

## Synthesis of Tetranuclear Zinc(II) Azomethine Complex: A Comparative Appraisal Between Conventional and Microwave-Assisted Methods

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Symmetrical Schiff base ligand L1: 6,6'-(1E,1'E)-(1,3-phenylenebis(azan-1-yl-1-ylidene))-bis(methan-1-yl-1-ylidene)bis(2-methoxyphenol) was synthesized from a condensation reaction of *m*-phenylenediamine and *o*-vanillin in 1:2 molar ratio. The tetranuclear complex Zn<sub>4</sub>(L1)<sub>2</sub> was synthesized via two methods, namely (a) the conventional method of refluxing and (b) the green method of microwave irradiation. Structural elucidation of the products was carried out through elemental analysis, melting point, and infrared and <sup>1</sup>H-NMR spectroscopies. The signature ν(C=N) of L1 at 1616 cm<sup>-1</sup> experienced a shift towards a lower wavenumber at 1608-1613 cm<sup>-1</sup> upon coordination to Zn(II) centers. A quantitative comparison between the two complexation methods was performed in terms of product yield, reaction time, solvent, electricity, and water utilization. It was found that not only the microwave-assisted complexation method produced a higher yield and required a much shorter reaction time, it was also the more resource-efficient method in terms of solvent, electricity, and water usages.

**Key words:** Green chemistry; microwave-assisted; complexes; Schiff base; sustainability

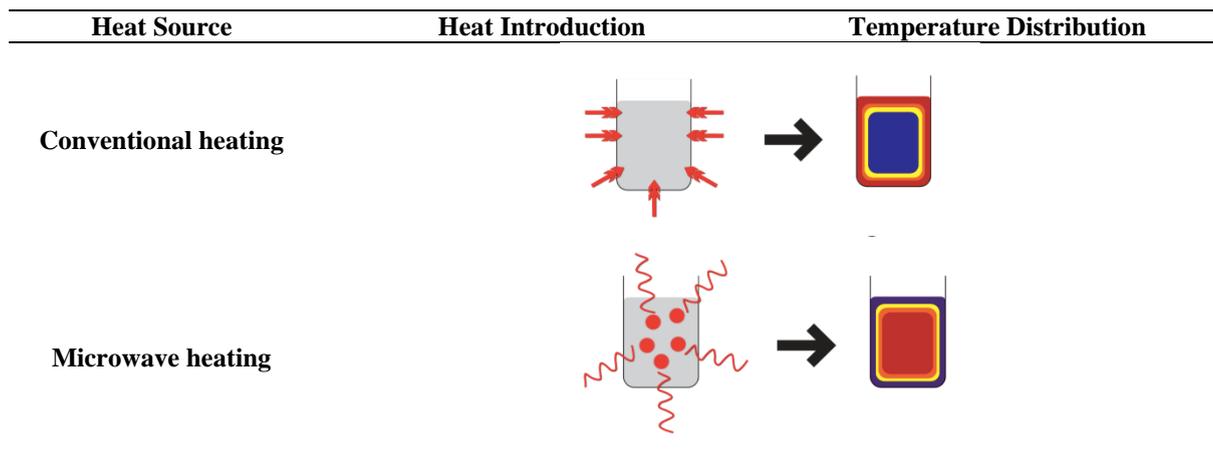
Received: December 2019; Accepted: June 2020

Green chemistry is a relatively recent evolution in chemistry to lessen the use of harmful substances and reduce carbon footprint by way of minimizing resource intensiveness of any chemical reactions for sustainability and safety of humans and the environment. Microwave-assisted synthesis is one of the components of green chemistry that uses microwave radiation to generate heat in chemical reactions (Chakraborty *et al.*, 2012). The main intentions of microwave approaches are to use less solvent, easy isolation of products, less reaction time with improved yields, and simpler operational procedure (Kassim & Hamali, 2017; Saini *et al.*, 2014). Microwave-assisted syntheses eliminate the traditional reflux procedure in the effort to minimize power and water consumption. High frequency microwave radiation heats the target molecules in polar solvents and reactant molecules by forcing them to vibrate and rotate in resonance with the applied microwave field and produce heat through collisions and vibrations of the molecules. Microwave radiation creates internal heat source that can heat the target compounds, hence increasing reaction rate and reducing reaction time. Additionally, the selective heating of microwave radiation allows heating of heterogenous systems effectively.

