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Synthesis, Characterization and Biological Activity of Novel Complexes of Zinc(II) Ibuprofen with Nitrogen Based Ligands

تحضير، تشخيص و دراسة الفعالية الحيوية لمركبات تحتوي ايون الزنك الثنائي الشحنة و حامض الايبوبروفين مع بعض القواعد النيتروجينية

This Thesis was submitted in partial fulfillment of the requirements for the Master's Degree in Applied Chemistry, from the Faculty of Graduate Studies at Birzeit University, Ramallah, Palestine.

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The findings, interpretations and the conclusions expressed in this study do not express the views of Birzeit University, the views of the individual members of the MSc. Committee or the views of their respective.

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Birzeit, April, 2013

Suhad Omar

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ABSTRACT

Nine Zn(II) complexes were prepared and characterized. The synthesis was started by preparation of zinc ibuprofen $[Zn_2(ibup)_4]$ **1**, after that, different nitrogen-donor ligands were reacted with complex **1** to produce the target complexes. The complexes were $[Zn(ibup)_2(2\text{-ampy})_2]$ **2**, $[Zn(ibup)_2(2\text{-ammethylpy})_2]$ **3**, $[Zn(ibup)_2(2,2`\text{-bipy})]$ **4**, $[Zn(ibup)_2(4,4`\text{-bipy})]_n$ **5**, $[Zn(ibup)_2(1,10\text{-phen})]$ **6**, $[Zn(ibup)_2(2,9\text{-dmphen})]$ **7**, $[Zn(ibup)_2(1,2\text{-dmimidazole})_2]$ **8** and $[Zn(ibup)_2(2\text{-am-6-picoline})_2]$ **9**. IR, ^{1}H NMR, $^{13}C\{^1H\}$ NMR and UV-Vis spectrophotometric techniques were used for characterization. The crystal structures of complexes **2** and **5** were determined by single-crystal X-ray diffraction. The investigation of *in-vitro* anti-bacterial activity for the prepared complexes against Gram-positive (*Micrococcus luteus, Staphylococcus aureus and Bacillus subtilis*) and Gram-negative (*Escherichia coli, Klebsiella pneumoniae and Proteus mirabilis*) bacteria was done using agar well-diffusion method. Complexes **1** and **5** showed anti-bacterial activity against G-positive bacteria. Complexes **2**, **3**, **8** and **9** did not exhibit any anti-bacterial activity.

Complexes **4**, **6** and **7** showed anti-bacterial activity and were chosen for further studies to determine IZD for different concentrations of each one and to set the MIC for each complex. The complexation of zinc-ibuprofen with 2,2`-bipy and 1,10-phen in complexes **4** and **6**, respectively decreased the anti-bacterial activity against most of the bacteria used. The complexation in **7** decreased the anti-bacterial activity in Gram-positive bacteria but in case of Gram-negative, the overall anti-bacterial activity of uncoordinated 2,9-dmphen was enhanced on coordination with zinc ibuprofen.

ARABIC ABSTRACT

تقدم هذه الدراسة وصفا تاماً لتحضير و تشخيص تسعة مركبات معقدة جديدة لأيون الزنك ثنائي الشحنة، حيث أن هذه المركبات المعقدة هي:

$[Zn_2(ibup)_4]$ **1**, $[Zn(ibup)_2(2\text{-ampy})_2]$ **2**, $[Zn(ibup)_2(2\text{-ammethylpy})_2]$ **3**, $[Zn(ibup)_2(2,2`\text{-bipy})]$ **4**, $[Zn(ibup)_2(4,4`\text{-bipy})]_n$ **5**, $[Zn(ibup)_2(1,10\text{-phen})]$ **6**, $[Zn(ibup)_2(2,9\text{-dmphen})]$ **7**, $[Zn(ibup)_2(1,2\text{-dmimidazole})_2]$ **8** and $[Zn(ibup)_2(2\text{-am-6-picoline})_2]$ **9**.

تم استخدام مطياف الأشعة تحت الحمراء (IR) و جهاز الرنين المغناطيسي (^{1}H NMR, ^{13}C{^{1}H} NMR) و مطياف الأشعة فوق البنفسجية و المرئية (UV-Vis) لتحديد الصيغة البنائية للمركبات، هذا و تم تحديد البنية البلورية لكل من المركبات المعقدة **2** و **5** باستخدام جهاز دراسة العينات أحادية البلورة باستخدام الأشعة السينية (X-ray).

تم اختبار فعالية هذه المركبات المعقدة ضد البكتيريا آيجابية غرام (*M. luteus, S. aureus and B. subtilis*) و كذلك ضد سلبية غرام (*E. coli, K. pneumoniae and P. mirabilis*) باستخدام طريقة الانتشار في الفتحات المعمولة في الآجار. كلاً من المركبين **1** و **5** أظهر فعالية ضد بكتيريا آيجابية غرام بينما حمض الآيبوبروفين نفسه لم يُبدِ أية فعالية. المركبات **2** و **3** و **8** و **9** لم تبدِ أية فعالية لكلا النوعين من اللكبتيريا. المركبات **4** و **6** و **7** أظهرت فعالية ضد البكتيريا و تم اختيارها لمزيد من الدراسة.

ارتباط القواعد النيتروجينية (2,2`-bipy) و (1,10-phen) مع أيون الزنك في المركبات **4** و **6** قلل- بالغالب- الفعالية ضد البكتيريا. أما ارتباط (2,9-dmphen) مع ايون الزنك قلل الفعالية لبكتيريا آيجابية غرام أما في حالة بكتيريا سالبة غرام فإن الفعالية ضدها زادت مع ارتباطه بأيون الزنك.

ABBREVIATIONS

Acronym	Definition
aliph	Aliphatic
2-am-6-picoline	2-amino-6-picoline
2-ampy	2-amonopyridine
2-ammethylpy	2-aminomethyl pyridine
ar	Aromatic
2,2`-bipy	2,2`-bipyridine
4,4`-bipy	4,4`-bipyridine
2,9-dmphen	2,9-dimethylphenanthroline
1,2-dmimidazole	1,2-dimethylimidazole
DMSO	Dimethyl sulfoxide
Hibup	Carboxylic acid of ibuprofen
ibup	Ibuprofen
IR	Infrared
IR intensities	
br : broad	
v: very	
s: strong	
m: medium	
w: weak	
IZD	Inhibition Zone Diameter
MIC	Minimum Inhibition Concentration
m.p	Melting point
Na(ibup)	Sodium ibuprofen
NMR	Nuclear Magnetic Resonance
NMR multiplicity	
s: singlet	
d: doublet	
t: triplet	
m: multiplet	
dd: doublet of doublet	
bs: broad singlet	
1,10-phen	1,10-phenanthroline
UV-Vis	Ultraviolet-Visible

1. INTRODUCTION

1.1 General background

Carbon, hydrogen, nitrogen, oxygen, phosphorus and sulfur are the six main elements present for cellular components such as proteins, lipids membranes, polysaccharides etc[1]. C, N, H and O comprise 99% of the human body[2]. Living systems cannot complete their cycle using these elements only, so other elements are needed[1]. These elements are inorganic elements, such as; Na, Zn, Ni, Mn, Fe, Cu, that act as ecosystem in our biosphere[3]. The term of trace element was raised and after numerous researches each one of trace elements: (V, Mn, Fe, Co, Cu, Ni, Zn, Mo and W) has its well defined cycle where these metals play a crucial role in controlling the life cycle[1]. We can say that metals are found as natural components of proteins, Zn^{+2} for example present in most RNA and DNA polymerases[4].

The Periodic Table below shows the abundant and essential elements. It is divided into three categories; **s**-, **d**-, and **p**-blocks (**f**-block is not represented at all). Each block has its general functions that differ from other blocks[2].

s-block		**d-block**										**p-block**				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
H																
Li	Be											**B**	**C**	**N**	**O**	**F**
Na	**Mg**											Al	**Si**	**P**	**S**	**Cl**
K	**Ca**	Sc	Ti	**V**	**Cr**	**Mn**	**Fe**	**Co**	**Ni**	**Cu**	**Zn**	Ga	Ge	**As**	**Se**	**Br**
Rb	Sr	Y	Zr	Nb	**Mo**	Tc	Ru	Rh	Pd	Ag	Cd	In	**Sn**	Sb	Te	**I**
Cs	Ba	La	Hf	Ta	**W**	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At

Figure 1.1. Abundant elements in the biosphere (shaded) and essential elements in living organisms (Bold)[2]

s-Block elements are the most abundant metal ions in biology, they are found in most cells at high concentrations (~ mM). They are important in building bone tissue (Ca^{+2}), they are considered as activators of enzyme action (K^{+}, Mg^{+2}) and stabilizers of bio-molecular structures (Mg^{+2}, Ca^{+2}). **d**-Block elements are usually found in trace amounts (~μM). They are important in metalloproteins, functioning in catalytic, structural and regulatory roles and control of gene activity (Zn^{+2}). They are important in electron transfer, respiratory chain (Fe^{+3}, Cu^{+2}), photosynthesis (Mn^{+2}, Fe^{+2}, Cu^{+2}), O_2 storage and transport (Fe^{+2}, Cu^{+2}), and H_2, O_2, N_2, and CO_2 activation. **p**-Block elements are constituents of living matter (H_2O and organic compounds, carbohydrates, nucleic acids and proteins)[2].

Another classification considers carbohydrates, fats and proteins as macronutrients which act as metabolic fuel in our body. Vitamins and minerals are essential micronutrients for various biochemical reactions. Minerals can be further subdivided into (i) macrominerals, which are required by adults in amount greater than 100 mg/day, (these include sodium, potassium, chloride, calcium, magnesium and phosphorus) (ii) trace minerals, that are required in amounts between 1-100 mg/day by adult, (these includes iron, copper, and zinc ions) and (iii) ultra-trace minerals, that are required in amounts less than 1 mg/day, (these include chromium, manganese, fluoride, iodide, cobalt, selenium, silicon, arsenic, boron, vanadium, nickel, cadmium, lithium, lead, and molybdenum)[5].

Table (1.1) shows the concentration of some elements in the mammalian blood plasma and mammalian cells[1,2].

Table 1.1: Concentrations of some elements in the mammalian blood plasma and mammalian cells[1,2]

Element	Blood plasma (μM)	Cell/Tissue (μM)
Cl	1×10^5	…
Na	$(1\text{-}1.4) \times 10^5$	1×10^4
Mg	200-500	9×10^3
K	$(1\text{-}4) \times 10^3$	1.5×10^5
Ca	$(2\text{-}3) \times 10^3$	1×10^3
Co	$2.5 \times 10\text{-}^5$	…
Cu	8-24	68
Fe	22	0.001-10
Mn	0.1	180
Ni	0.04	2
V	0.07	0.5-30
Zn	17	180

The importance of these elements (especially inorganic metals) in the functioning of the human body is well known, Tables (1.2) and (1.3) show functions and ailments or disease caused by deficiency or excess of some elements.

Table 1.2: Functions of some elements in the body[2]

Body component or function	Element
Teeth and body construction	Ca, F, P
Transport and storage of O_2	Fe
Blood pressure and blood coagulation control	Na, Cl, Ca
Muscle contraction	Mg, Ca
Respiration	Fe, Cu
Cell division	Ca, Fe, Co
Control of pH in the blood	Zn

Table 1.3: Diseases caused by a deficiency or excess of some elements

Ailments or disease	Element
Anemia	Fe^{*}, Co^{*}, Cu^{*}, Mo^{**}
Lung disease	Si^{**}, Ni^{**}, Cr^{**}
Psychiatric disorder	Mn^{**}
Heart failure	Co^{**}
Wilson's disease, Menke's syndrome	$Cu^{**,*}$
Inhibited growth	Si^{*}, V^{*}, Ni^{*}, Zn^{*}, As^{*}, Mo^{*} and Mn^{*}

* ≡ deficiency, ** ≡ excess

Metal ions have special properties that give them the ability to play diverse roles in cellular biochemistry, for example Cu catalyzes oxidation reduction reactions and Zn^{+2} ion acts as Lewis acid in hydrolytic enzymes[1].

1.2 Zinc metal chemistry

Zinc metal is one of the transition elements, its atomic weight is 65.37 g/mole, it belongs to 12/IIB of the Periodic Table. By losing its *4s* electrons, a Zn(II) cation is formed with filled d^{10} structure[6].

The divalent zinc ion is redox inactive. Its d^{10} configuration has no *d-d* transitions, and therefore no absorption in the visible range. Coordination number and geometry are therefore dictated only by ligand size and charge. This means that zinc can adopt highly flexible coordination geometry[7].

In HSAB classification, Zn(II) is considered a borderline acidic metal[4] and will bind in the body to nitrogen or sulfur donor ligands in human body, especially histidines and cysteine[8]. On the other hand, it can bind oxygen ligands especially aspartate and water for the same reason[7]. Zinc has specific chemical properties which make it more important than other metals, these include **(i)** a strong electronic binding capacity related to the small zinc ion size that gives a concentrated positive charge, **(ii)** the ability to react as a strong Lewis acid, forming bonds with bases[6], **(iii)** good Zn(II) solubility in the body at the millimolar concentrations[4], **(iv)** a single oxidation state Zn(II). Besides the above mentioned properties it is considered one of the metals essential to life. It is difficult to imagine living organisms able to carry out their metabolic activity with its absence [1].

1.2.1 Zinc metal in the human body

Zinc is the second most abundant trace element in the human body after iron; an average adult has 3 g of zinc[7,9-11]. It is the most abundant trace metal in the brain, therefore, zinc deficiency impairs brain development and capabilities of learning and memory, otherwise it is mainly distributed in the blood, kidney, liver and bone[12]. It is the only metal that appears in all enzyme classes[7,11]. Nowadays more than 300 zinc containing enzymes are known, they play both a catalytic and a structural role[1,6,7].

The human body does not store zinc; therefore, it requires a constant dietary intake. Zinc is more abundant and easily absorbed from red meat and animal proteins, but can also be obtained from seafood, dairy products, cereals and nuts. The presence of phytate which is a component of plants that chelates zinc make vegetables not a good source of zinc, because phytate prevent its absorption[13].

Recommended Daily Intake of zinc RDI is 8 mg/day for females and 11 mg/day for males[5]. The effects of zinc deficiency are reduced growth rate, reduced immunity, increased susceptibility to infection, impaired taste acuity and poor wound healing[14,15].

1.2.2 Biological role of zinc

Metal ions play several important biological roles in the body , which includes **(i)** enhancement of the stability of biomolecules, **(ii)** promotion of essential conformational changes in proteins, **(iii)** modification of the function of biomolecules, **(iv)** enhancement of enzymatic activity when metal ions or complexes act as cofactors[2]. Zn(II) dependent enzymes are widespread among all

categories of enzymes[3], and biological systems prefers it on other metal ion. As mentioned in Section 1.2, Zn(II) with completely filled *d* shell have several advantages[3,6,16]:

- **(i)** It has no ligand field stabilization energy and also no *d-d* transition, so it has no ligand field constrain on its coordination geometry.
- **(ii)** It is considered as a border line acid, so it binds to oxygen, nitrogen and sulfur based ligands.
- **(iii)** It is relatively labile, so it undergoes ligand exchange reaction rapidly.
- **(iv)** It is redox inactive, therefore neither the potential oxidized form, Zn(III), nor the potential reduced form, Zn(I), is accessible under physiological conditions.
- **(v)** Zn(II) is more abundant than other metals (except for iron).
- **(vi)** Zinc ion has a small size and a highly concentrated charge density; therefore it is a strong Lewis acid.

The coordination number of Zn(II) in enzymes and proteins is usually 4 and it generally adopts tetrahedral geometry. However, because of the spherically symmetrical d^{10} electron distribution without any specific preference as in the square planar Cu(II) d^9 system, the coordinating structure of Zn(II) is rather flexible, readily taking other rearrangements and other coordination numbers [3].

Zinc dependent enzymes can be found in all known classes of enzymes, these enzymes are involved with the metabolism of protein, carbohydrate, fat and alcohol[17]. Zinc functions in biology are numerous, but can be separated into three main categories: **(i)** Catalytic: the metal ion is directly involved in catalysis processes, so zinc metal is the active site, participating directly in bonds making or breaking steps. Carbonic anhydrase is an example which converts CO_2 into bicarbonate and the same enzyme transforms the bicarbonate back into CO_2 in the

lungs for exhalation. **(ii)** Structural: in this case the ion is necessary for the maintenance of the tertiary and often also quaternary structures and its activity is affected only in terms of overall conformational stability. An example is Cu-Zn SOD which catalyzes the disproportionation reaction of superoxide $\cdot O_2^-$, the Cu is the catalytic site and the Zn plays the structural role. **(iii)** Regulatory: the metal ion regulates but it is not essential to other protein processes. Such as zinc finger proteins that have been found to regulate gene expression by acting as transcription factors[2,3,11,18,19]. Zinc enzymes could be mono, di or multinuclear[7], Figure (1.2) shows examples of mono and dinuclear zinc enzymes. The ligands are part of long chain protein (His = histidines. Asp = aspartate. Cys = cysteine. Glu = glutamate. Lys = lysine).

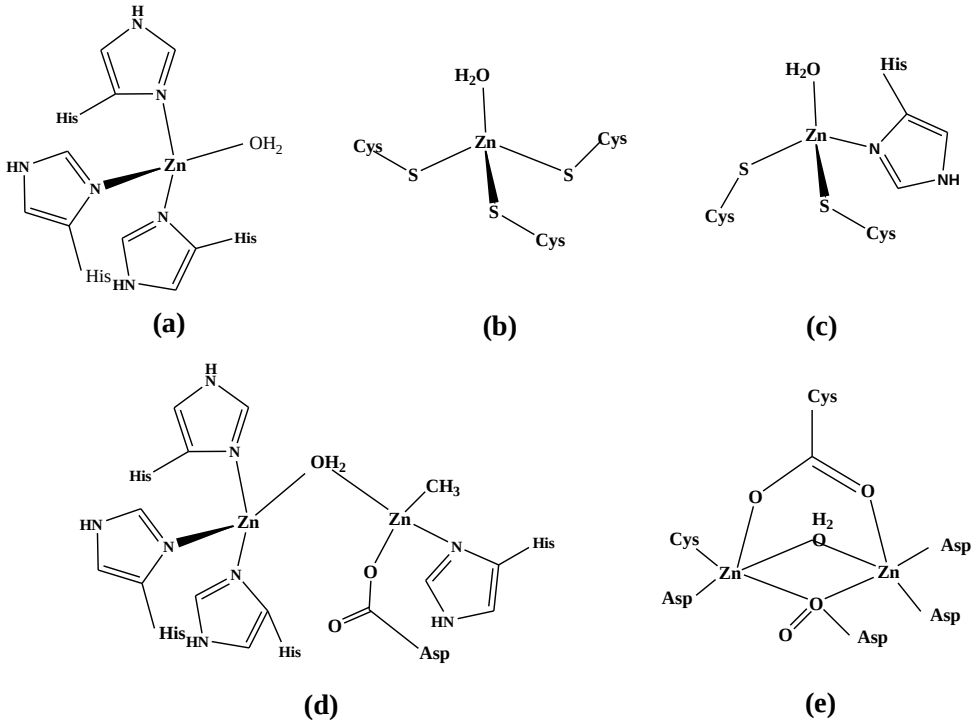


Figure 1.2. Active sites of mononuclear and dinuclear zinc enzymes: (a) human carbonic anhydrase, (b) 5-aminolaevulinate, (c) alcohol dehydrogenase, (d) metallo-β-lactamase, and (e) leucine aminopeptidase[1,3,7].

1.2.3 Zinc metal in medicine

Biomedical inorganic chemistry, which is also known as elemental medicine, is an important area of chemistry. It helps in understanding hard diseases. Metal ions can play an important role in the mechanism of action of organic drugs. Design of active compound depends on control and metal targeting to specific tissues or cells where the activity is needed. Toxicity of an element depends on the element oxidation state and the coordinated ligands, nature and number of ligands, in addition to the dose itself[1,20].

About 24 elements are currently thought to be essential for mammalian life: H, C, N, O, F, Na, Mg, Si, P, S, Cl, K, Ca, V, Mn, Fe, Co, Ni, Cu, Zn, Se, Mo, Sn, and I. Figure 1.3 bellow shows some of the key areas of medicinal inorganic chemistry[20,21].

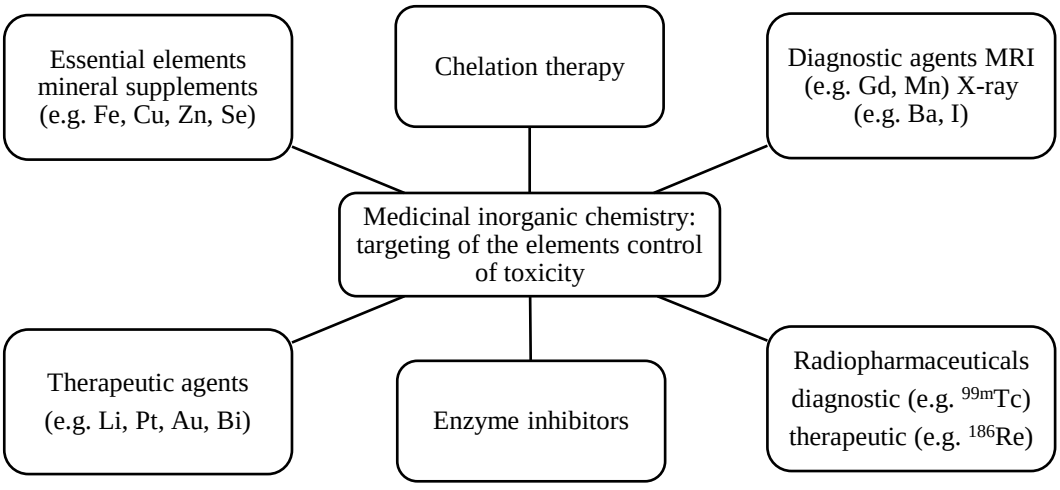


Figure 1.3. Some of the key areas of medicinal inorganic chemistry[21]

Table 1.4: A summary for some metals in medicine[20,21]

Metal	Medicinal usage	Metal	Medicinal usage
Ti	Anti-cancer drug therapy	**Fe**	MRI contrast agent
V	Insulin mimics	**Nb**	Anticancer drugs therapy
Cr	Insulin receptor activation	**Au**	Antiarthritic drugs therapy
Mn	MRI contrast agent, SOD mimics	**Ru**	Anticancer agent
Zn	Inflammatory agent	**Pt**	Anticancer therapy, diabetes and Alzheimer's

Uptake, transport, delivery, and excretion of metals is programmed in the body; these programs are mainly based on proteins which recognize specific complexes utilizing both thermodynamic (oxidation state, number and types of ligands, coordination geometry) and kinetic (ligand exchange) aspects of the properties[21]. Compared to several other metal ions with similar chemical properties, zinc is relatively harmless. Only exposure to high doses has toxic effects, making acute zinc intoxication a rare event[15].

1.2.4 Zinc as anti-bacterial gent

A study found zinc ion is suitable cross-linking agents for alginate[22]. Metal complexes of biologically active ligands may be more effective than the free ligand, these free ligands may be carboxylate like oxolinic acid that is used as anti-bacterial drug, norfloxacin which acts as anti-bacterial agent against Gram positive (G^+) and Gram negative (G^-) bacteria or they may be nitrogen based ligands like theophylline, urea, imidazole, benzimidazole, pyrazoles, pyridine and pyrimidine that are well known for their therapeutic properties and are widely used to treat various diseases[23-27]. It has been observed that metal ions have

considerable effect on the anti-microbial activity of antibiotics[28], Therefore the presence of metal with the biologically active ligands, like benzimidazole, for example, enhances the biological activity of organic molecules[29]. Kralova et al. studied the inhibition of oxygen evolution rate, algal growth and chlorophyll production in *Chlorella vulgaris* by Cu(II) complexes with some biological ligands[24]. The metal complexes were found to have different and various degrees of inhibitory effect against the algae[30].

