1.0 INTRODUCTION

The ever increasing world population and the critical need to feed it compelled man for the enhanced agricultural production. To achieve this, man has been devising various methods of combating pests which cause substantial destruction to crops. Ancient man used copper and zinc coated wires of which copper has a repellent and/or toxic effect to all fouling agents and borers. These products proved to be costly. Alternatively he switched over to comparatively cheaper materials which were mostly poisonous inorganic compounds such as lead arsenate, sodium fluosilicates, Paris green, zinc phosphides etc. Improper application of these chemicals proved to be phytotoxic to crops and were poisonous not only to pests but also to man and domestic animals. The inimical properties of these chemicals prompted man to search for safer compounds. Some plant extracts such as nicotine, pyrethrum, rotenone etc. were used as pest control agents. The pesticidal activity of plant extracts fascinated the organic chemists to test many natural products and synthetic compounds for their pesticidal properties. Hence, DDT though initially synthesized in 1874 was rediscovered as an insecticide in 1939. The discovery of DDT and its effectiveness against a wide variety of arthropods earned for Muller the Nobel prize in 1948. It appeared commercially as the first wonder insecticide and was soon followed by benzene hexachloride (BHC).
Insects, mites and nematodes are major pests which tamper the agricultural production. Approximately 10,000 of the 700,000 known species of insects are identified as pests, and about 30% of the food grains grown in the world still feeds them rather than people. At least 1,500 of the 15,000 species of nematodes cause serious damage to plants. Other than the damage caused to crops, they carry and transmit some of the most debilitating diseases which mankind has to endure such as bilharzia, sleeping sickness, yellow fever, plague and many others. Hence, man has engaged in a continuous struggle against voracious and ruthless natural enemies which have claimed a greater toll on human life.

Chemical agents have been the focal point of pest management. Hence, numerous compounds were synthesized and tested for pesticidal activity. After certain rigorous tests, those which have satisfactory pesticidal activity were introduced commercially. The properties of an ideal pesticide should be:

1. Cheap to produce
2. Very potent against target pest
3. Harmless to non-targets
4. Non-toxic to man, his pets and to the environment
5. Decompose to harmless constituents.

Pest control by chemicals has been playing a vital role, in increasing the production of crops and in checking human diseases.
But it has created some problems also, such as the appearance of resistant strains of pests, resurgence of pest due to destruction of parasites and predators, low yields due to non-seedling of seeds as a result of the destruction of pollinators. The environmental and toxicological hazards posed by numerous persistent/non-persistent pesticides and the increasing tolerance of many pest species to these, engaged scientists throughout the world, in working out the causes and consequent solutions to the problems associated with.

Intensive and extensive use of modern organic pesticides has led to the segregation of resistant strains of some pests and created unexpected difficulties, in their control, while giving clear definition for resistance, it is mentioned that the terms susceptibility, tolerance and resistance should be taken as indicating differences in degree and not in kind. Resistance has been observed in bed bugs to DDT in Musca domestica nebulosa to aldrin.

1.1 Conventional Formulations

Chemicals used to destroy pests need dilution, because very little amount of the active agent is required for treating a large area. The materials used for dilution should not reduce the activity, rather (at least) should enhance the persistence of the active agent or be an attractant of pests. These materials in general referred to as inert materials. The mixture of active and the inert materials is Pesticide Formulation.
Along with the high biocidal activity for various pests, pesticide formulations must be safe to handle and non-toxic to humans, domestic animals, useful plants and beneficial insects and microorganisms. Plants treated with any pesticide must after specified period contain only such residual amount that complete safety is assured in their use as food.

Standards have been set up for the maximum content of pesticides in food stuffs for both human and domestic animals. The interval between plant treatments are recommended such that at the harvest, the pesticide applied should have completely or nearly completely decomposed to its safer constituents so that the food materials do not contain amounts of pesticide residues harmful to human health. In determining the degree of toxicity of a formulation, it is necessary to give attention to its chronic toxicity. The possibility of accumulation in the body, the reversibility of the toxic effect, the route of entry and a number of other factors as well as the toxicity of the products of its metabolism.

1.1.1 Classification of pesticides

There are many ways of classifying the chemical pesticides and the most appropriate one is based upon the use to which the chemical is applied. The classification in general is as follows:

A) Chemicals for insect control: Insecticides
   i. Stomach poison, contact poison and fumigant insecticides
ii. Attractants

iii. Repellents

iv. Auxiliary substances

B) Chemicals for fungus control: Fungicides

i. Eradicant and protective fungicides

ii. Fungistats

C) Chemicals for weed control: Herbicides

The aim in applying any pesticide is that, it should come in contact with the pest to be destroyed. To attain this goal, it is necessary to formulate the active agent suitably. The success of a pesticide depends to a large extent on the formulation and the conditions under which the toxicant is brought into contact with the target. To control different target organisms, it is necessary to produce a large number of formulations suitable for practical applications. There are many types of formulations of which the important ones are granules, wettable powders, solutions in water and organic solvents, emulsive concentrates, dusts, aerosols, fumigants and internal applications.