Microwave field energy is converted to heat by different amounts in different parts of the system. Figure 1 shows the comparison of heating mechanisms

between conventional heating method (CM) and microwave heating method (MM). In CM, the heat energy transfers from the hot oil bath to the reaction vessel and then the hot surface heats the content of the vessel. The hot surface sometimes can lead to overheating particularly over a prolonged period, decomposing any heat sensitive components of the reaction. In contrast, microwave heating is more efficient due to internal heating by direct coupling of microwave energy with ions or molecules present in the reaction mixture. The microwave irradiation passes through the vessel wall and heats the reaction mixture by direct interaction with the molecules of the solvent or reactants (Glasnov, Groschner, & Kappe, 2009).

Since the introduction by Hugo Schiff in 1864, Schiff bases, also known as imines or azomethines, have gained a remarkable good reputation among researchers mainly due to their ease of synthesis, air stability, and relatively cheap starting materials. They are good chelating agents particularly those with possible coordinating functional groups such as S-H or O-H near the site of condensation (Tadavi *et al.*, 2017). Their capacity to chelate metal cations is greatly boosted by placing donor atoms at strategic positions in the molecule, allowing a huge array of metal complexes with fascinating structural architectures such as binuclear (Beheshti *et al.*, 2017) and polynuclear (Bahron *et al.*, 2013).



**Figure 1.** Illustration of heat introduction and temperature distribution into reaction mixture in conventional heating and microwave heating (wiki.anton-paar.com)

This paper describes the synthesis and characterization of Schiff base L1 derived from ortho-vanillin with meta-phenylenediamine with its tetranuclear zinc(II) complex  $Zn_4(L1)_2$ . It highlights a quantitative comparison between conventional and microwave-assisted syntheses in terms of yield, length of reaction time, and resources employed.

## MATERIALS AND METHODS

### 1. Materials

The chemicals used in this investigation were of analytical grade. Ortho-vanillin, meta-phenylenediamine, zinc(II) acetate dihydrate, absolute ethanol, and chloroform were purchased from Sigma Aldrich (St Louis, US). All chemicals and solvents were used as purchased without prior purification.

### 2. Physical Measurements

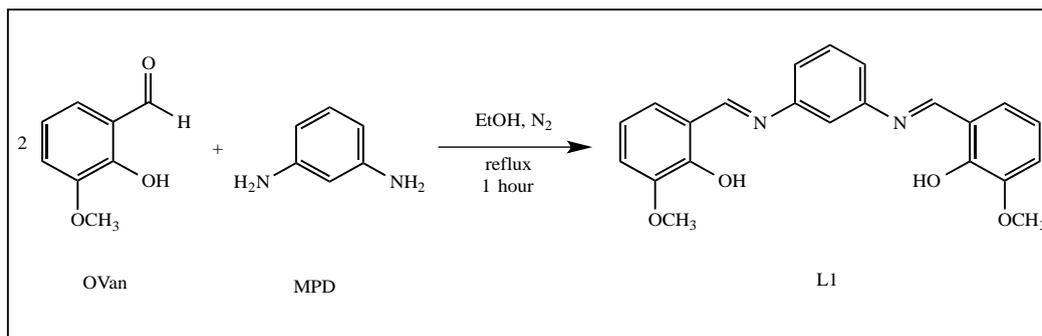
Elemental analyses (carbon, hydrogen, and nitrogen) were performed on Thermo Finnigan Flash EA 110 Elemental Analyzer. Infrared spectra were recorded as KBr discs at  $4000\text{--}400\text{ cm}^{-1}$  on Perkin-Elmer FT-IR 1600 spectrometer and  $^1\text{H}$  spectra were recorded in deuterated chloroform, on Bruker Avance 500 MHz.