Zn(II) has an important anti-bacterial and anti-viral effects[31]. It inhibits the growth of a lot of bacteria, e.g. *Escherichia coli, Streptococcus faecalis* and some strains of soil bacteria[32]. Zinc complexes with bioactive ligands are considered to have pharmaceutical effects because they catalyze many enzymatic processes in biological systems. Researchers found that zinc ion concentrations of 10^{-5}-10^{-7} M are required for *in-vitro* optimal bacterial growth of most microorganisms, but high zinc ion concentrations may have some anti-bacterial properties[33]. Yao et al. found that the effect of Zn(II) on *E. coli* growth depends on the Zn(II) concentration; low concentration had a promoting action on the *E. coli* growth, but a high concentration had an inhibition action[24]. Zinc and other metals like copper and silver are used for water purification, actually zinc is effective in eliminating coliforms from contaminated water, especially *E. coli* strain 0157:H7 which causes large number of diseases, like diarrhea, kidney damage, and occasionally death, and that is commonly found in contaminated water in rivers and dams[34].

The heterocyclic compounds play significant role in biological systems that are a part of some vitamins and drugs. The interactions between metal ions or metal carboxylate complexes with N-donor heterocyclic ligands that are present in living system and are used in medicaments. Zinc(II) aliphatic and aromatic carboxylate have been studied especially, in biological fields[32,35]. Györyová, K et al. studied the biological effect of Zinc(II) propionate complexes with N-donor heterocyclic ligands and found that the anti-microbial effect of the prepared compounds depends on the type of bacteria (G^+, G^-). Zn(II) complexes were more active against G^- bacteria which could be due to the specific structure of the cell wall in this type of bacteria that is thinner than the G^+ cell wall and chemically less resistant[36]. Alternatively, both ligands and metal ion, especially, Zn(II) may ineract with different steps of the pathogen life cycle. Literature indicates that ligands/drugs become more bacteriostatic on complexation as compared to unchelated ones[28], an interesting approach for designing novel zinc complexes derivatives for anti-bacterial drugs is one of the main objectives of the present work.

1.3 Metal carboxylate chemistry

Carboxylic acids are important substrates in biological processes[37]. Metal carboxylates were subjected to research for few decades. They have been used as model compounds of metalloenzymes or as anti-bacterial agents[38]. Metal ions can coordinate to carboxylate in different ways (Figure 1.5); ionic, syn/anti monodentate, bidentate chelating or bridging [39]. The carboxylate functional group has four lone pairs of electrons on the two oxygen atoms which are available for

metal binding. These lone pairs can be divided into syn- and anti-lone pairs. It has been suggested that the syn-lone pairs are more basic than those in the anti-position (Figure 1.4)[40].

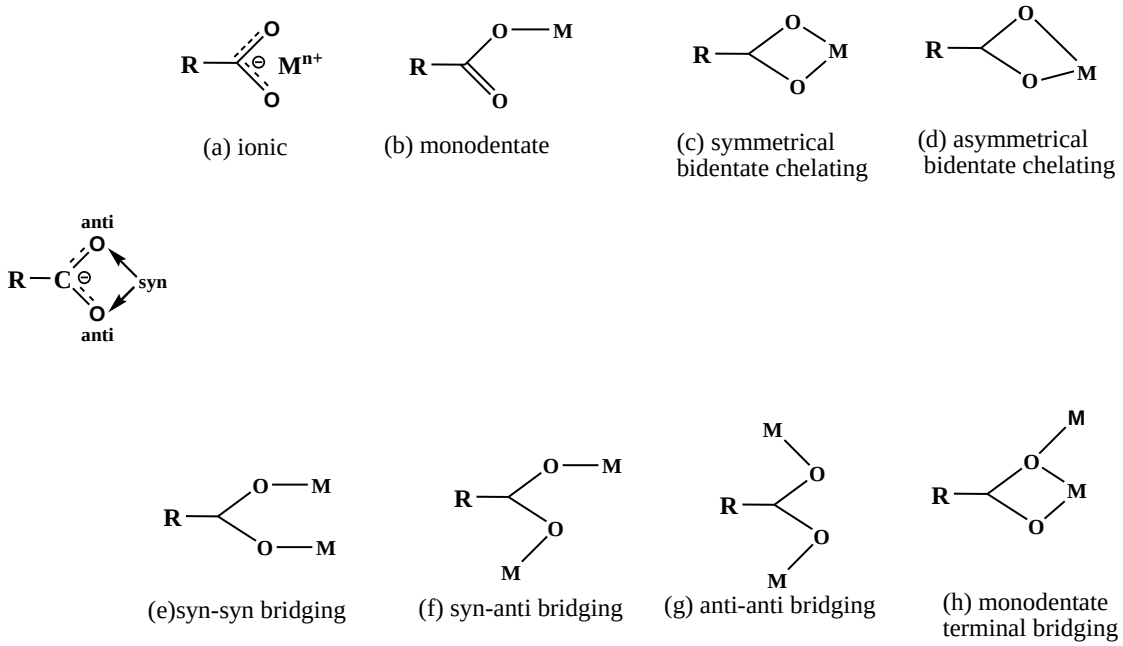


Figure 1.4. Coordination modes of metal carboxylates[40]

To determine the mode of carboxylate binding, infrared spectroscopy (IR) is used[38]. The frequency of the asymmetric carboxylate vibration ν_{as} (COO^-), and the magnitude of the separation between the carboxylate stretches, $\Delta = \nu_{as}$ (COO^-) – ν_s (COO^-) are often used as spectroscopic criterions to determine the mode of the carboxylate binding. Generally, the order below is proposed for divalent metal carboxylates[38]:

$$\Delta(\text{chelating}) < \Delta(\text{bridging}) < \Delta(\text{ionic}) < \Delta(\text{monodentate})$$

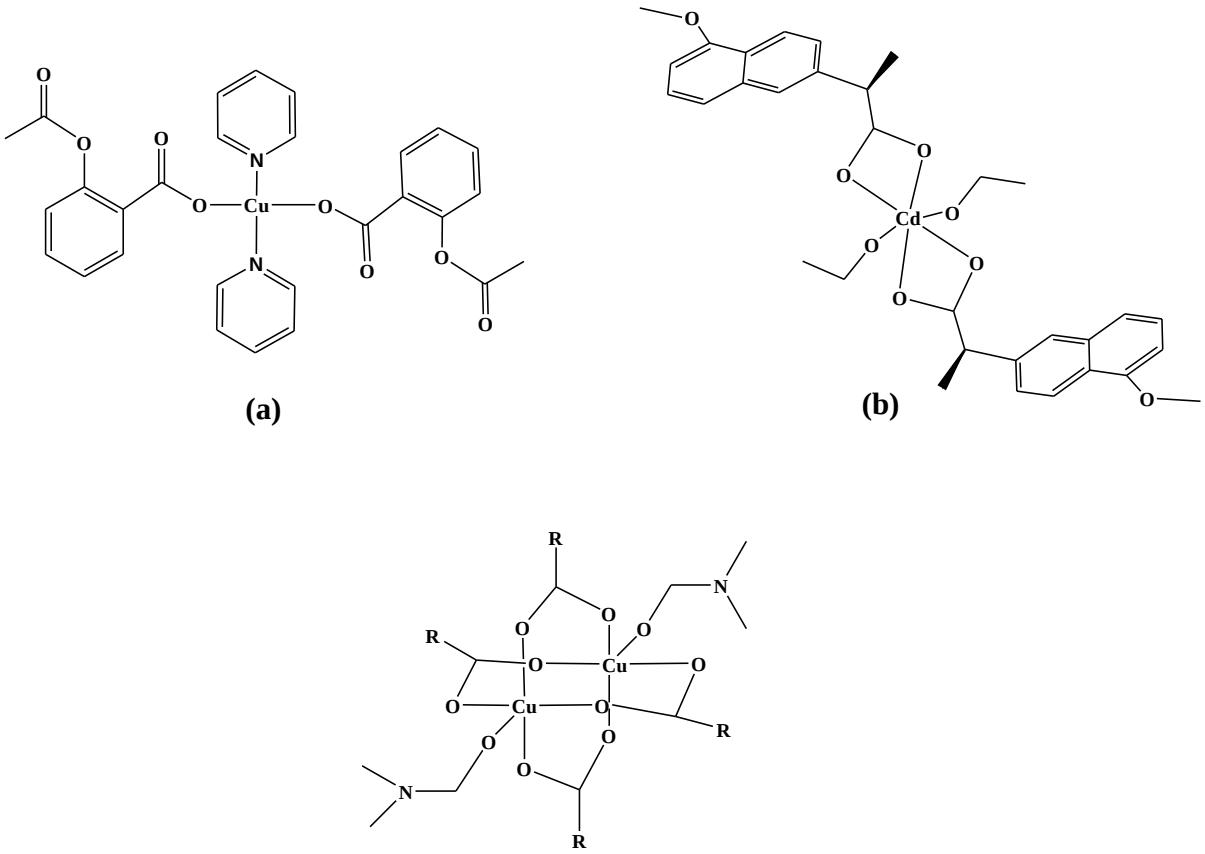


Figure 1.5. Metal carboxylates modes (a) $[Cu(Asp)_2(py)_2]$, monodentate[41]; (b) $[Cd(nap)_2(EtOH)_2]$, bidentate chelate; (c) $[Cu_2(Indo)_4(DMF)_2]$, RCOO: indomethacinate; bidentate bridging[42].

1.3.1 Zinc carboxylates

In biological systems the catalytic binding sites in zinc enzymes often contain Asp or Glu that contain carboxylate side chains that bind to Zn in either monodentate or bidentate mode. Average Zn-O bond length is around 1.8-2.0 Å in monodentate mode while it is around 2.1-2.4 Å in bidentate mode[43]. From this point of view, mono and dinuclear zinc carboxylates are important in biological models to mimic those in the body[37]. It is known that zinc carboxylates have anti-septic and anti-fungal properties and have been used as catalysts, wood preservative,

waterproofing agents, auxiliary drying agents in paints and anti-stick agents in the rubber and plastic industries. For example: zinc salicylate and some substituted salicylates are employed in the coating of carbonless copying papers[44]. Zinc(II) picolinate and zinc(II) aspartate are effective for the treatment of the disease caused by Herpes simplex virus[45].

Many metal(II) carboxylate complexes are polymeric due to the bridging of metals by carboxylate groups[46-48]. A common structure for zinc carboxylates is that in which two zinc atoms are linked by three syn-syn bridging carboxylate ligands to form a binuclear unit $[Zn_2(O_2CR)_3]^+$, R = alkyl or aryl. These units are linked to one another by a syn-anti bridging carboxylate ligand to produce a linear polymer[46,47]. Zinc *o*-chlorobenzoate has been reported in the form of a linear polymer where chains of zinc atoms are linked by pairs of syn-syn bridging carboxylate ligands to give a bridged polymer structure[49].

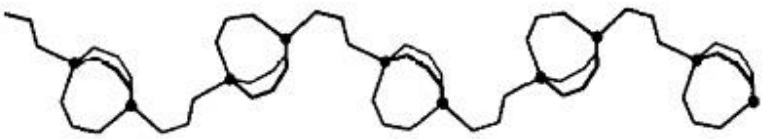
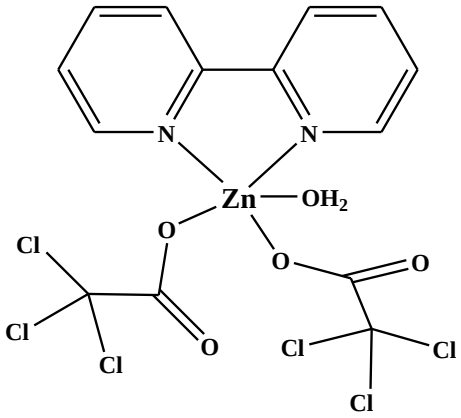
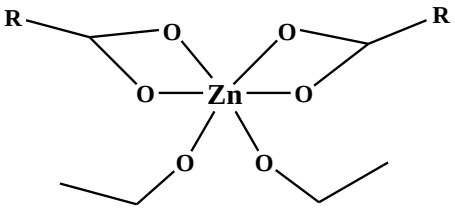


Figure 1.6. Backbone of the polymer chain, side chains of the carboxylate ligands not shown.

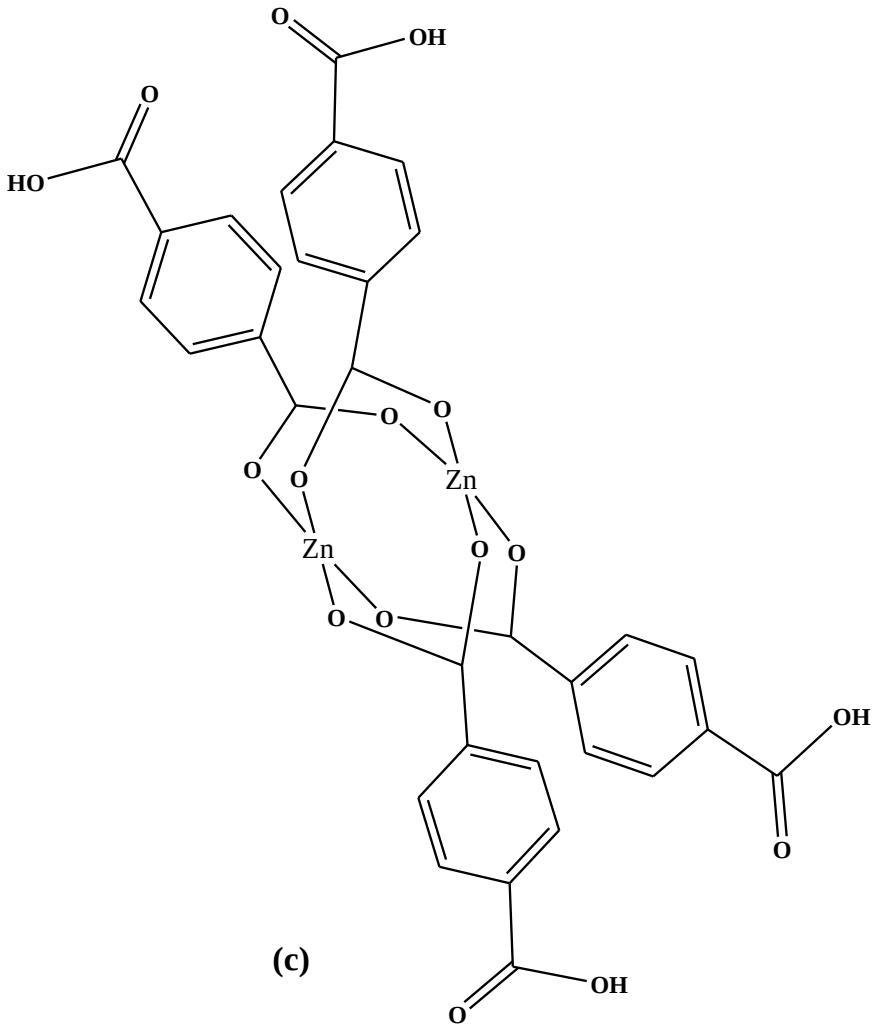
Zinc carboxylates complexes have binding modes like those of metal carboxylates that previously mentioned (Figure 1.7).



(a)



(b)



(c)

Figure 1.7. Zinc carboxylates binding modes: (a) $[Zn(2,2\text{-bipy})\ (CCl_3CO_2)_2H_2O]$[50], (b) $[Zn(Indo)_2(EtOH)_2]$, RCOO = Indomethacin[51], (c) $[Zn_2(terephthalic\ acid)_4]$[52]

1.3.2 Nitrogen ligands coordination with zinc carboxylates

Zinc(II) carboxylate complexes with nitrogen donor organic ligands are interesting because of their potential biological activity[53,54].

N-donor compounds, especially, those with six membered rings- those called heterocyclic nitrogen donor or bioactive ligands- such as pyridine and related molecules, have many different chemical, physical and biological properties. In addition, they act as a component of several vitamins and drugs and they are found in nature in enzymes, coenzymes, porphyrines, and nucleic acids, therefore a lot of extensive work and research was performed on them[37,55-57]. Caffeine is an example of heterocyclic nitrogen donor ligand which is the most widely used as behavioral active substance in the world. It is well known as hydrotropic agent and has the ability to solubilize a wide variety of therapeutic drugs. It contains two aromatic rings that affect the solubility of the aromatic anti-malarial agent[58]. Some caffeine complexes were found to be biologically active as anti-cancer agent like $[PtCl_3(Caffeine)]$[59].

Metal-caffeine and adenine complexes have shown significant anti-tumor activities on different animal cancer models, in this context, a work published in 2010 involved the synthesis and characterization of mixed ligand complexes of caffeine, adenine and thiocyanate with Co(II), Ni(II), Cu(II), Zn(II) and Cd(II)[57], with general formula $[M(CA)_2(AD)X_2]$ (Figure 1.8). Thermal and spectral properties of zinc(II) salicylate and 4-chloro salicylate complexes with caffeine were studied and showed that, the thermal behavior of these compounds depends

on the organic ligands where the hydrated compounds release water at first, then organic ligands, and finally the carboxylate[53,54,60].

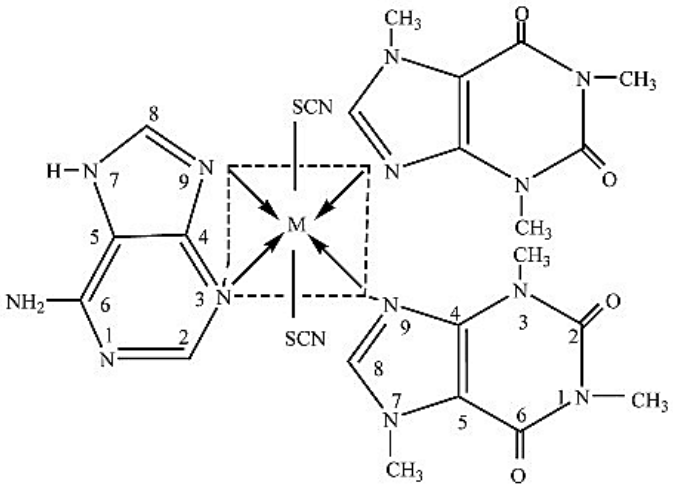


Figure 1.8. Structure of metal-caffeine and adenine complexes, M = Co(II), Ni(II), Cu(II), Zn(II) and Cd(II)[58]

Pyridines and their derivatives are very important anti-microbial, anti-bacterial, anti-tumoral and anti-malarial nitrogen based ligands. The importance of pyridine in coordination chemistry comes from the lone pair of electrons on the imine nitrogen which gives it both basic and nucleophilic properties that afford interaction side with transition metals[61].

The crystal structure of bis(2-aminopyridine-N)bis(benzoate-O) zinc was determined to attempt understanding the structure behavior of nitrogen containing ligands when coordinated to zinc carboxylates. It was found that the compound adopted slightly deformed tetrahedral structure[62] (Figure1.9).

The coplanar bidentate ligands 2,9-dmphen, 1,10-phen and 2,2`-bipy are considered to have moderate to strong field, they become fundamental ligands due to their versatility in coordination to almost any metal[63,64]. They exhibit anti-

bacterial, anti-microbial anti-fungal anti-viral and anti-tumor activities which depend on the nature of the ligand and the type of the metal ion[65-70].

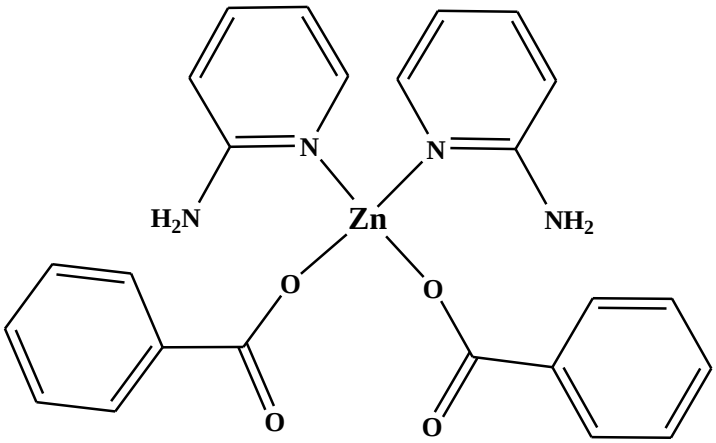


Figure 1.9. Bis(2-aminopyridine-N)bis(benzoate-O) zinc[62]

4,4`-Bipyridine and its derivatives usually adopt bridging coordination mode[71], a few examples with 4,4`-bipyridine as monodentate ligand have been explored[72]. A symmetric ligand favors a bridging mode between metal centers which can form a variety of spatial structures including linear, zigzag, rail type, square lattice and octahedron structures (Figure 1.10). A wide range of infinite one, two, and three-dimensional coordination frameworks, including helicates, honeycomb, brick wall, square or rectangular grid, molecular bilayers, diamondoid, T-shaped, octahedral, and other uncommon frameworks have been generated[73-75]. On the other hand, useful coordination polymers of this ligand and its derivatives are known and have applications in catalysis, electrical conductivity and purification[50,76,77].

Imidazole, its derivatives and pyrazoles with zinc complexes have been also widely studied because of their special coordination chemistry and biochemistry properties[78,79].

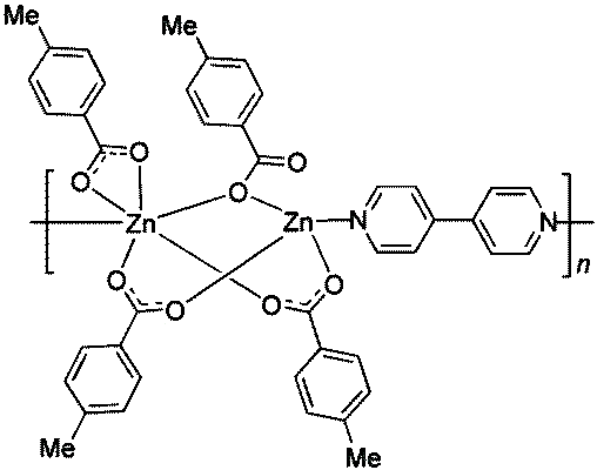


Figure 1.10. 4,4̀-Bipyridine bridging coordination between two metal centers in one-dimensional zinc coordinated polymer

Nine bioactive nitrogen base compounds were chosen in the present work: **(a)** 2-aminopyridine, (2-ampy); **(b)** 2-aminomehtylpyridine, (2-ammpy); **(c)** 2,2̀-bipyridine, (2,2̀-bipy); **(d)** 4,4̀-bipyridine, (4,4̀-bipy); **(e)** 1,10-phenanthroline, (1,10-phen); **(f)** 2,9-dimethyl-1,10-phenanthroline, (2,9-dmphen); **(g)** imidazole, (imid); **(h)**1,2-dimethylimidazole; (dmimid) and **(i)** 2-amino-6-picoline, (2-ampic) (Figure 1.11).