1.1.2 Types of formulations

A) Granules

A granular formulation is defined as the formulation in which the particle size range from 4 to 80 mesh. Granules release the
sorbed toxicant by mechanical disintegration, dissolving the toxicant at a water interface, displacement of the toxicant by water and volatilization. To release all the active agent, it takes several weeks.

B) Wettable powders

Wettable powders are dust concentrates that contain surface active agents, which when diluted with water become stable and form sprayable colloidal suspensions.

C) Solutions in water and organic solvents

The water soluble pesticides are dissolved and diluted in water and used as sprays. Water insoluble organic pesticides are often solubilized in petroleum distillates and used as sprays. This method is not satisfactory. Kerosene, for instance, causes leaf burn in many agricultural crops and careful application is needed to destroy the target without unpleasant changes to the desired plant.

D) Emulsive concentrates

Most organic pesticides are not water soluble, so application through aqueous system requires the use of an emulsifier. Such materials are characterized by a chemical structure in which the molecule is divided into two moieties. One part of the structure is hydrophilic (water soluble) and the other part is hydrophobic (water insoluble). Usually the hydrophobic moiety is soluble in organic
liquids. Essentially the emulsifier allows the homogeneous dispersion of insoluble agents in water.

E) Aerosols

It is possible by suitable means to produce suspension of solids and liquids in air, the individual particles which are of colloidal dimensions. Such colloidal suspensions are termed as aerosols. The most common method of producing aerosols is by means of the release of compressed gas with which the toxicant is mixed.

F) Fumigants

The application of pest-control chemicals in the gaseous state is termed fumigation, such a method of application is limited to those substances which exist in the gaseous state at temperatures and pressures attainable under practical conditions.

In few cases the toxicant is introduced into the living organism in such a way as to produce resistance to insect or disease attack, for eg. plants fed on selenium are resistant to green house pests. Since most toxicants are harmful to the host, as well as the pest, this method requires careful regulation and is not widely used.

The conventional formulations could not satisfactorily control the pest in single application and posed a threat to environmental pollution and the critical need to feed the growing world population
demands newer and safer methods of pest control. The best and safe way of pest control would be the total elimination of chemical pesticides and to control by developing, Biocontrol Technology. Biocontrol methods of combating the pest is in its preliminary stages and takes a long time to develop and till then the use of chemicals are a must. Consequences of which led to the discovery of new formulation technology Controlled Release Formulation Technology.

1.2 Controlled Release Formulations

Controlled delivery of chemicals, though new to modern technology occurs in nature. Nature operates through controlled release systems to control contiguous competitive vegetation by maintaining optimum phytotoxic chemical concentrations. Oxygenation of blood and delivery, and control of the passage of food and waste are other examples of controlled release.

The concept of controlled release is a novel approach to the safe and effective use of any active ingredient, whether a pesticide, drug or fertilizer. Controlled release technology paramounts to solve the problems involved in the application of conventional formulations like for example, to respond only to the specific purpose for which it is applied and to avoid other responses to a greater extent. Development of controlled release systems is an attempt to simulate nature's processes and to improve the efficiency of the delivery and utilization of active ingredients at the target site.
The drug industry is the first beneficiary of this technology. Major developments in the field of polymer science has paved the way to the development and commercial success of many controlled release formulations for medical, pharmaceutical, agricultural, forestry, public health, and veterinary applications.

An ideal controlled release system should deliver the optimum amount of the active ingredient at a controlled rate for a desired period without causing any damage to the non-target systems. The principle advantage of the controlled release technology is that minimum amount of the active ingredient is required for the same period of activity than is recommended in conventional methods of application. Thus controlled release technology holds great promise for improving the efficiency of existing drugs and pesticides, and for reducing the problems associated with others. Controlled release technology aims and promises to a greater extent to solve the conflict between the absolute need to use pest control agents in agricultural and public health applications and man's great desire to preserve the environment free from toxic materials. A successful application of controlled release technology for preserving environment is the best until better control techniques are developed other than chemical control.

1.2.1 Advantages

Notable features of controlled release systems are localization,
prolongation of the desired action with minimum side effects and single application. Controlled release technology offers an ideal solution to many problems for example, the insect growth regulator, methoprene is so unstable in the aquatic environment that its practical application is possible only with controlled release methods. Commercial acceptance of many new pesticides is possible only when they are stabilized long enough to effect control through controlled release technology. Economic and environmental advantages are also gained by the constant release of lower concentrations of toxicants than are possible with conventional formulations.

The conventional modes of application of pesticides, drugs, fertilizers, and other biocides, relatively high doses are administered at periodic intervals. Thus, the concentration of the active agent raises to a high level in the system treated, which may produce undesirable local effects in the target area or contaminate the environment. As time passes the concentration begins to fall because of natural processes, and before the next application it may fall below the optimum level for the desired response. These factors inflate the cost of treatment and is inefficient. Most of the problems posed by conventional pesticide formulations are eliminated in controlled release pesticide formulation. Hence, inherent advantages present in the controlled release systems have already led many controlled release formulations to commercial success.
1.3 Methods of Controlled Release

The methods to prepare controlled release pesticide formulations can be classified broadly into (1) chemical methods (2) physical methods.