All measurements were carried at room temperature and pressure.

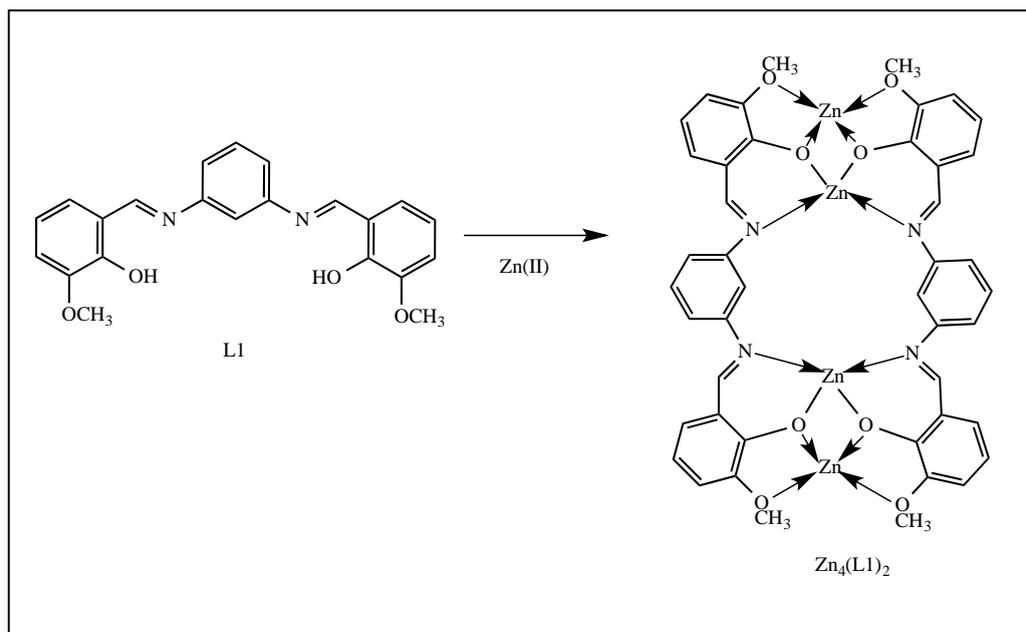
### 3. Synthesis of L1 Ligand

Ligand L1 was prepared as presented in Scheme 1 by dissolving ortho-vanillin (4.565 g; 30 mmol) and meta-phenylenediamine (1.622 g; 15 mmol) in absolute ethanol (20 mL) according to the protocol reported by Mohd Tajuddin *et al.* (2010). The reaction mixture was refluxed for one hour. The light orange crystalline precipitate yielded was filtered off, washed with cold ethanol, and air dried before being kept in a vial and stored at room temperature.

Yield: 95.08%. Color: Orange solid. Analytical calculation for L1, analyzed as  $C_{22}H_{20}N_2O_4$  (%): Calc (found) C 70.12 (70.18) H 5.36 (5.15) N 7.44 (7.14). Melting Point ( $^{\circ}\text{C}$ ) 134-136. IR bands (KBr pellet,  $\text{cm}^{-1}$ ):  $\nu(\text{C}=\text{N})$  1617,  $\nu(\text{C}-\text{O})$ phenolic 1273,  $\nu(\text{C}-\text{O})$ methoxy 1251.  $^1\text{H-NMR}$  (500 MHz,  $\text{CDCl}_3$ ):  $\delta(\text{OH})$  13.15 (s, 2H),  $\delta(\text{HC}=\text{N})$  9.05 (s, 2H),  $\delta(\text{CH})$ aromatic [7.57 (s, 2H), 7.36 (dd,  $J = 7.9, 2.0$  Hz, 2H), 7.27 (dd,  $J = 7.9, 1.3$  Hz, 2H), 7.16 (dd,  $J = 8.10, 1.2$  Hz, 2H), 6.94 (t,  $J = 7.9$  Hz, 2H)],  $\delta(\text{OCH}_3)$  3.84 (s, 6H).



