Preface

Bio-inorganic chemistry is important in elucidating the implications of electron-transfer proteins, substrate binding and activation as well as metal properties in biological chemistry. Many reactions in life process involve water and metal ions are often at the catalytic centers (active sites) of metalloenzymes. Aerobic life makes extensive use of metal ions such as iron, copper and manganese. Heme is utilized by red blood cells in the form of haemoglobin for oxygen transport. Oxidases and oxygenases are metal systems found throughout nature that take advantage of oxygen to carry out important reaction such as energy generation or small molecule oxidation in cytochrome P450. Some metalloprotein are designed in such a way they can protect a biological process from the potentially harmful effects of oxygen and other reactive oxygen-containing molecules such as H₂O₂. These systems include peroxodases, catalases and superoxide dismutases. This thesis entitled “O₂ and H₂: Activation and Reduction using Bio-inspired Small Molecules” mimicks the structural and functional properties of these metallo-enzyme active sites and understanding the geometric and electronic structural contribution to their reactivity. All these work are done at Indian Association for the Cultivation of Science (IACS), Kolkata.

In Chapter 1, we have synthesized iron porphyrin complexes with an axial thiolate and imidazole ligands, covalently attached to the porphyrin ring with a goal of understanding the role of these ligands in tuning the electronic structure. We used a combination of Electron Paramagnetic Resonance (EPR) and resonance Raman (rR) spectroscopy and Density Functional Theory (DFT) to answer a very old question, “why the thiolate bound iron porphyrin complex in a coordinating solvent like methanol is low spin though thiolate is a weak field ligand than imidazole ligand?”.

In Chapter 2, we have synthesized another iron porphyrin complex with an axial phenolate ligand which is covalently attached to the porphyrin macrocycle. Then we further showed that the higher covalency of the thiolate ligand is responsible for the lower Fe-N_pyr vibration whereas the greater electrostatic stabilization of the Fe^{III}-OPh bond is responsible for lowering the Fe^{III/II} E⁰ of the phenolate complex in organic solvent, though phenolate is less covalent than thiolate complex.
In Chapters 3 and 4, using these synthesized active site models we worked towards elucidating the role of these axial ligands in O₂ activation. Subsequently trapped Fe^{III}-superoxide intermediate at -80 °C and their Fe-O and O-O vibrations were characterized using resonance Raman spectroscopy. These models help us to quantify the “push effect” and suggest that, of the three known axial ligands that bind heme in nature, the thiolate has the greatest “push effect”. Then we further investigated O₂ reduction studies under heterogeneous conditions using rotating disc electrochemistry (RDE) and rotating ring disc electrochemistry (RRDE) to conclude from the 2nd order rate constant that the rate of O-O bond cleavage by thiolate complex is 100 times faster relative to a neutral ligand like imidazole and 10 times relative to an anionic, less covalent phenolate ligand.

In Chapters 5 and 6, we have seen that protein dielectric constant of solvent and hydrogen bonding plays a key role in tuning Fe^{III/II} reduction potential (E⁰) in Cytochrome P450 and catalase models by as much as ~600 mV. We have also discovered that the thiolate bound iron porphyrin complexes exhibit valence tautomerism between ferric thiolate and ferrous thyl radical states in organic solvents, at room temperature. The ferric thiolate state is favored by greater enthalpy and the ferrous thyl state is favored by entropy which is prevalent at RT. The ferrous thyl form react with O₂ leading to degradation of these ferric complexes in air; a property unique to ferric thiolate complexes. We synthesized the deuterated ligand to establish the source of entropic stabilization of this ferrous thyl radical state and established that hydrogen bonding to the ferric thiolate form is preferred over the ferrous thyl form in aqueous THF, akin to the one observed in the active site of P450, lead to stabilization of the ferric thiolate state, imparting stability to these compounds against degradation in the presence of O₂.

In Chapter 7, we focus on understanding the factors that lead to lowering of overpotential in hydrogen evolution reaction (HER) by bio-inspired synthetic models of [FeFe] hydrogenases. DFT studies used accurately to correlate between E⁰, the average C-O stretching vibrations [ν(CO)avg], hammet-σ parameter of the para substituents in a series of aryl amine bridged complexes and on the gas phase proton affinities (PA) of a series of alkyl amine bridged complexes observed in the experimental data. It is concluded that
while for alkyl amine bridged complexes an interaction between the nitrogen lone pair with the C-S σ* is responsible for the shift in $E^0$, the inductive and mesomeric effects of the substituents in the aryl ring is responsible for the shift in $E^0$ in aryl amine bridged complexes. We are now able to effectively electrochemically reduce $H^+$ in acidic aqueous solutions to produce $H_2$ using H2ase models with much lower over potential by understanding the importance of aryl substitution on the bridging nitrogen of an azadithiolate ligand used to form these synthetic models and utilizing it.

I hope this thesis contributes to the development in the field of O$_2$ activation and H$_2$ evolution by iron based catalysts.