A controlled release system is prepared by either physically trapping or chemically binding the active ingredient to a suitable material generally a polymer so that the optimum quantity of the active agent is released at a desired rate for predetermined time at the site of action. 

1.3.1 Chemical methods

In a chemical approach the pesticide is directly or indirectly covalently or ionically bound to a preformed natural or synthetic polymer as pendent group. Another approach is to prepare polymerizable pesticide monomer and its further polymerization alone or with a co-monomer to a polymeric pesticide. Bifunctional pesticides are polymerised by intermolecular condensation to afford controlled release polymers. The chemical approach helps to incorporate large amounts of active ingredients in comparatively small quantities of polymer matrix. The chemical bond between the pesticide and the polymer immobilizes the active agent until it is broken in the environment. The main limiting factor of this method is that only pesticides and polymers having suitable naturally reactive functional groups are amenable to this approach. The active agent is released
by the slow and sequential hydrolysis of the pesticide-polymer bond under the environmental conditions of application. This retro-chemical synthesis is triggered by moisture, soil microbes or natural light. It is necessary that the polymer-biocide bond must cleave more readily than any other bond in the system. Ester, anhydride or amide linkages are the most useful.

The utility of pesticide-polymer controlled release formulations is governed by their rate of pesticide release. The factors which influence the rate of release are the nature and stereochemistry of the pesticide-polymer linkage, the presence of other functional groups, the level of substitution, hydrophobicity and accessibility of the substrate-biocide bonds to the degrading agents, and the extent of cross-linking and the degree of polymerization of the substrate. Fenone, tris(2,4-dichlorophenoxyethyl) phosphite, is the first example of an attempt to covalently link a pesticide to a polymer. Later Faerber synthesized fungicidally active polymers by the homo- and co-polymerization of m-chlorophenyl acetate and demonstrated the potential use of polymers as a vehicle for controlled pesticide delivery systems. To develop sustained release pesticide formulations, alkyl resins were modified by the tolomeric incorporation of 2,4-dichlorophenoxy acetic acid (2,4-D).

A) Direct bonding to preformed polymers

Direct bonding of pesticides to preformed polymers, involves
the reaction of a pesticide or its derivative with a polymer containing a suitable functional group. The resulting pesticide-polymer bond must degrade in the environment to release the active ingredient. To achieve a high degree of pesticide substitution, the reaction condition must be carefully manoeuvred. Much work was done by Allan and Coworkers\textsuperscript{14} on direct binding herbicides with carboxyl or hydroxyl groups via covalent bonds as pendent substituents to preform natural polymers containing carboxyl or hydroxyl groups. Some synthetic polymers containing hydroxyl and acid chloride groups have also been used for covalently binding pesticides. On converting herbicides containing carboxyl groups to acid chlorides, it is possible to attain a link with polymers containing hydroxyl or amino groups. Natural biodegradable polymers containing cellulose were acylated with 2,4-dichlorophenoxy acetylchloride (Scheme 1). The evaluation of the duration of herbicide released from these products in the soil was carried out by observing the inhibition of the germination of lettuce seed that was sown daily\textsuperscript{15}. Natural polymers, such as, cellulose, chitin, chitosan, lignin, starch, alginic acid or lignocellulosic bark are best suitable for chemically bonding herbicides\textsuperscript{16}. Table 1 shows some of the natural and synthetic polymers that have been converted into herbicide-polymer combinations. It is reported\textsuperscript{17} that treatment of a herbicide acid above its melting point with a natural polymer results in the formation of covalent bond between them. Hence, on heating 2,4-D and Douglas-fir bark at 150°C for 3 h, yields a
Scheme 1
controlled release product containing 20% herbicide. Such polymer esters were also synthesized by exchange reactions. The anhydride forms of herbicidal acids have also been used to esterify polymers. Mixed anhydrides of the pesticide and polymer can be easily synthesized and are feasible controlled release systems (Scheme 2).

Pesticides with hydroxyl groups react with synthetic polymers containing pendent acid chloride. Several pesticides have been treated with polyacryloyl chloride and polymethyl acryloyl chloride (Scheme 3).

The synthesis of many antifouling co-polymers by treating polymers containing anhydride groups with trialkyl stannoles \( R_2SnOSnR_2 \) are reported. Polyfunctional macro-molecules prepared from hexa-alkyl distannoxanes and polymers containing maleic anhydride were observed to be capable of cross linking (Scheme 4).

Some typical pesticides and polymers suitable for chemical binding are shown in Table 2.

Polymers containing pendent hydroxyl groups have also been treated with aldehydes having pesticidal activity. This reaction favours an acetal linkage that is susceptible to acid-catalyzed hydrolysis (Scheme 5).

