SUMMARY

Pesticides may undergo a variety of chemical reactions on formulation and storage following the application to crops. In more recent years, it has been observed that some of the growth promoting substances, when applied under different conditions of concentration and temperature, become effective herbicides for certain species of harmful or unwanted plants grown along with the crops. The mode of action of these substances is perhaps least understood aspect of pesticide science. Several theories have been proposed to explain the mode of action of plant growth substances; but the metal-complexation hypothesis proposed by Heath and Clark seems to be most controversial and important. These workers could not produce detailed experimental and theoretical evidence in support of their hypotheses. A survey of chemical literature of trace elements and their relationships to enzymes reveals that more and more enzymes are metal containing or metal dependent. The precise mode of action of plant growth
regulators is far from understood. Hence, a detailed study of metal complexation hypothesis of plant growth regulators (e.g., 2-chlorophenoxyacetic acid; 2,4-dichlorophenoxyacetic acid; 2,4,5-trichlorophenoxyacetic acid, indole-3-acetic acid, etc.) has, therefore, undertaken at the suggestion of Dr. K. Sahai in order to establish their mode of action based on the role of metal ions in biological systems. The metal-complexation chemistry of plant growth regulators presented in this thesis, using potentiometric pH-titration, refractometric, differential refractometric and spectrophotometric techniques in solution and a theoretical quantitative treatment of H$_2$Ad principle for metal-phenoxycetate interactions, is an attempt towards establishing the mode of action of these plant growth substances and herbicides. A brief summary of the results obtained has been described below:

**COMPLEXATION OF SOME PLANT GROWTH REGULATORS WITH METAL IONS OF BIOLOGICAL INTEREST**

In order to explore complexation as a possible mode of action of plant growth regulators, a detailed equilibrium analysis of complexation of indole-3-acetic acid (IAA); indole-3-propanoic acid (IPA); indole-3-butanoic acid (IBA); naphthalene-1-acetic acid (NAA); 2-chlorophenoxyacetic acid (2-CPA); 2,4-dichlorophenoxyacetic acid (2,4-u); 2,5-dichlorophenoxyacetic acid (2,5-u) and 2,4,5-trichlorophenoxyacetic acid (2,4,5-T)

A part of this work has been published in the following Journals:

with Mg(II), Al(III), Ca(II), Fe(III), Co(II), Ni(II), Cu(II),
Zn(II), Zr(IV), La(III) and Th(IV), has been carried out poten-
tiometrically as employed by Irving and Rossoitti. From the
shifts of the titration curves, values of the average number
of protons associated with ligand ($n_p$), the average number of
ligands associated with a metal ion ($\bar{n}$) and free ligand
exponent ($p_l$) have been calculated by Irving-Rossoitti's compu-
tational methods. The values of protonation and stepwise
stability constants of metal-ligand complexes have been reported
in 50% aq. dioxan (v/v) at constant ionic strength ($\mu = 0.1$ M,
$KN_3$) and temperature (25°C).

From potentiometric titration curves, the dissociation of
these acids have been represented by the equilibrium: $HL \rightleftharpoons H^+ + L^-$. No significant differences in the protonation and overall stabi-
ity constants of IAA, IPA and IBA have been observed. The
general order of the stability of these complexes in terms of
metal ions have been found to be:

$$
\text{Th}^{IV} > \text{Zr}^{IV} > \text{Al}^{III} > \text{Cu}^{II} > \text{Co}^{II} > \text{Ni}^{II} > \text{Zn}^{II} \quad \text{(for IAA; IPA and IBA)}
$$

and,

$$
\text{Th}^{IV} > \text{Zr}^{IV} > \text{Al}^{III} > \text{Co}^{II} > \text{Cu}^{II} > \text{Ni}^{II} > \text{Zn}^{II} \quad \text{(for NAA)}.
$$

Similarly, in the phenoxyacetic acid series the order is

$$
\text{Th}^{IV} > \text{Zr}^{IV} > \text{Al}^{III} > \text{Cu}^{II} > \text{Co}^{II} > \text{Ni}^{II} > \text{Zn}^{II},
$$
irrespective of the nature of the ligand considered showing similarity in the mode of interaction of these metal ions with plant growth substances.

