1 INTRODUCTION

1.1 Introduction

Ruthenium (Ru) is a hard and white metal with atomic number 44. The electronic configuration is [Kr] $(5s)^1(4d)^7$. It is a second transition series element in the Periodic Table and the most common oxidation state are II, III, and IV. It does not tarnish at room temperature, but is oxidized in air at about 800 °C.

For the past several years, the chemistry of ruthenium(II) complexes with azoimine (-N=N-C=N-) and polypyridyl (-N=C-C=N-) ligands have been extensively studied because of their σ-donor and π-acceptor properties. The azoimine functional unit has a strong ability to stabilize low valent metal redox states such as Ru(II), Os(II), Pd(II), Pt(II), Ag(I), and Cu(I). (Lu, *et al.*,2003)

The polypyridyl ligands are symmetric bidentate ligands such as 2,2′-bipyridine (bpy) and 1,10-phenanthroline (phen). The chemistry of ruthenium-bipyridine complexes have been widely investigated during the last decade. For example, the polypyridyl mixed-ligand ruthenium(II) complex, $[Ru(bpy)_2(HPIP)](PF_6)_2.H_2O$ where bpy = 2,2′-bipyridine and HPIP = 2-(2-hydroxyphenyl)imidazo[4,5-*f*][1,10]phenanthroline, can intercalate into DNA base pairs via the ligand HPIP that useful for acting as luminescent probe in DNA (Liu, *et al.*, 1999). Besides, the $[Ru(phen)_2(taptp)]^{2+}$ and $[Ru(phen)_2(dptatp)]^{2+}$ complexes, where taptp = 4,5,9,18-tetraazaphenanthreno[9,10-b] triphenylene and dptatp = 2,3-diphenyl-1,4,8,9-tetraazatriphenylene can bind with double-stranded calf thymus DNA via intercalative mode which are used as a sensitive probes for DNA conformation (Zhen, *et al.*, 2000).

The azoimine ligands which have azoimine moiety in molecule are π-acidic. In addition, the azo group is one of the potential functional units which may be photochromatic, pH-responsive, redox active, and mediate electronic communications

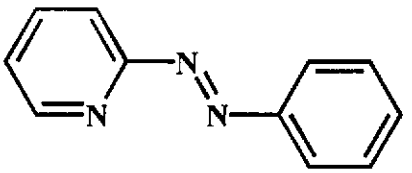
between photoredox active groups (Misra, *et al.*, 1998). One ligand of this type is 2-(phenylazo)pyridine (azpy) which is an asymmetric bidentate ligand and stronger π-acidity than bpy (Krause and Krause, 1980). There are many applications of the ruthenium(II)-azoimine complexes. For example, the $[Ru(azpy)_2Cl_2]$ complexes have been used as catalysts in epoxidation reaction (Barf and Sheldon, 1995). Moreover, the α-$[Ru(azpy)_2Cl_2]$ complex exhibited remarkably high cytotoxicity against a series of tumor cell lines (Velders, *et al.*, 2000). Futhermore, the water-soluble compound α-$[Ru(azpy)_2(NO_3)_2]$ showed the strong binding of the DNA-model bases 9-ethylguanine (9egua) and guanosine (guo) (Hotze, *et al.*, 2000). The achievements in the azoimine chemistry of azopyridine have encouraged many researchers to explore the chemistry of this function in other heterocycles. For example, 2-(arylazo)pyrimidines (aapm) are the new design in this group which consist of a pyrimidine heterocycle ring in molecule. Moreover, aapm are the better π-acceptor than azopyridine ligands. Thus, the azopyrimidine ligands can stabilize ruthenium(II) better than the azopyridine ligands (Santra, *et al.*, 1999).

In addition, the benzothiazole derivatives have many interesting properties such as 6-arylamino-4,7-dioxobenzothiazoles which showed the potent antifungal activity (Ryu, *et al.*, 2003). The fluorinated $3'$-cyano-substituted 2-(4-aminophenyl) benzothiazole exhibited the potent antitumor activity in human cancer cell lines (Hutchinson, *et al.*, 2003). Moreover, benzothiazole can act as a bridging ligand in triruthenium clusters (Dilshad, *et al.*, 1999).