The synthetic combination of phenoxy herbicide acids and natural polymers such as amino polysaccharides, chitosan or fish waste are best exemplified.
2,4-D + 1,3-bis(p-carboxyphenoxy)propane

2,4-D + Sebacic acid

2,4-D + Poly(acrylic acid)

Scheme - 2
Scheme 3

\[ \text{P-OH} + \left[ \begin{array}{c} \text{OC} \\ \text{Cl} \end{array} \right]_n \rightarrow \left[ \begin{array}{c} \text{OC} \\ \text{O-P} \end{array} \right]_n \]

\[ \begin{array}{c} \text{H}_3\text{C} \\ \text{OH} \end{array} \begin{array}{c} \text{N} \\ \text{Cl} \end{array} \begin{array}{c} \text{Cl} \\ \text{Cl} \end{array} + \left[ \begin{array}{c} \text{CH}_2 \\ \text{C} \end{array} \right]_n \]

\[ \left[ \begin{array}{c} \text{H}_3\text{C} \\ \text{N} \\ \text{O} \end{array} \begin{array}{c} \text{Cl} \\ \text{Cl} \end{array} \begin{array}{c} \text{Cl} \\ \text{Cl} \end{array} \right] \]

\[ \begin{array}{c} \text{Cl} \\ \text{Cl} \end{array} \begin{array}{c} \text{OH} \\ \text{Cl} \end{array} \begin{array}{c} \text{Cl} \\ \text{Cl} \end{array} + \left[ \begin{array}{c} \text{CH}_2 \\ \text{C} \end{array} \right]_n \]

\[ \left[ \begin{array}{c} \text{H}_3\text{C} \\ \text{Cl} \end{array} \begin{array}{c} \text{N} \\ \text{Cl} \end{array} \begin{array}{c} \text{Cl} \\ \text{Cl} \end{array} \right] \]
Scheme 4
Scheme - 5
### Table 1: Herbicide-Polymer Combinations

<table>
<thead>
<tr>
<th>Herbicide</th>
<th>Polymer</th>
<th>Liberated Herbicide %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trichloro acetic acid (TCA)</td>
<td>Kraft lignin bark</td>
<td>6 - 9</td>
</tr>
<tr>
<td>4-chloro-2-methyl phenoxyacetic acid</td>
<td>Kraft lignin bark</td>
<td>23 - 39</td>
</tr>
<tr>
<td>2,4-Dichlorophenoxy acetic acid (2,4-D)</td>
<td>Polyvinyl alcohol</td>
<td>29 - 51</td>
</tr>
<tr>
<td>2,4-Dichlorophenoxy acetic acid (2,4-D)</td>
<td>Cellulose</td>
<td>56.1</td>
</tr>
<tr>
<td></td>
<td>Bark</td>
<td>4 - 32</td>
</tr>
<tr>
<td></td>
<td>Chitin</td>
<td>5 - 34</td>
</tr>
<tr>
<td></td>
<td>Polyvinyl alcohol</td>
<td>23 - 39</td>
</tr>
<tr>
<td></td>
<td>Polyethyleneimine</td>
<td>3 - 24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>42.8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>78.0</td>
</tr>
</tbody>
</table>

### Table 2: Direct Bonding

<table>
<thead>
<tr>
<th>Pesticide</th>
<th>Polymer&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pentachlorophenol</td>
<td>Polyacryloyl chloride</td>
</tr>
<tr>
<td>Phenylazo-2-naphthol</td>
<td>Polymethacryloyl chloride</td>
</tr>
<tr>
<td>Hydroxyphenylazo-2-naphthol</td>
<td>Polymaleic anhydride</td>
</tr>
<tr>
<td>2,4,6-trichlorophenol</td>
<td>Co-polymer of maleic anhydride with vinyl monomer</td>
</tr>
<tr>
<td>Triethyltin hydroxide</td>
<td></td>
</tr>
<tr>
<td>Tri-n-butyltin hydroxide</td>
<td></td>
</tr>
<tr>
<td>1-Hydroxyimidazole</td>
<td></td>
</tr>
<tr>
<td>1-Hydroxyimidazole-3-oxide</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Containing acid chloride or anhydride groups
Scheme 6
1) \( \text{P-CO}_2\text{H} + \text{CH}_3\text{-C-O-CH=CH}_2 \xrightarrow{\text{Hg(OAc)}_2, \text{H}_2\text{SO}_4} \text{P-C-O-CH=CH}_2 + \text{CH}_3\text{-CO}_2\text{H} \)

2) \( \text{P-CO}_2\text{H} + \text{HO-C}\left[\text{CH}_2\right]_n\text{C=CH}_2 \xrightarrow{\text{DCC}} \text{P-C-O-C}\left[\text{CH}_2\right]_n\text{C=CH}_2 \)

3) \( \text{P-CO}_2\text{H} \xrightarrow{\text{SOCl}} \text{P-C-Cl} \xrightarrow{\text{HO-C}\left[\text{CH}_2\right]_n\text{C=CH}_2, \text{Base}} \text{P-C-O-C}\left[\text{CH}_2\right]_n\text{C=CH}_2 \)

\[ \text{Scheme - 7} \]
4) \[ P-OH + Cl-C\cdots C\cdots C=CH_2 \rightarrow P-O-C\cdots C=CH_2 \]

\[ \text{Cl}\cdots \text{Cl}\cdots \text{OH} + \text{CH}_2\cdots \text{C-Cl} \rightarrow \text{CH}_2\cdots \text{C-O-Cl} \]

