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Controlled pesticide release from biodegradable polymers

Review Article

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Abstract: Polymers have been widely used in agriculture for applications including controlled release of pesticides and other active ingredients. The ability to predict their delivery helps avoid environmental hazards. Macromolecular matrices used as carriers in controlled release of agricultural active agents, especially pesticides, are reviewed. The review focuses on the advantages and mechanisms of controlled release. It includes biodegradable polymers in agriculture, their manufacturing methods, and their degradation mechanisms and kinetics. The article also presents a critical account of recent release studies and considers upcoming challenges.

Keywords: *Controlled Release • Biopolymer • Agrochemicals • Degradation • Controlled Release Systems*

1. Introduction

The contribution of agriculture to health, nutrition and economic development has been globally recognized [1]. Increased yield has been due to improved seed and crops, applications of fertilizers and pesticides, and advanced agricultural machinery. However, there have been numerous criticisms: among them are environmental concerns including soil erosion, salinization and flooding of heavily irrigated soils, aquifer depletion, deforestation and environmental pollution from excessive pesticide and other agrochemical use [2-5]. Some substances used are carcinogenic, mutagenic, or cause developmental and reproductive anomalies [6-8].

Synthetic chemical pesticides and herbicides (*e.g.* carbamates and organophosphates) are widely used to combat crop loss. Their toxic residues have caused great harm to humans and the environment. The European Union (EU) has established a maximum allowable concentration of a single pesticide in the environment and drinking water of 0.1 mg L^{-1}; 0.5 mg L^{-1} is the maximum allowable total concentration of all pesticides [9]. Reduced-risk pesticides and herbicides based on biodegradable plant essential oils [10] may prove an excellent alternative.

2. Controlled release in agriculture and its advantages

First used in 1930, synthetic pesticides became widespread after World War II and agriculture has grown dependent on them. Only 0.1% of the chemicals used in crop protection reach the target pest while the rest enters the environment and may cause hazards to non-target organisms, including humans [11]. Controlled release technology has emerged as a versatile tool to reduce these problems.

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"Controlled release (CR) is the permeation-regulated transfer of an active ingredient from a reservoir to a targeted surface to maintain a predetermined concentration level for a specified period of time" [12]. Comparative release profiles of conventional and CR assisted delivery are shown in Fig. 1. Conventional application gives a high initial dose which rapidly falls below the effective level. A CR formulation can maintain an effective level for a longer and controllable time. CR has been applied in the agricultural, biomedical, food, and pharmaceutical industries to deliver pesticides, herbicides, fertilizers, biomolecules, and drugs [13-19]. CR technology has applications where crop protection is required for an extended period [20,21]. Some of its advantages are constant level of active agent over an extended period, smaller doses, reduction of evaporative losses, reduction of phytotoxicity, decrease in environmental pollution, and ease in handling [22,23]. The main objectives are more effective treatment, reduced side effects, prolonged efficacy, and enhanced safety and reliability [24-27].

An ideal pesticide formulation would maintain an active ingredient level adequate for pest control but leave minimum crop and environmental residue. Encapsulation in a polymeric matrix can help achieve these goals. Polymer encapsulated formulations are superior to non-encapsulated commercial formulations in extending activity [28,29] as well as reducing evaporative and degradation losses [30], leaching [31], and dermal toxicity [32]. When the normal half-life of a potent pesticide is short these formulations are especially advantageous [33,34].

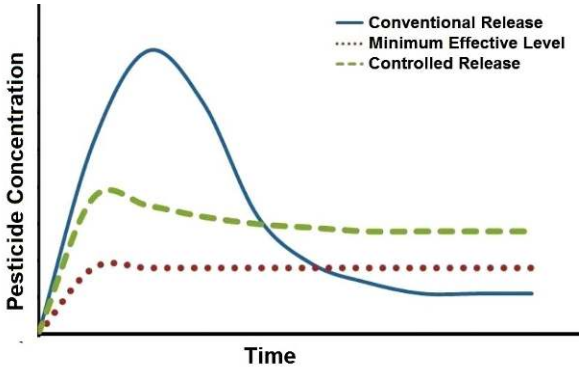

Figure 1. Theoretical pesticide active site concentrations from conventional and controlled release.

2.1. Polymer controlled release types

Polymer properties can be controlled by varying the repeat structure and molecular weight. Chain flexibility can be varied through the polarity, branching, and side chain length [35,36]. The shape, size and nature of the vehicle carrying the active agent are also important. Various delivery systems in use are shown in Fig. 2.

2.1.1. Nano and microparticles

Nanotechnology exploits the observation that some materials have very different properties at a scale of few nanometers than at the micro or macro levels. Nanoparticles vary in size from 10 to 1000 nm. The active ingredients are dissolved, entrapped, encapsulated or attached to nanoparticles [37,38].

