

EFFECT OF TEMPERATURE ON THE CATALYTIC ACTIVITY OF NEW SYMMETRICAL TETRADENTATE PALLADIUM(II) SCHIFF BASE COMPLEXES IN COPPER-FREE SONOGASHIRA REACTION

(Kesan Suhu Terhadap Aktiviti Pemangkinan Kompleks Baru Paladium(II) Tetradentat Bes Schiff Bersimetri dalam Tindak Balas Sonogashira Tanpa Kuprum)

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Abstract

This paper reports the synthesis of two tetradentate Schiff bases namely 2,2'-(((2,2-dimethylpropane-1,3-diyl)bis(azanylylidene))bis(methanylylidene))bis(4-methoxyphenol), LM, and 2,2'-(((2,2-dimethylpropane-1,3-diyl)bis(azanylylidene))bis(methanylylidene))bis(4-nitrophenol), LN. The Schiff bases were reacted with palladium(II) acetate in 1:1 molar ratio yielding two palladium(II) complexes, PdLN and PdLM. The compounds were characterized through elemental analysis, infrared spectroscopy, ¹H and ¹³C Nuclear Magnetic Resonance (NMR), magnetic susceptibility, molar conductivity and melting point. Complexation was indicated to have occurred by the shifting of the characteristic $\nu(\text{C}=\text{N})$, $\nu(\text{C}-\text{O})$ and $\delta(\text{HC}=\text{N})$ peaks. This was supported by appearance of new peaks of $\nu(\text{M}-\text{N})$ and $\nu(\text{M}-\text{O})$ as well as disappearance of $\delta(\text{O}-\text{H})$ peak on the IR and ¹H NMR spectra of the palladium(II) complexes. The diamagnetic and non-electrolytic nature of the complexes suggested square planar d^8 palladium(II) geometry and absence of counter ions, respectively. The catalytic activity of the palladium(II) complexes was investigated for copper-free Sonogashira reaction between iodobenzene and phenylacetylene in dimethylsulfoxide (DMSO) at 80 °C, 100 °C and 140 °C. The conversion of iodobenzene at 12 h reaction time was monitored by GC-FID. At 100 °C, the most active catalyst was PdLN, indicating that the electron withdrawing substituent $-\text{NO}_2$, has the ability to enhance catalytic properties of the complexes. At 140 °C, both palladium(II) complexes successfully converted 100% of iodobenzene.

Keywords: Schiff base, palladium(II) complexes, Sonogashira, temperature change

Abstrak

Kertas kajian ini melaporkan sintesis dua bes Schiff tetradentat iaitu 2,2'-(((2,2-dimetilpropana-1,3-diyl)bis(azanylylidena))bis(methanylylidena))bis(4-metoksifenol), LM and 2,2'-(((2,2-dimetilpropana-1,3-diyl)bis(azanylylidena))bis(methanylylidena))bis(4-nitrofenol), LN. Bes Schiff tersebut telah ditindakbalaskan dengan palladium(II) asetat dengan nisbah mol 1:1, menghasilkan dua kompleks palladium(II), iaitu PdLN dan PdLM. Sebatian telah dicirikan melalui analisis unsur, spektroskopi inframerah (IM), Resonans Magnetik Nuklear (RMN) ¹H dan ¹³C, kerentanan magnetik, kekonduksian molar dan takat lebur. Pengkompleksan ditunjukkan telah berlaku dengan penganjakan puncak $\nu(\text{C}=\text{N})$, $\nu(\text{C}-\text{O})$ dan $\delta(\text{HC}=\text{N})$. Ia dikukuhkan lagi dengan munculnya puncak baru $\nu(\text{M}-\text{N})$ dan $\nu(\text{M}-\text{O})$ dan hilangnya puncak $\delta(\text{O}-\text{H})$ pada spektrum IM dan ¹H RMN kompleks palladium(II). Sifat diamagnetik dan bukan elektrolit kompleks mencadangkan geometri satah segiempat sama d^8 paladium(II) dan ketiadaan ion kaunter, masing-masing. Aktiviti pemangkinan kompleks paladium(II) dikaji bagi tindakbalas Sonogashira tanpa kuprum antara iodobenzena dan fenilasetilena dalam dimetilsulfoksida (DMSO) pada 80 °C, 100 °C dan 140 °C. Peratusan

penukaran iodobenzena pada jam ke-12 tindak balas dipantau dengan GC-FID. Pada 100 °C, pemangkin yang paling aktif adalah PdLN, menandakan bahawa kumpulan tertukar ganti penarik elektron, $-\text{NO}_2$, boleh meningkatkan sifat pemangkinan kompleks. Pada 140 °C, kedua-dua kompleks paladium(II) berjaya menukarkan 100% iodobenzena.