5) \[ P-NH_2 + Cl-C\cdots C=CH_2 \rightarrow P-NH-C\cdots C=CH_2 \]

\[ \text{(CH}_3\text{)}^3\text{C} \text{N} \text{H}_2 + \text{Cl-C-CH=CH}_2 \rightarrow \text{(CH}_3\text{)}^3\text{C} \text{N} \text{H-C-CH=CH}_2 \]

6) \[ P-NH_2 \xrightarrow{\text{Cl-C-Cl} \text{2HCl}} P-NCO \xrightarrow{\text{H}_2\text{N-C-CH=CH}_2} P-NH-C\cdots NH-C\cdots CH=CH_2 \]

\[ \text{(CH}_3\text{)}^3\text{C} \text{N} \text{H}_2 + \text{Cl-C-Cl} \rightarrow \text{(CH}_3\text{)}^3\text{C} \text{N} \text{H-C-CH=CH}_2 \]

7) \[ P-NCO + HO\{\text{CH}_2\}_n\text{NH-C-CH=CH}_2 \]

\[ P-NH-C\cdots O\{\text{CH}_2\}_n\text{NH-C-CH=CH}_2 \]

\[ \text{(CH}_3\text{)}^3\text{C} \text{N} \text{H-C-O-CH}_2\text{CH}_2\text{NH-C-CH=CH}_2 \]

\[ \text{(CH}_3\text{)}^3\text{C} \text{N} \text{H-C-O-CH}_2\text{CH}_2\text{NH-C-CH=CH}_2 \]

Scheme - 7
B) Indirect bonding to preformed polymers

It is not possible always for the biocide and the substrate to possess mutually reactive functional groups, which are necessary for direct bonding. Further, the intrinsic strength of the bonds formed between the preformed polymers and the pendent active ingredients are not favourable for useful release rates. The inhibition caused by these factors, in the preparation of controlled release systems, can often be overcome by interposing a multifunctional entity to bridge the incompatible groups. The bond between the pesticide and the binding compound must be, more easily cleaved in the environmental condition of application than any other bond in the system to provide a suitable release rate of the active agent.

The bridged controlled release formulation can be synthesized either by reacting equimolar amounts of the pesticide and the bridging compound and then the resulting product is reacted with the polymer by means of the remaining active moiety, or it can be carried out in the reverse order\(^2^3\). It is important to avoid side reactions which do not bind active agent and which may only cross link the polymer substrate\(^2^4\).

Pesticides containing hydroxy or amino groups have been successfully attached by covalent bonds with the aid of bridging molecules to polymers containing hydroxy or amino groups. Polyfunctional molecules such as; toluene diisocyanate\(^2^5\), carbonyl chloride, phosphoryl...
chloride and silicon chloride have been successfully used for bridging (Table 3). This technique has been successfully applied in the preparation of controlled release formulations of plant hormones belonging to the cytokinin group\textsuperscript{26} (Scheme 6).

C) **Polymerization of pesticide monomers**

Polymerization of pesticide monomers\textsuperscript{12,27,28} can be applied to pesticide molecule which contain suitable functional group that can be converted to a polymerizable derivative. The presence of functional groups, such as carboxyl (-CO\textsubscript{2}H), hydroxyl (-OH), sulfhydryl (SH) and amino groups (-NH\textsubscript{2}) in pesticides are more amenable to this approach. The application of this technique to herbicides is tremendous. In the process of polymerizing a herbicide, it is first converted to a monomer by the interaction with a vinyl group and then its further polymerization. The fungicide monomers usually contain easily hydrolyzable bonds.

Herbicide containing carboxylic groups are converted to vinyl derivatives by the mercuric acetate-sulfuric acid catalyzed reaction of the acid with vinyl acetate\textsuperscript{27,29-35}. This reaction involves the exchange of the vinyl group present in the acetate, to the pesticide by replacing the acidic hydrogen (Scheme 7). For example, vinyl (4-chloro-2-methylphenoxy)acetate has been prepared and polymerized to give polymers with herbicide as a pendant substituent directly attached to the polymeric back bone. The rate of hydrolysis for
Table 3: Indirect Bonding via Bridging Molecule

<table>
<thead>
<tr>
<th>Pesticide</th>
<th>Polymer</th>
<th>Bridging Molecule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pentachlorophenol</td>
<td>Softwood kraft lignin</td>
<td>Cyanuric chloride</td>
</tr>
<tr>
<td>2,4-D</td>
<td>Proteins</td>
<td>Phosphoryl chloride</td>
</tr>
<tr>
<td>4-Amino-3,5,6-tri-chloropicolinic acid</td>
<td>Polyethylene-imines</td>
<td>Silicon chloride</td>
</tr>
<tr>
<td>Metribuzin</td>
<td>Polyvinyl alcohol</td>
<td>Toluenediisocyanate</td>
</tr>
<tr>
<td>Cytokinins</td>
<td></td>
<td>Carbonylchloride</td>
</tr>
</tbody>
</table>
such compounds was observed to be extremely slow and is due to the hydrophobic nature of the polymer. Hence, increasing the hydrophilicity of the polymer, one can expect an enhanced hydrolytic cleavage, which can be achieved by copolymerizing the herbicide with an appropriate amount of acrylic acid.