STACKED TERNARY COMPLEXES OF Co(II), Ni(II), Cu(II) and Zn(II) WITH 2,2'-BIPYRIDYL OR 1,10-PHENANTHROLINE AS A PRIMARY LIGAND AND SOME PLANT GROWTH REGULATORS AS SECONDARY LIGANDS

Since the stability constant data of binary complexes have been found to be indistinguishable and some specific structural requirements are also essential for complexation to occur and for a compound to show activity, mixed ligand complexes of the type \( {\text{MAL}}^+ \) (where \( M = \text{Co(II)}, \text{Ni(II)}, \text{Cu(II)} \) or \( \text{Zn(II)} \); \( A = 2,2'-\text{bipyridyl} \) or \( 1,10\)-phenanthroline and \( L = \text{PAA; 2-cPA; 2,5-D; 2,4-D or 2,4,5-T} \) have, therefore, been studied by potentiometric pH-titration technique in \( 50\% \) aq. dioxan (v/v) at constant ionic strength (0.1 M, KNO\(_3\)) and temperature (25°C).

The stability constants of \( 1:1:1 \) ternary complexes, \( \text{MAL}^+ \), have been evaluated assuming that the species, \( \text{MA}^{2+} \), is first formed completely before the addition of secondary ligand, \( L \), takes place to it according to following equilibrium.

\[
\text{MA}^{2+} + L^- \rightleftharpoons \text{MAL}^+; \quad K_{\text{MAL}} = \frac{[\text{MAL}^+]}{[\text{MA}^{2+}][L^-]}
\]  

The values of characterizing factors, \( \Delta \log K_{\text{MAL}} \), and \( \log X' \), have been evaluated using the following relations:

A part of this work has been published in the following journals:
\[ \Delta \log K_M = \log K_{MAL}^M - \log K_{ML}^M \]

\[ = \log K_{MLA}^M - \log K_{MA}^M \]

and

\[ \log X = 2 \log \beta_{MAL}^M - (\log \beta_{MA_2}^M + \log \beta_{ML_2}^M) \]

\[ = (\log K_{MAL}^M - \log K_{ML_2}^M) + (\log K_{MLA}^M - \log K_{MA_2}^M) \]

where \( X \) is defined by the following equilibrium,

\[ MA_2^{2+} + ML_2 \rightleftharpoons 2 MAL^+ \]

\[ X = \frac{[MAL^+]^2}{[MA_2^{2+}][ML_2]} \]

\[ \log \beta_{MAL}^M = \log K_{MA}^M + \log K_{MAL}^M \]

\[ \log K_{MLA}^M = \log \beta_{MAL}^M - \log K_{ML}^M \]

The \( \Delta \log K_M \) and \( \log X \) values have been used to interpret the extent of \( M(\text{d}^n) \rightarrow N(\text{d}^n) \) interactions. The values of \( \Delta \log K_M \) have always been found to be positive except those of \( \text{Ni(II)-phenoxyacetate complexes} \) where low positive, zero or low negative values have been observed. The positive values of \( \Delta \log K_M \) may also be due to absence of Coulombic repulsion between the two dissimilar ligands bound to the same metal ion.
The increased stability of ternary complexes has also been described on the basis of intramolecular aromatic ring stacking which is more pronounced in the cases of IPA, IAA and IBA but less in PAA; 2-CPA; 2,4-D; 2,5-D and 2,4,5-T, because in the former series the aromatic ring system is associated with side chain of varying lengths to produce considerable intramolecular aromatic ring stacking while in the latter series, it may only be due to increase in the size of substituted aromatic ring systems. This effect finds further support from ΔΔ log $K_M$ and Δ log $X$ values as calculated by the following relations:

$$
\Delta \Delta \log K_M = \Delta \log K_M^{M(A)}(IPA) - \Delta \log K_M^{M(A)}(IAA) \quad \ldots (5)
$$