Kata kunci: Bes Schiff, kompleks paladium(II), Sonogashira, perubahan suhu

Introduction

A Schiff base is typically formed through condensation reaction between a primary amine with an aldehyde or a ketone with removal of a water molecule [1]. It is also known as imine or azomethine and dubbed as a nitrogen analogue of an aldehyde or ketone, in which the carbonyl group ($\text{C}=\text{O}$) is replaced by an imine ($\text{C}=\text{N}$) [2]. Schiff bases and their transition metal complexes have been reported to have wide applications such as anticancer, antibacterial, antiviral [3], corrosion inhibition [4] and catalysis [5]. Schiff base metal complexes have been extensively investigated as homogeneous and heterogeneous catalysts in various chemical reactions including carbon-carbon coupling reactions [5]. They are reported to have outstanding catalytic activities and can withstand high temperatures of more than 100 °C, functioning effectively even in the presence of moisture [5].

Sonogashira reaction is an sp^2 carbon-carbon bond formation, usually between aryl or vinyl halide and terminal acetylene [6]. It has received enormous attention due to its wide application in synthesis of natural products, biologically active molecules, heterocycles, molecular electronics, dendrimers and conjugated polymers or nanostructures [6]. The original reaction has been modified since its discovery in 1975 by varying the palladium environment, base, catalyst loading, solvent, additive and temperature [7]. The movement towards copper-free Sonogashira reaction is increasing over the years as the application of copper salts as co-catalysts has experimentally proven to be the culprit of Glaser-type oxidative dimerization of the alkyne substrate [8] that caused contamination of the desired alkyne product.

The application of phosphine-based complexes as catalysts is common to enhance the performance of C-C formation reactions. However, these complexes have certain demerits in that they are sensitive towards air and moisture, relatively costly and environmentally harmful [9]. Nitrogen-based complexes like Schiff bases are believed to be good candidates to substitute phosphine-based complexes as the former are air- and moisture-stable, relatively cheaper and environmentally benign. Furthermore, Schiff bases are able to stabilize many different metals in various oxidation states, enhancing the performance of metals [10]. These advantages have popularised Schiff bases metal complexes in recent catalytic studies. Although the application of Schiff base complexes, for example, salen complexes in Heck and Suzuki coupling reaction is exhaustive, its application in copper-free Sonogashira reactions is still limited.

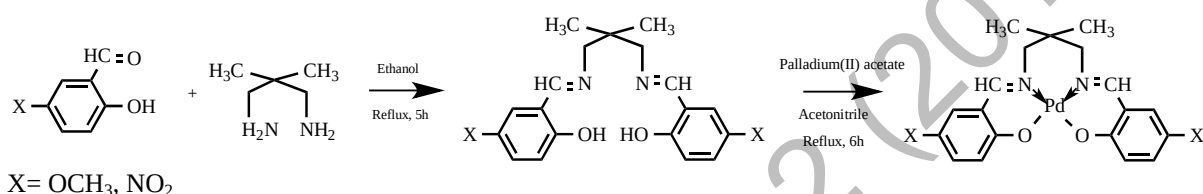
Much work has been devoted to optimize the reaction conditions for Sonogashira coupling reactions in which the optimum temperatures, catalyst loadings, solvents and bases were explored. Reaction conditions typically vary from one reaction to another depending on the types of substrates and catalysts used. An optimum temperature can be as low as room temperature [11, 12] as high as 140 °C [13]. The search for optimum reaction temperature is significant as inappropriate supply of heat to the reaction may inhibit the reaction and impede catalysts from performing effectively. Additionally, finding the optimum temperature is important for cost effectiveness. Optimization is essential particularly when palladium complexes are employed as catalysts because palladium black may occur if the reaction temperature is too high, causing deactivation of the catalytic sites. On the other hand, if the reaction temperature is too low, the percent conversion of reactants may be low.