Similarly, pesticides containing hydroxyl groups, amino group\textsuperscript{30} have been treated with an acid or acid chloride suitably containing a vinyl group, to yield corresponding polymerizable pesticide derivatives.

The best method to polymerize a pesticide monomer is the bulk polymerization. The other methods are by solution and emulsion free radical techniques\textsuperscript{28}. In the process of bulk polymerization, the monomer is heated with about 1% of a free radical initiator (azobisisobutyronitrile) for several hours. Total polymerization, usually, does not occur and the product contains unreacted monomer which is difficult to remove.

1.3.2 Physical methods of controlled release

In the physical approach the active ingredient is dissolved, dispersed or microencapsulated in a polymer matrix. The active agent is released to the environment generally by diffusion through the polymer.

The physical methods of controlled release may be classified into the following categories (Table 4).
Table 4: Categorization of Controlled Release Physical Systems

A. RESERVOIR SYSTEMS WITH RATE-CONTROLLING MEMBRANE
   i. Microencapsulation

B. RESERVOIR SYSTEMS WITHOUT RATE-CONTROLLING MEMBRANE
   i. Hollow fibres
   ii. Poroplastic and sustrelle ultramicroporous cellulose triacetate
   iii. Porous polymeric substrates and foams (Hydrogels).

C. MONOLITHIC SYSTEMS
   i. Physically dissolved in nonporous polymeric or elastomeric matrix.
   ii. Physically dispersed in nonporous polymeric or elastomeric matrix.

D. LAMINATED STRUCTURES
   i. Reservoir layer chemically similar to outer control layers
   ii. Reservoir layer chemically dissimilar to outer control layers

E. OTHER PHYSICAL METHODS
   i. Osmotic pumps
   ii. Adsorption onto ion-exchange resins.
(A) **Reservoir systems with rate-controlling membranes**

In such systems the active agent is either subjected to a thin uniform polymeric coating or incorporated in the polymeric membrane. The process of polymeric coating around the active agents, whether small solid particles, or droplets of liquid or dispersions of solids in liquid is uniform and reproducible, with the size of the resulting capsules ranging from a few-tenths of a micrometer to several thousand micrometers. The procedure is termed microencapsulation. Capsules greater than 2000-3000 μm are called macrocapsules. The terms micro and macrocapsules relate only to the size of the particle and not to the release characteristics or to the type of active agent that can be encapsulated. The different methods to microencapsulate the active agents are:

(a) **Coacervation and phase separation**

The phenomenon of phase separation in colloidal system is termed coacervation. This process involves three steps, performed under continuous agitation (Fig. 1a). In the first step, three immiscible chemical phases are formed, which are a vehicle, a core material, and a coating material phase. The core material is dispersed in a solution of coating material. The vehicle is the solvent for coating material. Phase separation is brought about by changing the temperature of the coating material solution. The second step involves the coating of the core material by liquid polymer by controlled
FIG. 1a PHASE SEPARATION PROCESS

- Core material
- Coating material
- Liquid vehicle
mixing of the polymer in the vehicle. If the polymer is adsorbed at the interface formed between the core material and the vehicle, deposition is effective. The final step involves solidifying the coating by thermal, crosslinking or desolvation methods to give self sustained microcapsules.

(b) Interfacial polymerization

Microencapsulation by interfacial polymerization is exemplified by the reaction between an aqueous solution of a diamine and an organic phase containing the diacid chloride.

The active ingredient to be encapsulated is dissolved in organic phase. Addition of a non ionic surfactant and vigorous stirring favours the formation and stabilization of the emulsion and producing a continuous dispersion of oil droplets containing the diacid chloride in the aqueous phase. The addition of diamine to the aqueous phase of the emulsion results in an instantaneous polymerization at the interface of each oil droplet to form a film completely enclosing the droplet containing the active ingredient. Polymerization proceeds, since the diamine diffuses through the polymer to react with all the diacid chloride. An acid acceptor present in the aqueous phase helps to remove the HCl formed and makes all the diamine available for polymer formation (Fig. 1b). The microcapsules formed are filtered and dried.
FIG. 1b  INTERFACIAL POLYMERIZATION
(c) The Wruster process

A process was invented to coat the particles by Prof. D.E. Wruster\textsuperscript{37}. In this process the particles to be coated are fluidized on an upward moving air stream. A cyclic flow of the particle is produced when the particles enter the high velocity spout, they are accelerated and physically separated from each other. At this instance the coating material is applied through a spray nozzle mounted at the base of the spout. The process air that fluidizes the particles also serve to dry the coating. If the droplets are large, the particles tend to stick together and the removal of the solvent becomes slow which also enhance the agglomeration of particles. This method is used when the particle size of the coated product is larger than 140 mesh (160\,\mu m) (Fig. 2).

Among the other controlled release devices in this system, polymeric film membranes play an important role. They release the active agent by diffusion from a reservoir.