$$
\Delta \Delta \log K_M = \Delta \log K_M^{M(A)}(IBA) - \Delta \log K_M^{M(A)}(IAA) \quad \ldots (6)
$$

$$
\Delta \log X = \log X_M^{M(A)}(IPA) - \log X_M^{M(A)}(IAA) \quad \ldots (7)
$$

and,

$$
\Delta \log X = \log X_M^{M(A)}(IBA) - \log X_M^{M(A)}(IAA) \quad \ldots (8)
$$

for IAA, IPA and IBA, and

$$
\Delta \Delta \log K_M = \Delta \log K_M^{M(A)}(2,4-D) - \Delta \log K_M^{M(A)}(PAA) \quad \ldots (9)
$$

$$
\Delta \Delta \log K_M = \Delta \log K_M^{M(A)}(2,4,5-T) - \Delta \log K_M^{M(A)}(PAA) \quad \ldots (10)
$$

etc., for phenoxyacetic acid series. Most of these values have been found to be positive indicating the occurrence of intramolecular aromatic ring stacking. These results find further support from the work of Sigel et al. on intramolecular hydrophobic interaction in ternary complexes of aliphatic amino acids.
INTRAMOLECULAR AROMATIC RING STACKING AND STRUCTURE-STABILITY-
ACTIVITY CORRELATIONS IN TERNARY COMPLEXES OF PHENOXYACETIC 
ACIDS AND SOME D-AMINO ACIDS.  

Amino acids are very common in biological systems and ternary complexes where intramolecular aromatic ring stacking occurs may create specific structure. It, thus, became necessary to study ternary complexes of the type MAAcL (where M = Cu(II) or Zn(II); Aa = DL-tryptophan, DL-phenylalanine or DL-tyrosine and L = PAA; 2-CPA; 2,5-D; 2,4-D or 2,4,5-T). The overall effect due to the π-accepting properties of two ligands, substituents and intramolecular aromatic ring stacking between them in a ternary complex has been predicted from \( \Delta \log K_M \) values calculated from Eq. (3). These values are always negative and follow the sequence:

\[
\text{tryptophan} > \text{phenylalanine} > \text{tyrosine}
\]

Further, it has been observed that \( \Delta \log K_M \) values do not follow the basicity of the secondary ligand and follow the trend:

\[
2,4,5-T > 2,4-D > 2,5-D > 2-CPA
\]

with the exception of PAA.

The values of dissociation and stability constants of binary and ternary complexes have shown linear correlations with Hammett substituent constants (\( \sigma \)). The representative regression lines of linear correlations of \( pK_a \), \( \log K_{Cu} \) and \( \log K_{CuL} \) with \( \sigma \)-values have been shown below:  

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e, A paper based on this material has been communicated for publication.
\[ pK_a = 4.44 - 0.465 \sigma, \quad r = 0.999 \]

\[ \log K_{\text{Cu}} = 3.27 - 0.117 \sigma, \quad r = 0.81 \]

\[ \log K_{\text{CuA}} = 3.005 - 0.04 \sigma, \quad r = 0.67 \quad \text{(for tryptophan)} \]

These correlations show that \( pK_a \) and stability constants of binary and ternary complexes are affected by the nature of substituent group present at the ring.

The effect of intramolecular aromatic ring stacking has also been observed from the values of \( \Delta \Delta \log K_M \) and \( \Delta \log X \) calculated as follows:

\[ \Delta \Delta \log K_M = \Delta \log K_M^{(\text{Aa})(2,4,5-T)} - \Delta \log K_M^{(\text{Aa})(L')} \quad \ldots \quad (11) \]

and,

\[ \Delta \log X = \log X_M^{(\text{Aa})(2,4,5-T)} - \log X_M^{(\text{Aa})(L')} \quad \ldots \quad (12) \]

where \( L' = \text{PAA}; \ 2\text{-CPA}; \ 2,5\text{-D} \) or \( 2,4\text{-D} \). The high values of \( \Delta \Delta \log K_M \) for tryptophan have been observed due to the influence of intramolecular aromatic ring stacking on the stability of ternary complexes.