This work reports the synthesis of two new complexes of palladium(II) with symmetrical tetradentate Schiff base ligands bearing ONNO donor atoms. The catalytic performance of the complexes was appraised on copper-free Sonogashira reaction between iodobenzene and phenylacetylene in dimethylsulfoxide (DMSO) for 12 hours at different temperatures. The findings reported herein are beneficial in understanding the catalytic performance of Schiff base complexes in homogenous Sonogashira reaction system with the absence of the conventional co-catalyst, copper(I) salt.

Materials and Methods

General

Ethanol, acetonitrile, 2,2-dimethyl-1,3-propanediamine, 5-methoxysalicylaldehyde and 5-nitrosalicylaldehyde purchased from commercial suppliers were used without prior purification. The micro-analytical data (C, H, and N) of all ligands and complexes were obtained from Thermo Scientific Flash 2000 Elemental Analyser. Melting points were determined on Stuart SMP10. Perkin-Elmer Spectrum One FTIR spectrometer using KBr pellets was employed to record infrared (IR) spectra of ligands and complexes between 450–4000 cm^{-1} . ^1H and ^{13}C NMR spectra were recorded on a Bruker Varian-600MHz spectrometer as CDCl_3 solutions and expressed in parts per million (δ , ppm). The magnetic susceptibility of the palladium(II) complexes was measured using Sherwood Auto Magnetic Susceptibility Balance. The molar conductivity of the complexes was determined using Mettler Toledo Inlab 730 conductivity meter in 10^{-3} M of DMSO solution. The percent conversion of iodobenzene was monitored using Gas Chromatography-Flame Ionization Detection (GC-FID) model Agilent 6890N. The syntheses of ligands and complexes are presented in Scheme 1.



Scheme 1. The synthesis of LM and LN and their palladium(II) complexes

Synthesis of LM and LN ligands

A hot solution of 2,2-dimethyl-1,3-propanediamine $\text{C}_5\text{H}_{14}\text{N}_2$ (1 mmol, 0.1022 g) in absolute ethanol (10 mL) was added to a stirred solution of 5-methoxysalicylaldehyde $\text{C}_8\text{H}_8\text{O}_3$ (2 mmol, 0.3044 g) or 5-nitrosalicylaldehyde $\text{C}_7\text{H}_5\text{NO}_4$ (2 mmol, 0.3342 g) in absolute ethanol (5 mL) for LM and LN, respectively. The solution was refluxed for 5 hours, cooled and chilled overnight. The yellow solid obtained was filtered off, washed with cold ethanol and air dried.

Synthesis of PdLM and PdLN complexes

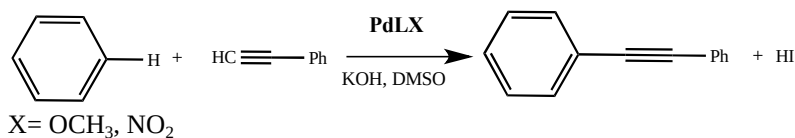
Palladium(II) acetate (1 mmol, 0.2248g) was dissolved in 10 mL of dry acetonitrile in a round-bottomed flask. The ligand LN (1 mmol, 0.4004 g) or LM $\text{C}_{21}\text{H}_{26}\text{N}_2\text{O}_4$ (1 mmol, 0.3705 g) was also dissolved separately in 10 mL of dry acetonitrile, then added dropwise into the metal solution. The mixture was refluxed for 6 hours. The orange (PdLM) or yellow (PdLN) solid obtained was washed with 5 mL of cold acetonitrile, filtered off and air-dried.

Copper-free Sonogashira reaction

A round-bottomed flask was charged with iodobenzene (1.0 mmol), phenylacetylene (1.5 mmol), palladium(II) Schiff base complex (0.02 mmol) and KOH (2.0 mmol), with stirring under aerobic condition in 7 mL of DMSO (Scheme 2). The mixture was heated at 80 $^\circ\text{C}$, 100 $^\circ\text{C}$ and 140 $^\circ\text{C}$ for 12 hours and monitored every 3 hours by Gas Chromatography-Flame Ionization Detection (GC-FID) to determine the percentage conversion of iodobenzene, calculated using equation 1:

$$\% \text{ Conversion} = (\text{A}_{\text{int}} - \text{A}_{\text{final}}) / \text{A}_{\text{int}} \quad (1)$$

where A_{int} is peak area of iodobenzene before reaction and A_{final} is peak area of iodobenzene after reaction.