**Scheme 1.** Synthesis of L1



Scheme 2. Synthesis of  $Zn_4(L1)_2$

#### 4. Synthesis of Tetranuclear Complex – $Zn_4(L1)_2$

The tetranuclear  $Zn_4(L1)_2$  complex was prepared via conventional reflux method and microwave irradiation method according to Scheme 2.

##### 4.1 Conventional Method for Synthesis of $Zn_4(L1)_2$ (CM) Complex

L1 (0.500 g; 1.2 mmol) and zinc(II) acetate dehydrate (0.527 g; 2.4 mmol) were dissolved in 5 ml  $CHCl_3$  and 10 ml ethanol, respectively. Both solutions were mixed in a round-bottomed flask in the presence of 1.3 mL of triethylamine (TEA), refluxed, and stirred for 24 hours. After allowing the resulting solution to cool to room temperature, the yellowish orange precipitate formed was filtered off, washed several times with cold ethanol, and let to dry in vacuum desiccator over blue silica gel.

Yield: 34.7%. Color: Yellow solid. Analytical calculation for  $Zn_4(L1)_2(CM)$ , analyzed as  $C_{44}H_{36}N_4O_8Zn_4(2H_2O)$ (%): Calc (found) C 50.50 (50.56) H 4.43 (3.85) N 5.35 (5.39). Melting Point ( $^{\circ}C$ ) > 300. IR bands (KBr pellet,  $cm^{-1}$ ):  $\nu(C=N)$  1613,  $\nu(C-O)$ phenolic 1270.  $^1H-NMR$  (500 MHz,  $CDCl_3$ ):  $\delta(HC=N)$  8.27 (s, 2H),  $\delta(HC=N)$ aromatic [7.72 (dd, J = 6.1, 3.3 Hz, 2H), 7.21 (m, 2H), 6.95 (d, J = 7.6 Hz, 2H), 6.72 (d, J = 7.3 Hz, 2H), 6.57 (t, J = 7.8 Hz, 2H)],  $\delta(OCH_3)$  3.87 (s, 6H).

##### 4.2 Microwave-Assisted Method for Synthesis of $Zn_4(L1)_2$ (MM) Complex

The method was adapted from Glasnov *et al.* (2009) with some modifications. L1 (0.301 g; 0.8 mmol) and zinc(II) acetate dihydrate (0.351 g; 1.6 mmol) were

mixed in 10 mL of ethanol:chloroform mixture (2:1 volume ratio). 1.3 mL of TEA was added and the mixture was subjected to a microwave irradiation for 10 minutes to the temperature of  $140^{\circ}C$  with rotation speed of 1000 rpm using Monowave 450 (Anton Paar). The reaction mixture was then allowed to cool to room temperature and kept in a chiller overnight. The yellow precipitate obtained was filtered off, washed several times with cold ethanol, air-dried, and stored in a dessicator over blue silica gel.

Yield: 64.5%. Color: Yellow solid. Analytical calculation for  $Zn_4(L1)_2(MM)$ , analyzed as  $C_{44}H_{36}N_4O_8Zn_4(H_2O)$  (%): Calc (found) C 58.58 (58.52) H 4.47 (4.27) N 6.21 (6.31). Melting Point ( $^{\circ}C$ ) > 300. IR bands (KBr pellet,  $cm^{-1}$ ):  $\nu(C=N)$  1608,  $\nu(C-O)$ phenolic 1243,  $\nu(C-O)$ methoxy 1219,  $\nu(Zn-N)$  529,  $\nu(Zn-O)$  430.  $^1H-NMR$  (500 MHz,  $CDCl_3$ ):  $\delta(HC=N)$  9.05 (s, 2H),  $\delta(CH)$ aromatic [7.57 (s, 2H), 7.36 (dd, J = 7.9, 2.0 Hz, 2H), 7.27 (dd, J = 7.9, 1.3 Hz, 2H), 7.16 (dd, J = 8.10, 1.2 Hz, 2H), 6.94 (t, J = 7.9 Hz, 2H)],  $\delta(OCH_3)$  3.84 (s, 6H).