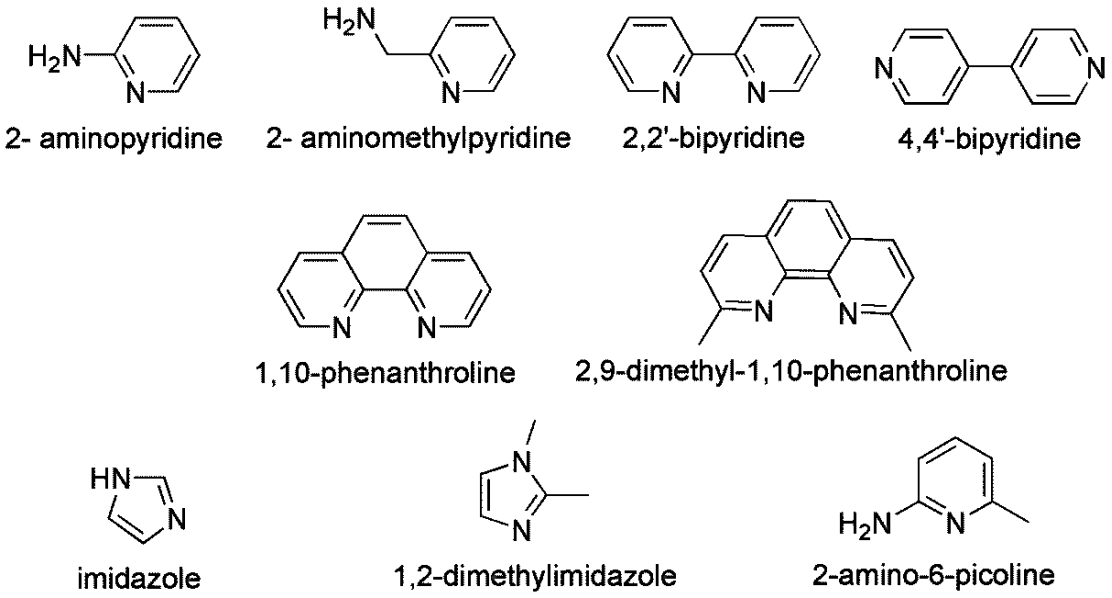


Figure 1.11. Heterocyclic N-donor ligands

1.3.3 Metal ibuprofen complexes

There are side effects associated with clinical use of non-steroidal anti-inflammatory drugs (NSAIDs); therefore numerous studies were done in order to reduce these side effects. One strategy that has met with success has been the use of d-block metal complexes of NSAIDs as therapeutic agent, this approach is based on the observation that some *d*-block metal ions, like Cu(II) and Zn(II), can act as anti-inflammatory agents in their own right[80,81], or sometimes this interaction may lead to a better understanding of the metal ion antagonism[82]. For example, Zn(II) complex of aspirin has a better therapeutic index (2.64 times) than aspirin itself and has improved physicochemical characteristics, therefore Zn-aspirin complex is more effective in therapy and less ulcerogenic than either aspirin alone or a physical mixture of aspirin and $ZnSO_4$[83-85].

The need to develop potent and less gastro-intestinally damaging NSAIDs than those used for human and veterinary pharmaceuticals has led to the preparation, characterization, and veterinary use of divalent metal salts of indomethacin[42,86], especially the Cu(II) complexes and the human anti-inflammatory drug, indomethacin.

Cu(II)-NSAIDs complexes have been reported[41]; in particular mononuclear and dinuclear copper(II) complexes with NSAID phenylalkanoic acids tolmentin, naproxen, ibuprofen, suprofen, indomethacin and diclofenac have been characterized and their crystal structure are available in literature[86-91].

Studies of ibuprofen coordination with Cu(II) have shown that it contains dinuclear units with bridging carboxylates like familiar copper acetate and many

other copper carboxylates[91-93]. Many Cu(II) carboxylates form dinuclear complexes with basic ligands[93], also form mononuclear adducts with certain bases (Figure 1.12). In general, they form mononuclear complexes by increasing the acidity of the alkyl (or aryl) carboxylate ligand, such as through halogenations of alkyl groups or by increasing the basicity of other ligands[88,90,94,95].

Cu(II) carboxylates and their nitrogen donor adducts have been found to have pharmacological effects, such as anti-tumor, superoxide dismutase, catecholase and anti-viral activity[88,94,96-98]. Cu(II) ibuprofen with 2,2-bipy, 1,10-phene and 2,9-dmphenan were synthesized and spectrochemically characterized[99].

A study published in 2000 was the first study to relate the anti-inflammatory and anti-ulcerogenic properties of a Ru_2(II,III)-ibuprofenato complex with ibuprofen, although the mechanisms of anti-ulcer effect of such complexes with ibuprofen are yet unknown, this study had provided important insight to the therapeutic properties of these complexes[100].

Coordination of transition metal and d^{10} metal ion- like Cd(II) and Zn(II)- with anti-inflammatory carboxylate agents, tolmentin, ibuprofen and naproxen were studied in the attempt to examine their binding mode[82,90,91].

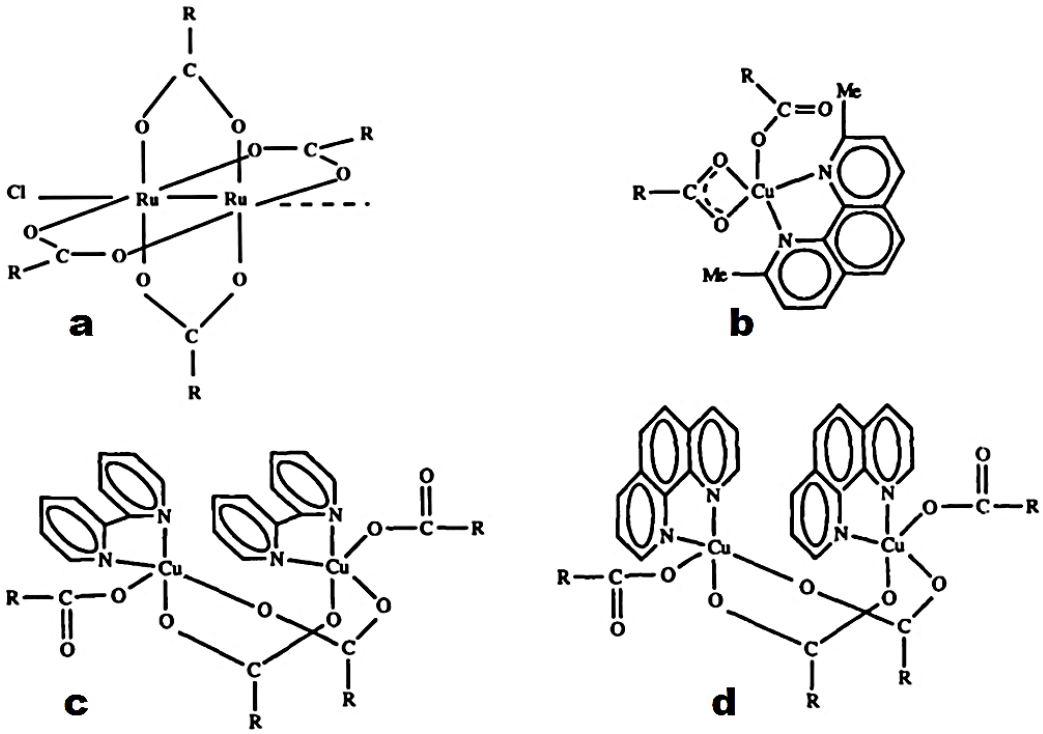


Figure 1.12. Metal ibuprofen complexes, (RCOO = ibuprofenate anion): (a) $[Ru_2Cl(ibup)_4]$, it is a polymeric chain, the mood of coordination is bidentate double bond, (b) $[Cu(ibup)_2$2,9-dmphenan], there are two moods of interaction, monodentate and bidentate chelate, (c) $[Cu_2(ibup)_4(2,2\text{-bipy})_2]$ and (d) $[Cu_2(ibup)_4(phenan)_2]$, two moods of interaction monodentate and bidentate double bond[99,100].

1.4 Aim of the research.

The main purpose of the present work was to synthesize and characterize new zinc(II)-containing complexes that would have novel structural features and may possess effective anti-microbial biological activities. The complexes contain ibuprofen as carboxylate ligand with heterocyclic nitrogen based ligands.

Ten novel complexes were synthesized and characterized, these complexes are:

- $[Zn_2(ibup)_4]$ **(1)**
- $[Zn(ibup)_2(2\text{-ampy})_2]$ **(2)**

- $[Zn(ibup)_2(2\text{-ammethylpy})_2]$ **(3)**
- $[Zn(ibup)_2(2,\dot{2}\text{-bipy})]$ **(4)**
- $[Zn(ibup)_2(4,\dot{4}\text{-bipy})]_n$ **(5)**
- $[Zn(ibup)_2(1,10\text{-phen})]$ **(6)**
- $[Zn(ibup)_2(2,9\text{-dmphen})]$ **(7)**
- $[Zn(ibup)_2(1,2\text{-dmimidazole})_2]$ **(8)**
- $[Zn(ibup)_2(2\text{-am-6-picoline})_2]$ **(9)**

These complexes were characterized using IR-spectroscopy, NMR, UV-visible spectroscopy and, X-ray structural analysis was carried out, when possible. Evaluation the anti-microbial activity of the new complexes *in-vitro* was carried out, as anti-bacterial agents against Gram-positive and Gram-negative bacteria.

2. EXPERIMENTAL

2.1 Materials

All chemicals and solvents were purchased from commercial sources and, they were used without further purification. Gram positive bacteria *(Micrococcus luteus*, *Staphylococcus aureus*, *Bacillus subtilis)* and Gram negative ones *(Escherichia coli*, *Klebsiella pneumonia*, and *Proteus mirabilis)* were obtained from the Biology and Biochemistry Department at Birzeit University.

2.2 Physical measurements

Melting points were measured in capillary tubes using MPA120 EZ-Melt apparatus. **NMR** spectra were recorded on a Varian Unity Spectrometer operating at 300 MHz for ^{1}H measurements and 75 MHz for the $^{13}C\{^{1}H\}$ were recorded in deuterated chloroform ($CDCl_3$). Chemical shifts are given in ppm downfield from the internal standard Me_4Si, coupling constants are given in Hz. **Infrared (IR)** spectra were recorded in the 400-4000 cm^{-1} region using a Varian 660 FT-IR Spectrometer using KBr pellets. **UV-Vis** spectra were recorded using Hewlett Packard 8453 photo diode array spectrophotometer in the 200-800 nm region using DMSO and ethanol as solvents.

2.3 Preparation of Zn(II) complexes

All Zn(II) complexes were synthesized at room temperature in ambient conditions.

2.3.1 Synthesis of $[Zn_2(ibup)_4]$ (1)

Ibuprofen (6.18 g, 0.03 mol) was allowed to dissolve in a solution of sodium hydroxide (1.20 g, 0.03 mol) in 100 ml water. To this solution was slowly added with stirring a solution of zinc chloride (2.05 g, 0.015 mol) in 30 ml of water in molar ratio 2:1. The mixture was allowed to stir for an hour[92]. The white precipitate that formed was collected, washed with cold water and dried in vacuum. The compound is soluble in: DMSO, ethanol, chloroform, 6.50 g, ~ 90% yield, m.p = 86.8-94.3 ˚C. *^1H NMR ($CDCl_3$):* δ (ppm) 0.89 (d, 6H, CH_3, $^3J_{H-H}$ = 6.6 Hz), 1.36 (d, 3H, CH_3, $^3J_{H-H}$ = 6.9 Hz), 1.82 (m, 1H, CH), 2.42 (d, 2H, CH_2, $^3J_{H-H}$ = 7.2 Hz), 3.62 (q, 1H, CH, $^3J_{H-H}$ = 7.2 Hz), 7.03 (d, 2H, CH, $^3J_{H-H}$ = 8.1 Hz), 7.15 (d, 2H, CH, $^3J_{H-H}$ = 8.1 Hz). *$^{13}C\{^1H\}$ NMR ($CDCl_3$):* δ (ppm) 19.41 (CH_3), 22.67 (CH_3), 30.42 (CH), 45.32 (CH), 47.24 (CH_2), 127.44 (CH), 129.41 (CH), 138.65 (C), 140.51 (C), 189.46 (C=O). *IR (KBr, cm^{-1}):* 3090 w, 2953 s, 2925 s, 2867 m, 1706 w, 1544 vs, 1512 m, 1414 vs, 1366 m, 1290 m, 1121 w, 1070 m, 848 m, 786 w, 740 w, 607 w, 548 w, 430 w. *UV-Vis (EtOH, λ (nm)):* 315.

2.3.2 Synthesis of $[Zn(ibup)_2(2\text{-ampy})_2]$ (2)

2-Ampy (0.56 g, 5.95 mmol) was dissolved in acetone and gradually added to stirred acetone solution of $[Zn_2(ibup)_4]$ (**1)** (1.43 g, 1.50 mmol). The solution was stirred for three hours then evaporated to dryness under vacuum to get a solid residue. The solid product was then washed with ether and allowed to dry in air. Suitable crystals for X-ray structural analysis were obtained by recrystallization from acetone. The compound is soluble in: DMSO, ethanol, dichloromethane,

THF, DMF, 1.28 g, ~ 64% yield, m.p = 151.2-152.7 ˚C. *^{1}H NMR ($CDCl_3$):* δ (ppm) 0.84 (d,6H, CH_3, $^{3}J_{H-H}$ = 6.6 Hz), 1.32 (d, 3H, CH_3, $^{3}J_{H-H}$ = 6.9 Hz), 1.79 (m, 1H, $CH_{(ibup)}$), 2.38 (d, 2H, CH_2, $^{3}J_{H-H}$ = 6.9 Hz), 3.54 (q, 1H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 6.9 Hz), 6.45 (bs, 2H, NH_2), 6.53 (m, 2H, CH), 7.02 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 7.5 Hz), 7.19 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 7.8 Hz) 7.42 (t, 1H, CH, $^{3}J_{H-H}$ = 15.3 Hz), 7.74 (d, 1H, CH, $^{3}J_{H-H}$ = 4.8 Hz). *$^{13}C\{^{1}H\}$ NMR ($CDCl_3$):* δ (ppm) 20.33 (CH_3), 22.66 (CH_3), 30.11 ($CH_{(ibup)}$), 44.79 ($CH_{(ibup)}$), 46.53 (CH_2), 110.09 (CH), 112.15 (CH), 127.63 ($CH_{(ibup)}$), 129.02 ($CH_{(ibup)}$), 1.38.83 (CH), 139.07 ($C_{(ibup)}$), 141.23 ($C_{(ibup)}$), 147.04 (CH), 160.06 (C-NH_2), 179.82 (C=O). *IR (KBr, cm^{-1}):* 3370 s, 3339 s, 3225 s, 3030 vw, 2954 s, 2925 m, 2866 m,1640 s, 1624 vs, 1566 s, 1502 vs, 1454 s, 1378 s, 1352 s, 1272 s, 1165 m, 1066 m, 1009 m, 885 w, 850 s, 769 s, 740 m, 725 w, 633 w, 543 w, 457 m, 414 w. *UV-Vis (DMSO, λ (nm)):* 301.

2.3.3 Synthesis of $[Zn(ibup)_2(2\text{-ammethylpy})_2]$ (3)

The same procedure was followed as for compound **2** except with 2-ammethylpy (0.15 ml, 0.14 g, 1.27 mmol) and $[Zn_2(ibup)_4]$ (**1**) (0.30 g, 0.32 mmol). The compound is soluble in: DMSO, chloroform, dichloromethane, acetonitrile, ethyl acetate, THF, DMF, 0.27 g, ~ 62% yield, m.p = 154.8-156.9 ˚C. *^{1}H NMR ($CDCl_3$):* δ (ppm) 0.85 (d, 6H, CH_3, $^{3}J_{H-H}$ = 5.7 Hz), 1.23 (d, 3H, CH_3, $^{3}J_{H-H}$ = 6.3 Hz), 1.77 (m, 1H, $CH_{(ibup)}$), 2.34 (d, 2H, $CH_{2(ibup)}$, $^{3}J_{H-H}$ = 6.3 Hz), 3.42 (q, 1H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 7.2 Hz), 3.53 (bs, 2H, NH2), 3.94 (bd, 2H, CH2, $^{3}J_{H-H}$ = 5.4 Hz), 6.96 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 7.5 Hz), 7.10 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 9.6

Hz), 7.35 (t, 1H, CH, $^{3}J_{H-H}$ = 5.1 Hz), 7.46 (d, 1H, CH, $^{3}J_{H-H}$ = 7.5 Hz), 7.89 (m, 1H, CH), 8.42 (d, 1H, CH, $^{3}J_{H-H}$ = 4.8 Hz). *$^{13}C\{^{1}H\}$ NMR ($CDCl_3$):* δ (ppm) 20.59 (CH_3), 22.68 (CH_3), 30.13 ($CH_{(ibup)}$), 44.76 ($CH_{(ibup)}$), 44.88 ($CH_{2(ibup)}$), 46.99 (CH2), 122.56 (CH), 123.18 (CH), 127.58 ($CH_{(ibup)}$), 128.83 ($CH_{(ibup)}$), 136.39 (CH), 138.75 ($C_{(ibup)}$), 141.91 ($C_{(ibup)}$), 148.11 (CH), 161.07 (C), 179.46 (C=O). *IR (KBr, cm^{-1}):* 3288 m, 3125 w, 2955 s, 2924 m, 2868 m, 1672 s, 1605 vs, 1546 w, 1508 s, 1487 vs, 1455 s, 1435 m, 1387 w, 1361 m, 1287 s, 1254 s, 1220 m, 1129 m, 1097s, 1064 s, 1040 m, 1016 m, 877 m, 850 s, 787 m, 759 w, 733 m, 708 s, 673 m, 640 m, 593 m, 491 w, 463 m, 448 s, 441 w. *UV-Vis (EtOH, λ (nm)):* 315.

2.3.4 Synthesis of [Zn(ibup)$_2$(2,2̀-bipy)] (4)

The same procedure was followed as for compound **2** except with 2,2̀-bipy (0.30 g, 1.92 mmol) and [Zn_2(ibup)$_4$] (**1**) (0.52 g, 0.55 mmol). The compound is soluble in: DMSO, ethanol, dichloromethane, THF, 0.23 g, ~ 33% yield, m.p = 143.6-146.3 ˚C. *^{1}H NMR ($CDCl_3$):* δ (ppm) 0.86 (d, 6H, CH_3, $^{3}J_{H-H}$ = 6.6 Hz), 1.43 (d, 3H, CH_3, $^{3}J_{H-H}$ = 6.9 Hz), 1.80 (m, 1H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 6.6 Hz), 2.39 (d, 2H, CH2, $^{3}J_{H-H}$ = 7.2 Hz), 3.72 (q, 1H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 7.2 Hz), 6.96 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 8.1 Hz), 7.18 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 8.4 Hz), 7.37 (bs, 1H, CH), 7.91 (dt, 1H, CH, $^{3}J_{H-H}$ = 8.4 Hz), 8.04 (d, 1H, CH, $^{3}J_{H-H}$ = 8.1 Hz), 8.69 (bs, 1H, CH). *$^{13}C\{^{1}H\}$ NMR ($CDCl_3$):* δ (ppm) 19.82 (CH_3), 22.65(CH_3), 30.44 ($CH_{(ibup)}$), 45.31 ($CH_{(ibup)}$), 46.38 (CH_2), 121.02 (CH), 127.55 (CH), 127.56 ($CH_{(ibup)}$), 129.08 ($CH_{(ibup)}$), 139.35 (CH), 139.54 ($C_{(ibup)}$), 140.62 ($C_{(ibup)}$), 149.59

(CH), 150.01 (C=O). *IR (KBr, cm^{-1}):* 3069 w, 3054 w, 2956 s, 2864 m, 1609 s, 1597 s, 1567s, 1508 s, 1444 s, 1388 s, 1358 s, 1315 m, 1281 m, 1252 w, 1157 m, 1116 w, 1062 m, 1025 s, 892 m, 850 m, 773 vs, 735 m, 652 m, 604 m, 532 w, 418 m. *UV-Vis (EtOH, λ (nm)):* 308.

2.3.5 Synthesis of $[Zn(ibup)_2(4,4\grave{}\text{-bipy})]_n$ (5)

The same procedure was followed as for compound **2** except with 4.4̀-bipy (0.30 g, 1.92 mmol) and $[Zn_2(ibup)_4]$ (**1)** (0.52 g, 0.55 mmol). Suitable crystals for X-ray structural analysis were obtained by recrystallization from ethanol. The compound is soluble in: DMSO, ethanol, chloroform, 0.45 g, yield, m.p = 206.0-211.2 ˚C. *^1H NMR ($CDCl_3$):* δ (ppm) 0.82 (d, 6H, CH_3, $^3J_{H\text{-}H}$ = 6.5 Hz), 1.27 (d, 3H, CH_3, $^3J_{H\text{-}H}$ = 6.9 Hz), 1.75 (m, 1H, $CH_{(ibup)}$), 2.33 (d, 2H, CH2, $^3J_{H\text{-}H}$ = 7.0 Hz), 3.44 (q, 1H, $CH_{(ibup)}$, $^3J_{H\text{-}H}$ = 7.2 Hz), 6.99 (d,2H, $CH_{(ibup)}$, $^3J_{H\text{-}H}$ = 8.1 Hz), 7.15 (d,2H, $CH_{(ibup)}$, $^3J_{H\text{-}H}$ = 8.3 Hz), 7.82 (m, 1H, CH), 8.68 (m, 1H, CH). *$^{13}C\{^1H\}$ NMR ($CDCl_3$):* 19.42 (CH3), 22.82 (CH3), 29.14 (CH(ibup)), 43.38 (CH(ibup)), 45.78 (CH(ibup)), 121.30 (CH), 128.90 CH(ibup)), 129.08 CH(ibup)), 132.30 (C(ibup)), 139.26 (C(ibup)), 144.22 (C), 149.91 (C), 150.82 (C), 178.21 (C=O). *IR (KBr, cm^{-1}):* 3420 b, 3213 w, 2958 s, 2926 m, 2869 m, 1600 vs, 1491m, 1461 m, 1418s, 1377 s, 1276 m, 1221m, 1121 w, 1068 s, 1010 m, 883m, 850 m, 812 vs, 784 m, 756 m, 672 w, 638 s, 606 w, 496 w. *UV-Vis (EtOH, λ (nm)):* 315.

2.3.6 Synthesis of $[Zn(ibup)_2(1,10\text{-phen})]$ (6)

The same procedure was followed as for compound **2** except with 1,10-phen

(1.13 g, 6.30 mmol) and $[Zn_2(Ibup)_4]$ (**1)** (1.50 g, 1.57 mmol). The oily product was then washed with petroleum ether then the solid was allowed to dry in air. The compound is soluble in: DMSO, ethanol, chloroform, dichloromethane, acetonitrile, DMF. 1.86 g, ~ 90% yield, m.p = 87.1-93.6 ˚C. *^1H NMR ($CDCl_3$):* δ (ppm) 0.84 (d, 6H, CH_3, $^3J_{H-H}$ = 6.6 Hz), 1.42 (d, 3H, CH_3, $^3J_{H-H}$ = 7.2 Hz), 1.77 (m, 1H, $CH_{(ibup)}$), 2.37 (d, 2H, CH_2, $^3J_{H-H}$ = 7.2 Hz), 3.69 (q, 1H, $CH_{(ibup)}$, $^3J_{H-H}$ = 6.9 Hz), 6.92 (d, 2H, $CH_{(ibup)}$, $^3J_{H-H}$ = 8.1 Hz), 7.16 (d, 2H, $CH_{(ibup)}$, $^3J_{H-H}$ = 7.8 Hz), 7.66 (t,2H, CH, $^3J_{H-H}$ = 12.6 Hz), 7.83 (s, 2H, CH), 8.336 (dd, 2H, CH, $^3J_{H-H}$ = 9.6 Hz), 9.02 (d, 2H, CH, $^3J_{H-H}$ = 3.3 Hz). *$^{13}C\{^1H\}$ NMR ($CDCl_3$):* δ (ppm) 19.68 (CH_3), 22.65 (CH_3), 30.44 ($CH_{(ibup)}$), 45.29 ($CH_{(ibup)}$), 46.70 (CH_2),124.52 (CH), 126.90 (CH), 127.508 ($CH_{(ibup)}$), 128.88 (C), 129.057 ($CH_{(ibup)}$), 134.07 (CH), 137.89 ($C_{(ibup)}$), 140.83 ($C_{(ibup)}$), 150.04 (CH), 150.23 (C=O). *IR (KBr, cm^{-1}):* 3409 b, 3057 w, 2953 s, 2925 m, 1610 m, 1561 vs, 1517 s, 1500 w, 1459 s, 1426 vs, 1383 m, 1356 m, 1286 m, 1255 w, 1224 m, 1145 s, 1104 s, 1063 m, 1001 w, 854 s, 785 m, 750 m, 727 vs, 643 m, 588 w, 423 m. *UV-Vis (EtOH, λ (nm)):* 326.