Scheme 2. Copper-free Sonogashira reaction

Results and Discussion

Elemental analysis and melting point

The experimental percentages of elements C, H and N of the compounds are presented in Table 1 and are in close accord with the theoretical values. Based on the elemental analysis results, the structures of the ligands and palladium(II) complexes are as those predicted in Scheme 1. The temperature ranges for melting points listed in Table 1 represent the points at which the compounds started to melt and completely molten [14]. The melting points of the complexes are higher than their parent ligands, likely because of the increased molecular sizes and the presence of strong ionic and dative covalent bonds.

Table 1. Physicochemical properties of LM, LN and their respective palladium(II) complexes

Compound	Color	Percent Yield (%)	Chemical Formula	Melting Point (°C)	Elemental Analysis % (Calculated)		
					C	H	N
LM	Yellow	92.0	C ₂₁ H ₂₆ N ₂ O ₄	101-105	68.09 (67.91)	7.07 (7.94)	7.56 (7.54)
LN	Yellow	91.0	C ₁₉ H ₂₀ N ₄ O ₆	210-212	57.00 (55.56)	5.04 (4.97)	13.99 (14.64)
PdLM	Orange	67.3	C ₂₁ H ₂₄ N ₂ O ₄ Pd	200-205	53.12 (51.63)	5.09 (5.47)	5.90 (6.19)
PdLN	Yellow	90.5	C ₁₉ H ₁₈ N ₄ O ₆ Pd	>300	45.21 (44.03)	3.59 (3.56)	11.10 (12.48)

Infrared spectroscopy

The IR spectra of LM, LN and their Pd(II) complexes are presented in Figure 1 and significant peaks listed in Table 2. The $\nu(\text{C}=\text{N})$ peaks of ligands appeared in the range of 1611-1638 cm^{-1} , shifted by 10-31 cm^{-1} to lower frequencies of 1607-16201 cm^{-1} in the Pd(II) complexes, indicating that the C=N experienced a lowering in bond strength upon complexation through azomethine nitrogen. The lone pair of electrons on N was donated to the metal center in a Lewis acid-base interaction, resulting in the reduction of π -electron density on C=N, hence weakening it. The shifting of the C-O band from 1034 cm^{-1} in LM to 1041 cm^{-1} in PdLM, and from 1097 cm^{-1} in LN to 1100 cm^{-1} in PdLN, indicated coordination between ligands and palladium(II) through phenolic oxygen. A couple of new bands appeared in the range of 468-480 cm^{-1} and 540-571 cm^{-1} for palladium(II) complexes assignable to Pd-O and Pd-N, respectively, assenting with the values reported by Bahron et al. [16]. Other significant peaks that deserve some attention are the C=C stretch (1544-1592 cm^{-1}), and C-H sp^2 stretch (3008-3069 cm^{-1}), indicating the presence of benzene rings in the structure. The appearance of C-H sp^3 stretch in the range of 2943-2967 cm^{-1} are indicators that methyl (CH_3) groups are part of the chemical structures.