Controlled release particles include microcapsules, microspheres, coated granules and granular matrices. During the last 20 years much research has been devoted to microcapsules in particular [39]. In a microcapsule an active ingredient in the core is surrounded by a shell or membrane. There may be several cores and several shells. The core can be solid, liquid, gaseous, or a combination. The protective matrix may be an organic or inorganic polymer or even a metal oxide [40]. The shell protects the active ingredient from reactions, evaporation, and prevents its direct exposure to the environment. Microcapsules can also be utilized as micro-reactors where the membrane is used as a separator [41]. Microencapsulation has a wide range of applications including pharmaceuticals, dyes, perfume, agriculture, printing, adhesives, cosmetics, and food products [42]. Techniques include spray-drying, spray-cooling, extrusion, freeze-drying, co-crystallization, emulsification, and photo-polymerization [43,44].

A microsphere is a monolithic system where the active ingedient is dissolved or dispersed in a polymer matrix [45]. They are 20 nm to 2000 μm spherical or irregularly shaped particles composed of one or more polymers. Molecular tailoring makes the desired active ingredient release possible [46,47]. For instance, release

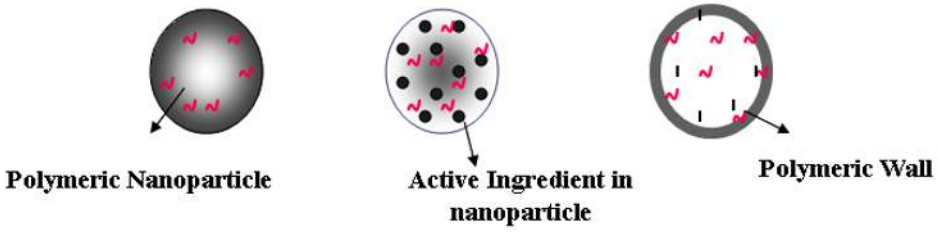

Figure 2. Polymeric nanoparticles for controlled release.

of a highly hydrophobic compound can be enhanced by decreasing the particle size, increasing the surface area [48].

Polymers may be biodegradable or non-biodegradable. The most commonly used natural polymers are the polysaccharides cellulose, agarose, dextran, alginates, carrageenans, starch, chitosan [49-51] and proteins including gelatin and albumin [52,53]. The most frequently used synthetic polymers are polystyrene, polyacrylamide, polymethylacrylate, polyamides, polyesters, polyanhydrides, polyurethanes, amino resins and polycyanoacrylates [54]. Inorganic materials for microspheres include silica, zeolites, inorganic oxides, glass beads, and ceramics [55].

Roy *et al.* [56] prepared calcium alginate - starch microspheres using $CaCl_2$ as crosslinker. They were loaded with an insecticide, chlorpyriphos, and both the unloaded and loaded microspheres were characterized by FTIR and SEM to understand the structure and morphology.

Natural plant products such as essential oils have gained interest for use in pest control because of their low environmental impact. They can be effective in controlling parasitic mites infesting honeybee colonies, but effective encapsulates are needed to provide sustained targeted delivery to minimize the amount of active ingredient used. Glenn *et al.* [57] reported essential oil encapsulation in easily dispersible porous microspheres comparable in size to pollen. The microspheres were prepared by pumping a gelatinous aqueous 8% high-amylose starch melt through an atomizing nozzle. The atomized droplets were air-classified into two fractions and collected in ethanol. The mean particle size for the largest fraction was approximately 100 µm with a range from 5 µm to over 300 µm. The large particle size was attributed to merging of smaller particles that collided before they solidified. The smaller fraction had a mean size of approximately 5 µm. The porous microspheres were loaded with 16.7% (w/w) essential oils including thymol (5-methyl-2-isopropylphenol), clove, origanum, and camphor white oil. The oils appeared to be largely sequestered within the pore structure, since the spheres remained a free-flowing powder and exhibited little if any agglomeration in spite of their high loading. Further, SEM micrographs verified that the pore structure was stable, as the pores persisted in spheres that had first been loaded and then had the oil removed by solvent extraction.

Cea *et al*. [58] incorporated atrazine, an herbicide used for broadleaf weed control, into ethyl cellulose controlled release formulations (CRFs) by solvent evaporation. Allophanic clays and nano-clay modified the matrix. The formulations were characterized by scanning electron microscopy and infrared spectroscopy. Dissipation studies and soil column experiments were carried out in comparison with commercial formulations. All CRFs increased the atrazine activity and reduced leaching loss. Reductions in seedling emergence were similar but more seedling death was observed with the CRFs, especially when nano-clay was added to the formulation. The prolonged efficacy can give longer application intervals, minimizing the environmental impact.

Sarijo and coworkers [59] observed that the release of the herbicides 2-chloro-;4-chloro-; and 2,4,5-trichloro-phenoxyacetates (2CPA, 4CPA and TCPA) from nanohybrids into aqueous salt solutions decreased $CO_3^{-2} > SO_4^{-2} > Cl^{-1}$ and 2CPA > 4CPA > TCPA. Thus phenoxy herbicide release can be tuned by varying the incoming and outgoing anions.

Celis *et al.* [60] observed that ground water contamination from rapid leaching of highly soluble pesticides can be minimized by applying the pesticide adsorbed on a carrier, limiting the amount immediately available. The adsorption of hexazinone by two montmorillonites saturated with various inorganic and organic cations was determined. The ability of the two with the highest adsorption capacities (Fe^{3+}-saturated Wyoming montmorillonite and hexadecyltrimethylammonium-saturated Arizona montmorillonite) to act as carriers for slow hexazinone release was evaluated.