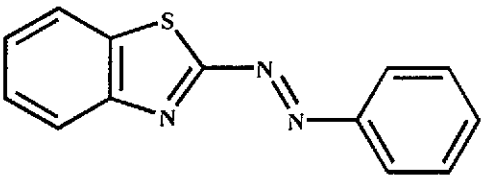
In the present work, the new azoimine ligand, 2-(phenylazo)benzothiazole (bsazpy), and the isomeric $[Ru(bsazpy)_2Cl_2]$ complexes have been synthesized. The bsazpy ligand and the complexes are characterized by elemental analysis, FAB-MS spectrometry, IR spectroscopy, UV-Visible absorption spectroscopy and NMR spectroscopy. The cyclic voltammetric technique is selected to study the electrochemical

properties of all compounds. Moreover, the molecular structures of two *cis*-isomers have been determined by X-ray crystallography.

The bsazpy ligand is a new asymmetric bidentate ligand in azoimine family. It can act as π-acceptor and its structure is similar to azpy but it is different in the heteroycle ring by the replacement of pyridine ring with benzothiazole ring as in Figure 1.



2-(Phenylazo)pyridine (azpy)



2-(Phenylazo)benzothiazole (bsazpy)

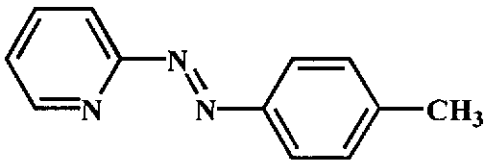
Figure 1. The structures of the azpy and bsazpy ligands.

1.2 Literature reviews

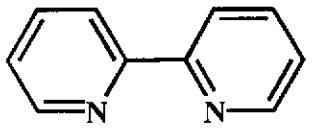
Krause and Krause, (1980) studied the synthesis of 2-(phenylazo)pyridine (azpy) ligand and the isomeric $[Ru(azpy)_2Cl_2]$ complexes. Three isomers of $[Ru(azpy)_2Cl_2]$ were obtained as *cis-trans-cis* (*ctc* or α), *cis-cis-cis* (*ccc* or β), and *trans-cis-cis* (*tcc* or γ) with coordinating pairs in the order Cl, N (N(pyridine)), and N′(N(azo)). The complexes were characterized by IR spectroscopy, UV-Visible

absorption spectroscopy and ^{13}C NMR techniques. The results from cyclic voltammetric data showed that the azpy ligand was a better π-acceptor than bpy ligand.

Goswami, *et al.*, (1981) studied the synthesis, characterization, and electron transfer behavior of two types of ruthenium(II) complexes as RuX_2L_2 and $[Ru(bpy)_2L](ClO_4)_2.H_2O$ where X = Cl, Br, I and L = 2-(phenylazo)pyridine or 2-(m-tolylazo) pyridine, bpy = 2,2'-bipyridine. These complexes were characterized by spectroscopic and electrochemical methods. From the electrochemical studies, both RuX_2L_2 and $[Ru(bpy)_2L]^{2+}$ showed reversible or nearly reversible Ru(III)/Ru(II) couples at platinum electrode. Moreover, the Ru(III)/Ru(II) redox potentials of RuX_2L_2 were considerably higher than that of *cis*-$RuCl_2(bpy)_2$ and several other dichlororuthenium(II) species. Thus, the azopyridine ligand stabilized (in the respect of oxidation) ruthenium(II) better than bpy ligand.



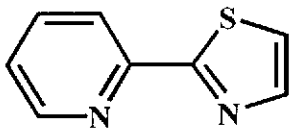
2-(m-tolylazo)pyridine (tap)



2,2'-bipyridine (bpy)

Fitzpatrick and Goodwin, (1982) studied ruthenium complexes of 2-(2-pyridyl) thiazole as bivalent complexes ($[RuL_3]^{2+}$, $[RuL_2bipy]^{2+}$, $[RuL(bipy)_2]^{2+}$) and trivalent complexes ($[RuL_3]^{3+}$, $[RuL_2bipy]^{3+}$, $[RuL(bipy)_2]^{3+}$) where L = 2-(2-pyridyl)thiazole. All complexes were characterized by spectroscopic and electrochemical techniques. From absorption spectra, the bivalent and trivalent complexes exhibited MLCT transition at lower energies than that of $[Ru(bipy)_3]^{3+/2+}$ and the shift to lower energies increased as the number of coordinated thiazole molecules increased. These were probably associated

with a slightly greater π-acceptor capacity of the thiazole ring which corresponded to the higher potentials shift of Ru(III)/Ru(II) reduction potentials with increased coordination of thiazole.