2.3.7 Synthesis of $[Zn(ibup)_2(2,9\text{-dmphen})]$ (7)

The same procedure was followed as for compound **6** except with 2,9-dmphen (1.43 g, 6.30 mmol) and $[Zn_2(ibup)_4]$ **(1)** (1.50 g, 1.57 mmol). The compound is soluble in: DMSO, ethanol, ether, dichloromethane, acetonitrile, ethylacetate, THF, DMF, 2.16 g, ~ 97% yield, m.p = 104.4-112.5 ˚C. *^1H NMR ($CDCl_3$)* δ (ppm) 0.81 (d, 6H, $CH_{3(ibup)}$, $^3J_{H-H}$ = 6.3 Hz), 1.42 (d, 3H, $CH_{3(ibup)}$, $^3J_{H-H}$ = 7.2

Hz), 1.73 (m, 1H, $CH_{(ibup)}$), 2.33 (d, 2H, CH_2, $^3J_{H-H}$ = 7.5 Hz), 2.90 (s, 6H, CH_3), 3.73 (q, 1H, $CH_{(ibup)}$, $^3J_{H-H}$ = 7.2 Hz), 6.92 (d, 2H, $CH_{(ibup)}$, $^3J_{H-H}$ = 7.5 Hz), 7.18 (d, 2H, $CH_{(ibup)}$, $^3J_{H-H}$ = 7.5 Hz), 7.38 (d, 2H, CH, $^3J_{H-H}$ = 4.5 Hz), 7.43 (d, 2H, CH, $^3J_{H-H}$ = 6.9 Hz), 8.02 (dd, 2H, CH, $^3J_{H-H}$ = 11.7 Hz). *$^{13}C\{^1H\}$ NMR ($CDCl_3$):* 19.66 ($CH_{3(ibup)}$), 22.40 ($CH_{3(ibup)}$), 25.90 (CH_3), 30.22 ($CH_{(ibup)}$), 45.02 ($CH_{(ibup)}$), 46.58 ($CH_{2(ibup)}$), 123.46 (CH), 126.68 (CH), 127.29 ($CH_{(ibup)}$), 128.77 ($CH_{(ibup)}$), 136.26 (CH), 138.95 ($C_{(ibup)}$), 140.83 ($C_{(ibup)}$), 145.13 (C), 159.17 (C), 18.91 (C=O). *IR (KBr, cm^{-1}):* 3053 vw, 2954 s, 2926 m, 2868 m, 1618 vs, 1595 w, 1509 s, 1460 m, 1378 vs, 1157 m, 1062 m, 861 s, 781 s, 730 s, 603 w, 551 m, 436 w. *UV-Vis (EtOH, λ (nm)):* 297.

2.3.8 Synthesis of [Zn(ibup)$_2$(1,2-dmimidazole)$_2$] (8)

1,2-Dmimidazole (1.52 g, 15.8 mmol) was dissolved in ether and gradually added to stirred ether solution of [Zn_2(Ibup)$_4$] (**1)** (0.68 g, 0.71 mmol). The product was immediately precipitated. The solid product was then washed with ether and allowed to dry in air. The compound is soluble in: DMSO, ether, dichloromethane, acetonitrile, ethylacetate, THF, DMF, 0.73 g, ~ 77% yield, m.p = 115-130.2˚C. *^1H NMR ($CDCl_3$):* δ (ppm) 0.88 (d, 6H, $CH_{3(ibup)}$, $^3J_{H-H}$ = 6.6 Hz), 1.43 (d, 3H, $CH_{3(ibup)}$, $^3J_{H-H}$ = 6.9 Hz), 1.81 (m, 1H, $CH_{(ibup)}$), 2.13 (s, 3H, CH3), 2.40 (d, 2H, CH_2, $^3J_{H-H}$ = 7.2 Hz), 3.45 (s, 3H, CH3), 3.62 (q, 1H, $CH_{(ibup)}$, $^3J_{H-H}$ = 7.2 Hz), 6.65 (s, 1H, CH), 6.88 (s, 1H, CH), 6.98 (d, 2H, $CH_{(ibup)}$, $^3J_{H-H}$ = 8.1 Hz), 7.25 (d, 2H, $CH_{(ibup)}$, $^3J_{H-H}$ = 4.2 Hz). *$^{13}C\{^1H\}$ NMR ($CDCl_3$):* δ (ppm) 11.85 (CH_3), 19.82 ($CH_{3(ibup)}$), 22.64 ($CH_{3(ibup)}$), 30.51

($CH_{(ibup)}$), 33.39 (CH_3), 45.32 ($CH_{(ibup)}$), 47.51 (CH_2), 120.42 (CH), 126.65 (CH), 127.78 ($CH_{(ibup)}$), 128.82 ($CH_{(ibup)}$), 139.07 ($C_{(ibup)}$), 141.63 ($C_{(ibup)}$), 144.70 (C), 181.09 (C=O). *IR (KBr, cm^{-1}):* 3121 s, 2956 s, 2925 m, 2867 s, 1622 vs, 1550 w, 1511 s, 1458 m, 1418 s,, 1375 vs, 1283 m, 1244 w, 1155 s, 1063 m, 1008 m, 881 m, 850 m, 778 m, 750 w, 673 s, 650 m, 601 m, 550 w, 446 m. *UV-Vis (EtOH, λ (nm)):* 361.

2.3.9 Synthesis of [Zn(ibup)$_2$(2-am-6-picoline)$_2$] (9)

The same procedure was followed as for compound **2** except with 2-am-6-picoline (0.68 g, 6.3 mmol) and [Zn_2(ibup)$_4$] (**1)** (1.5 g, 1.57 mmol). The compound is soluble in: DMSO, dichloromethane, ethylacetate, 1.13 g, ~ 52% yield, m.p = 110.3-113.3 ˚C. *^1H NMR ($CDCl_3$):* δ (ppm) 0.88 (d, 6H, $CH_{3(ibup)}$, $^3J_{H-H}$ = 6.6 Hz), 1.37 (d, 3H, $CH_{3(ibup)}$, $^3J_{H-H}$ = 7.2 Hz), 1.81 (m, 1H, $CH_{(ibup)}$), 2.23 (s, 3H, CH3), 2.40 (d, 2H, CH_2, $^3J_{H-H}$ = 7.2 Hz), 2.58 (s, 2H, NH_2), 3.62 (q, 1H, $CH_{(ibup)}$, $^3J_{H-H}$ = 14.1 Hz), 6.21 (d, 1H, CH, $^3J_{H-H}$ = 8.1 Hz), 6.35 (d, 1H, CH, $^3J_{H-H}$ = 6.9 Hz), 6.98 (d, 2H, $CH_{(ibup)}$, $^3J_{H-H}$ = 8.1 Hz), 7.15 (d, 2H, $CH_{(ibup)}$, $^3J_{H-H}$ = 7.8 Hz), 7.25 (t, 1H, CH, $^3J_{H-H}$ = 15.9 Hz). *$^{13}C\{^1H\}$ NMR ($CDCl_3$):* 19.38 ($CH_{3(ibup)}$), 22.43 ($CH_{3(ibup)}$), 23.26 (CH_3), 30.25 ($CH_{(ibup)}$), 45.08 ($CH_{(ibup)}$), 47.16 (CH_2), 106.89 (CH), 112.67 (CH), 127.37 ($CH_{(ibup)}$), 128.91 ($CH_{(ibup)}$), 139.01 (CH), 139.48 ($C_{(ibup)}$), 139.90 ($C_{(ibup)}$), 150.59 (C), 158.19 (C), 182.81 (C=O). *IR (KBr, cm^{-1}):* 3376 s, 3222 s, 3075 vw, 2954 s, 2926 m, 2866 m, 1661 s, 1612 vs, 1566 m, 1487 s, 1457 m, 1393 s, 1358 m, 1279 s, 1256 m, 1170 m, 1116 w, 1092 w, 1060 m, 1002 m, 896 w, 844 m, 781 s, 745 m, 688 w,

609 m, 534 w, 492 s. *UV-Vis (EtOH, λ (nm)):* 367.

2.4 X-ray crystallography

Single crystals suitable for X-ray measurements of complexes **2** and **5** were attached to a glass fiber with epoxy glue, and transferred to a Bruker SMART APEX CCD X-ray diffractometer system controlled by a Pentium-based PC running the SMART software package, (SMART-NT V5.6, Bruker AXS GMBH, Karlsruhe, Germany).

The crystal was mounted on a three-circle goniometer with χ fixed at +54.76°. The diffracted graphite-monochromated Mo Kα radiation (λ = 0.71073 A) was detected on a phosphor screen held at a distance of 6.0 cm from the crystal operating at -43 °C. A detector array of 512 X 512 pixels, with a pixel size of approximately 120 μm, was employed for data collection. The detector centroid and crystal-to-detector distance were calibrated from a least-squares analysis of the unit cell parameters of a carefully centered YLID reference crystal.

After the crystal of the complex had been carefully optically centered within the X-ray beam, a series of 30 data frames measured at 0.3° increments of ω were collected with three different 2θ and φ values to assess the overall crystal quality and to calculate a preliminary unit cell. For the collection of the intensity data, the detector was positioned at a 2θ value of -28° and the intensity images were measured at 0.3° intervals of ω for duration of 20 sec. each. The data frames were collected in four distinct shells which, when combined, measured more than 1.3 hemispheres of intensity data with a maximum 2θ of 46.5°.

Immediately after collection, the raw data frames were transferred to a second PC computer for integration by the SAINT program package (SAINT-NT V5.0, BRUKER AXS GMBH, Karlsruhe, Germany). The background frame information was updated according to the equation B' = (7B+C)/8, where B' is the update pixel value, B is the background pixel value before updating, and C is the pixel value in the current frame.

The integration was also corrected for distortion induced by the detector. In addition, pixels that reside outside the detector active area or behind the beam stop were masked during frame integration.

The integrated intensities for the four shells of data were merged to one reflection file. The data file was filtered to reject outlier reflections. The rejection of a reflection was based on the disagreement between the intensity of the reflection and the average intensity of the symmetry equivalents to which the reflection belongs.

In the case of strong reflections ($I>99\sigma(I)$) which contain only two equivalents, the larger of the two equivalents was retained. The structure was solved and refined by the SHELXTL software package (SHELXTL-NT V6.1, BRUKER AXS GMBH, Karlsruhe, Germany). Crystal data and more details of the data collections and refinements are summarized in Table 2.1.

Table 2.1: Crystal data and structure refinement for complexes **2** and **5**.

Identification code	**2**		**5**	
Empirical formula	C36 H46 N4 O4 Zn		C36 H46 N2 O6 Zn	
Formula weight	664.14		668.12	
Temperature	295(1) K		293(1) K	
Wavelength	0.71073 Å		0.71073 Å	
Crystal system	Triclinic		Triclinic	
Space group	P-1		P-1	
Unit cell dimensions	a = 11.166(1) Å	α= 70.797(2)°.	a = 5.6865(5) Å	α= 88.802(1)°.
	b = 11.232(1) Å	β= 81.611(2)°.	b = 11.495(1) Å	β= 78.262(1)°.
	c = 16.251(2) Å	γ = 75.996(2)°.	c = 13.675(1) Å	γ = 79.215(1)°.
Volume	1862.6(3) $Å^3$		859.57(13) $Å^3$	
Z	2		1	
Density (calculated)	1.184 Mg/m^3		1.291 Mg/m^3	
Absorption coefficient	0.699 mm^{-1}		0.760 mm^{-1}	
F(000)	704		354	
Crystal size	0.33 x 0.25 x 0.07 mm^3		0.26 x 0.20 x 0.07 mm^3	
Theta range for data collection	1.88 to 27.99°.		2.34 to 27.00°.	
Index ranges	-14<=h<=14, -14<=k<=14, -21<=l<=20		-7<=h<=7, -14<=k<=14, -17<=l<=17	
Reflections collected	20963		9514	
Independent reflections	8572 [R(int) = 0.0350]		3716 [R(int) = 0.0227]	
Completeness to theta = 27.00°	95.40%		98.90%	
Absorption correction	None		multi-scan	
Refinement method	Full-matrix least-squares on F^2		Full-matrix least-squares on F^2	
Data / restraints / parameters	8572 / 2 / 409		3716 / 0 / 237	
Goodness-of-fit on F^2	0.964		1.178	
Final R indices [I>2sigma(I)]	R1 = 0.0629, wR2 = 0.1663		R1[a] = 0.0593, wR2 = 0.1425	
R indices (all data)	R1 = 0.1191, wR2 = 0.1978		R1 = 0.0633, wR2 = 0.1446	
Largest diff. peak and hole	0.860 and -0.279 $e.Å^{-3}$		1.059 and -0.373 $e.Å^{-3}$	

[a] $R1=\Sigma||F_o|-|F_c|| / \Sigma F_o$, $wR2 = \{\Sigma[w(F_o^2 - F_c^2)^2] / \Sigma[w(F_o^2)^2]\}^{1/2}$

2.5 Anti-bacterial activity

Three Gram positive bacteria (*Micrococcus luteus*, *Staphylococcus aureus*, and *Bacillus subtilis*) and three Gram negative bacteria (*Escherichia coli*, *Klebsiella pneumonial* and *Proteus mirabilis*), were used to test the compounds anti-bacterial activity. The tests were carried out using the agar-well diffusion method[101].

The wells (6 mm in diameter) were dug in the media with the help of sterile glassy borer. Single bacterial colonies were dissolved in sterile saline until the suspended cells reached the turbidity of Mc Farland 0.5 Standard. The bacterial inocula were spread on the surface of the Muller Hinton nutrient agar with help of a sterile cotton swab. 50 µL of the test samples (30 mg/5 mL DMSO) were introduced in the respective wells. Another well was supplemented with DMSO for negative control. The plates were incubated immediately at 37 °C for 24 hours. The anti-bacterial activity was determined by measuring the diameter of complete growth inhibition zone in millimeter (mm). The results are the average of three trials and they are stated as average ± standard deviation.

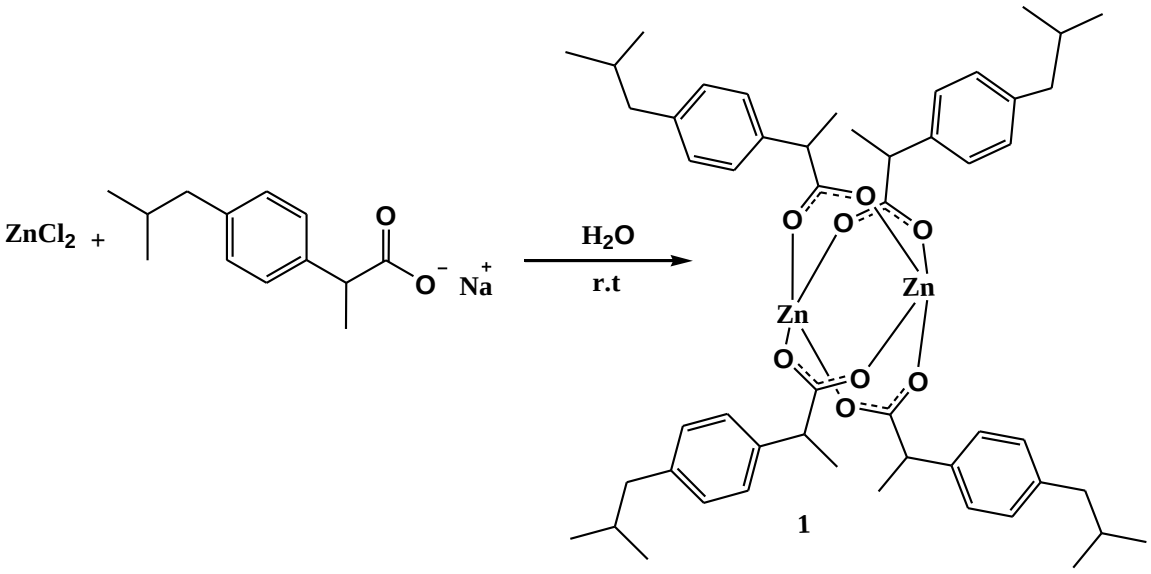
Complexes **4, 6** and **7** were selected for further anti-bacterial studies. Serial dilutions of these complexes and their parent ligands were prepared. The diluted solutions were tested in similarly prepared plates using the same procedure. The inhibition zone diameter (IZD) at 30, 15 and 7.5 mg/ 5mL DMSO and the minimum inhibition concentration (MIC) were determined for the complexes and their parent ligands.

3. RESULTS AND DISCUSSION

3.1 Synthesis of zinc complexes

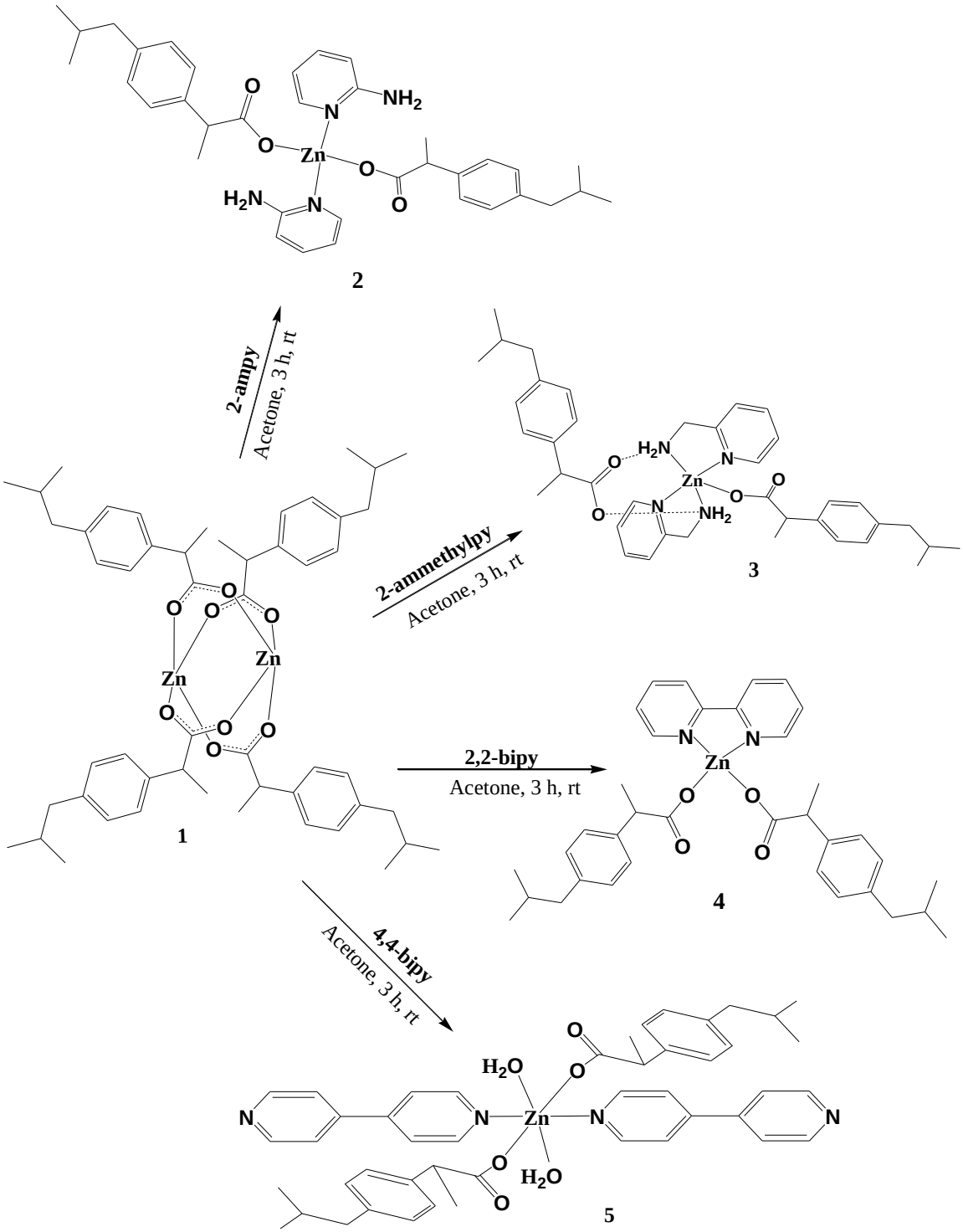
Complex **1** was prepared by simple reaction which involve deprotonation of the ligand by (1:1) NaOH solution followed by complexation with $ZnCl_2$ in 1:2 molar ratio (Scheme **3.1**). The compound was white and was obtained at high yield ~ 90%, the melting point was determined and it is soluble in different solvents (Table 3.1).

Scheme 3.1: Synthesis of $[Zn_2(ibup)_4]$ **(1)**.



Mixed ligand complexes were prepared by adding different nitrogen based ligands to **1** mostly in 1:4 molar ratio in acetone with stirring for three hours; Schemes 3.2 and 3.3 show the synthesis and the proposed structures of the prepared complexes. Melting point, yield and solubility for these novel complexes are tabulated in Table 3.1.

Scheme 3.2: Synthesis and proposed structures of complexes **2-5**.



Scheme 3.3: Synthesis and proposed structures of complexes **6-9**.