Biological active agents microencapsulated in polymeric films have been developed for specialized applications such as protective packaging, reverse osmosis, dialysis, hyperfiltration and ion exchange. This device has been successfully applied in the field of drugs. Polymers like polydimethyl siloxane (PDMS)\textsuperscript{38-40}, ethylene vinylacetate\textsuperscript{41,42} (EVA), polyethylene\textsuperscript{43-45} and poly-n-butylmethacrylate\textsuperscript{46} are widely used in this technique.
Controlled particle flow
Coating partition
Coating spray
Air flow
Air distribution plate
Hydraulic nozzle

WURSTER COATING CHAMBER

FIG. 2
B) Reservoir systems without rate controlling membrane

The systems of this kind, hold the active agent in tiny open tubes or pores of the plastics, include hollow fibers\textsuperscript{47-49}, chemical-impregnated porous plastics such as MPS porous PVS sheet, millipore fibers and cellgard, porous polypropylene\textsuperscript{50}, foams and possibly hydrogels\textsuperscript{51} and ultramicroporous cellulose triacetate\textsuperscript{52,53}. The release of the active agent to the environment is basically by diffusion phenomenon.

i. Hollow fibers

Hollow fibers are tiny tubes holding the active agent in the hollow space which are sealed at one end. The active agent is released by diffusion through the air layer above the system. The release of the active agent to the environment is more complex with systems involving impregnated porous plastics but in all cases, the active agent is retained by capillary action or physically embedded in the pores. The desired release rates from hollow fibers can be achieved by varying the internal diameter of the fiber or for a cluster of fibers, by varying the number of fibers in the cluster and by varying the lengths of the fibers. The release rate also depends on the nature of the active material.
ii. **Poroplastic or ultramicroporous cellulose triacetate**

Ultramicroporous open-celled form of cellulose triacetate\(^{52,53}\) is another such system which is gaining commercial importance. The film or membrane configuration has the trade name Poroplastic and the powder or microbead form is trade named Sustrelle.

These products are essentially molecular sponges with a cellulose triacetate matrix. Large quantities of liquid can be strongly retained within the matrix by capillary action since the pore dimensions are extremely small and the internal surface area is very large.

The unique properties of poroplastic and sustrelle are\(^ {54} \):

1. Extremely small yet variable pore size-characteristic pore diameters range from 14 Å to over 250 Å.

2. High liquid content. Liquid content can be adjusted from 70 to 98%; this holds true for almost any kind of solution.

3. Irreversible shrinkage on drying. As the liquid in poroplastic evaporates, the pore structure progressively collapses. The process is irreversible because the swollen state is not thermodynamically preferred over the partially or completely dry state.

4. Homogeneous and transparent. The hydrolytic permeability and the diffusive permeability of poroplastic are inversely proportional to thickness. Also, because of the extremely
small size of the pores and the lattice structure, poroplastic
does not scatter light but is transparent.

5. Strong, crystalline and noncross-linked.

The release of the agent from ultramicroporous cellulose
triacetate is basically, diffusion-controlled. The difference in the
release rates between the film and powder forms can be explained
by the difference in surface area-to-volume ratio between the film
and powder. The controlled release process can be considered to
occur in three steps: (1) impregnation (2) fixation and (3) diffusional
release. The controlled release applications of ultramicroporous
cellulose triacetate products depend on its regulated pore size, shrinkage,
deformation and liquid or vapor expulsion.

iii. Hydrogels

Hydrogels are polymeric materials that absorb substantial
amounts of water, forming three dimensional network with an equili-
brium water content. Hydrogels may contain entrapped within them
such active chemicals as antibiotics, antibacterial agents, contracep-
tives, anticancer drugs and even macromolecules such as proteins.\textsuperscript{51,55-57} Transport across a hydrogel membrane is largely a function of the
water solubility of the agent and involves primarily the entrapped
aqueous phase rather than dissolution of the agent in the polymer
itself. Some synthetic polymers\textsuperscript{58} especially the hydroxy alkyl acry-
lates, gained significance because of the ease of adjusting their
permeability via the degree of hydration a property that can be varied by changing the comonomer ratios, cross-linking agent concentration and conditions of polymerization.

C) Monolithic systems

In monolithic systems the active agent is uniformly dispersed in an inert polymeric or elastomeric matrix. The active agent is physically blended with the polymer powder and the mixture is fused together\textsuperscript{58} or it is blended with elastomeric material in presence of some additives\textsuperscript{59}.

In either case, the active agent dissolves in the polymeric or elastomeric matrix, generally until saturation is reached. As the agent evaporates or is otherwise removed from the surface or the monolithic device, more agent diffuses out from the interior to the surface in response to the decreased concentration gradient leading to the surface.

A monolithic device can be categorised into two, depending on the nature of the polymer as erodible\textsuperscript{60-63} and non-erodible\textsuperscript{64-66} systems.

(a) Erodible systems

In erodible systems the polymer used is either soluble in ambient fluids or degrades during its intended use and the release
of the active agent is by diffusion and erosion etc. The basic advantage of this system is that after the accomplishment of the device, it chemically or biologically degrades effecting minimal contamination of the environment.

(b) Non-erodible systems

Whereas, a non-erodible system retain its polymeric matrix physically intact. In most of the cases, release of the active agent is triggered by an environmental agent, such as water, which plasticiizes the polymeric matrix allowing the physically bound active agent to diffuse out.