## RESULTS AND DISCUSSION

The physical properties and elemental analyses data for Schiff base L1 and the complexes showed that the experimental percentages of C, H, and N were in close accord with the theoretical values. The melting points of the complexes were higher than that of the ligand, likely due to increased molecular sizes and the presence of stronger dative covalent and ionic bonds (Bahron *et al.*, 2019).

### 1. Infrared Spectroscopy

The infrared spectra provided valuable information on functional groups present in the compounds (Liu,

2016). The spectrum of the free Schiff base exhibited a high intensity band at  $1616\text{ cm}^{-1}$  attributed to  $\nu(\text{C}=\text{N})$  stretching in concordance with the report by Tajuddin *et al.* (2015). This band was observed to be shifted to lower frequencies of  $1613$  and  $1608\text{ cm}^{-1}$  in CM and MM complexes, respectively, due to coordination of metal to the imine nitrogen through sharing of N lone pair of electrons in a dative manner. The lowering of the frequency indicated a weakening of the C=N bond upon coordination to the metal center caused by a decrease in the  $\nu$ -electron density due to inductive effect (Tajuddin *et al.*, 2016).

The involvement of deprotonated phenolic oxygen in chelation was indicated by the shifting of the  $\nu(\text{C}-\text{O})$  phenolic peak to lower frequencies. Upon complexation, the medium intensity peak for  $\nu(\text{C}-\text{O})$  methoxy in L1 also shifted to lower wavenumbers. The coordination of nitrogen and oxygen to metal centers was supported by the appearance of weak peaks of  $\nu(\text{Zn}-\text{N})$  at  $529\text{ cm}^{-1}$  and  $\nu(\text{Zn}-\text{O})$  at  $430\text{ cm}^{-1}$ . This observation is in good agreement with previous assignments by Osman & Kassim (2015).

## 2. $^1\text{H}$ -NMR Spectroscopy

The  $^1\text{H}$  data for L1,  $\text{Zn}_4(\text{L1})_2(\text{CM})$ , and  $\text{Zn}_4(\text{L1})_2(\text{MM})$  are listed in the methodology section. The  $^1\text{H}$ -NMR spectra showed consistent integrations and multiplicities with the proposed structure. The peak at  $13.15\text{ ppm}$  for L1 represented the signal for the -OH proton. In the spectra of the complexes, deprotonation of OH was observed by the disappearance of the -OH proton signal as similarly reported by Abo-Aly *et al.* (2015). The signal of azomethine proton (-HC=N-) was shielded in the spectrum of  $\text{Zn}_4(\text{L1})_2(\text{CM})$  at  $8.27\text{ ppm}$  compared to the free Schiff base at  $9.05\text{ ppm}$  inferring coordination of Zn(II) to L1 ligand through azomethine nitrogen. This observation is in good agreement as reported by Singh *et al.* (2016). The ligand and Zn(II) complex spectra showed aromatic proton chemical shifts in the ranges of  $6.94$ - $7.57$  and  $6.57$ - $7.72\text{ ppm}$ , respectively. The non-equivalent aromatic protons interacted with each other to produce spin-spin splitting patterns indicative of meta and ortho interactions with J coupling values of  $1.4$ - $3.3\text{ Hz}$

and  $6.1$ - $8.0\text{ Hz}$ , respectively. Methoxy signals appeared unsplit and stood out as tall sharp singlets at the upfield region of  $3.84$  and  $3.87\text{ ppm}$  in L1 and  $\text{Zn}_4(\text{L1})_2(\text{CM})$ , respectively.