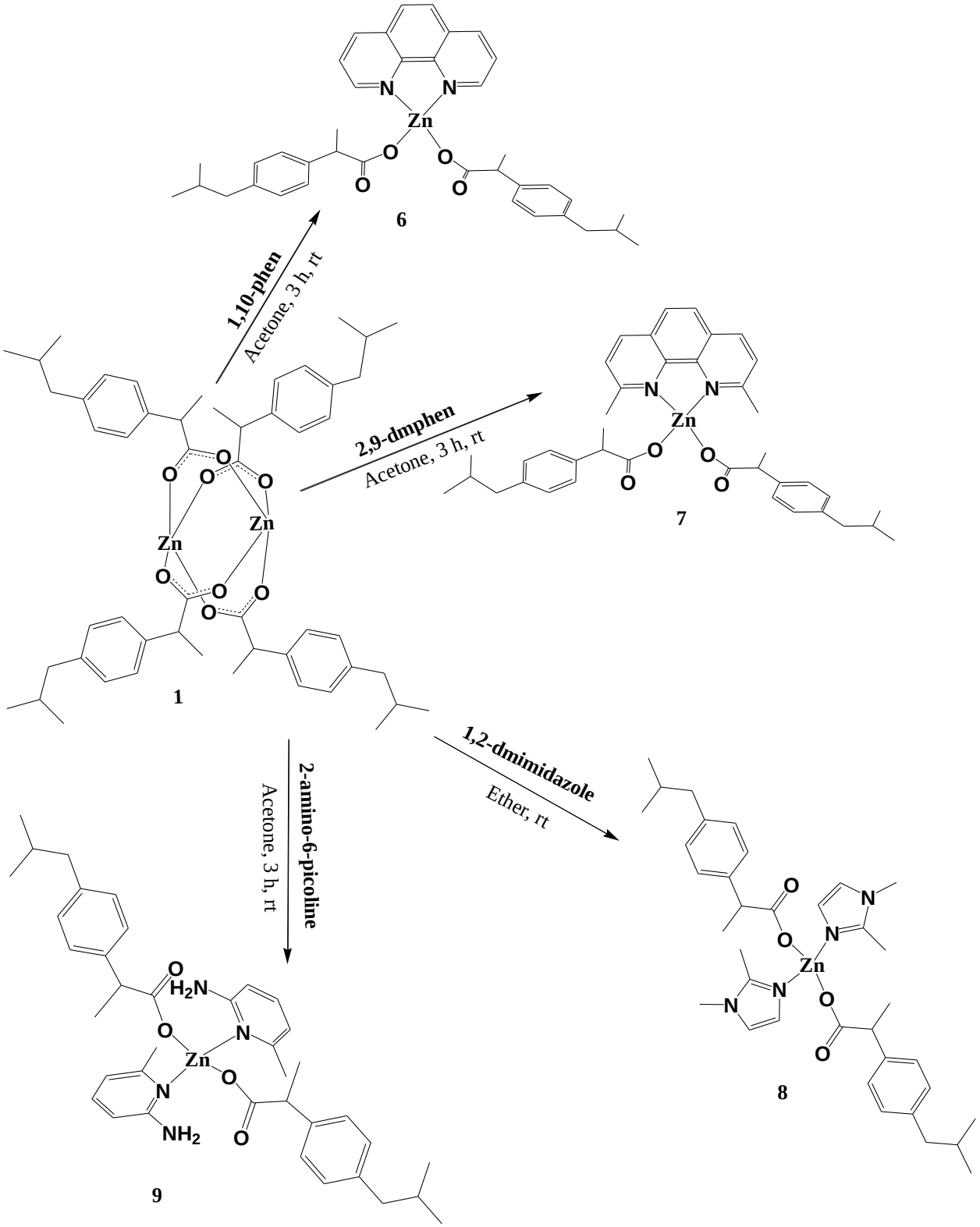


Table 3.1: Physical properties of complexes **1-9.**

Complex	**m.p (˚C)**	**% yield**	**Solubility**
$[Zn_2(ibup)_4]$ (**1)**	86.8-94.3	90	Ethanol, chloroform, DMSO.
$[Zn(ibup)_2(2\text{-ampy})_2]$ (**2)**	151.2-152.7	64	DMSO, ethanol, THF, DMF, dichloromethane.
$[Zn(ibup)_2(2\text{-ammethylpy})_2]$ (**3)**	154.8-156.9	62	THF, acetonitrile, chloroform DMSO, DMF, ethylacetate, dichloromethane.
$[Zn(ibup)_2(2,2`\text{-bipy})]$ (**4)**	143.6-146.3	33	DMSO, ethanol, THF, dichloromethane,
$[Zn(ibup)_2(4,4`\text{-bipy})]_n$ (**5)**	206.6-211.2	-	DMSO, ethanol, chloroform.
$[Zn(ibup)_2(1,10\text{-phen})]$ (**6)**	87.1-93.6	90	DMSO, ethanol, chloroform, dichloromethane, acetonitrile, DMF.
$[Zn(ibup)_2(2,9\text{-dmphen}]$ (**7)**	104.4-112.5	97	DMSO, ethanol, ether, dichloromethane, acetonitrile, ethylacetate, THF, DMF.
$[Zn(ibup)_2(1,2\text{-dmimidazole})_2]$ (**8)**	115-130.2	77	DMSO, ethanol, acetonitrile, ethylacetate, THF, DMF, dichloromethane.
$[Zn(ibup)_2(2\text{-am-6-picoline})_2]$ (**9)**	110.3-113.3	52	DMSO, dichloromethane, ethylacetate.

3.2 X-ray crystallographic studies

The crystal structures of complexes **2** and **5** have been determined, suitable crystals were obtained by recrystallization from acetone and ethanol, respectively. Crystal data and parameters for data collection are reported in Table 2.1. The complete crystallographic information files (CIF) are given in the Appendices.

3.2.1 X-ray crystal structure of $[Zn(ibup)_2(2\text{-ampy})_2]$ (2)

The asymmetric unit of the title complex, contains a Zn(II) cation, two ibuprofen groups and two 2-ampy ligands (Figure 3.1).

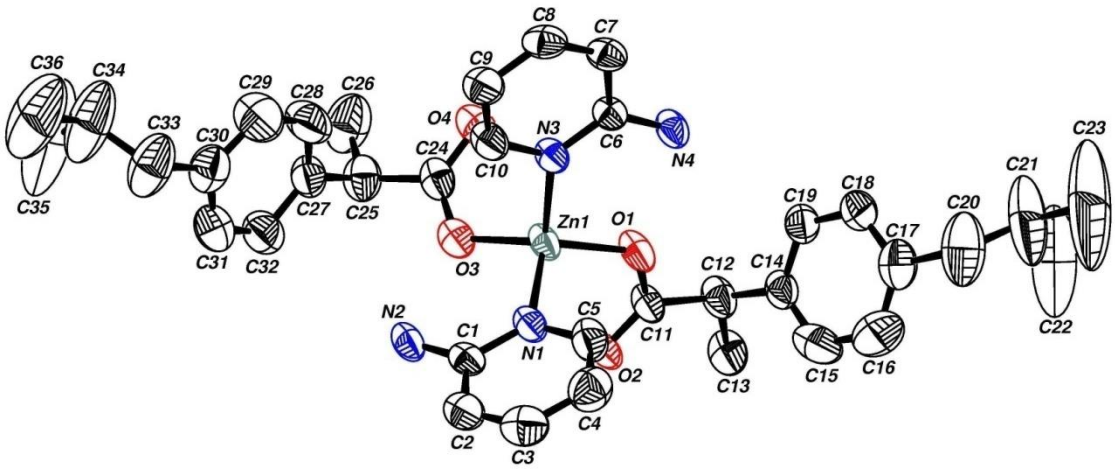


Figure 3.1. The molecular structure view of **2**, showing the atom labeling scheme.

Zn(II) is surrounded by two monodentate ibuprofen ligands with O-Zn coordination distances 1.920(2) Å and 1.907(3) Å which are little shorter than similar reported distances[102,103]. The 2-ampy ligands with distances involving pyridyl nitrogen and Zn being 2.055(3) and 2.043(3)Å which are in accord with similar previously reported distances(2.048Å in average)[102,103]. Number of selected interatomic distances and angles are tabulated in Table 3.2.

Table 3.2: Selected bond lengths [Å] and angles [°] for **2**.

Bond distance (Å)		Bond distance (Å)		Bond angle (˚)		Bond angle (˚)	
C(11)-O(2)	1.212(4)	C(1)-C(2)	1.407(6)	O(2)-C(11)-O(1)	123.5(3)	C(11)-O(1)-Zn(1)	119.1(2)
C(11)-O(1)	1.269(4)	C(24)-O(3)	1.276(5)	O(2)-C(11)-C(12)	122.7(3)	O(3)-Zn(1)-O(1)	123.29(12)
C(11)-C(12)	1.545(5)	N(1)-Zn(1)	2.055(3)	O(1)-C(11)-C(12)	113.3(3)	O(3)-Zn(1)-N(3)	110.49(12)
C(5)-N(1)	1.352(5)	N(3)-Zn(1)	2.043(3)	C(5)-N(1)-C(1)	118.6(4)	O(1)-Zn(1)-N(3)	106.53(10)
C(1)-N(2)	1.323(5)	O(1)-Zn(1)	1.920(2)	C(5)-N(1)-Zn(1)	114.6(3)	O(3)-Zn(1)-N(1)	105.06(13)
C(1)-N(1)	1.352(4)	O(3)-Zn(1)	1.907(3)	C(1)-N(1)-Zn(1)	126.6(3)	O(1)-Zn(1)-N(1)	110.01(13)
				N(2)-C(1)-N(1)	118.9(4)	N(3)-Zn(1)-N(1)	98.75(11)

Zn(II) center displays a distorted tetrahedral geometry. The deviation from regular tetrahedral is significantly observed from binding angles, O3-Zn1-O1 = 123.29(12), O3-Zn1-N3 = 110.49(12), O1-Zn1-N3 = 106.53(10), O3-Zn1-N1= 105.06(13), O1, Zn1-N1 = 110.01(13) and N3- Zn-N1 = 98.75(11)˚.

Table 3.3 shows the intramolecular and intermolecular hydrogen bonds. The first two bonds belong to the former while the last two bonds belong to the later type.

Table 3.3: Hydrogen bonds for **2** [Å] and [°].

D-H...A	d(D-H)	d(H...A)	d(D...A)	<(DHA)
N(4)-H(1N4)...O(1)	0.95	2.04	2.901(4)	149.9
N(2)-H(1N2)...O(3)	1	2	2.858(5)	143.4
N(4)-H(2N4)...O(4)#1	0.89	2.14	3.000(4)	163.7
N(2)-H(2N2)...O(2)#2	0.95	1.99	2.921(4)	166

Symmetry transformations used to generate equivalent atoms:
#1 -x+2,-y+1,-z+1 #2 -x+1,-y+2,-z+1

3.2.2 X-ray crystal structure of $[Zn(ibup)_2(4,4`\text{-bipy})]_n$ (5)

Figure 3.2 shows the atomic scheme and atom connectivity for complex **5**, in which Zn(II) is covalently bonded to two ibuprofen and two 4,4`-bipy ligands in polymeric form. Selected interatomic distances and angles are found in Table 3.4.

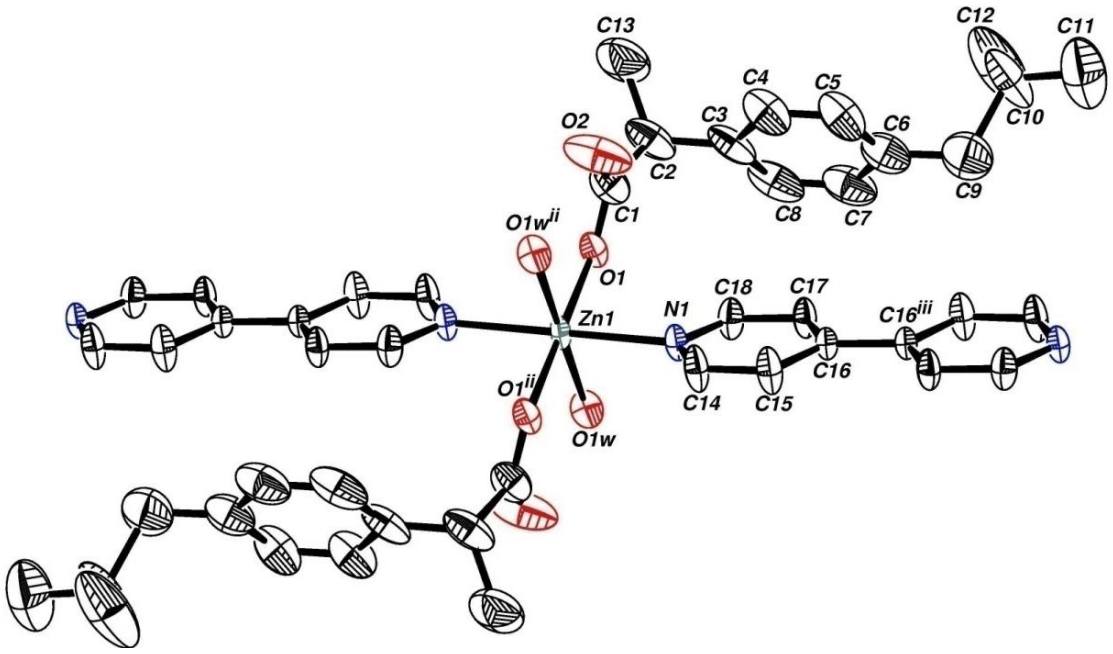


Figure 3.2. The molecular structure view of **5**, showing the atom labeling scheme.

The complex has perfect octahedral geometry, in which Zn1-O1 and Zn1-O1#2 have the same bond distance (2.1020(19) Å). The ibuprofen groups bonded in monodentate coordination mode.

The other oxygen atom of the monodentate ibuprofen is not covalently bonded to the zinc atom; this is easily proven by analyzing of C-O distances, C1-O1 and C1-O2 bond distances are 1.258(4) and 1.230(5) Å respectively, in which the later one has the shorter bond distance that is considered as an indication of ibuprofen nondelocalization ligand due to monodentate coordination.

The bond distance of Zn-N1is 2.194(2) Å which agrees with other metal complexes of 4,4`-bipy ligand[104]. The angles reflect the typical ZnO_2N_2 square planar view; N1-Zn1-N1#2 is exactly 180˚, O(1)-Zn(1)-N(1)#2, O(1)-Zn(1)-N(1) and O(1)#2-Zn(1)-N(1) are 90.73(8), 89.27(8) and 90.73(8)˚, respectively.

Table 3.4: Selected bond distances (Å) and bond angles (˚) for **5**.

Bond distance (Å)		Bond distance (Å)	
C(1)-O(2)	1.230(5)	C(17)-C(18)	1.380(4)
C(1)-O(1)	1.258(4)	C(18)-N(1)	1.328(3)
C(1)-C(2)	1.532(5)	N(1)-Zn(1)	2.194(2)
C(14)-N(1)	1.332(4)	O(1)-Zn(1)	2.1020(19)
C(14)-C(15)	1.379(4)	O(1W)-Zn(1)	2.123(2)
C(15)-C(16)	1.388(4)	Zn(1)-O(1)#2	2.1020(19)
C(16)-C(17)	1.376(4)	Zn(1)-O(1W)#2	2.123(2)
C(16)-C(16)#1	1.482(4)	Zn(1)-N(1)#2	2.194(2)
Bond angle (˚)		Bond angle (˚)	
O(2)-C(1)-O(1)	125.1(3)	C(1)-O(1)-Zn(1)	125.5(2)
O(2)-C(1)-C(2)	117.5(3)	O(1)-Zn(1)-O(1)#2	180
O(1)-C(1)-C(2)	117.4(3)	O(1)-Zn(1)-N(1)#2	90.73(8)
C(18)-N(1)-C(14)	116.1(2)	O(1)-Zn(1)-N(1)	89.27(8)
C(18)-N(1)-Zn(1)	120.23(18)	O(1)#2-Zn(1)-N(1)	90.73(8)
C(14)-N(1)-Zn(1)	123.52(18)		

The intramolecular and intermolecular hydrogen bonds interaction do exist (Table 3.5). The first bond belongs to intermolecular while the last two are for intramolecular hydrogen bonds.

Table 3.5: Hydrogen bonds for complex **5** [Å] and [°].

D-H...A	d(D-H)	d(H...A)	d(D...A)	<(DHA)
O(1W)-H(1W)...O(1)#3	0.82	2.05	2.832(3)	159.2
O(1W)-H(2W)...O(2)#2	0.89	1.73	2.598(4)	165.8
O(1W)-H(2W)...O(1)#2	0.89	2.64	3.071(3)	110.7

Symmetry transformations used to generate equivalent atoms:
#1 -x+2,-y+1,-z+1 #2 -x+2,-y,-z+1 #3 -x+1,-y,-z+1

As mentioned before this complex forms a polymer in which the adjacent zinc ions are bridged via 4,4'-bipyridine molecules forming a one dimensional linear chain rather than zigzag due to a bond angle of N1-Zn1-N1#2 (180˚). The chains are interconnected to a layer through intermolecular hydrogen bonding, so in this case we can talk about a three dimensional coordination polymer exactly as in case of $[Zn(4,4\text{-bipy})_2(H_2O)_2]_n(4,4\text{-bipy})_2(H_2O)_n(pic)_{2n}$ polymer[105].

For both complexes **2** and **5**, Zn-O distances are in the range of 1.84-2.33 Å of monodentate acetate complexes[106]. The average C-O bond distances of coordinated oxygen are 1.273 and 1.258 Å, respectively; while the average of non-coordinated C-O oxygen are 1.212 and 1.230 Å, respectively. The difference in the bond distances between the coordinate and non-coordinated C-O are considered as an indication of ibuprofen nondelocalization ligand due to monodentate coordination. The average O-C-O bond angles of complexes **2** and **5** are 123.8 and 125.1˚, respectively; as it is expected for monodentate carboxylate coordination.

3.3 IR results

IR spectroscopy is a useful tool in diagnosing the nature of carboxylate coordination. Extensive infrared studies have been performed on metal complexes of carboxylic acids. The carboxylate ion may coordinate to a metal in one of three modes (Figure 3.3)[107].

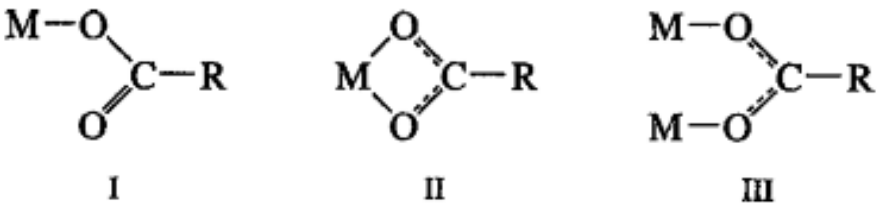


Figure 3.3. Coordination modes of carboxylate ions.

In metal carboxylate complexes, the major characteristic of the IR spectra is the frequency of the υ asymmetric (υ_{as}) and υ symmetric (υ_s) of carbonyl (COO^-) stretching vibrations and the difference between them $\Delta\upsilon(COO^-)$. The frequency of these bands depends upon the coordination mode of the carboxylate ligand. Monodentate complexes (structure I) exhibit $\Delta\upsilon(COO^-)$ values that are much greater than the ionic complexes. Chelating (bidentate) complexes (structure II) exhibit $\Delta\upsilon(COO^-)$ values that are significantly less than the ionic values. $\Delta\upsilon(COO^-)$ values for bridging complexes (structure III) are greater than those of chelating complexes, and close to the ionic values[107].

Infrared spectra (400-4000 cm^{-1}) were recorded, and the data of zinc complexes that were prepared as KBr pellets are summarized in the following tables below. The IR frequencies for sodium ibuprofen salt and **1** are given in Table 3.6. The $\upsilon_{as}(COO^-)$ and $\upsilon_s(COO^-)$ stretching vibrations for sodium ibuprofen have been observed at 1550 and 1400 cm^{-1}, respectively, and the separation between them $\Delta\upsilon(COO^-)$ = 150 cm^{-1}. In complex **1**; $\upsilon_{as}(COO^-)$ is at 1545 cm^{-1} and $\upsilon_s(COO^-)$ at 1414 cm^{-1}, $\upsilon(COO^-)$ = 131 cm^{-1} which is close to that of sodium ibuprofenate which supports a coordination mode for complex **1** as bridging bidentate to form $[Zn_2(ibup)_4]$[82,108-112]. There is no O-H vibration frequency in the range of 3000-

3600 cm-1 which indicates the absence of water molecule in the coordination geometry.

Dendrinou-Samara et al. synthesized $[Zn(ibup)_2(H_2O)_2]$ complex using the same procedure but they used methanol\water as solvent, for the complex, $\upsilon_{as}(COO^-)$ occurs at 1605 cm^{-1} and $\upsilon_s(COO^-)$at 1390 cm^{-1}, $\Delta\upsilon(COO^-)$ = 215 cm^{-1}, they suggested monodentate coordination mode[82]. In accordance with literature data υ(Zn-O) stretching vibrations of complexes (**1-9**) are found in the 414-593 cm^{-1} region.

Table 3.6: Principal IR peaks for Na(ibup) and **1** (cm^{-1}).

Assignments	Na(ibup)	**1**
$\upsilon(C\text{-}H)_{ar}$	3060, 3066	3090
$\upsilon(C\text{-}H)_{aliph}$	2962, 2867	2953, 2925, 2867
$\upsilon_{as}(COO^-)$	1550	1545
$\upsilon_s(COO^-)$	1400	1414
υ(ring)+δ(C-H)	1476, 1367	1366, 1462, 1512
$\Delta\upsilon(COO^-)$	150	131

Complexes **2** and **3** exhibited $\upsilon_{as}(COO^-)$ at 1624 and 1605 cm^{-1}, on the other hand; $\upsilon_s(COO^-)$ occur at 1352 and 1361 cm^{-1}, $\Delta\upsilon(COO^-)$ are 272 and 244 cm^{-1}, respectively that is larger than $\Delta\upsilon(COO^-)_{Na(ibup)}$ = 150 cm^{-1}, this supports monodentate coordination mode of ibuprofenate groups, which is confirmed by X-ray structure determination of complex **2**.

As it is expected for **2**, two absorption frequencies at 3339 and 3225 cm^{-1} have been assigned to 1˚-NH_2 group. The corresponding N-H peak of complex **2** is lowered by 108 cm^{-1} due to complexation through the pyridine nitrogen atoms.

The difference in NH_2 stretching for **2** ($\upsilon_{as(N-H)}$ - $\upsilon_{s(N-H)}$) is 114 cm^{-1}, while that of NH_2 in free 2-ampy ligand is 262 cm^{-1}, this indicates a hydrogen bond in complex **2**[113], that is actually confirmed by the crystal structure of **2**.

The complexation with NH_2 will cause a larger shift for the two NH_2 peaks[113]. 2-aminomethylpy in complex **3** binds to zinc through pyridine nitrogen and the amino group appears to be in a chelating bidentate coordination mode as supported by the presence of 3288 cm^{-1} [114-117]. In contrast two peaks exist at 3364 and 3289 cm^{-1} for 2-aminomethylpy free ligands. Metal complexes of 2-aminomethylpy that exhibit strong hydrogen bonding between the amine nitrogens and the carboxylate oxygens show one broad peak at the υ (NH_2) region[118]. In addition, **3** shows Zn-NH_2 stretching frequency at 448 cm^{-1} [119].

Table 3.7: Selected IR peaks for **2**, **3**, **4** and **5**.

Assignments	**2**	**3**	**4**	**5**
υ_{as}(N-H)	3339 s	3288 m	-	-
υ_{s}(N-H)	3225 s	3125 w	-	-
υ(C-H)ar	3030 vw	3125 w	3069 vw	3213 w
υ(C-H)aliph	2954 s, 2925 m, 2866 m	2955 s, 2924 m, 2868 m	2956 s, 2864 m	2958 s, 2926 m, 2869 m
υ(ring)	1640 s	1672 s	1609 s	-
υ_{as}(COO-)	1624 vs	1605 vs	1597 vs	1600 vs
υ(ring) + δ(C-H)	1566 s, 1502 s	1508 s, 1455 s	1508 s, 1444 s	1491m, 1461 m
υ_{s} (COO-)	1352 s	1361 s	1388 s	1377 s
υ(ring)	1272 s, 1066 m	1287 s, 1220m, 1129 m, 1097 s	1419 s, 1314 s, 1225 w, 1025 s	1276 m, 1221 m
ϒ(C-H)	850 s	850 s	850 m	850 m
δ(COO-)	769 s, 740 m	759 w	773 vs	784 m
υ(ring)	725 w	733 m	735 m	756 m
Δ(COO-)	272	244	209	223

For complexes **4**, **5**, **6** and **7** the asymmetric stretches $\upsilon_{as}(COO^-)$ are 1597, 1600, 1561 and 1618 cm^{-1}, the symmetric stretches $\upsilon_s(COO^-)$ have been observed at 1388, 1377, 1383 and 1378 cm^{-1}, respectively. The large values of $\Delta\upsilon(COO^-)$ = 209, 223, 178 and 240 cm^{-1}, respectively are an indication of monodentate coordination of the ibuprofen groups; since all separation frequencies are higher than that of sodium ibuprofen ($\Delta\upsilon(COO^-)$ = 150 cm^{-1}), this mode of coordination is unambiguously confirmed by the crystal structure of **5**. These values are in agreement with other zinc carboxylate complexes that exhibit monodentate coordination[50].