Liu *et al.* [61] proposed a model pesticide, bifenthrin, prepared in nanoparticles by flash nano precipitation. A multi-inlet vortex mixer was developed to provide rapid micro mixing, high supersaturation and rapid bifenthrin nanoparticle nucleation and growth. Several polymeric stabilizers were tested. With pesticide loading increase from 50 to 91% nanoparticle size increased from 100 to 200 nm. The stability of the dispersions was followed for more than 12 days. Nanoparticle pesticides potentially provide higher efficiency, better uniformity of coverage, and less worker exposure than compounds in organic solvents.

Boehm *et al*. [62] developed nanospheres to improve the delivery of a new insecticide to plants. Stable polymeric nanospheres containing approximately 3.5% insecticide, with a size near 135 nm were obtained by nanoprecipitation with Eudragit S100 polymer. Using a classical suspension as reference, aphid-infested cotton plants were studied to estimate contact with the insects and active ingredient penetration of the plant. The speed of action and sustained release were not as good as the reference but the formulation improved plant penetration. They concluded that nanospheres do not control release but their small size enhances penetration.

Polyurea microcapsules containing Dursban (Chlorpyrifos, O,O-diethyl O-(3,5,6-trichloro-2-pyridinyl ester) were prepared by Hashemi and coworkers [63] by reaction of toluene diisocyanate with diethylene triamine. Microcapsule formation depended on temperature, type and amount of emulsifier, co-emulsifier, matrix forming agent, stirring speed, organic phase, *etc*.

Rochmadi and coworkers [64] observed that urea - formaldehyde (UF) polymerization took place simultaneously in solution and at the microcapsule surface. The reaction in solution produced UF polymer microparticles, while reaction at the microcapsule surface resulted in a microcapsule shell. The polymer microparticles precipitated as a fine powder attached to the microcapsule shell. Higher microencapsulation temperature reduced the amount of microcapsules and increased the microparticles. The process was best conducted at 50°C, with 30 min of homogenization and 3 h microencapsulation time.

Asrar & coworkers prepared microparticle controlled-release formulations from oil-in-water emulsions [65]. Carriers were prepared from poly (methyl methacrylate) (PMMA) and poly (styrene-*co*-maleic anhydride) (PSMA). Different low molecular weight and polymeric additives lowered the glass transition temperature and enhanced the diffusion controlled tebuconazole (Raxil, Bayer AG) release rate into water. Soil-applied CR formulations from a PMMA or PSMA matrix modified with poly (vinyl acetate) were as effective in controlling wheat rust (*Puccinia recondita*) as foliar-applied tebuconazole. The results suggested that CR systemic fungicide applied as either a soil or seed treatment may control foliar diseases, reducing or eliminating traditional foliar applications.

2.1.2. Nanocomposites

Nanocomposites are conventionally prepared by combination of an organic polymer matrix and nanodimension inorganic filler. The resulting hybrids can exhibit high durability, high strength, light weight and process flexibility, and are used in transportation, agriculture, aerospace, defense, sporting goods, food manufacturing, packaging and energy infrastructure [66,67].

To maintain soybean seed quality during storage, polymer and clay based coats containing azadirachtin A were prepared by Kumar *et al.* [68]. Gum acacia, gum tragacanth, rosin, ethyl cellulose, hydroxyethyl cellulose, polyethyl methacrylate, methyl cellulose, polyethylene glycol, polyvinyl chloride, polyvinyl acetate, polyvinyl pyrrolidone and Agrimer VA 6 polymers and bentonite clay were used as carriers. The time for 50% release of azadirachtin-A into water ranged from 8.02 to 21.36 h. Its half-life in the seed coats ranged from 4.37 to 11.22 months, compared to 3.45 months in azadirachtin-A WP, showing an increase by a factor of 1.3-3.3. The coats apparently acted as a moisture barrier reducing azadirachtin A degradation and preventing fungal proliferation. Polyethyl methacrylate, polyvinyl acetate and polyvinyl pyrrolidone were significantly superior to the other polymers. Azadirachtin A showed significant positive correlation with seed germination and vigor and negative correlation with moisture content.

Controlled release formulations of the insecticide cartap hydrochloride were prepared by Kumar *et al*. [69] using commercially available polyvinylchloride (emulsion and suspension) and carboxymethyl cellulose with clays like bentonite, kaolinite and fullers' earth. The cartap hydrochloride - sodium carboxymethyl cellulose - kaolinite formulation provided superior control (3.33%) of rice leaf folder in field grown rice (*Oryza sativa L*.)

2.2. Active ingredient (AI) release from polymeric matrices

Controlled AI release can be achieved by several mechanisms such as diffusion through a rate-controlling membrane, osmosis, ion exchange, or matrix degradation as shown in Fig. 3.