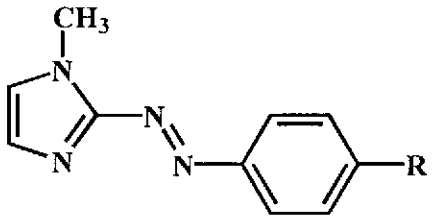
2-(2-pyridyl)thiazole

Krause and Krause, (1982) synthesized the $[Ru(azpy)_2(AB)]^{n+}$ complexes where AB = 2-(phenylazo)pyridine (azpy), 2,2'-bipyridyl, 4,4'-bithazole, 1,2-diaminoethane, 2,4-pentanedione anion, and X_2 ($X = NO_2^-$, CN^-, Br^-, N_3^-, and thiourea). The complexes were characterized by spectroscopic and electrochemical methods. The infrared spectra of all complexes exhibited the azpy azo stretching mode to be diagnostic of the coligand (AB) π-accepting behavior, with strongly π-accepting coligands giving the highest azpy ν(N=N). Moreover, the results from cyclic voltammetric data supported the strong π stabilization.

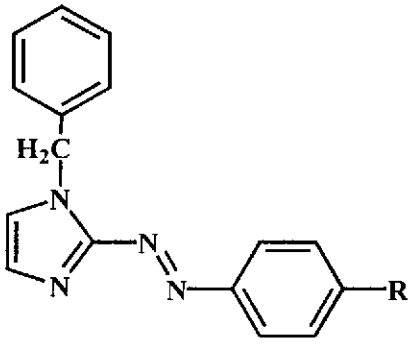
Wolfgang, *et al.*, (1984) studied the spectral and photophysical properties of ruthenium(II) complexes with 2-(phenylazo)pyridine ligand, $Ru(azpy)_2L_2^{n+}$ where azpy = 2-(phenylazo)pyridine and L = various monodentate ligands or a bidentate ligand. The resonance Raman spectra showed a relatively localized MLCT excited state with large distortions of the azo N=N bond. The emission maxima of the luminescent complexes were significantly red shifted relative to those for other Ru(II) diimine complexes. In addition, quenching by a series of related oxidative and reductive quenchers corresponded to the calculated energetics of the photoinduced redox processes.

Barf and Sheldon, (1995) had used the isomeric $[Ru(azpy)_2Cl_2]$ complexes to investigate the influence of the nature of the coordination on the selectivity to epoxide. From this study, both *cis*- and *trans*-$[Ru(azpy)_2Cl_2]$ were new catalyst and showed good selectivity in epoxidation reactions.

Misra, *et al.*, (1998) studied the chemistry of isomeric $[RuL_2Cl_2]$ complexes where L = 1-methyl-2-(arylazo)imidazole, 1-benzyl-2-(arylazo)imidazole, R = H, Me, OMe, Cl, NO_2. The complexes were characterized by spectroscopic and electrochemical data. The isomeric structures had been confirmed by X-ray crystallography. The IR and ^1H NMR data supported the isomer configurations. The electrochemical data revealed that the Ru(III)/Ru(II) couple was shifted to more positive potential and the MLCT bands were blue shifted on going from azoimidazole to azopyridine-ruthenium(II) complexes. This may be due to the decreased π-acidity of the five-membered heterocycle imidazole compared to the six-membered pyridine.