Infrared spectra of metal complexes of 2,2`-bipy have been studied extensively[50]. In general, the bands in the high-frequency region are not metal-sensitive since they originate in the heterocyclic or aromatic ring of the ligand. Thus, the main interest has been focused on the low frequency region, where M-N and other metal sensitive vibrations appear. It has been difficult, however, to assign υ(M-N) empirically since several ligand vibrations also appear in the same frequency region[107]. The peaks appearing at 3069, 3054, 1567 and 773 cm^{-1} are apparently the characteristic absorptions of 2,2`-bipy present in **4**[50]. The presence of water molecule in **5** was confirmed, additionally to X- ray, by IR spectral peaks at 3420 cm^{-1}. The peaks at 1517, 1426, 1104, 854, 727 and 588 cm^{-1} are characteristic absorptions of 1,10-phenanthroline present in **6**[50].

Table 3.8: Selected IR peaks for **6**, **7**, **8** and **9**.

Assignments	**6**	**7**	**8**	**9**
υas(N-H)	-	-	-	3376 s
υs(N-H)	-	-	-	3222 s
υ(C-H)ar	3057 w	3053 vw	3121 s	3075 vw
υ(C-H)aliph	2953 s, 2925 m	2954 s, 2926 m, 2868 m	2956 s, 2925 m, 2867 s	2954 s, 2926 m, 2866 m
υ(ring)	1610 m	-	-	1661 s
υas(COO-)	1561 vs	1618 vs	1622 vs	1612 vs
υ(ring) + δ(C-H)	1517 s, 1500 w	1509 s, 1460 m	1511 s, 1458 m	1487 s, 1457 m
υs (COO-)	1383 m	1378 vs	1375 vs	1393 s
υ(ring)	1286 m, 1224 m, 1063 m	1200 w, 1157 m, 1062 m	1283 m, 1244 w, 1063 m	1279 s, 1256 m, 1060 m
ϒ(C-H)	854 s	861 s	850 m	844 m
δ(COO-)	785 m, 750 m	781 m	778 m	781 s
υ(ring)	727 vs	730 s	750 w	745 m
Δ(COO-)	178	240	247	219

The monodentate coordination mode of complexes **8** and **9** is characterized; $\upsilon_{as}(COO^-)$ were observed at 1622 , 1612 cm^{-1}, $\upsilon_s(COO^-)$ at 1375, 1393 cm^{-1}, respectively, $\Delta\upsilon(COO^-)$ = 247 and 219 $cm^{-1,}$ respectively, since the separation frequencies are higher than that of sodium ibuprofenate ($\Delta\upsilon(COO^-)$ = 150 cm^{-1}).

For complex **9**, υ_{as}(N-H) = 3376 cm^{-1}, υ_s(N-H) = 3222 cm^{-1}, $\Delta\upsilon$ (NH_2)= 154cm^{-1}, for 2-amino-6-picoline υ_{as}(N-H) = 3461 cm^{-1}, υ_s(N-H)= 3171 $cm^{-1}$and $\Delta\upsilon$ (NH_2)= 290 cm^{-1}. $\Delta\upsilon$ (NH_2) of complex **9** is lower than that of the free ligand, so a hydrogen bond can be indicated between NH_2 of 2-amino-6-picoline and (COO) of ibuprofen[113].

3.4 Electronic absorption spectral results

There are three electronic transitions involved in the coordination complexes in solid state: (1) metal ion *d-d* transition ligand field absorption bands; this often occurs in the visible and near infrared regions, and the intensity of the band is weak. (2) charge transfer based on the ligand: this charge transfer (LC) is similar to that of a general organic compound and often occurs in the Ultraviolet region. (3) Charge-transfer absorption spectra that are produced by charge transfer between the ligand and metal ion, which are fundamentally of two types: (a) metal-to-ligand charge transfer (MLCT); (b) ligand-to-metal charge transfer (LMCT), which often occur in the ultraviolet and visible regions[120,121].

Because all the complexes are colorless, a spatial configuration of d^{10} track in the metal ion Zn(II) and the *d* orbital is completely filled, therefore *d-d* electronic transition cannot happen.

From the results that are tabulated in Table 3.9 below, no LMCT can be observed. The bands are assigned to LC; where the spectra of the complexes are similar to those of nitrogen parent ligands with very small shifts values caused by zinc coordination.

Table 3.9: UV-Vis data of **1-9**.

Compound	λ_{max} (nm)
1	315
ibup	298
2	301
2-ampy	316
3	315
2-ammethylpy	304
4	308
2,2`-bipy	307
5	315
4,4`-bipy	299
6	326
1,10-phen	311
7	297
2,9-dmphen	305
8	-
1,2-dmimidazole	282
9	364
2-am-6-picoline	324

3.5 ^{1}H-NMR and ^{13}C{^{1}H} NMR spectral data

^{1}H-NMR and ^{13}C{^{1}H} NMR spectral data of complex **1** and ibuprofen are listed in Table 3.10. Comparison of the ^{1}H-NMR spectra of complex **1** and ibuprofen showed the absence of the O-H resonance in the spectra in addition to slight upfield shift for mostly all resonances. In the ^{13}C{^{1}H} NMR of **1** the C=O resonance was shifted downfield form 181.35 to 189.46 ppm, this deshielding effect indicating the donation of electrons from the carboxylate ibuprofen ion to Zn(II) ion. Downfield shift for the resonance of the carbon atom adjacent to carbonyl group was also observed, i.e. CH 45.08 to 45.32 ppm and CH_3 18.15 to 19.41 ppm which prove the interaction of the carboxyl part of ibuprofen to Zn(II).

Table 3.10: ^{1}H-NMR and ^{13}C{1H} NMR spectral data of complex **1** and ibuprofen.

^{1}H-NMR		**^{13}C{^{1}H} NMR**	
1	H(ibup)[122]	**1**	H(ibup)[123]
0.89 (d, 6H, CH_3, $^{3}J_{H-H}$ = 6.6 Hz)	0.89	19.41 (CH_3)	18.15
1.35 (d, 3H, CH_3, $^{3}J_{H-H}$ = 6.9 Hz)	1.49	22.67 (CH_3)	22.47
1.82 (m, 1H, CH)	2.84	30.42 (CH)	30.25
2.42 (d, 2H, CH_2, $^{3}J_{H-H}$ = 7.2 Hz)	2.44	45.32 (CH)	45.08
3.62 (q, 1H, CH, $^{3}J_{H-H}$ = 7.2 Hz)	3.70	47.24 (CH_2)	45.11
7.03 (d, 2H, CH, $^{3}J_{H-H}$ = 8.1 Hz)	7.09	127.44 (CH)	127.36
7.15 (d, 2H, CH, $^{3}J_{H-H}$ = 8.1 Hz)	7.21	129.41 (CH)	129.47
	(-OH)11	138.65 (C)	137.02
		140.51 (C)	140.93
		189.46 (C=O)	181.35

^{1}H-NMR and ^{13}C{^{1}H} NMR spectral data of complexes **2-9** in addition to their parent nitrogen based ligands are listed in Tables 3.11 – 3.18.

Table 3.11: ^{1}H-NMR and ^{13}C{1H} NMR spectral data of complex **2** and 2-ampy.

^{1}H-NMR		**^{13}C{^{1}H} NMR**	
2	2-ampy[124]	**2**	2-ampy[125]
0.84 (d, 6H, CH_3, $^{3}J_{H-H}$ = 6.6 Hz)		20.33 (CH_3)	
1.32 (d, 3H, CH_3, $^{3}J_{H-H}$ = 6.9 Hz)		22.66 (CH_3)	
1.79 (m, 1H, CH(ibup))		30.11 ($CH_{(ibup)}$)	
2.39 (d, 2H, CH_2, $^{3}J_{H-H}$ = 6.9 Hz)		44.79 ($CH_{(ibup)}$)	
3.54 (q, 1H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 6.9 Hz)		46.53 (CH_2)	
6.45 (bs, 2H, NH_2)	4.45	110.09 (CH)	108.66
6.53 (m, 2H, CH)	6.48, 6.63	112.15 (CH)	113.67
7.02 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 7.5 Hz)		127.63 ($CH_{(ibup)}$)	
7.19 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 7.8 Hz)		129.02 ($CH_{(ibup)}$)	
7.42 (t, 1H, CH, $^{3}J_{H-H}$ = 15.3 Hz)	7.41	138.83 (CH)	137.66
7.74 (d, 1H, CH, $^{3}J_{H-H}$ = 4.8 Hz)	8.06	139.07 ($C_{(ibup)}$)	
		141.22 ($C_{(ibup)}$)	
		147.04 (CH)	147.98
		160.05 (C-NH_2)	158.85
		179.82 (C=O)	

Table 3.12: ^{1}H-NMR and ^{13}C{1H} NMR spectral data of complex **3** and 2-ammethylpy.

^{1}H-NMR		**^{13}C{^{1}H} NMR**	
3	2-ammethylpy[126]	**3**	2-ammethylpy[127]
0.85 (d, 6H, CH_3, $^{3}J_{H-H}$ = 5.7 Hz)		20.59 (CH_3)	
1.23 (d, 3H, CH_3, $^{3}J_{H-H}$ = 6.3 Hz)		22.68 (CH_3)	
1.772 (m, 1H, $CH_{(ibup)}$)		30.13 ($CH_{(ibup)}$)	
2.34 (d, 2H, $CH_{2(ibup)}$, $^{3}J_{H-H}$ = 6.3 Hz)		44.76 ($CH_{(ibup)}$)	
3.41 (q, 1H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 7.2 Hz)		44.88 ($CH_{2(ibup)}$)	
3.529 (bs, 2H, NH2)	1.84	46.99 (CH2)	47.76
3.94 (bd, 2H, CH2, $^{3}J_{H-H}$ = 5.4 Hz)	3.97	122.56 (CH)	
6.96 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 7.5 Hz)		123.18 (CH)	121.09, 121.64
7.10 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 9.6 Hz)		127.58 ($CH_{(ibup)}$)	
7.35 (t, 1H, CH, $^{3}J_{H-H}$ = 5.1 Hz)	7.15	128.83 ($CH_{(ibup)}$)	
7.46 (d, 1H, CH, $^{3}J_{H-H}$ = 7.5 Hz)	7.26	136.39 (CH)	136.39
7.89 (m, 1H, CH)	7.62	138.75 ($C_{(ibup)}$)	
8.42 (d, 1H, CH, $^{3}J_{H-H}$ = 4.8 Hz)	8.55	141.91 ($C_{(ibup)}$)	
		148.11 (CH)	149.14
		161.07 (C)	162.07
		179.45 (C=O)	

Table 3.13: ^{1}H-NMR and ^{13}C{1H} NMR spectral data of complex **4** and 2,2`-bipy.

^{1}H-NMR		**^{13}C{^{1}H} NMR**	
4	2,2`-bipy[128]	**4**	2,2`-bipy[129]
0.86 (d, 6H, CH_3, $^{3}J_{H-H}$ = 6.6 Hz)		19.82 (CH_3)	
1.43 (d, 3H, CH_3, $^{3}J_{H-H}$ = 6.9 Hz)		22.65(CH_3)	
1.80 (m, 1H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 6.6 Hz)		30.44 ($CH_{(ibup)}$)	
2.39 (d, 2H, CH_2, $^{3}J_{H-H}$ = 7.2 Hz)		45.31 ($CH_{(ibup)}$)	
3.72 (q, 1H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 7.2 Hz)		46.38 (CH_2)	
6.96 (d,2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ =8.1 Hz)		121.02 (CH)	121.00
7.18 (d,2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ =8.4 Hz)		-	123.63
7.37 (bs, 1H, CH)	7.12	127.56 ($CH_{(ibup)}$)	
7.91 (dt, 1H, CH, $^{3}J_{H-H}$ =8.4 Hz)	7.66	129.08 ($CH_{(ibup)}$)	
8.04 (d, 1H, CH, $^{3}J_{H-H}$ =8.1 Hz)	8.50	139.35 (CH)	136.75
8.69 (bs, 1H, CH)	8.59	139.54 ($C_{(ibup)}$)	
		140.62 ($C_{(ibup)}$)	
		149.59 (CH)	149.12
		150.01 (C=O)	
		-	156.14

Table 3.14: ^{1}H-NMR and ^{13}C{1H} NMR spectral data of complex **5** and 4,4`-bipy.

^{1}H-NMR		**^{13}C{^{1}H} NMR**	
5	4,4-bipy[130]	**5**	4,4`-bipy[131]
0.82 (d, 6H, CH_3, $^{3}J_{H-H}$ = 6.5 Hz)		19.42 (CH_3)	
1.27 (d, 3H, CH_3, $^{3}J_{H-H}$ = 6.9 Hz)		22.62 (CH_3)	
1.75 (m, 1H, $CH_{(ibup)}$)		29.14 ($CH_{(ibup)}$)	
2.33 (d, 2H, CH_2, $^{3}J_{H-H}$ = 7.0 Hz)		43.38 ($CH_{(ibup)}$)	
3.44 (q, 1H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 7.2 Hz)		45.78 ($CH_{(ibup)}$)	
6.99 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 8.1 Hz)		121.30 (CH)	121.37
7.15 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 8.3 Hz)		128.90 $CH_{(ibup)}$)	
7.82 (m, 1H, CH)	7.53	129.08 $CH_{(ibup)}$)	
8.68 (m, 1H, CH)	8.74	132.30 ($C_{(ibup)}$)	
		139.26 ($C_{(ibup)}$)	
		144.22 (C)	145.42
		149.91 (C)	
		150.82 (C)	150.66
		178.21 (C=O)	

Table 3.15: ^{1}H-NMR and ^{13}C{1H} NMR spectral data of complex **6** and 1,10-phen.

^{1}H-NMR		**^{13}C{^{1}H} NMR**	
6	1,10-phen[132]	**6**	1,10-phen[133]
0.84 (d, 6H, CH_3, $^{3}J_{H-H}$ = 6.6 Hz)		19.68 (CH_3)	
1.42 (d, 3H, CH_3, $^{3}J_{H-H}$ = 7.2 Hz)		22.65 (CH_3)	
1.77 (m, 1H, $CH_{(ibup)}$)		30.44 ($CH_{(ibup)}$)	
2.37 (d, 2H, CH_2, $^{3}J_{H-H}$ = 7.2 Hz)		45.28 ($CH_{(ibup)}$)	
3.69 (q, 1H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 6.9 Hz)		46.70 (CH_2)	
6.92 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 8.1 Hz)		124.52 (CH)	123.4
7.16 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 7.8 Hz)		126.90 (CH)	126.8
7.66 (t, 2H, CH, $^{3}J_{H-H}$ = 12.6 Hz)	7.58	127.51 ($CH_{(ibup)}$)	
7.83 (s, 2H, CH)	8.20	128.88 (C)	129.1
8.34 (dd, 2H, CH, $^{3}J_{H-H}$ = 9.6 Hz)	8.22	129.06 ($CH_{(ibup)}$)	
9.02 (d, 2H, CH, $^{3}J_{H-H}$ = 3.3 Hz)	9.18	134.07 (CH)	136.3
		137.89 ($C_{(ibup)}$)	
		140.83 ($C_{(ibup)}$)	
		-	146.5
		150.04 (CH)	150. 6
		150.23 (C=O)	

Table 3.16: ^{1}H-NMR and ^{13}C{1H} NMR spectral data of complex **7** and 2,9-dmphen.

^{1}H-NMR		**^{13}C{^{1}H} NMR**	
7	2,9-dmphen[134]	**7**	2,9-dmphen[135]
0.74 (d, 6H, $CH_{3(ibup)}$, $^{3}J_{H-H}$ = 15 Hz)		19.66 ($CH_{3(ibup)}$)	
1.18 (d, 3H, $CH_{3(ibup)}$, $^{3}J_{H-H}$ = 21 Hz)		22.40 ($CH_{3(ibup)}$)	
1.73 (m, 1H, $CH_{(ibup)}$)		25.90 (CH_3)	25.79
2.44 (d, 2H, CH_2, $^{3}J_{H-H}$ = 9 Hz)		30.22 ($CH_{(ibup)}$)	
2.74 (s, 6H, CH_3)	2.92	45.02 ($CH_{(ibup)}$)	
3.47 (q, 1H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 24 Hz)		46.58 ($CH_{2(ibup)}$)	
6.88 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 9 Hz)		123.46 (CH)	123.44
7.01 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 6 Hz)		-	125.40
7.56 (d,2H, CH, $^{3}J_{H-H}$ = 18 Hz)	7.46	126.68 (CH)	126.78
7.82 (d, 2H, CH, $^{3}J_{H-H}$ = 12 Hz)	7.69	127.29 ($CH_{(ibup)}$)	
8.28 (d, 2H, CH, $^{3}J_{H-H}$ = 15 Hz)	8.10	128.77 ($CH_{(ibup)}$)	
		136.26 (CH)	136.23
		138.95 ($C_{(ibup)}$)	
		140.83 ($C_{(ibup)}$)	
		145.13 (C)	145.27
		159.17 (C)	159.23
		181.91 (C=O)	

Table 3.17: ^{1}H-NMR and ^{13}C{1H} NMR spectral data of complex **8** and 1,2-dmimidazole.

^{1}H-NMR		**^{13}C{^{1}H} NMR**	
8	1,2-dmimidazole[132]	**8**	1,2-dmimidazole[132]
0.88 (d, 6H, $CH_{3(ibup)}$, $^{3}J_{H-H}$ = 6.6 Hz)		11.85 (CH_3)	12.77
1.43 (d, 3H, $CH_{3(ibup)}$, $^{3}J_{H-H}$ = 6.9 Hz)		19.83 ($CH_{3(ibup)}$)	
1.81 (m, 1H, $CH_{(ibup)}$)		22.64 ($CH_{3(ibup)}$)	
2.13 (s, 3H, CH_3)	2.35	30.51 ($CH_{(ibup)}$)	
2.40 (d, 2H, CH_2, $^{3}J_{H-H}$ = 7.2 Hz)		33.39 (CH_3)	32.67
3.45 (s, 3H, CH_3)	3.52	45.32 ($CH_{(ibup)}$)	
3.62 (q, 1H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 7.2 Hz)		47.51 (CH_2)	
6.65 (s, 1H, CH)	6.77	120.42 (CH)	120.36
6.88 (s, 1H, CH)	6.86	126.65 (CH)	126.79
6.98 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 8.1 Hz)		127.78 ($CH_{(ibup)}$)	
7.25 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 4.2 Hz)		128.82 ($CH_{(ibup)}$)	
		139.07 ($C_{(ibup)}$)	
		141.63 ($C_{(ibup)}$)	
		144.70 (C)	14.80
		181.09 (C=O)	

Table 3.18: ^{1}H-NMR and ^{13}C{1H} NMR spectral data of complex **9** and 2-am-6-picoline.

^{1}H-NMR		**^{13}C{^{1}H} NMR**	
9	2-am-6-picoline[126]	**9**	2-am-6-picoline[127]
0.81 (d, 6H, $CH_{3(ibup)}$, $^{3}J_{H-H}$ = 6 Hz)		19.38 ($CH_{3(ibup)}$)	
1.27 (d, 3H, $CH_{3(ibup)}$, $^{3}J_{H-H}$ = 9 Hz)		22.43 ($CH_{3(ibup)}$)	
1.75 (m, 1H, $CH_{(ibup)}$)		23.26 (CH_3)	23.95
2.17 (s, 3H, CH3)	2.36	30.25 ($CH_{(ibup)}$)	
2.35 (d, 2H, CH_2, $^{3}J_{H-H}$ = 6 Hz)		45.08 ($CH_{(ibup)}$)	
3.33 (s, 2H, NH_2)	4.60	47.16 (CH_2)	
3.47 (q, 1H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 7.2 Hz)		106.89 (CH)	105.43
6.16 (d, 1H, CH, $^{3}J_{H-H}$ = 6 Hz)	6.28	112.67 (CH)	112.76
6.27 (d, 1H, CH, $^{3}J_{H-H}$ = 9 Hz)	6.48	127.37 ($CH_{(ibup)}$)	
6.98 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 8 Hz)		128.91 ($CH_{(ibup)}$)	
7.14 (d, 2H, $CH_{(ibup)}$, $^{3}J_{H-H}$ = 4.2 Hz)		139.01 (CH)	137.99
7.63 (m, 1H, CH)	7.29	139.48 ($C_{(ibup)}$)	
		139.90 ($C_{(ibup)}$)	
		150.59 (C)	156.66
		158.19 (C)	158.46
		182.81 (C=O)	

Upon complexation slight chemical shifts in the ^{1}H and ^{13}C NMR were noticed. The integration of the ^{1}H-NMR signals is used to determine the coordination

number of the complexes. The ratio between the nitrogen based ligands and ibuprofen was 1:1 in complexes **2**, **3**, **5**, **8** and **9**. However the ratio was 1:2 in complexes **4**, **6** and **7**.

In addition to IR, NMR can be used to diagnose the binding mode. The $^{13}C\{^{1}H\}$ NMR chemical shifts of carbonyl group depends on the coordination number and the coordination mode of the complexed metal[22]. To determine the carboxylate binding mode it is necessary to use a reference in the spectra. The terminal methyl group of ibuprofen can be used as a reference which is less affected by complexation. The $^{13}C\{^{1}H\}$ NMR chemical shifts of carbonyl group of different modes are in the following order[22]:

$\delta\ ^{13}C\ (COO^-)_{ionic} > \delta\ ^{13}C\ (COO^-)_{chelating} > \delta\ ^{13}C\ (COO^-)_{bridging} > \delta^{1}\ ^{3}C\ (COO^-)_{monodentate.}$

Therefore, the $^{13}C\{^{1}H\}$ NMR chemical shifts of the carbonyl group were calculated and tabulated in Table 3.19.

Table 3.19: Binding modes of **1**-**9** depending on $^{13}C\{^{1}H\}$ NMR data.

Complex	**$\delta\ ^{13}C(CH_3)$ (ppm)**	**$\delta\ ^{13}C\ (COO^-)$ (ppm)**	**$\delta\ ^{13}C\ (COO^-)_{cal.}$* (ppm)**	**Binding mode**
H(ibup)	22.47	181.35	158.88	-
Na(ibup)	22.80	201.00	178.20	Ionic
1	22.67	189.46	166.79	bridging bidentate
2	22.66	179.82	157.16	Monodentate
3	22.68	179.46	156.78	Monodentate
4	22.65	150.01	127.36	Monodentate
5	22.62	178.21	155.59	Monodentate
6	22.65	150.23	127.58	Monodentate
7	22.40	181.91	159.51	Monodentate
8	22.64	181.10	158.46	Monodentate
9	22.43	182.81	160.38	Monodentate

*$\delta\ (COO^-)_{calculated} = (\delta\ ^{13}C(COO^-) - \delta\ ^{13}C(CH_3))$.

Undoubtedly, complexes **2** and **5** show a monodentate coordination mode, the crystal structure of them are discussed in Section 3.2. Complex **2** exhibit carbonyl group chemical shift ($\delta(COO^-)_{cal.}$) value around 157 ppm, complex that has a value close to or less than this value was considered as having monodentate coordination mode. Depending on this guess-work, complexes **3**, **4**, **6**-**9** have monodentate coordination mode which agree with the results obtained using IR spectroscopy. Complex **1** has the largest value of $\delta(COO^-)_{cal.}$ this enhance the results of IR spectroscopy that suggest bridging bidentate mode.

3.6 *In-vitro* anti-bacterial activity results

Three Gram positive bacteria (*Micrococcus luteus*, *Staphylococcus aureus*, and *Bacillus subtilis*) and three Gram negative bacteria (*Escherichia coli*, *Klebsiella pneumonial and Proteus mirabilis*), were used to test the compounds anti-bacterial activity.