2.2.1 Polymer–AI conjugates

These systems are the most important carriers and have received great emphasis. The active compound is covalently bound to the polymer by a labile bond at the end(s) or repeating pendant sites. Release depends on the rate of chemical or biological cleavage of the polymer-active agent bonds [70]. Controlled formulations based on amidated polyacrylamide gel derivatives with pendant herbicide (2, 4-D) residues have been reported [71], as well as CRFs obtained by treating a Metribuzin isocyanate derivative with polyvinyl alcohol.

A method for preparing novel biodegradable fungicide polymers containing Diniconazole was devised [72]. Under application the pesticide-polymer was hydrolyzed or depolymerized at a controlled rate and protected the plants for a reasonable time. The activity against cucumber *Erysiphe cucurbitacerarum* was almost the same as that of conventionally applied Diniconazole. Measured by a preliminary biochemical test, bioactivity lasted for at least 30 days.

2.2.2. Matrix-based systems

The active ingredient is dispersed in a monolithic polymer. If the polymer is not biodegradable release is controlled by diffusion through the matrix. If the chain contains hydrophobic polyanhydrides or polyorthoesters release is controlled by degradation [73]. Matrices

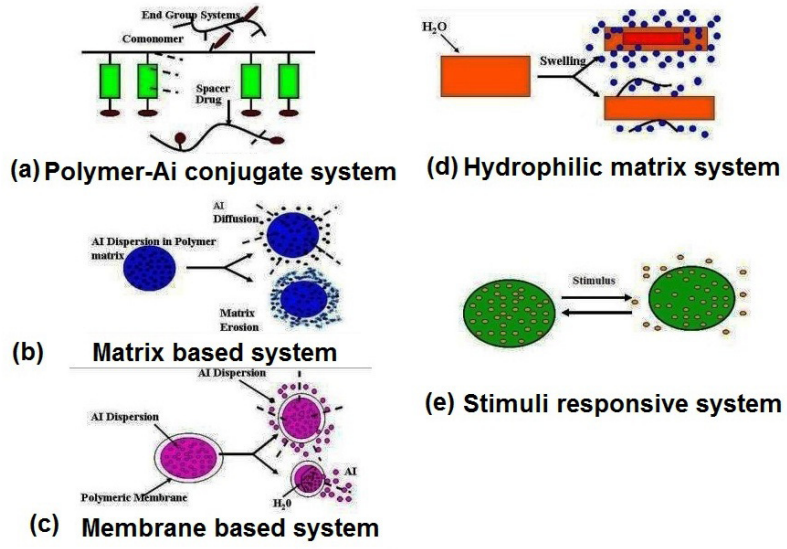

Figure 3. Controlled release systems: (a) polymer-AI conjugate, (b) matrix based, (c) membrane based, (d) hydrophilic matrix, and (e) stimulus responsive.

include rubber, polyvinylchloride, gypsum-wax mixture, polyester and acrylic resins, polyvinyl acetate, cellulose, starch, and gels such as alginate and lignin.

From an engineering viewpoint the matrix is a three-dimensional network containing an active agent and other substances such as solvents and excipients. The matrices can be hydrophilic (hydroxypropyl methylcellulose, methylcellulose, sodium carboxymethyl cellulose, alginates *etc.*) or hydrophobic (wax, polyethylene, polypropylene and ethyl cellulose). There are several approaches to polymer monolithic system preparation. The simplest is to compress the desired ratio of polymer, active agent and excipients. A mixture of active agent (thin powder) with prepolymer can be polymerized. A matrix can be immersed in a highly concentrated matrix-swelling solution of active agent. The solvent is then removed, but this can be very expensive and delicate operation.

2.2.3. Membrane based systems

These systems have an active ingredient reservoir in a membrane. There are two main types: (1) devices where the release is achieved by diffusion across the membrane, and (2) osmotic systems, which present a semipermeable membrane which permits osmotic water entrance and AI delivery through a small orifice [74].

2.2.3.1. Diffusion controlled

AI release is controlled by diffusion across the membrane (porous or not, biodegradable or not) according to Fick's law, depending on the diffusion coefficient and layer thickness. These systems exhibit zero order kinetics: the release rate is constant, independent of time [75,76].

2.2.3.2. Osmotic

This device uses a polymeric membrane permeable to water but not the AI, containing a small delivery orifice. As the core is a concentrated AI solution, osmotic flow of water across the membrane forces drug solution out the orifice. These systems present several advantages: release rates are independent of the AI; they can deliver macromolecules or ionic species; and they may give relatively high flux [77].

2.2.4. Hydrophilic matrices

This category includes hydrophilic systems in which release is controlled by water entrance (excluding osmotic devices). Water penetration leads to matrix swelling or degradation and AI release [78].

Xiao and coworkers [79] prepared slow release polymeric fertilizers containing multiple nutrients by condensation polymerization of homemade low-molecular weight urea-formaldehyde, potassium dihydrogen phosphate and phosphoric acid. The proportion was N : P_2O_5 : K_2O = 1 : 0.75 : 0.13 to satisfy the requirements of maize. Field experiment showed that the maize yield increased by 16.56% using the polymeric fertilizer alone, by 56.51% when applying the product plus farmyard manure, and by 49.11% when applying standard fertilizer plus manure.