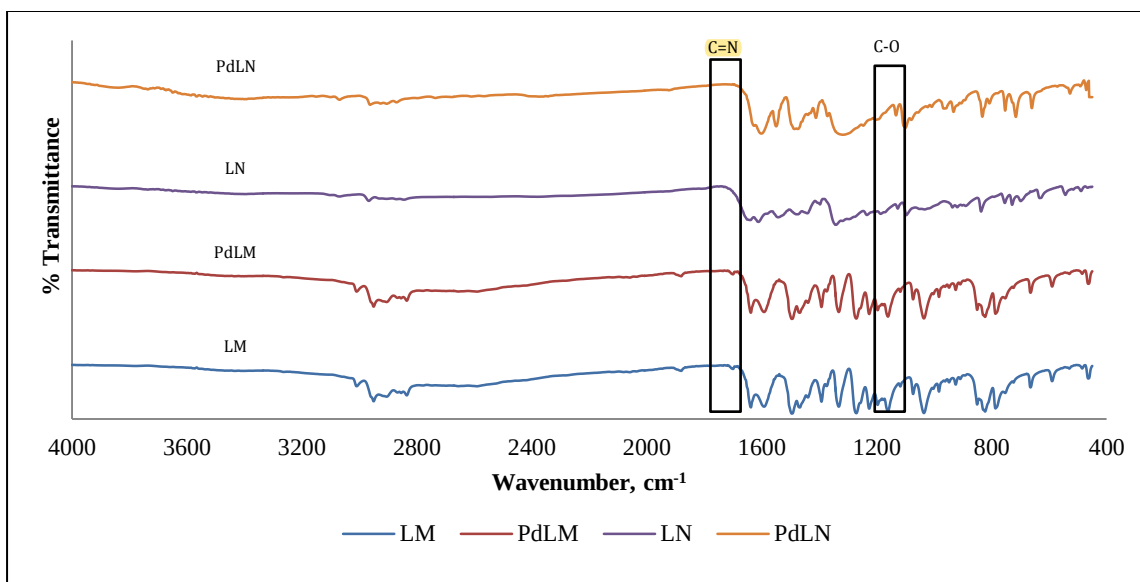


Figure 1. FTIR spectra of LM, LN and their Pd(II) complexes

Table 2. Selected infrared spectral data of LM, LN and their respective palladium(II) complexes

	Frequency, ν (cm ⁻¹)			
	LM	PdLM	LN	PdLN
C=N	1638(s)	1607(s)	1611(s)	1601(s)
C-O	1034(s)	1041(w)	1097(m)	1100(m)
Pd-N	-	571(w)	-	540(w)
Pd-O	-	468(w)	-	480(w)
C=C stretch	1592(s)	1541(s)	1544(m)	1550(m)
C-H sp ² stretch	3008(w)	3014(w)	3069(w)	3068(w)
C-H sp ³ stretch	2951(w)	2943(w)	2967(w)	2963(w)
C-H sp ³ bend	1363(s)	1365(w)	1397(w)	1371(w)
CH ₂ bend	1492(s)	1490(w)	1441(w)	1411(w)

br: broad, s: strong, m: medium, w: weak

Nuclear magnetic resonance spectroscopy

Table 3 presents ¹H NMR data of LM and PdLM. The spectra of LN and PdLN were not obtained due to their insolubility. The OH signals of LM appeared as a broad peak at the downfield region of 13.10 ppm in LM, indicating the existence of hydrogen bondings [15]. Due to the electronegative oxygen that withdrew electron density from the phenolic proton, the latter was highly deshielded from the magnetic field, causing the chemical shift to appear at the downfield region. The absence of the phenolic proton peak in the spectrum of PdLM shows that the coordination was established between phenolic oxygen and metal center through deprotonation of the hydroxyl group. The chemical shifts of aromatic hydrogen appeared as multiplets at 6.79-6.97 ppm. The values of coupling constants as tabulated in Table 3 are in the range of 1-3 Hz and 6-9 Hz, suggesting the existence of *meta* and *ortho* aromatic protons, respectively. This is in agreement with the chemical shifts reported by Amalina et al. [17]. These hydrogens were deshielded due to diamagnetic anisotropy contributed by circulating π electrons in the aromatic rings. The number of hydrogens was in concordance with the proposed structure. An evidence of

complexation can be seen through the shifting of $\delta(\text{HC}=\text{N})$ singlet from 8.32 ppm in free LM to 7.56 ppm in PdLM, suggesting a shielding of the azomethine proton by the Pd(II) center. The presence of methyl group, CH_3 , CH_2 and OCH_3 protons was detected as singlets at 1.10, 3.47 and 3.80 ppm in LM, respectively. These chemical shifts experienced very little or no shifting at all upon complexation, signifying their non-involvement.

