, 2 Ph), 6.66 (s, 1H, NH). ^{31}P-NMR (101 MHz, DMSO-d_6): δ 82.29 (s, 1P). IR (KBr, λ cm^{-1}): 3435, 1436 (N-H); 3094, 689 (C-H); 1688 (C=O); 1381 (C-N); 1107 (P-N). Elemental analysis for $C_{17}H_{14}Cl_2N_3OPPd$ calcd (found): C: 42.13 (41.95); H: 2.91 (2.85); N: 8.67 (9.28).

$[Pd(L_4)Cl_2]$ (white yellow solid); yield: 37%. ^{1}H-NMR (300 MHz, DMF-d_7): δ 10.27 (dd, $J = 8.5$, 4.2 Hz, 1H, Qn), 10.07 (d, $J = 8.5$ Hz, 1H, Qn), 8.34 (s, 2H, Qn), 8.30 (d, $J = 2.9$ Hz, 1H, Qn), 8.27 (s, 1H, NH), 8.23 (d, $J = 6.0$ Hz, 3H, Ph), 8.18–8.10 (m, 2H, Ph), 8.04 (d, $J = 1.4$ Hz, 1H, Ph), 8.03–8.01 (m, 1H, Ph), 7.99 (d, $J = 1.5$ Hz, 1H, Qn), 7.97 (d, $J = 2.8$ Hz, 1H, Ph), 7.92 (dd, $J = 11.4$–4.3 Hz, 2H, Ph), 7.82 (dd, $J = 8.0$–1.1 Hz, 1H, Ph), 7.60 (dd, $J = 14.9$–7.5 Hz, 3H, Ph), 7.51–7.45 (m, 1H, Ph), 7.35 (d, $J = 9.0$ Hz, 1H, Qn), 7.28 (d, $J = 8.9$ Hz, 1H, Ph or Qn), 7.14 (d, $J = 8.9$ Hz, 1H, Ph or Qn). ^{31}P-NMR (101 MHz, $CDCl_3$): δ 78.38 (s). IR (KBr, λ cm^{-1}): 3442, 1510 (N-H); 834, 773 (P-N). Elemental analysis for $C_{21}H_{17}Cl_2N_3OPPd$ calcd (found): C: 49.88 (48.53); H: 3.39 (3.70); N: 5.54 (6.01).

$[Pd(L_5)Cl_2]$ (red solid); yield: 40%. ^{1}H-NMR (300 MHz, DMF-d_7): δ 9.63 (s, 1H, NH), 9.46 (dd, $J = 5.2$–1.3 Hz, 1H, Qn), 9.03 (dd, $J = 8.4$–1.3 Hz, 1H, Qn), 8.31 (d, $J = 8.0$ Hz, 1H, Qn), 8.21 (s, 3H, Ph), 8.18–8.10 (m, 3H, Ph), 8.10–7,97 (m, 2H, Ph), 6.01 (s, 1H, Qn). ^{31}P-NMR (121 MHz, DMF-d_7): δ 79.64 (s). Elemental analysis for $C_{21}H_{17}Cl_2N_2PPd$ calcd (found): C: 49.88 (48.56); H: 3.39 (3.77); N: 5.54 (5.48).

$[Pd(L_6)Cl_2]$ (yellow solid); yield: 35%. ^{1}H-NMR (300 MHz, DMF-d_7): δ 8.9 (s, 1H, NH), 8.69 (d, $J = 8.2$ Hz, 2H, Qn), 8.61 (t, $J = 5.6$ Hz, 2H, Qn), 8.53 (s, 2H, Qn), 8.31 (d, $J = 6.7$ Hz, 1H, Qn), 8.20 (d, $J = 10.8$ Hz, 3H, Qn), 8.11–7.86 (m, 4H, Ph), 7.80 (dd, $J = 14.1$, 7.2 Hz, 2H, Ph), 7.71 (dd, $J = 11.7$, 4.9 Hz, 1H, Ph), 7.24 (d, $J = 6.8$ Hz, 1H, Qn), 7.17 (dd, $J = 15.1$, 6.9 Hz, 1H, Qn). ^{31}P-NMR (121 MHz, DMF-d_7): δ 78.92 (s). IR (KBr, λ

cm^{-1}): 3340, 1440 (N-H); 952, 747 (P-N). Elemental analysis for $C_{21}H_{17}Cl_2N_2PPd$ calcd (found): C: 49.88 (48.03); H: 3.39 (3.50); N: 5.54 (5.18).

[Pd(L$_7$)Cl$_2$] (yellow solid); yield: 55%. ^{1}H-NMR (300 MHz, $CDCl_3$): δ 10.56 (dd, $J = 5.4–1.4$ Hz, 1H, Qn), 8.43 (dd, $J = 8.2–1.4$ Hz, 1H, Qn), 8.01–7.89 (m, 4H, Qn), 7.64–7.38 (m, 10H, 2 Ph). ^{31}P-NMR (101 MHz, $CDCl_3$): δ 114.5 (s). Crystallographic data for $C_{21}H_{16}NOPPdCl_2$ ($M = 506.66$ g mol^{-1}): monoclinic, space group $P2_1/n$ (no. 14), $a = 10.565(5)$ Å, $b = 11.311(5)$ Å, $c = 17.038(7)$ Å, $\beta = 99.28(2)°$, $V = 2009.2(16)$ Å^3, $Z = 4$, $T = 296.15$ K, μ(Mo Kα) = 1.280 mm^{-1}, $D_{calc} = 1.6748$ g cm^{-3}, 21 645 reflections measured ($4.34° \leq 2\Theta \leq 51.98°$), 3913 unique ($R_{int} = 0.1343$, $R_{sigma} = 0.1086$), which were used in all calculations. The final R_1 was 0.0453 [$I \geq 2u(I)$], and wR_2 was 0.0940 (all data).

6.6 | Catalytic essays

A mixture of catalyst (0.075 mmol), iodobenzene (7.5 mmol), diethylamine (2.4 mL) and Et_3N (1.5 mL) dissolved in DMF (10 mL) was introduced in a previously purged, glass-lined stainless-steel, high-pressure capable autoclave fitted with temperature and pressure control. The autoclave was then charged with CO (30 bar), and the temperature set up to 90°C ($t = 0$). Samples were collected every hour and analysed by gas chromatography (GC). The products obtained in the catalytic reaction were determined by GC–mass spectrometry (MS) in University of Chile's CEPEDEQ (Centro de Estudios para el Desarrollo de la Quimica). Pseudo first-order kinetic rate k for every entry was determined by the logarithmic plot of the initial rate vs. substrate concentration.

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