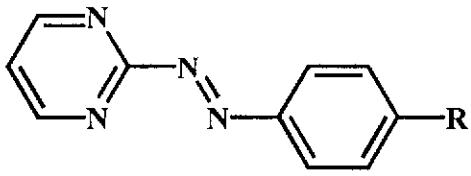
1-methyl-2-(arylazo)imidazole



1-benzyl-2-(arylazo)imidazole

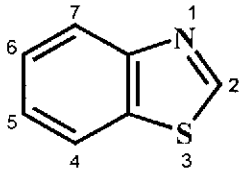
Santra, *et al.*, (1999) synthesized the new *N.N'*-chelating ligand, 2-(arylazo) pyrimidines (aapm), and the isomeric $[Ru(aapm)_2Cl_2]$ complexes. Three isomers of $[Ru(aapm)_2Cl_2]$ were obtained as *trans-cis-cis* (*tcc*), *cis-trans-cis* (*ctc*), and *cis-cis-cis* (*ccc*) configurations with reference to the order of coordination pairs as Cl, N (N(pyrimidine)), and N′ (N(azo)). The structures of *tcc*- and *ccc*-isomers were

confirmed by X-ray crystallography. The isomer configurations were supported by IR and ^{1}H NMR data. Absorption spectra of the complexes showed $t_2(Ru) \rightarrow \pi^*(aapm)$ MLCT transitions in the visible region. From the cyclic voltammetric studies, both *cis*-complexes (*ctc* and *ccc*) exhibited Ru(III)/Ru(II) couple at higher potentials than that of *trans*-complexes (*tcc*).



2-(arylazo)pyrimidines (aapm) (**R** = H, Me, Cl)

Dilshad, *et al.*, (1999) synthesized triruthenium clusters from the reaction between $[Ru_3(CO)_{12}]$ and benzothiazole. The X-ray diffraction analysis of the compounds showed that the benzothiazole was a bridging ligand which was coordinated through the imino-nitrogen and C-2 carbon atoms in $[Ru_3(\mu\text{-H})(\mu\text{-2,3-}\eta^2\text{-NSC}_7H_4)(CO)_{10}]$ complexes. For $[Ru_3(\mu\text{-H})(\mu_3\text{-1,2,3-}\eta^3\text{-NSC}_7H_4)(CO)_9]$, benzothiazole was coordinated through the sulfur, the imino nitrogen, and the C-2 carbon atoms as suggested by IR, ^{1}H NMR, and Mass spectral data.



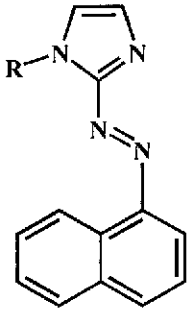
benzothiazole

Hotze, *et al.*, (2000) studied the synthesis and characterization of α-$[Ru(azpy)_2(NO_3)_2]$ where azpy = 2-(phenylazo)pyridine and α indicated the isomer in which the coordinating pairs ONO_2, N(pyridine), and N(azo) was *cis-trans-cis*,

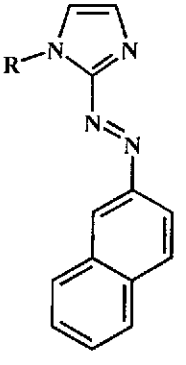
respectively. The structure of the complex had been confirmed by X-ray crystallography. Moreover, they studied the binding of the DNA-model bases 9-ethylguanine (9egua) and guanosine (guo) to α-[Ru(azpy)$_2$(NO$_3$)$_2$] complex. The binding DNA complexes were determined by ^{1}H NMR and 2D NMR techniques.

Velders, *et al.*, (2000) presented the different cytotoxicity data of three isomeric [Ru(azpy)$_2$Cl$_2$] complexes (α-, β-, and γ-isomers). The cytotoxicity data revealed that the α- [Ru(azpy)$_2$Cl$_2$] exhibited remarkably high cytotoxicity against a series of tumor-cell lines, which was in contrast to the low cytotoxicity of its isomeric complexes (β - and γ - isomers). This may be due to the coordination of guanine derivatives to the α – isomer was sterically less hindered than were the cases for β - , γ - isomers and the *cis*-[Ru(bpy)$_2$Cl$_2$].