2.2.5. Swelling controlled systems

This phenomenon occurs only in glassy polymers which swell in water, undergoing a glass/rubber transition and forming a hydrogel-like material. The solvent penetration front controls release, allowing incorporated AI to diffuse through the swollen polymer. The release is controlled by

the uncoated area and probably by structural changes during swelling [80,81].

Pourjavadi *et al.* [82] developed a new type of agar superabsorbent hydrogel. The effects of varying concentrations of acrylic acid, crosslinker (MBA) and polymerization initiator on its swelling capacity were studied. The structure was characterized by FTIR and the morphology examined by scanning electron microscopy. Swelling of the optimized hydrogel in different swelling media was investigated. The maximum distilled water absorbed was 1.100 g g^{-1}. It was also loaded with potassium nitrate and its controlled potassium release was investigated conductimetrically.

Li *et al*. [83] investigated the water absorbing and retaining mechanisms of polymeric materials and studied the types, properties, and actions of superabsorbent polymers in agriculture to enhance their salt resistance, lower their costs, and increase their degradability. They prepared a functional superabsorbent.

Roy *et al.* [84] prepared unloaded and cypermethrin-loaded calcium alginate - gelatin beads with $CaCl_2$ crosslinker. The molecular structure and morphology were characterized by FTIR and environmental scanning electron microscopy. The results were analyzed by Fick's equations and possible release mechanisms under different experimental conditions were examined.

Hekmat and coworkers [85] prepared ammonium nitrate loaded polymeric hydrogels of acrylamide, potassium acrylate, and polyvinyl alcohol. The effects of varying amounts of monomer and linear polymer on the swelling rate, equilibrium swelling, and ammonium nitrate release were investigated.

Mohdy [86] prepared novel highly swelling carboxymethyl cellulose/polyacrylamide (CMC/PAM) hydrogels by grafting cross-linked PAM chains onto CMC by γ-initiated free radical polymerization. The release rate of trapped potassium nitrate increased with its loading.

Kimoto *et al.* [87] developed insecticide coated water-swelling granules. The lag time and release profile were controlled by the low-density polyethylene - talc membrane composition.

Xu *et al.* [88] prepared a series of amphoteric superabsorbent poly(acrylic acid-co-diallyldimethyl ammonium chloride) polymers with different anionic: cationic group ratios by solution polymerization and investigated their swelling behaviors and agrochemical release. Solution pH, salt concentrations, and temperature were varied. Diffusion appeared Fickian at lower temperatures but non-Fickian at higher temperatures. A copolymer hydrogel with a low anionic: cationic group ratio showed higher swelling capacity in water and higher salt tolerance but the ratio was not dominant in determining water retention. A poly (acrylic acid-co-diallyldimethylammonium chloride) hydrogel could effectively control agrochemical release.

2.2.6. Dissolution controlled systems

Carrier dissolution is controlled by water swelling. AI with poor water solubility can be released in a controlled way [89,90]. Dissolution may be very slow because the matrix must initially unfold (if semicrystalline) then the chains must disentangle [91].

2.2.7. Stimulus responsive systems

Some herbicides target root receptors, inhibiting glycolysis (Fig. 4) and starving the weed [92]. Their application to soil with insufficient moisture may lead to loss as vapor. As we are unable to predict rainfall accurately herbicides cannot be applied anticipating rain. According to the industry, pesticide reformulation in microcapsules has triggered revolutionary changes including the ability to control the conditions for active ingredient release. It can also extend patent protection, increase solubility, reduce worker contact with active ingredients, and reduce runoff.

2.3. Release from biodegradable systems

AI may be released from biodegradable systems (Fig. 5). The active moiety may be covalently attached to the polymer and released by bond cleavage. It may also be dispersed or dissolved in the same way as in a non-biodegradable polymer; release is controlled by diffusion, by a combination of diffusion and erosion or solely by matrix biodegradation [93,94].

Biodegradable polymers break down by homogenous (bulk) and heterogeneous (surface) degradation; most break down by a combination of the two [95,96].

Homogenous degradation appears most common; hydrolysis usually proceeds by loss of molecular weight [97]. The rate varies with polymer composition and size or shape [98].

Surface degradation rate depends on surface area and geometry; *i.e.*, the erosion time is controlled by the radius to thickness ratio rather than the volume [99-101]. There is no significant change in polymer molecular weight with time. This mechanism requires that surface degradation be faster than water penetration into the matrix [102]. Zero order AI release is obtained with systems such as poly(anhydrides) or poly(orthoesters). Design is simpler because release rates can be controlled by changing thickness and total AI content [103]. Hopfenberg *et al.* [104] proposed Eq. 1 for AI release from surface degrading slabs, spheres and infinite cylinders. Their model assumes that erosion is the rate-limiting step and that AI release occurs from the surface without seepage from the matrix.