## 3. Quantitative Comparison of Conventional Method (CM) and Microwave Method (MM)

The comparative analysis for the synthesis of  $\text{Zn}_4(\text{L1})_2$  tetranuclear complex via conventional method (Bahron *et al.*, 2013) and microwave-assisted method in terms of reaction time, resources utilization, and yield are presented in Table 1. The conventional heating method using a hot plate as the heat source was comparatively slow and energetically inefficient since the heat energy was transferred from the hot metal block to surface of the reaction vessel, thus heating the content of the reaction vessel. This heating process required a longer time of 24 hours and could possibly lead to overheating, causing decomposition of sensitive materials, resulting in a low percentage yield of 34.7%. On the other hand, the microwave irradiation provided a more efficient way of heating the reaction by direct coupling of microwave energy with the ions or molecules present in the reaction mixture. The microwave passed through the vessel wall and heated the reaction mixture, allowing for a faster activation of the reactants to form the product. Only 10 minutes of microwave irradiation was required to detect formation of a yellow solid precipitate. This reaction time for microwave method is 0.7% of conventional method. A higher product yield of 64.5% was obtained, very likely due to the rapid heating that prevented the formation of by-products (Glasnov *et al.*, 2009).

The conventional method required quite a high water consumption during reflux to chill the reflux condenser for solvent condensation. This method required a large amount of solvent to allow successful reflux. In contrast, microwave heating was done in a closed vessel which required only a small amount of solvent (10 mL) with no water needed for chilling of vapor.

**Table 1.** Comparative analysis of conventional reflux and microwave-assisted syntheses for  $\text{Zn}_4(\text{L1})_2$  tetranuclear complex

	Conventional Method (CM)	Microwave-assisted Method (MM)
Reaction time (min)	1440 minutes (24 hours)	10 minutes (0.7% of CM)
Solvent used (mL)	30 mL	10 mL (30% of CM)
Product yield (%)	34.7%	64.5% (1.85 times greater than CM)
Electricity usage	43200 kJ	212.4kJ (0.49% of CM)
Water usage	Running water for chilling of reflux condenser for 24 hours	No water used

In terms of energy consumption, as calculated and reported by Mitra and co-workers (Mitra *et al.*, 2018), the conventional heating method consumed 43,200 kJ of electrical energy in 24 hours to reach and maintain the reaction temperature of 80°C. On the other hand, the microwave heating consumed only 212.4 kJ in 10 minutes, and it reached a higher temperature of 140°C, which clearly demonstrated the higher efficiency of the microwave approach. The comparative analysis found that there was a drastic reduction in total reaction time, solvent, and power consumption, as well as improvement in percentage yield. This would be highly advantageous for inorganic synthesis of high nuclearity complexes, opening a whole new route to green and sustainable laboratory practices.

### CONCLUSION

Ligand L1 and its tetranuclear zinc(II) complex,  $Zn_4(L1)_2$ , were successfully synthesized and characterized. Schiff base L1 acted as a polydentate ligand and coordinated to metal centers through its azomethine N, phenolic O, and methoxy O. The appearance of new peaks assignable to  $\nu(Zn-N)$  and  $\nu(Zn-O)$  in the IR spectra of the complexes evidenced the involvement of azomethine N and phenolic O in complexation. The disappearance of phenolic OH peak in the  $^1H-NMR$  spectra supported the coordination of the metal ion via phenolic O. The comparative analysis between the conventional and microwave-assisted methods of the synthesis of  $Zn_4(L1)_2$  found that there was a drastic reduction in total reaction time, amount of solvent, and power consumption as well as improvement in percentage yield.

### ACKNOWLEDGEMENT

The authors wish to thank Universiti Teknologi MARA for the research funding (600-IRMI/PERDANA 5/3 BESTARI (046/2018)) and the MyBrainSc scholarship by the Ministry of Higher Education of Malaysia. Universiti Teknologi MARA is gratefully acknowledged for the research facilities provided.

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