The tests were carried out using the agar-well diffusion method. Bacteria were inoculated on Muller Hinton agar after staining a cell density in sterile saline (0.9 % NaCl) equivalent to 0.5 Mc Farland standard. After inoculation with the bacteria wells were dug into the agar and 50 µL of the test samples (30 mg/5 mL DMSO = 6 g/ L DMSO) were introduced in the respective wells. One of the wells was supplemented with DMSO for negative control. The plates were incubated immediately at 37 °C for 24 hours. The anti-bacterial activity was determined by measuring the diameter of complete growth inhibition zone in millimeter (mm). The results are the average of three trials and they are stated as average ± standard deviation and they are tabulated in Table 3.20.

The parent ligand sodium ibuprofen and Zn(II) (as $ZnCl_2$) did not show anti-bacterial activity against any of the tested microorganisms.

Table 3.20: *In-vitro* anti-bacterial activity data of complexes **1**-**9**.

Compound	***B. subtilis***	***M. luteus***	***S. aureus***	***E. Coli***	***K. pneumoniae***	***P. mirabilis***
	G+	**G+**	**G+**	**G-**	**G-**	**G-**
$ZnCl_2$	-	-	-	-	-	-
H(ibup)	-	-	-	-	-	-
1	10.3 ± 0.6	11.0 ± 1.4	12.0 ± 3.5	-	-	-
2	-	-	-	-	-	-
3	-	-	-	-	-	-
4	12.3 ± 1.5	13.0 ± 3.5	15.0 ± 1.7	14.1 ± 0.1	11.3 ± 0.6	14.1 ± 0.3
5	9.3 ± 0.6	10.3 ± 0.6	8.6 ± 1.2	-	12.1 ± 1.0	-
6	25.3 ± 1.5	23.3 ± 2.3	18.6 ± 1.2	24.0 ± 0.0	24.0 ± 0.6	26.7 ± 2.1
7	27.7 ± 1.5	15.3 ± 4.0	21.7 ± 2.1	11.7 ± 0.6	11.0 ± 0.6	9.3 ± 1.2
8	-	-	11.0 ± 0.6	-	-	-
9	-	-	-	-	-	-

Inhibition zone diameter (IZD) in mm, all microorganisms were resistant to DMSO.

It can be seen from Table 3.20, that complex **1** exhibited anti-bacterial activity only against Gram-positive bacteria with inhibition zone diameter (IZD) in the range between 10-12 mm.

Complexes **2**, **3**, **8** and **9** did not exhibit any activity against neither Gram-positive or Gram negative bacteria with the exception of complex **8** against *S. aureus*. The efficiency of complexes **4** and **6** against all tested microorganisms is good with IZD in the range between 11-15 mm for **4** and 18-26 mm for **6**. Complex **5** showed good activity against Gram-positive. Complex **7** showed activity against Gram-positive more than activity against Gram-negative.

Complexes **4**, **6**, and **7** were chosen for further studies because of their higher IZD values. The complexes have been studied with their parent nitrogen donor

ligands against all tested Gram-positive and Gram-negative bacteria that were mentioned before; the aim of this step was to determine the effect of the complexation on anti-bacteria activity. Dilutions of the complexes and their parent ligands were prepared in DMSO using the same procedure; the complex and the parent ligand were tested in the same plate to reserve the same conditions for both. All anti-bacterial data are listed in Tables 3.21-3.23 below.

Table 3.21: Anti-bacterial activity data for complex **4** and 2,2`-bipy.

Concentration (g/L DMSO)	***B. subtilis***	***M. luteus***	***S.aureus***	***E.Coli***	***K. pneumoniae***	***P. mirabilis***
	G+	**G+**	**G+**	**G-**	**G-**	**G-**
	IZD of **4** (mm)					
6	12.3	13.0	15.0	14.1	11.3	14.1
3	9	8	13	11	8	12
1.5	-	-	9	8	7	11
	IZD of 2,2`-bipy (mm)					
6	21	28	12	27	27	22
3	11	21	10	26	21	19
1.5	-	15	9	14	15	16

Table 3.22: Anti-bacterial activity data for complex **6** and 1,10-phen.

Concentration (g/L DMSO)	***B. subtilis***	***M. luteus***	***S.aureus***	***E.Coli***	***K. pneumoniae***	***P. mirabilis***
	G+	**G+**	**G+**	**G-**	**G-**	**G-**
	IZD of **6** (mm)					
6	25.3	23.3	18.6	24.0	24.0	26.7
3	21	20	20	23	22	23
1.5	17	16	17	21	20	20
	IZD of 1,10-phen (mm)					
6	35	30	31	32	33	34
3	31	26	30	31	30	33
1.5	28	18	28	30	28	30

It is clear from above results that the complexation of zinc-ibuprofen with 2,2`-bipy and 1,10-phen in complexes **4** and **6**, respectively decreased the anti-

bacterial activity against most tested bacteria.

Table 3.23: Anti-bacterial activity data for complex **7** and 2,9-dmphen.

Concentration (g/L DMSO)	***B. subtilis***	***M. luteus***	***S. aureus***	***E. Coli***	***K. pneumoniae***	***P. mirabilis***
	G+	**G+**	**G+**	**G-**	**G-**	**G-**
	IZD of **7** (mm)					
6	27.7	15.3	21.7	11.7	11.0	9.3
3	26	8	20	-	-	7
1.5	23	-	19	-	-	-
	IZD of 2,9-dmphen (mm)					
6	28	20	29	-	-	-
3	25	18	23	-	-	-
1.5	22	12	17	-	-	-

The complexation in 7 decreased the anti-bacterial activity in Gram-positive bacteria but in the case of Gram-negative, the overall anti-bacterial activity of uncoordinated 2,9-dmphen was enhanced on coordination with zinc ibuprofen.

In general, the activity was dependent on the concentration of the complex; this is obvious by the direct proportion found between the concentration and the IZD value. Compounds are considered significantly active when IZD is larger than 15 mm, moderately active when IZD is between 7 and 14 mm and weakly active for IZD less than 7 mm[136].

The lowest concentration that inhibits bacterial growths is the minimum inhibition concentration (MIC). MIC for complexes 4, 6 and 7 were determined

side by side with their parent nitrogen donor ligands. Table 3.24 below summarizes the data:

Table 3.24: Minimum inhibition concentration (MIC) of complex **4**, **6**, **7** and their parent ligands.

Compound	Minimum inhibition concentration MIC (g/ L DMSO)					
	B. subtilis	***M. luteus***	***S.aureus***	***E.Coli***	***K. pneumoniae***	***P. mirabilis***
	G+	**G+**	**G+**	**G-**	**G-**	**G-**
4	3	3	1.5	1.5	1.5	1.5
2,2`-bipy	3	0.188	1.5	1.5	1.5	1.5
6	0.375	0.75	0.375	0.375	0.375	0.75
1,10-phen	0.375	1.5	0.375	0.188	0.188	0.375
7	0.188	3	0.188	6	6	3
2,9-dmphen	0.188	0.75	0.188	> 6	> 6	> 6

As shown in Table 3.24 above, the MIC values for **4** are close to those of the free 2,2`-bipy ligand, which indicate a weak effect of complexation on anti-bacterial activity. In the case of complex **6** the MIC values especially for Gram-negative bacteria are larger than those of the free 1,10-phen ligand which indicate that the complexation with zinc ibuprofen decreases the anti-bacterial activity. The MIC concentrations for **7** in Gram-negative are less than the 2,9-dmphen itself, so the complexation enhances the anti-bacterial activity against Gram-negative bacteria and did not affect the activity against Gram-positive bacteria. Although it is not clear why some compounds exhibit different bacterial activity with Gram-positive and Gram-negative bacteria, it may be ascribed to the difference in the overall structure of their cell walls[33].

4. CONCLUSION

The synthesis and characterization of nine new Zn(II) complexes with the non-steroidal anti-inflammatory drug ibuprofen in the absence (complex **1)** or presence of N-donor heterocyclic ligands 2-ampy, 2-ammethylpy, 2,2`-bipy, 4,4`-bipy, 1,10-phen, 2,9-dmphen, 1,2-dmomodazole and 2-am-6-picoline have been achieved. X-ray diffraction of complexes **2** and **5** reveal distorted tetrahedral and octahedral geometry of the Zn(II) ion, respectively, with two monodentate ibuprofen groups and two 2-ampy for former and with two ibuprofen groups and two 4,4`-bipy in polymer form for the later.

The rest of complexes were characterized using IR, ^{1}H NMR, ^{13}C{^{1}H} NMR and UV-Vis. For complexes **3**, **4**, **6**, **7**, **8** and **9** monodentate 'Zn-ibup' molecular structure were reported with two ibuprofen groups for each core. In complex **3**, two groups of 2-ammethylpy coordinated via pyridine nitrogen and the amino group in a bidentate coordination mode. In complexes **4**, **6** and **7** one group of 2,2-bipy, 1,10-phen and 2,9-dmphen respectively was determined for each complex. In complexes **8** and **9**, two groups of 1,2-dmimidazole and two groups of 2-am-6-picoline, respectively, were found per each core.

Complexes **4**, **6** and **7** showed anti-bacterial activity *in-vitro* and have been chosen for further studies; to determine IZD for different concentrations and to set the MIC for each complex.

The complexation of zinc-ibuprofen with 2,2`-bipy and 1,10-phen in complexes **4** and **6**, respectively lowered the anti-bacterial activity against most of the bacteria used. The complexation in **7** decreased the anti-bacterial activity in Gram-

positive bacteria but in case of Gram-negative, the overall anti-bacterial activity of uncoordinated 2,9-dmphen was enhanced on coordination with zinc ibuprofen. For future work, these complexes can be tested for other biological activity like DNA-binding or whether they can act as mimics for enzymes or organometallics in the body.

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APPENDICES

Crystal structure data of $[Zn(biup)_2(2\text{-}ampy)_2]$ (2)

Table A 1: Crystal data and structure refinement for **2**.

Empirical formula	C36 H46 N4 O4 Zn
Formula weight	664.14
Temperature	295(1) K
Wavelength	0.71073 Å
Crystal system	Triclinic
Space group	P-1
Unit cell dimensions	a = 11.166(1) Å α= 70.797(2)°
	b = 11.232(1) Å β= 81.611(2)°
	c = 16.251(2) Å γ = 75.996(2)°
Volume	1862.6(3) $Å^3$
Z	2
Density (calculated)	1.184 Mg/m^3
Absorption coefficient	0.699 mm^{-1}
F(000)	704
Crystal size	0.33 x 0.25 x 0.07 mm^3
Theta range for data collection	1.88 to 27.99°
Index ranges	-14<=h<=14, -14<=k<=14, -21<=l<=20
Reflections collected	20963
Independent reflections	8572 [R(int) = 0.0350]
Completeness to theta = 27.00°	95.4 %
Absorption correction	None
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	8572 / 2 / 409
Goodness-of-fit on F_2	0.964
Final R indices [I >2 sigma(I)]	R1 = 0.0629, wR2 = 0.1663
R indices (all data)	R1 = 0.1191, wR2 = 0.1978
Largest diff. peak and hole	0.860 and -0.279 $e.Å^{-3}$

Crystal structure data of $[Zn(biup)_2(2\text{-}ampy)_2]$ (2)

Table A 2: Atomic coordinates ($x10^4$) and equivalent isotropic displacement parameters ($Å^2 x10^3$) for **2**.

	x	y	z	U(eq)
C(1)	4753(3)	8852(3)	4299(3)	69(1)
C(2)	3825(4)	9323(4)	3704(4)	92(1)
C(3)	4118(5)	9437(5)	2852(4)	110(2)
C(4)	5350(6)	9098(5)	2554(4)	114(2)
C(5)	6219(5)	8667(5)	3151(3)	99(1)
C(6)	8672(3)	5226(3)	4324(2)	63(1)
C(7)	8719(4)	3955(3)	4336(3)	77(1)
C(8)	7766(4)	3384(4)	4712(3)	84(1)
C(9)	6756(4)	4038(4)	5111(3)	94(1)
C(10)	6769(4)	5248(4)	5101(3)	90(1)
C(11)	8896(3)	9507(4)	4068(3)	79(1)
C(12)	10173(4)	9839(4)	3707(3)	95(1)
C(13)	10241(4)	11130(4)	3665(3)	104(2)
C(14)	10557(4)	9501(4)	2844(3)	83(1)
C(15)	10305(6)	10307(6)	2077(5)	145(2)
C(16)	10730(8)	9962(8)	1299(5)	168(3)
C(17)	11397(6)	8737(7)	1355(4)	117(2)
C(18)	11645(5)	7954(5)	2163(4)	108(2)
C(19)	11220(4)	8335(4)	2879(3)	86(1)
C(20)	11886(8)	8304(9)	543(5)	191(4)
C(21)	13207(12)	8197(13)	307(8)	276(7)
C(22)	13719(13)	9322(17)	223(9)	375(12)
C(23)	13607(15)	7729(18)	-487(10)	503(16)
C(24)	7320(4)	6913(5)	6571(3)	82(1)
C(25)	6622(5)	6901(5)	7435(3)	103(1)
C(26)	7367(6)	6293(7)	8209(4)	160(3)
C(27)	5465(4)	6348(5)	7515(3)	94(1)
C(28)	5536(5)	5145(5)	7466(5)	145(2)
C(29)	4524(6)	4614(6)	7568(5)	151(3)
C(30)	3389(6)	5270(7)	7667(3)	116(2)
C(31)	3278(5)	6526(7)	7613(4)	130(2)
C(32)	4285(5)	7064(5)	7522(4)	116(2)
C(33)	2238(6)	4709(8)	7798(4)	165(3)
C(34)	1967(8)	3940(11)	8651(6)	237(6)
C(35)	1830(12)	4496(15)	9375(7)	394(13)
C(36)	852(9)	3327(11)	8697(6)	290(7)
N(1)	5948(3)	8528(3)	4011(2)	73(1)
N(2)	4478(3)	8680(3)	5145(2)	80(1)
N(3)	7700(2)	5857(3)	4704(2)	68(1)
N(4)	9585(3)	5830(3)	3904(2)	81(1)
O(1)	8866(2)	8345(2)	4170(2)	93(1)
O(2)	8051(2)	10251(3)	4309(2)	99(1)
O(3)	6805(2)	7756(3)	5911(2)	86(1)
O(4)	8316(3)	6163(3)	6525(2)	108(1)
Zn(1)	7434(1)	7691(1)	4767(1)	70(1)

U(eq) is defined as one third of the trace of the orthogonalized U^{ij} tensor.

Crystal structure data of $[Zn(biup)_2(2\text{-}ampy)_2]$ (2)

Table A 3: Bond lengths [Å] and angles [°] for **2**.

N(1)-Zn(1)	2.055(3)	C(11)-C(12)-C(14)	108.9(3)
N(2)-H(1N2)	0.9958	C(13)-C(12)-H(12)	106.2000
N(2)-H(2N2)	0.9504	C(11)-C(12)-H(12)	106.2000
N(3)-Zn(1)	2.043(3)	C(14)-C(12)-H(12)	106.2000
N(4)-H(2N4)	0.8871	C(12)-C(13)-H(13A)	109.5000
N(4)-H(1N4)	0.9477	C(12)-C(13)-H(13B)	109.5000
O(1)-Zn(1)	1.920(2)	H(13A)-C(13)-H(13B)	109.5000
O(3)-Zn(1)	1.907(3)	C(12)-C(13)-H(13C)	109.5000
N(2)-C(1)-N(1)	118.9(4)	H(13A)-C(13)-H(13C)	109.5000
N(2)-C(1)-C(2)	121.4(4)	H(13B)-C(13)-H(13C)	109.5000
N(1)-C(1)-C(2)	119.7(4)	C(15)-C(14)-C(19)	117.5(5)
C(3)-C(2)-C(1)	120.5(4)	C(15)-C(14)-C(12)	123.9(5)
C(3)-C(2)-H(2)	119.8000	C(19)-C(14)-C(12)	118.6(4)
C(1)-C(2)-H(2)	119.8000	C(14)-C(15)-C(16)	121.6(6)
C(2)-C(3)-C(4)	119.9(5)	C(14)-C(15)-H(15)	119.2000
C(2)-C(3)-H(3)	120.0000	C(16)-C(15)-H(15)	119.2000
C(4)-C(3)-H(3)	120.0000	C(17)-C(16)-C(15)	119.7(6)
C(5)-C(4)-C(3)	117.6(5)	C(17)-C(16)-H(16)	120.2000
C(5)-C(4)-H(4)	121.2000	C(15)-C(16)-H(16)	120.2000
C(3)-C(4)-H(4)	121.2000	C(18)-C(17)-C(16)	116.0(5)
N(1)-C(5)-C(4)	123.7(5)	C(18)-C(17)-C(20)	121.6(7)
N(1)-C(5)-H(5)	118.2000	C(16)-C(17)-C(20)	122.3(7)
C(4)-C(5)-H(5)	118.2000	C(17)-C(18)-C(19)	121.7(5)
N(3)-C(6)-N(4)	119.3(3)	C(17)-C(18)-H(18)	119.2000
N(3)-C(6)-C(7)	120.5(3)	C(19)-C(18)-H(18)	119.2000
N(4)-C(6)-C(7)	120.2(3)	C(14)-C(19)-C(18)	123.5(5)
C(8)-C(7)-C(6)	119.9(4)	C(14)-C(19)-H(19)	118.3000
C(8)-C(7)-H(7)	120.0000	C(18)-C(19)-H(19)	118.3000
C(6)-C(7)-H(7)	120.0000	C(21)-C(20)-C(17)	116.0(7)
C(7)-C(8)-C(9)	119.5(3)	C(21)-C(20)-H(20A)	108.3000
C(7)-C(8)-H(8)	120.2000	C(17)-C(20)-H(20A)	108.3000
C(9)-C(8)-H(8)	120.2000	C(21)-C(20)-H(20B)	108.3000
C(10)-C(9)-C(8)	118.3(4)	C(17)-C(20)-H(20B)	108.3000
C(10)-C(9)-H(9)	120.8000	H(20A)-C(20)-H(20B)	107.4000
C(8)-C(9)-H(9)	120.8000	C(20)-C(21)-C(22)	116.8(11)
N(3)-C(10)-C(9)	123.1(4)	C(20)-C(21)-C(23)	112.1(11)
N(3)-C(10)-H(10)	118.4000	C(22)-C(21)-C(23)	111.0(10)
C(9)-C(10)-H(10)	118.4000	C(20)-C(21)-H(21)	105.3000
O(2)-C(11)-O(1)	123.5(3)	C(22)-C(21)-H(21)	105.3000
O(2)-C(11)-C(12)	122.7(3)	C(23)-C(21)-H(21)	105.3000
O(1)-C(11)-C(12)	113.3(3)	C(21)-C(22)-H(22A)	109.5000
C(13)-C(12)-C(11)	113.4(3)	C(21)-C(22)-H(22B)	109.5000
C(13)-C(12)-C(14)	115.4(4)	H(22A)-C(22)-H(22B)	109.5000

Crystal structure data of $[Zn(biup)_2(2\text{-}ampy)_2]$ (2)

Table A 3: Continued.

C(21)-C(22)-H(22C)	109.5000	C(34)-C(33)-H(33A)	108.4000
H(22A)-C(22)-H(22C)	109.5000	C(30)-C(33)-H(33A)	108.4000
H(22B)-C(22)-H(22C)	109.5000	C(34)-C(33)-H(33B)	108.4000
C(21)-C(23)-H(23A)	109.5000	C(30)-C(33)-H(33B)	108.4000
C(21)-C(23)-H(23B)	109.5000	H(33A)-C(33)-H(33B)	107.4000
H(23A)-C(23)-H(23B)	109.5000	C(33)-C(34)-C(35)	118.5(9)
C(21)-C(23)-H(23C)	109.5000	C(33)-C(34)-C(36)	111.5(7)
H(23A)-C(23)-H(23C)	109.5000	C(35)-C(34)-C(36)	110.0(9)
H(23B)-C(23)-H(23C)	109.5000	C(33)-C(34)-H(34)	105.2000
O(4)-C(24)-O(3)	124.0(4)	C(35)-C(34)-H(34)	105.2000
O(4)-C(24)-C(25)	121.3(5)	C(36)-C(34)-H(34)	105.2000
O(3)-C(24)-C(25)	114.7(4)	C(34)-C(35)-H(35A)	109.5000
C(26)-C(25)-C(24)	115.5(5)	C(34)-C(35)-H(35B)	109.5000
C(26)-C(25)-C(27)	113.4(4)	H(35A)-C(35)-H(35B)	109.5000
C(24)-C(25)-C(27)	109.0(4)	C(34)-C(35)-H(35C)	109.5000
C(26)-C(25)-H(25)	106.1000	H(35A)-C(35)-H(35C)	109.5000
C(24)-C(25)-H(25)	106.1000	H(35B)-C(35)-H(35C)	109.5000
C(27)-C(25)-H(25)	106.1000	C(34)-C(36)-H(36A)	109.5000
C(25)-C(26)-H(26A)	109.5000	C(34)-C(36)-H(36B)	109.5000
C(25)-C(26)-H(26B)	109.5000	H(36A)-C(36)-H(36B)	109.5000
H(26A)-C(26)-H(26B)	109.5000	C(34)-C(36)-H(36C)	109.5000
C(25)-C(26)-H(26C)	109.5000	H(36A)-C(36)-H(36C)	109.5000
H(26A)-C(26)-H(26C)	109.5000	H(36B)-C(36)-H(36C)	109.5000
H(26B)-C(26)-H(26C)	109.5000	C(5)-N(1)-C(1)	118.6(4)
C(28)-C(27)-C(32)	114.0(5)	C(5)-N(1)-Zn(1)	114.6(3)
C(28)-C(27)-C(25)	122.1(5)	C(1)-N(1)-Zn(1)	126.6(3)
C(32)-C(27)-C(25)	123.4(5)	C(1)-N(2)-H(1N2)	129.7000
C(27)-C(28)-C(29)	123.1(5)	C(1)-N(2)-H(2N2)	108.5000
C(27)-C(28)-H(28)	118.4000	H(1N2)-N(2)-H(2N2)	119.7000
C(29)-C(28)-H(28)	118.4000	C(6)-N(3)-C(10)	118.5(3)
C(30)-C(29)-C(28)	121.9(6)	C(6)-N(3)-Zn(1)	127.3(2)
C(30)-C(29)-H(29)	119.0000	C(10)-N(3)-Zn(1)	114.2(2)
C(28)-C(29)-H(29)	119.0000	C(6)-N(4)-H(2N4)	118.1000
C(29)-C(30)-C(31)	116.2(6)	C(6)-N(4)-H(1N4)	123.5000
C(29)-C(30)-C(33)	123.6(7)	H(2N4)-N(4)-H(1N4)	116.3000
C(31)-C(30)-C(33)	120.1(6)	C(11)-O(1)-Zn(1)	119.1(2)
C(30)-C(31)-C(32)	122.3(6)	C(24)-O(3)-Zn(1)	119.2(3)
C(30)-C(31)-H(31)	118.9000	O(3)-Zn(1)-O(1)	123.29(12)
C(32)-C(31)-H(31)	118.9000	O(3)-Zn(1)-N(3)	110.49(12)
C(31)-C(32)-C(27)	121.5(5)	O(1)-Zn(1)-N(3)	106.53(10)
C(31)-C(32)-H(32)	119.2000	O(3)-Zn(1)-N(1)	105.06(13)
C(27)-C(32)-H(32)	119.2000	O(1)-Zn(1)-N(1)	110.01(13)
C(34)-C(33)-C(30)	115.6(6)	N(3)-Zn(1)-N(1)	98.75(11)

Symmetry transformations used to generate equivalent atoms

Crystal structure data of $[Zn(biup)_2(2\text{-}ampy)_2]$ (2)

Table A 4: Anisotropic displacement parameters ($Å^2 x10^3$) for **2**.