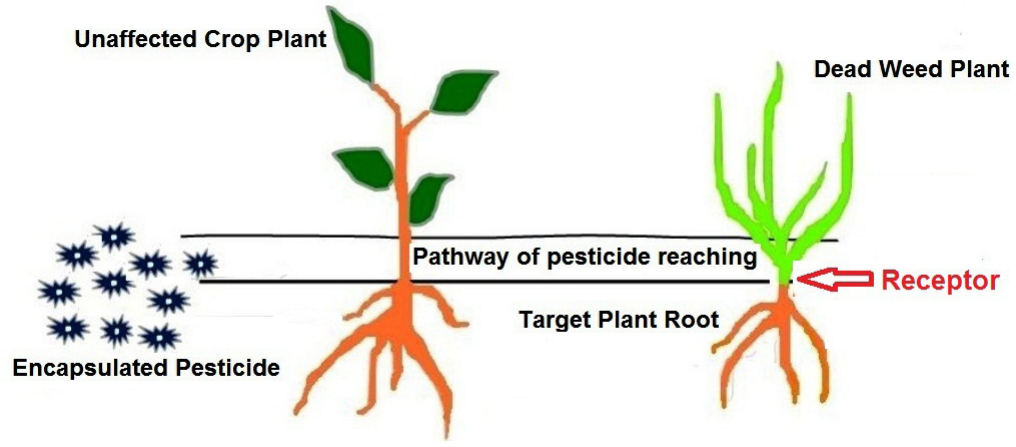

Figure 4. Targeted pesticide delivery to weed receptors.

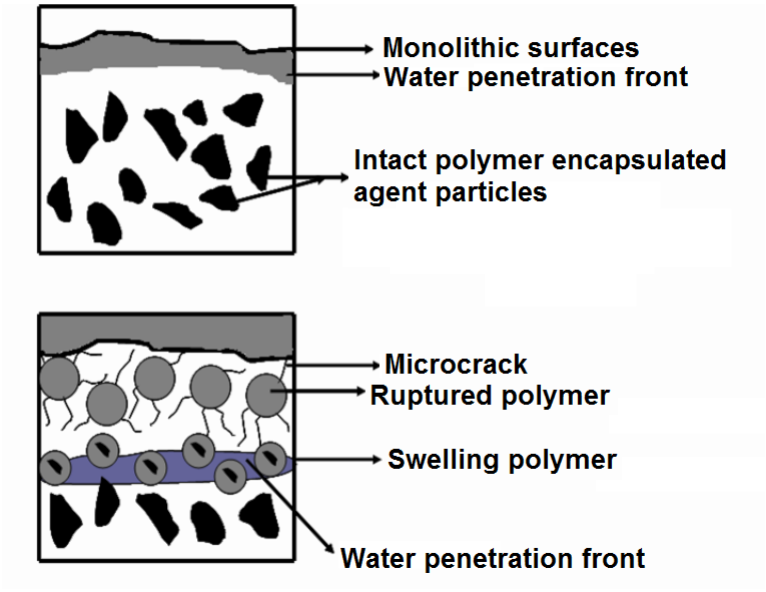

Figure 5. Encapsulated agent release from biopolymer matrix at water penetration front.

$$M_t/M_\infty = [1-k_0 t/C_0 a]^n \quad (1)$$

M_t/M_∞ is the fraction of AI released, C_0 is the initial AI concentration, a is the initial sphere or cylinder radius, k_0 is the zero order surface erosion rate constant and n is the shape factor.

3. Preparation of controlled release formulations for agriculture

There are several preparation techniques for controlled release formulations.

3.1. Chemical attachment

Chemically bound active agents are classified into two types: the first are obtained by attaching a polymerizable site to the active ingredient followed by polymerization of the new monomer. AIs may also be bound to a suitable polymer. For instance, active agents containing carboxyl groups have been converted to acid chlorides which were then attached to hydroxyl groups on natural polymers. In the second category primary amines on the active agent were reacted with phosgene to form isocyanates, which were then attached to the polymer. The release rate can be increased by decreasing the molecular weight or increasing the polymer hydrophilicity.

It also depends upon the degree of herbicide substitution on the polymer, the pH of the hydrolysis medium and the particle size. Such covalently bound combinations have found application in forestry and agriculture.

Helaly *et al.* [105] investigated marigold (*Calendula officinalis*) triterpene saponin molluscicidal activity in natural rubber, styrene-butadiene rubber, and starch matrices. The saponin release rate varied with the polymer, filler, and filler concentration. Release lasted more than 3 months when the physical properties were improved by fillers.

Two polymeric formulations containing dichlorobenzaldehyde (DCBA) were prepared by Kenawy *et al*. [106] by modification of both linear and crosslinked poly(glycidyl methacrylate). Linear and crosslinked polymer epoxides were modified to diols which were converted to acetals by reaction with DCBA. The crosslinked polymers' swelling in different solvents was also investigated.

3.2. Matrix encapsulation

One of the most common, convenient, and widely used methods is matrix encapsulation. There is no wall surrounding the active ingredient; it is dissolved or dispersed in many small cells in a continuous matrix. Excipients such as inorganic filler are often added. The products are ribbons, sheets or granules.

A study of the slow acetal group hydrolysis by low concentrations of lactic acid to release active ingredients was reported by Mosurkal and coworkers [107]. A prototype molecule containing cyclic acetals, dimethyl-2, 3-O-benzylidene-L-tartrate and the same molecule incorporated as a pendant group in a polyamide were studied. The release of benzaldehyde was monitored by UV-vis and ^{1}H NMR spectroscopy. The study was helpful in designing and synthesizing a polymer with covalently bound insecticidal/anti-microbial/anti-fungal materials for controlled release.