**Refractometric, Differential Refractometric and Spectrophotometric Determination of Stoichiometry and Stability Constants of Metal Complexes**

Refractometric and differential refractometric methods of determining stoichiometry and equilibrium constants of molecular
complexes as developed by Sahai et al.\textsuperscript{9} has been extended to metal-ligand complexes. The change in refraction, $\Delta n$, expressed by $\Delta n = n_{\text{theo}} - n_{\text{exp}}$ were plotted against molar ratio for two series of experiments taking different initial concentrations of the reactants. Then for the same value of $\Delta n$, the points on the two curves were determined by drawing a horizontal line parallel to the $x$-axis and the corresponding initial concentrations of the reactants have been used to determine the stoichiometry and stability constants of metal complexes. In differential refractometric method, the following equation has been used to evaluate refraction per cm$^3$ due to complex:

$$10^3 (\varphi - \varphi_L) - \mathcal{C}_M T^0_M = 6000 \frac{(n-n_L)n_L}{(n^2 + 2)^2} - \mathcal{C}_M T^0_M = \Delta \mathcal{C}_T_{ML}$$

where,

$$\mathcal{C}_A T^0_M = 10^3 (\varphi_M - \varphi_0) = 6000 \frac{(n_M - n_0)n_0}{(n_0^2 + 2)^2}$$

$$\varphi_0 = \frac{(n_0^2 - 1)}{(n_0^2 + 2)}$$

$$\varphi_M = \frac{(n_M^2 - 1)}{(n_M^2 + 2)}$$

$$\varphi_L = \frac{(n_L^2 - 1)}{(n_L^2 + 2)}$$

$$\varphi = \frac{(n^2 - 1)}{(n^2 + 2)}$$

The quantities $n_0$, $n_M$, $n_L$ and $n$ are the refractive indices of solvent, metal, ligand and solution (metal + ligand), respectively, and corresponding $\varphi$ values have their usual significance. From the two successive plots for two systems having different concentrations the equilibrium,

$$M + 2 L \rightleftharpoons ML_2,$$
is followed, hence

$$K = \frac{x}{(a-x)(b-x)} = \frac{x}{(a'-x)(b'-x)} \quad \ldots (14)$$

where $x$ is the equilibrium concentration of the complex, $a$ and $a'$ and $b$ and $b'$ are the initial concentrations of reactants in two sets of experiments. Then from the plots of $\Delta \Sigma T_{ML}$ vs molar ratio for the same $\Delta \Sigma T_{ML}$ value, the value of $x$ has been calculated using Eq. (14) as follows:

$$x = \frac{-[(b^2-b'^2+4(a'b'-ab))\pm\sqrt{(b^2-b'^2+4(a'b'-ab))^2-4[4(a+b)-a'+b']^2(xb^2-axb')]} - 4[(a+b)-(a'+b')]}{8[(a+b)-(a'+b')]} \quad \ldots (15)$$

which leads the value of $K$ from Eq. (14). The same equation has been used in spectrophotometric method for the same optical density and the results obtained are comparable to those obtained by potentiometric measurements.

**QUANTITATIVE TREATMENT OF HSAB PRINCIPLE AND ITS APPLICATION TO THE ACTIVITY OF SOME PLANT GROWTH REGULATORS**

Using Klopman's equations,

$$\begin{align*}
\mathcal{E}_m &= \mathcal{I}_m - a^2(\mathcal{I}_m - \mathcal{E}_m) - \frac{x_r(C_r^m)^2}{R_r} (1 - \frac{1}{\xi}) \left[ q_r + 2b^2x_r(C_r^m)^2 \right] \\
\mathcal{E}_n &= \mathcal{I}_n - b^2(\mathcal{I}_n - \mathcal{E}_n) - \frac{x_s(C_s^n)^2}{R_s} (1 - \frac{1}{\xi}) \left[ q_s - 2b^2x_s(C_s^n)^2 \right]
\end{align*} \quad \ldots (16)$$