	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
C(1)	60(2)	48(2)	109(3)	-34(2)	-1(2)	-16(2)
C(2)	72(3)	72(3)	134(4)	-31(3)	-3(3)	-21(2)
C(3)	107(4)	94(3)	128(5)	-27(3)	-28(4)	-19(3)
C(4)	132(5)	115(4)	97(4)	-32(3)	-7(4)	-28(3)
C(5)	93(3)	107(3)	100(4)	-45(3)	15(3)	-21(3)
C(6)	62(2)	59(2)	77(2)	-30(2)	-5(2)	-14(2)
C(7)	79(3)	56(2)	102(3)	-34(2)	-11(2)	-10(2)
C(8)	88(3)	53(2)	119(3)	-25(2)	-24(2)	-18(2)
C(9)	74(3)	67(2)	143(4)	-26(3)	0(3)	-29(2)
C(10)	64(2)	72(3)	139(4)	-42(3)	11(2)	-23(2)
C(11)	60(2)	75(2)	113(3)	-51(2)	18(2)	-21(2)
C(12)	76(3)	89(3)	131(4)	-53(3)	24(2)	-31(2)
C(13)	93(3)	95(3)	147(4)	-59(3)	19(3)	-49(3)
C(14)	69(2)	77(3)	106(3)	-34(3)	18(2)	-27(2)
C(15)	125(5)	120(5)	163(6)	-46(5)	-11(5)	28(4)
C(16)	189(7)	166(7)	103(5)	2(5)	-33(5)	0(6)
C(17)	118(4)	146(5)	95(4)	-51(4)	13(3)	-38(4)
C(18)	120(4)	91(3)	99(4)	-36(3)	24(3)	-7(3)
C(19)	79(3)	90(3)	87(3)	-30(2)	8(2)	-21(2)
C(20)	206(9)	293(11)	130(5)	-119(6)	46(6)	-113(8)
C(21)	264(13)	405(18)	241(11)	-221(12)	162(10)	-156(12)
C(22)	307(16)	690(40)	263(14)	-262(19)	158(12)	-290(20)
C(23)	600(30)	720(30)	430(20)	-470(20)	400(20)	-440(30)
C(24)	72(3)	87(3)	109(4)	-52(3)	13(2)	-37(2)
C(25)	101(3)	117(4)	106(4)	-47(3)	8(3)	-43(3)
C(26)	150(6)	219(8)	120(5)	-31(5)	-12(4)	-79(5)
C(27)	91(3)	96(3)	99(3)	-41(3)	18(2)	-26(3)
C(28)	94(4)	89(4)	241(8)	-50(4)	26(4)	-21(3)
C(29)	120(5)	107(4)	241(8)	-66(5)	17(5)	-49(4)
C(30)	109(4)	135(5)	103(4)	-24(3)	-3(3)	-45(4)
C(31)	80(3)	144(6)	152(5)	-36(4)	10(3)	-18(4)
C(32)	105(4)	104(4)	137(4)	-47(3)	11(3)	-18(3)
C(33)	149(6)	235(8)	119(5)	-10(5)	-19(4)	-112(6)
C(34)	205(9)	388(15)	142(7)	-5(8)	-15(6)	-208(10)
C(35)	410(20)	740(30)	151(9)	-109(14)	62(11)	-430(20)
C(36)	243(11)	389(16)	245(11)	22(10)	-27(8)	-240(12)
N(1)	59(2)	66(2)	100(2)	-37(2)	10(2)	-14(1)
N(2)	52(2)	82(2)	111(3)	-44(2)	13(2)	-15(2)
N(3)	55(2)	61(2)	96(2)	-34(2)	4(1)	-18(1)
N(4)	71(2)	68(2)	114(2)	-47(2)	25(2)	-23(2)
O(1)	64(2)	72(2)	161(3)	-68(2)	33(2)	-29(1)
O(2)	66(2)	81(2)	155(3)	-59(2)	23(2)	-10(1)
O(3)	73(2)	88(2)	105(2)	-44(2)	3(2)	-17(2)m
O(4)	75(2)	113(2)	141(3)	-56(2)	-1(2)	-9(2)
Zn(1)	50(1)	65(1)	107(1)	-45(1)	15(1)	-19(1)
The anisotropic displacement factor exponent takes the form: $-2\pi^2[h^2 a^{*2}U^{11} + ... + 2 h k a^* b^* U^{12}]$						

Crystal structure data of $[Zn(biup)_2(2\text{-}ampy)_2]$ (2)

Table A 5: Hydrogen coordinates (x 10^4) and isotropic displacement parameters ($Å^2$ x10^3) for **2**.

	x	y	z	U(eq)
H(2)	3004	9557	3900	111
H(3)	3500	9743	2463	131
H(4)	5570	9164	1968	137
H(5)	7044	8456	2955	118
H(7)	9409	3513	4084	92
H(8)	7782	2555	4705	101
H(9)	6089	3657	5377	113
H(10)	6103	5679	5381	108
H(12)	10764	9250	4126	113
H(13A)	9653	11747	3277	156
H(13B)	11059	11270	3452	156
H(13C)	10055	11228	4237	156
H(15)	9835	11128	2035	174
H(16)	10557	10562	756	202
H(18)	12121	7129	2233	129
H(19)	11402	7748	3424	103
H(20A)	11688	7472	638	229
H(20B)	11445	8911	50	229
H(21)	13610	7507	793	331
H(22A)	13369	10034	-253	562
H(22B)	14602	9118	113	562
H(22C)	13522	9548	755	562
H(23A)	13138	8297	-968	754
H(23B)	13465	6874	-354	754
H(23C)	14472	7720	-642	754
H(25)	6321	7807	7410	123
H(26A)	7762	5425	8228	240
H(26B)	6835	6284	8731	240
H(26C)	7985	6776	8170	240
H(28)	6311	4662	7359	175
H(29)	4638	3767	7566	181
H(31)	2491	7038	7639	156
H(32)	4165	7936	7463	139
H(33A)	1534	5415	7629	198
H(33B)	2335	4196	7406	198
H(34)	2679	3216	8777	285
H(35A)	2451	4007	9778	591
H(35B)	1024	4467	9673	591
H(35C)	1926	5374	9146	591
H(36A)	255	3926	8308	435
H(36B)	479	3117	9284	435
H(36C)	1128	2557	8528	435
H(1N2)	5036	8381	5631	96
H(2N2)	3650	9120	5226	96
H(2N4)	10256	5376	3698	97
H(1N4)	9659	6632	3943	97

Crystal structure data of $[Zn(biup)_2(2\text{-}ampy)_2]$ (2)

Table A 6: Hydrogen bonds for **2** [Å and °].

D-H...A	d(D-H)	d(H...A)	d(D...A)	<(DHA)
N(4)-H(1N4)...O(1)	0.95	2.04	2.901(4)	149.9
N(4)-H(2N4)...O(4)#1	0.89	2.14	3.000(4)	163.7
N(2)-H(2N2)...O(2)#2	0.95	1.99	2.921(4)	166
N(2)-H(1N2)...O(3)	1	2	2.858(5)	143.4

Symmetry transformations used to generate equivalent atoms:
#1 -x+2,-y+1,-z+1 #2 -x+1,-y+2,-z+1

Crystal structure data of $[Zn(biup)_2(4,4`\text{-bipy})]_n$ (5)

Table B 1: Crystal data and structure refinement for **5**.

Empirical formula	C36 H46 N2 O6 Zn
Formula weight	668.12
Temperature	293(1) K
Wavelength	0.71073 Å
Crystal system	Triclinic
Space group	P-1
Unit cell dimensions	a = 5.6865(5) Å α= 88.802(1)°
	b = 11.495(1) Å β= 78.262(1)°
	c = 13.675(1) Å γ = 79.215(1)°
Volume	859.57(13) $Å^3$
Z	1
Density (calculated)	1.291 Mg/m^3
Absorption coefficient	0.760 mm^{-1}
F(000)	354
Crystal size	0.26 x 0.20 x 0.07 mm^3
Theta range for data collection	2.34 to 27.00°.
Index ranges	-7<=h<=7, -14<=k<=14, -17<=l<=17
Reflections collected	9514
Independent reflections	3716 [R(int) = 0.0227]
Completeness to theta = 27.00°	98.90%
Absorption correction	multi-scan
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	3716 / 0 / 237
Goodness-of-fit on F_2	1.178
Final R indices [I >2 sigma(I)]	R1 = 0.0593, wR2 = 0.1425
R indices (all data)	R1 = 0.0633, wR2 = 0.1446
Largest diff. peak and hole	1.059 and -0.373 $e.Å^{-3}$

Crystal structure data of $[Zn(biup)_2(4,4`\text{-bipy})]_n$ (5)

Table B 2: Atomic coordinates (x 10^4) and equivalent isotropic displacement parameters ($Å^2$x 10^3) for **5**.

	x	y	z	U(eq)
C(1)	7151(6)	583(3)	7095(3)	63(1)
C(2)	4752(7)	1096(4)	7812(3)	80(1)
C(3)	4288(7)	2422(4)	7790(3)	73(1)
C(4)	5764(8)	3075(5)	8176(3)	82(1)
C(5)	5292(8)	4284(4)	8172(4)	85(1)
C(6)	3396(8)	4924(5)	7776(3)	84(1)
C(7)	1985(9)	4268(6)	7385(3)	94(2)
C(8)	2425(8)	3064(5)	7391(3)	89(2)
C(9)	2831(11)	6240(6)	7795(4)	108(2)
C(10)	1680(30)	6848(15)	8895(19)	117(7)
C(11)	1770(30)	8075(12)	8991(15)	155(6)
C(12)	-900(30)	6552(19)	9190(20)	177(11)
C(10')	600(60)	6704(15)	8578(13)	132(7)
C(11')	-260(50)	7950(17)	8367(12)	195(10)
C(12')	1310(50)	6597(18)	9565(11)	167(12)
C(13)	4745(12)	620(6)	8858(4)	117(2)
C(14)	11988(6)	2358(2)	4524(3)	55(1)
C(15)	12049(5)	3551(2)	4530(3)	55(1)
C(16)	9994(5)	4357(2)	4979(2)	33(1)
C(17)	7960(5)	3886(2)	5378(2)	45(1)
C(18)	8036(5)	2681(2)	5329(2)	47(1)
N(1)	10018(4)	1907(2)	4920(2)	39(1)
O(1)	7027(4)	331(2)	6219(2)	44(1)
O(2)	9053(6)	497(4)	7409(2)	110(1)
O(1W)	7379(4)	284(2)	4072(2)	51(1)
Zn(1)	10000	0	5000	34(1)

U(eq) is defined as one third of the trace of the orthogonalized Uij tensor.

Crystal structure data of $[Zn(biup)_2(4,4`\text{-bipy})]_n$ (5)

Table B 3: Bond lengths [Å] and angles [°] for **5**.

C(1)-O(2)	1.230(5)	C(14)-N(1)	1.332(4)
C(1)-O(1)	1.258(4)	C(14)-C(15)	1.379(4)
C(1)-C(2)	1.532(5)	C(14)-H(14)	0.9300
C(2)-C(3)	1.498(7)	C(15)-C(16)	1.388(4)
C(2)-C(13)	1.520(7)	C(15)-H(15)	0.9300
C(2)-H(2)	0.9800	C(16)-C(17)	1.376(4)
C(3)-C(8)	1.375(7)	C(16)-C(16)#1	1.482(4)
C(3)-C(4)	1.407(5)	C(17)-C(18)	1.380(4)
C(4)-C(5)	1.365(7)	C(17)-H(17)	0.9300
C(4)-H(4)	0.9300	C(18)-N(1)	1.328(3)
C(5)-C(6)	1.386(7)	C(18)-H(18)	0.9300
C(5)-H(5)	0.9300	N(1)-Zn(1)	2.194(2)
C(6)-C(7)	1.384(7)	O(1)-Zn(1)	2.1020(19)
C(6)-C(9)	1.486(7)	O(1W)-Zn(1)	2.123(2)
C(7)-C(8)	1.359(8)	O(1W)-H(1W)	0.8180
C(7)-H(7)	0.9300	O(1W)-H(2W)	0.8876
C(8)-H(8)	0.9300	Zn(1)-O(1)#2	2.1020(19)
C(9)-C(10')	1.50(2)	Zn(1)-O(1W)#2	2.123(2)
C(9)-C(10)	1.629(19)	Zn(1)-N(1)#2	2.194(2)
C(9)-H(91)	0.8765	O(2)-C(1)-O(1)	125.1(3)
C(9)-H(92)	0.8511	O(2)-C(1)-C(2)	117.5(3)
C(10)-C(11)	1.431(19)	O(1)-C(1)-C(2)	117.4(3)
C(10)-C(12)	1.54(2)	C(3)-C(2)-C(13)	112.8(4)
C(10)-H(10)	0.9800	C(3)-C(2)-C(1)	110.3(3)
C(11)-H(11A)	0.9600	C(13)-C(2)-C(1)	110.9(4)
C(11)-H(11B)	0.9600	C(3)-C(2)-H(2)	107.5000
C(11)-H(11C)	0.9600	C(13)-C(2)-H(2)	107.5000
C(12)-H(12A)	0.9600	C(1)-C(2)-H(2)	107.5000
C(12)-H(12B)	0.9600	C(8)-C(3)-C(4)	116.5(5)
C(12)-H(12C)	0.9600	C(8)-C(3)-C(2)	122.3(4)
C(10')-C(11')	1.47(2)	C(4)-C(3)-C(2)	121.2(4)
C(10')-C(12')	1.48(3)	C(5)-C(4)-C(3)	120.7(4)
C(10')-H(10')	0.9800	C(5)-C(4)-H(4)	119.6000
C(11')-H(11D)	0.9600	C(3)-C(4)-H(4)	119.6000
C(11')-H(11E)	0.9600	C(4)-C(5)-C(6)	122.3(4)
C(11')-H(11F)	0.9600	C(4)-C(5)-H(5)	118.8000
C(12')-H(12D)	0.9600	C(6)-C(5)-H(5)	118.8000
C(12')-H(12E)	0.9600	C(7)-C(6)-C(5)	116.2(5)
C(12')-H(12F)	0.9600	C(7)-C(6)-C(9)	121.2(5)
C(13)-H(13A)	0.9600	C(5)-C(6)-C(9)	122.5(5)
C(13)-H(13B)	0.9600	C(8)-C(7)-C(6)	122.0(5)
C(13)-H(13C)	0.9600	C(8)-C(7)-H(7)	119.0000

Crystal structure data of $[Zn(biup)_2(4,4`\text{-bipy})]_n$ (5)

Table B 3: Continued.

C(6)-C(7)-H(7)	119.0000	C(2)-C(13)-H(13C)	109.5000
C(7)-C(8)-C(3)	122.2(4)	H(13A)-C(13)-H(13C)	109.5000
C(7)-C(8)-H(8)	118.9000	H(13B)-C(13)-H(13C)	109.5000
C(3)-C(8)-H(8)	118.9000	N(1)-C(14)-C(15)	123.6(3)
C(6)-C(9)-C(10')	111.2(9)	N(1)-C(14)-H(14)	118.2000
C(6)-C(9)-C(10)	115.1(9)	C(15)-C(14)-H(14)	118.2000
C(10')-C(9)-C(10)	31.6(9)	C(14)-C(15)-C(16)	120.2(3)
C(6)-C(9)-H(91)	105.2000	C(14)-C(15)-H(15)	119.9000
C(10')-C(9)-H(91)	109.5000	C(16)-C(15)-H(15)	119.9000
C(10)-C(9)-H(91)	78.6000	C(17)-C(16)-C(15)	115.8(2)
C(6)-C(9)-H(92)	108.9000	C(17)-C(16)-C(16)#1	122.4(3)
C(10')-C(9)-H(92)	93.1000	C(15)-C(16)-C(16)#1	121.8(3)
C(10)-C(9)-H(92)	118.2000	C(16)-C(17)-C(18)	120.5(2)
H(91)-C(9)-H(92)	128.2000	C(16)-C(17)-H(17)	119.8000
C(11)-C(10)-C(12)	114.6(15)	C(18)-C(17)-H(17)	119.8000
C(11)-C(10)-C(9)	116.2(17)	N(1)-C(18)-C(17)	123.7(3)
C(12)-C(10)-C(9)	105.5(18)	N(1)-C(18)-H(18)	118.2000
C(11)-C(10)-H(10)	106.6000	C(17)-C(18)-H(18)	118.2000
C(12)-C(10)-H(10)	106.6000	C(18)-N(1)-C(14)	116.1(2)
C(9)-C(10)-H(10)	106.6000	C(18)-N(1)-Zn(1)	120.23(18)
C(11')-C(10')-C(12')	110.5(17)	C(14)-N(1)-Zn(1)	123.52(18)
C(11')-C(10')-C(9)	108.1(16)	C(1)-O(1)-Zn(1)	125.5(2)
C(12')-C(10')-C(9)	108(2)	Zn(1)-O(1W)-H(1W)	128.8000
C(11')-C(10')-H(10')	110.1000	Zn(1)-O(1W)-H(2W)	96.3000
C(12')-C(10')-H(10')	110.1000	H(1W)-O(1W)-H(2W)	108.9000
C(9)-C(10')-H(10')	110.1000	O(1)-Zn(1)-O(1)#2	180.0000
C(10')-C(11')-H(11D)	109.5000	O(1)-Zn(1)-O(1W)#2	93.24(8)
C(10')-C(11')-H(11E)	109.5000	O(1)#2-Zn(1)-O(1W)#2	86.76(8)
H(11D)-C(11')-H(11E)	109.5000	O(1)-Zn(1)-O(1W)	86.76(8)
C(10')-C(11')-H(11F)	109.5000	O(1)#2-Zn(1)-O(1W)	93.24(8)
H(11D)-C(11')-H(11F)	109.5000	O(1W)#2-Zn(1)-O(1W)	180.0000
H(11E)-C(11')-H(11F)	109.5000	O(1)-Zn(1)-N(1)#2	90.73(8)
C(10')-C(12')-H(12D)	109.5000	O(1)#2-Zn(1)-N(1)#2	89.27(8)
C(10')-C(12')-H(12E)	109.5000	O(1W)#2-Zn(1)-N(1)#2	87.52(8)
H(12D)-C(12')-H(12E)	109.5000	O(1W)-Zn(1)-N(1)#2	92.48(8)
C(10')-C(12')-H(12F)	109.5000	O(1)-Zn(1)-N(1)	89.27(8)
H(12D)-C(12')-H(12F)	109.5000	O(1)#2-Zn(1)-N(1)	90.73(8)
H(12E)-C(12')-H(12F)	109.5000	O(1W)#2-Zn(1)-N(1)	92.48(8)
C(2)-C(13)-H(13A)	109.5000	O(1W)-Zn(1)-N(1)	87.52(8)
C(2)-C(13)-H(13B)	109.5000	N(1)#2-Zn(1)-N(1)	180.00(13)
H(13A)-C(13)-H(13B)	109.5000		
Symmetry transformations used to generate equivalent atoms: #1 -x+2,-y+1,-z+1 #2 -x+2,-y,-z+1			

Crystal structure data of $[Zn(biup)_2(4,4`\text{-bipy})]_n$ (5)

Table B 4: Anisotropic displacement parameters ($Å^2x10^3$) for **5**.

	U_{11}	U_{22}	U_{33}	U_{23}	U_{13}	U_{12}
C(1)	49(2)	70(2)	65(2)	-16(2)	3(2)	-17(2)
C(2)	58(2)	110(4)	67(2)	-39(2)	13(2)	-29(2)
C(3)	51(2)	103(3)	60(2)	-43(2)	9(2)	-18(2)
C(4)	54(2)	102(3)	91(3)	-35(3)	-17(2)	-10(2)
C(5)	56(2)	97(3)	100(3)	-40(3)	-10(2)	-14(2)
C(6)	62(3)	110(4)	67(2)	-21(2)	12(2)	-10(2)
C(7)	63(3)	139(5)	69(3)	-30(3)	-9(2)	2(3)
C(8)	49(2)	147(5)	71(3)	-46(3)	-7(2)	-16(3)
C(9)	98(4)	117(5)	93(4)	-8(3)	13(3)	-9(3)
C(10)	104(10)	100(10)	132(16)	-73(11)	39(10)	-45(8)
C(11)	150(14)	90(9)	210(19)	-29(11)	7(13)	-28(9)
C(12)	112(12)	161(16)	220(20)	-106(15)	100(15)	-72(12)
C(10')	210(20)	76(9)	99(10)	-20(7)	-10(14)	-9(11)
C(11')	280(30)	138(15)	118(12)	-21(10)	-7(14)	56(17)
C(12')	220(20)	145(15)	76(8)	-32(9)	6(11)	78(17)
C(13)	129(5)	128(5)	75(3)	-20(3)	28(3)	-24(4)
C(14)	39(2)	26(1)	90(2)	-11(1)	8(2)	-1(1)
C(15)	37(2)	28(1)	91(2)	-9(1)	11(2)	-6(1)
C(16)	35(1)	20(1)	44(1)	-2(1)	-7(1)	-3(1)
C(17)	35(1)	24(1)	68(2)	-4(1)	4(1)	2(1)
C(18)	36(1)	28(1)	73(2)	0(1)	1(1)	-7(1)
N(1)	38(1)	22(1)	55(1)	-6(1)	-3(1)	-2(1)
O(1)	44(1)	34(1)	51(1)	-10(1)	0(1)	-7(1)
O(2)	58(2)	208(4)	63(2)	-38(2)	-7(1)	-23(2)
O(1W)	44(1)	48(1)	62(1)	-6(1)	-12(1)	-7(1)
Zn(1)	33(1)	18(1)	49(1)	-6(1)	-2(1)	-4(1)

The anisotropic displacement factor exponent takes the form:

$$-2\pi^2[\, h^2 a^{*2} U^{11} + \ldots + 2\, h\, k\, a^*\, b^*\, U^{12} \,]$$

Crystal structure data of $[Zn(biup)_2(4,4`\text{-bipy})]_n$ (5)

Table B 5: Hydrogen coordinates ($x10^4$) and isotropic displacement parameters ($Å^2x10^3$) for **5**.

	x	y	z	U(eq)
H(2)	3426	831	7571	96
H(4)	7075	2679	8437	98
H(5)	6278	4693	8445	102
H(7)	697	4663	7109	112
H(8)	1432	2662	7116	107
H(91)	4111	6458	7948	163
H(92)	2120	6474	7316	163
H(10)	2635	6423	9356	140
H(11A)	349	8550	8812	233
H(11B)	3213	8246	8557	233
H(11C)	1808	8253	9670	233
H(12A)	-1711	6917	9823	266
H(12B)	-781	5709	9233	266
H(12C)	-1827	6844	8691	266
H(10')	-681	6245	8562	158
H(11D)	830	8422	8537	293
H(11E)	-1873	8213	8757	293
H(11F)	-294	8029	7670	293
H(12D)	2901	6798	9506	250
H(12E)	1362	5798	9790	250
H(12F)	142	7126	10038	250
H(13A)	6137	790	9086	176
H(13B)	4821	-221	8847	176
H(13C)	3274	990	9302	176
H(14)	13401	1838	4226	66
H(15)	13470	3816	4234	66
H(17)	6523	4384	5682	54
H(18)	6620	2396	5598	57
H(1W)	6179	-21	4098	77
H(2W)	8427	65	3503	77

Crystal structure data of $[Zn(biup)_2(4,4`\text{-}bipy)]_n$ (5)

Table B 6: Hydrogen bonds for **5** [Å and °].

D-H...A	d(D-H)	d(H...A)	d(D...A)	<(DHA)
O(1W)-H(1W)...O(1)#3	0.82	2.05	2.832(3)	159.2
O(1W)-H(2W)...O(2)#2	0.89	1.73	2.598(4)	165.8
O(1W)-H(2W)...O(1)#2	0.89	2.64	3.071(3)	110.7

Symmetry transformations used to generate equivalent atoms:
#1 -x+2,-y+1,-z+1 #2 -x+2,-y,-z+1 #3 -x+1,-y,-z+1