The work of Xiao [79] (section 2.2.4) is relevant in this context.

3.3. Microencapsulation

Microencapsulation is the coating of small solid particles, liquid droplets, or gas bubbles with a thin coating. There is no universally accepted size but many workers classify capsules smaller than 1 µm as nanoparticles and greater than 1000 µm as microcapsules. Commercial microcapsules typically have a diameter between 3 and 800 µm and contain 10-90 wt% core. A wide range of active materials has been encapsulated including adhesives, agrochemicals, live cells, active enzymes, flavones, fragrances, pharmaceuticals and inks. Most shell materials are organic polymers, but fats and waxes are also used [108-111].

Krauth & coworkers [112] prepared a polyacrylamide for sediment and contamination reduction in irrigation and rain runoff. Compared to untreated runoff the products effectively reduced turbidity, total suspended solids, and phosphate concentration without increasing toxicity.

Mixed EVA-150 and starch composites were prepared by Tai and Zhu [113] for imazethapyr controlled release. Their compatibility and crystallinity were examined by SEM and DSC, and the controlled-release performance was investigated by UV. The composite has controlled-release behavior; imazethapyr release exceeded 50% at pH 4, pH 7, or pH 9 after nine days.

Dripping gelation was used by Yim and coworkers [114] to encapsulate aqueous herbal extract. The particle size, alginate M/G ratio, concentration, gelling cation concentration, and extract strength were studied. Under all conditions examined a sharp release of about 80% of the antioxidant was observed during initial gelation (first 20 min). After this time antioxidant release was significantly reduced. Thus prolonged encapsulation time resulted in about 10-20% encapsulation efficiency.

Pteu *et al.* [115] focused on emerging uses of polymer nano-encapsulated CPAs. These included fungicides, insecticides, herbicides, antibiotics, RNA-based vaccines for plant viruses, pheromones, repellents, allomones, microbial pesticides, insect and plant growth regulators, and micronutrients. The advantages and drawbacks of the most interesting advances were critically discussed and several plant-specific stimulus-based smart methods were anticipated for use with nano- or micro-capsules. The work of Glenn *et al*. [57] (section 2.1.1) may be noted here.

Microcapsules with chlorpyriphos cores and polyurea walls were synthesized by Zhang and co-workers [116] *via* interfacial polycondensation of oil-soluble 2, 4-tolylene diisocyanate and water-soluble ethylene diamine. The capsules were characterized by FTIR, ^{13}C NMR and ^{31}P NMR. Their morphology, particle size and distribution, and thermal properties were also evaluated. They exhibited clear, smooth surfaces and a mean diameter of 28.13 µm. They showed thermal stability for long-term use, and potentially minimized chlorpyriphos toxicity through controlled release.

Mayya *et al*. [117] encapsulated paraffin oil with gelatin and gum Arabic by complex coacervation. Dibutyltin dilaurate catalyst for EVA crosslinking in ester-silane exchange has been encapsulated with polycarbonate [118]. Smart microencapsulation by material selection has been described elsewhere [119]. Brown *et al*. [120] encapsulated dicyclopentadiene by

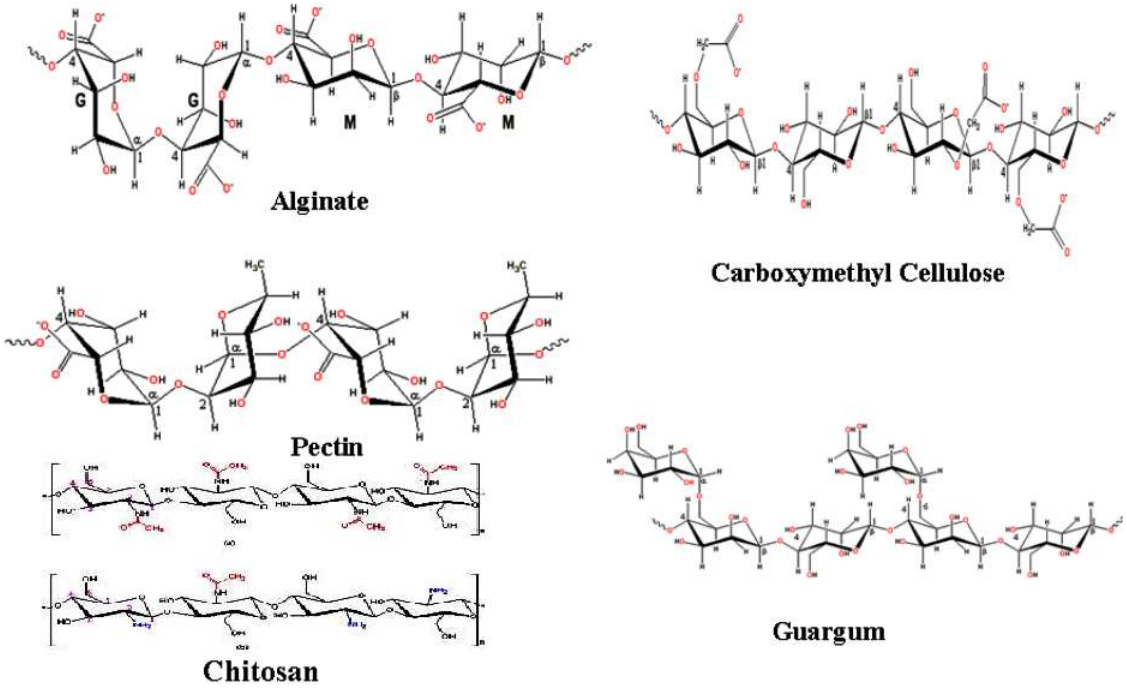

Figure 6. Selected biodegradable polymers commonly used for pesticide controlled release.