Table 3. ^1H NMR spectral data of LM and PdLM

	Chemical Shift, δ (ppm)	
	LM	PdLM
OH	13.10 (s, 1H)	-
HC=N	8.32 (s, 1H)	7.52 (s, 1H)
CH_3	1.10 (s, 2H)	1.10 (s, 3H)
CH_2	3.47 (s, 2H)	3.50 (s, 2H)
OCH_3	3.80 (s, 3H)	3.80 (s, 3H)
Aromatic proton (Ar-H)	6.79-6.97 (m, $J=1-3$, 6-9 Hz, 3H)	6.96-7.10 (m, $J=1-3$, 6-9 Hz, 3H)

s: singlet, m: multiplet

Table 4 presents ^{13}C NMR data of LM. The peak of carbon bonded to oxygen of the phenolic group, $\delta(\text{C}-\text{OH})$ appeared at 152.04 ppm, further upfield than the azomethine carbon which was detected at 165.45 ppm, demonstrating the bigger shielding effect of O than N. The signal for CH_3 , OCH_3 and CH_2 were found at 24.44, 55.95 and 68.29 ppm, respectively. Aromatic carbons were detected in the range of 114.83-119.41 ppm. There are no ^{13}C NMR spectra obtained for PdLM, LN and PdLN owing to poor solubility of the compounds.

Table 4. ^{13}C NMR spectral data of LM

	Chemical shift, δ (ppm)
	LM
C-OH	152.04
C=N	165.45
CH_3	24.44
OCH_3	55.95
CH_2	68.29
Aromatic carbon (Ar-C)	114.83-119.41

Magnetic susceptibility and molar conductivity

All complexes revealed 0 effective magnetic moment, μ_{eff} , indicating the absence of unpaired electrons, corresponding to the diamagnetic square planar d^8 palladium(II) system. The complexes showed molar conductivity of $0 \lambda_{\text{m}}/\Omega^{-1}\text{cm}^2 \text{mol}^{-1}$ suggesting their non-electrolytic nature, with absence of any counter ions.

Catalytic activity of palladium(II) Schiff base complexes for copper-free Sonogashira reaction

PdLM and PdLN were screened as catalysts in copper-free Sonogashira cross-coupling reaction of iodobenzene with phenylacetylene in the presence of potassium hydroxide (KOH) in dimethylsulfoxide (DMSO) at 80 °C, 100 °C, 140 °C with the catalyst loading of 2 mmol%. There was an increase in percent conversion of iodobenzene with temperature, and the percentage yield of the product of the coupling reaction was reported to be in direct proportion with temperature [18]. Table 5 shows that PdLN was a better catalyst than PdLM as the former reached 100% conversion of iodobenzene at 100 °C as opposed to 140 °C for the latter. PdLN had shown a better catalytic performance than the previously reported [13, 19] catalysed reaction which reached 100% conversion at 140 °C.

Table 5. Percentage of iodobenzene conversion

Catalyst	% Conversion of Iodobenzene		
	80 °C	100 °C	140 °C
PdLM	85	66	100
PdLN	85	100	100

The electron withdrawing group -NO₂, seemed to have enhanced the catalytic performance of PdLN more effectively than the electron donating group -OCH₃. Ahmad [20] reported the performance of an analogous unsubstituted palladium(II) complex as catalyst, showing 71% conversion of the iodobenzene, in between that of PdLM (66%) and PdLN (100%), at 100 °C. This clearly indicated the significance of the electronic environment of the Schiff base ligands on the catalytic activity of the central Pd(II). As there was no copper co-catalyst used, the undesired formation of the oxidative homocoupling product, a diyne, was not seen in the GC-FID chromatograms.

Conclusion

Two symmetrical tetradentate Schiff bases bearing *ONNO* donor atoms and their respective palladium(II) complexes namely PdLM and PdLN were successfully synthesized and characterized through elemental analysis, FTIR, ¹H and ¹³C NMR, magnetic susceptibility and molar conductivity. The spectral data obtained showed that complexation between ligands with palladium(II) was achieved through azomethine nitrogen and phenolic oxygen. Reaction temperature was found to be in direct proportion with the percent conversion of iodobenzene. PdLN, bearing an electron withdrawing -NO₂ substituents, showed a higher catalytic activity than PdLM, bearing an electron donating -OCH₃ substituents. In future, lower temperature is planned to be applied for homogenous Sonogashira reaction system by having biphasic solvent system i.e. DMSO:H₂O

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