Byabartta, *et al.*, (2001) studied the synthesis and spectral characterization of 1-alkyl-2-(naphthyl-(α / β)-azo)imidazoles (α -/ β - NaiR) ligands (where R = Me, Et, Bz) and the isomeric [Ru(NaiR)$_2$Cl$_2$] complexes. Two isomers were isolated as *trans-cis-cis* (*tcc*) and *cis-trans-cis* (*ctc*) isomers with coordinating pairs in the order Cl, N (N(imidazole)), and N′ (N(azo)). All compounds were characterized by elemental analysis and spectroscopic data. From the redox studies, the *ctc*-isomer displayed Ru(III)/Ru(II) couple at higher potentials than that of the *tcc*-isomer.

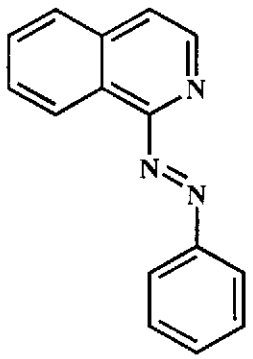


α-NaiR



β- NaiR

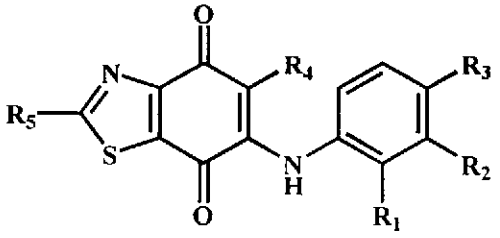
Lu, *et al.*, (2003) synthesized the 1-(phenylazo)isoquinoline (paiq) ligand and the isomeric $[Ru(paiq)_2Cl_2]$ complexes. Two isomers were separated by column chromatography as *trans-cis-cis* (*tcc*) and *cis-cis-cis* (*ccc*), in order of the coordinating pairs: Cl, N (N(isoquinoline)), and N′ (N(azo)). The X-ray crystal structure determination confirmed the crystal structures of the both isomers. In addition, the coordination geometry of both isomers were distorted octahedral.



1-(phenylazo)isoquinoline (paiq)

Hotze, *et al.*, (2003) developed the new water-soluble bis(2-phenylazopyridine) ruthenium(II) complexes which were derivatives of the highly cytotoxic α-$[Ru(azpy)_2Cl_2]$ (α denoting the coordinating pairs Cl, N(pyridine), and N(azo) as *cis-trans-cis*, respectively). From the cytotoxicity tests, the water-soluble compounds displayed a slightly lower activity than cisplatin but a higher or comparable activity relative to carboplatin.

Ryu, *et al.*, (2003) synthesized 6-arylthio-/6-arylamino-4,7-dioxobenzothiazoles. All compounds were tested for in vitro antifungal activity against *Candida* species and *Aspergillus niger*. The 6- arylamino-4,7-dioxobenzothiazoles showed potent antifungal activity.



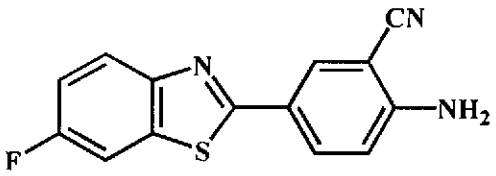
R_1, R_2, R_3 = H, F, Cl, ..

5 : $R_4 = R_5 = CH_3$

6 : $R_4 = R_5 = H$

6- arylamino-4,7-dioxobenzothiazoles

Hutchinson, *et al.*, (2003) described the synthesis of a new series of antitumor 2-(4-aminophenyl)benzothiazole analogues, substituted in the 3'-position by cyano or alkyl group. Comprehensive in vitro analysis showed that 5-fluorinated 3'-cyano substituted 2-(4-aminophenyl)benzothiazole was the most potent agent in antitumor benzothiazole-sensitive cell lines.



5-fluorinated 3'-cyano substituted 2-(4-aminophenyl)benzothiazole

1.3 Objectives

1. To synthesize the 2-(phenylazo)benzothiazole (bsazpy) ligand and the isomeric $[Ru(bsazpy)_2Cl_2]$ complexes.
2. To characterize the bsazpy ligand and the $[Ru(bsazpy)_2Cl_2]$ complexes by spectroscopic and electrochemical techniques.