Further, monolithic systems can on the basis of the active agents incorporation into the polymeric matrix, be classified in two ways as physically dissolved and physically dispersed in nonporous polymeric or elastomeric matrix. Each such classification of monolithic device may be either erodible or non erodible system. The release rate characteristics of monolithic devices are governed by various factors.

D) Laminated structures

This type of controlled release system is a specialized form of monolithic device in which the active agent is impregnated in a layer between two plastic outer layers. The inner layer act as a reservoir for the active ingredient, protecting it from oxidation
and degradation by the environment. The release of active agent at the surface to the environment is by volatilization, thermal or ultraviolet degradation, alkaline or acid hydrolysis or mechanical contact by humans, insects, rainfall, wind etc. The active agent migrates from the reservoir layer to the surface due to an imbalance of chemical potential. The laminated sheets may be cut into strips, ribbons, wafers, flakes, confetti or even sprayable granules or powders convenient for various application.

The release rate of the chemical is dependent on the concentration of the stored chemical and the composition and or construction of the plastic layer components. Typical examples are silicon rubber, polyethylene, polyvinyl chloride and nylon films. The diffusant is able to pass through the nonporous membrane by absorption, solution and diffusion down a gradient of thermodynamic activity, and desorption.

E) Other physical methods
i) Osmotic pumps

The use of osmotic pump technique as a physical method for controlled release of active agent is novel and useful. The osmotic pump consists of the active agent along with the osmotic attractant such as sodium chloride, encapsulated by a semi-permeable membrane with a small orifice. When the pump is placed in an aqueous environment, the osmotic attractant draws water towards it through the
semi-permeable membrane, this happens due to the pressure difference on either sides of the membrane. As the osmotic attractant gets saturated with water, it gets pumped out along with the active agent through the orifice. Since the membrane coating can not expand, these devices deliver materials at low rates for several weeks.

ii) Gels

Sols on precipitation form jelly like materials known as gels, which are fluid, colloidal solutions. It is possible to obtain the dispersed phase as rigid mass enclosing all the liquid within it, if the conditions are set properly. Thus, the gels can be used as controlled release devices, if it can trap the active agent while gel formation. Gels were prepared by cross linking the macromolecules in the solutions and the advantage of these gels are that they form instantaneously, heating and cooling are not required. The gels release this contents in substantially linear fashion.

iii) Adsorption onto ion-exchange resins

Adsorption of active agents onto ion exchange resins has been tried as a controlled release mechanism. Thus the adsorption forces of these resins would retard the release of an ionic species through an equilibrium favouring the resins adsorption sites. Renewal of this medium can result in very fast release.
1.4 Scope of the Present Work

Polymers have thus been widely used as a support for physisorption/chemisorption of pesticides and evaluated for controlled release. Although metal complexes with pesticides are known, there are no systematic studies for the evaluation of these complexes for controlled release. In a bid to explore alternate technology, systematic studies on complexation of pesticides with metals as a technique for controlled release is proposed, envisaging the following advantages.

Potential advantages of metal complexed pesticides

Increase of persistence

Complexation of pesticides with metals is designed through coordination of heteroatoms. Apart from the increased persistence, it is also conceived that formulation with medium persistence may result in, since the strength of the coordinate bond is in between the covalent and ionic bond.

Introduction of bifunctionality

Metals like Zn, Fe, Mn etc. are essential for the plants and hence termed as micronutrients. Some other metals (Zn, Cu, Co, Cr, Ni etc.) act as antifouling agents and fungicides. By complexation of appropriate to introduce bifunctionality. For example, pesticidal - fungicidal; pesticidal - micronutrient; pesticidal - fungicidal.
Conversion of non-systemic pesticides into systemic pesticides

It is well known that complexation improves/imparts ionophoric character of pesticides. Thus conversion of non-systemic pesticides into systemic pesticides can be effected.

Dust concentrates

Liquid pesticides in particular, on complexation usually affords solid products, which can be used directly as dust concentrates.

Increase of shelf life

The shelf life of unstable, volatile or hydrolyzable pesticides can be prolonged on complexation.

Further intercalation of pesticides in the interlamellars of metal-montmorillonite which is proposed by the author of this thesis, includes the following potential advantages.

Potential advantages of intercalated pesticide-metal-montmorillonite complexes

Increase of persistence

Here controlled release is dependent on two factors (1) cleavage of coordinated bond (2) diffusion of pesticides from montmorillonite interlayers. It is expected that they have longer persistence than pesticide-metal complexes.
**Introduction of bifunctionality**

It is possible to introduce bifunctionality as explained in case of pesticide-metal complexes.

**Dust concentrates**

As the products obtained through the intercalation of pesticides in the interlamellars of metal montmorillonite are solids; it is easy to obtain dust formulations. Various concentrated dust formulations can be made, suitable for different purposes without any dilution since clay is itself a filler.

**Increase of shelf life**

It is possible to increase shelf life of photosensitive and unstable pesticides.

**Non-contamination**

Since the clay is the part of the soil, there is no contamination from the support.

**Toxicity**

Reduction of mammalian toxicity is predicted for the complexes intercalated in montmorillonite.
References