$$\begin{align*}
\mathcal{E}_m &= \mathcal{I}_m - a^2(\mathcal{I}_m - \mathcal{E}_m) - \frac{x_r(C_r^m)^2}{R_r} (1 - \frac{1}{\xi}) \left[ q_r + 2b^2x_r(C_r^m)^2 \right] \\
\mathcal{E}_n &= \mathcal{I}_n - b^2(\mathcal{I}_n - \mathcal{E}_n) - \frac{x_s(C_s^n)^2}{R_s} (1 - \frac{1}{\xi}) \left[ q_s - 2b^2x_s(C_s^n)^2 \right]
\end{align*} \quad \ldots (17)$$
where, \( E^+_{m} \) = softness of a base  
\( E^+_{n} \) = softness of an acid  
IP = ionization potential  
EA = electron affinity  
\( a = 3/4, \quad b = 1/4, \quad c = 1 \)  
\( \varepsilon \) = dielectric constant of solvent  
R = radius of an atom whose softness is to be determined.  
q = charge on the atom  
\( x = q-(q-1)/K \), where \( K = 0.75 \).

The values of \( E^+_{m} \) and \( E^+_{n} \) have been calculated for a series of phenoxyacetate anions and metal cations in water, methanol and dioxan. The value of R has been derived on the basis of corrected effective nuclear charge due to partial charge on O-atom and the radius so calculated has been termed as effective radius (\( R_{\text{eff}} \)). The charge \( q \) has been taken as equal to the total electronic charge plus the partial charge developed on O-atom. The values of softness of phenoxyacetate anions have been termed as \( E^+_{m(\text{eff})} \). \( E^+_{m(\text{eff})} \) values of the bases show that the change of solvent affects the softness values of O-atoms.

In general, the behaviour of the bases in solvents having high dielectric constants is soft. The values of \( E^+_{m(\text{eff})} \) vary from solvent to solvent in the same way as it does in the case of \( E^+_{m(\text{eff})} \) values. The calculated values in a medium of high dielectric constant (water) are harder than those calculated in a medium of low dielectric constant (methanol or dioxan).
The effect of substituent on $E_{m(\text{eff})}^{\dagger}$ values is not so pronounced which may convert a soft base into a hard base or vice-versa. But, these values have shown significant correlations with Hammett sigma values showing a common mode of action of phenoxyacetic acids.

Hard-hard and soft-soft interactions have been expressed in terms of matching constant represented by the relation.

Matching constant = $\left| E_{n}^{\dagger} - E_{m(\text{eff})}^{\dagger} \right|$

A better match has been expected from higher values of $\Delta E_{nm}^{\dagger}$. The $\Delta E_{nm}^{\dagger}$ values have been correlated with established order of stability of non-transition metal complexes but these values for transition metal ions could only be correlated if CFSE is added. Matching constants for this class of metal ions may be expressed by the following relation:

Matching constant = $\left| E_{n}^{\dagger} - E_{m(\text{eff})}^{\dagger} \right| + \text{CFSE}$

Thus, the general order of matching constants for two classes of metal ions have been found to be the same as the established order of their complexes. These values have also shown linear correlations with $\sigma$-values as it has been observed for $E_{m(\text{eff})}^{\dagger}$ values.

**GENERAL CONCLUSION**

On the basis of stability constants of binary and ternary metal complexes discussed above, a new mechanism of plant growth regulators in modification of other workers has been proposed.
According to this mechanism, the plant growth regulating activity may be due to the formation of ternary complexes of plant growth regulators involving other biological materials, such as, metal ions, metallo-enzymes, amino acids, etc. Such species produce some specific structures which cause disturbance in all the enzymatic equilibria from their normal action resulting growth regulation. These findings find further support from the theoretical calculations based on HSAB principle where significant linear correlations of $q$, $E_m^{\text{eff}}$, and $\Delta E_{nm}$ (derived for metal-phenoxyacetate interaction) with Hammett substituent constant ($\sigma$) have been obtained indicating acid-base types of reactions of plant growth regulators with free metal ions or metalloenzymes.

REFERENCES