in situ polymerization of urea-formaldehyde. Salaun and Vroman [121] investigated the effect of core material on melamine-formaldehyde microcapsule thermal properties. Multilayer shell formation has been described by Radtchenko *et al*. [122] as well as Antipov and Sukhorukov [123]. Sun and Zhang [124] studied the mechanical strength of melamine-formaldehyde, urea-formaldehyde and gelatin-gum Arabic microcapsules. Yin *et al*. [125] encapsulated epoxy with urea formaldehyde resin for self-healing epoxy composites. Yang and Pan [126] patented a method to microencapsulate pesticide solution with urea formaldehyde resin.

In a novel study by Aouada *et al*. [127] the release kinetics of paraquat encapsulated in polyacrylamide and methyl cellulose was investigated.

4. Controlled release from biodegradable polymers

Interest in nontoxic biodegradable polymers such as amylose, cellulose, carboxymethyl cellulose, polylactic acid, polycaprolactone, *etc*. [128,129] has been growing (Fig. 6). Decomposition in soil can take place chemically or microbiologically. Usually one or more chemical steps take place (*e.g*. hydrolysis) followed by microbiological breakdown. As the chemical processes end relatively quickly the biological processes control the decomposition rate. Over the past decade efforts have focused on plastics disposal but biopolymers have been used in innumerable applications with little consideration of their ultimate disposability.

Biodegradation and biorecycling are attractive alternatives when waste polymer incineration causes pollution. Polymers such as polyethylene and polypropylene seem inappropriate for short-lived applications followed by disposal; their resistance to biodegradation is problematic. Biodegradable polymers are increasingly used in agricultural applications [130-132].

Microorganisms such as fungi, bacteria, and algae degrade biopolymers by enzymatic chain breakdown [133,134]. Natural polymers such as agar, starches, alginates, pectins and cellulose derivatives, along with synthetic biodegradable polymers such as polycaprolactone, polylactide and poly (vinyl alcohol) are convenient application candidates [135-138].

Some important carbohydrate biopolymers are:

- Aloe vera is a xerophytic plant with water storage tissue. The innermost part of the thick fleshy leaf is a clear, soft, moist, slippery tissue consisting of large thin walled parenchyma cells which hold water in viscous mucilage [139]. The leaves contain not only the cell wall carbohydrates cellulose and hemicelluloses but also acetylated mannan storage carbohydrates [140].

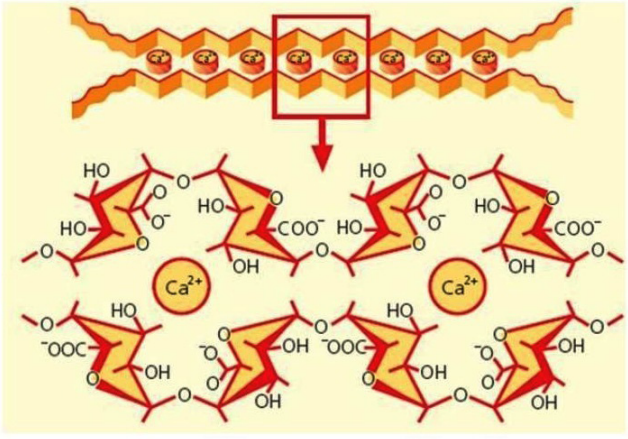

Figure 7. Egg crate model of calcium crosslinked pectin.

- Sodium, potassium and ammonium alginates are soluble in both hot and cold water, and can thicken and bind. Sodium alginate - the sodium salt of alginic acid - is a gum extracted from the cell walls of kelp. It is used by the food industry as a flavorless emulsifier and to increase viscosity. With strong agitation it can be diluted while cold, and it gels while cold in the presence of calcium. Sodium alginate can also be used to produce foams [141,142]. It is commonly used with calcium chloride to make caviar and spheres as well as in indigestion tablets.

- Chitin and chitosan are non-toxic biodegradable copolymers. Chitosan is extracted from chitin, the main structural component of squid pens, some fungal cell walls, and shrimp and crab shells. It regulates the immune system of plants and induces resistance enzyme excretion, improving disease and insect resistance. Application of chitosan, even without chemical fertilizer, can greatly increase the microbial population. It is a carbon source for soil microbes, accelerates transformation of organic into inorganic matter and assists roots in nutrient absorption [143-146].

- Cellulose accounts for 50% of plant dry weight and approximately 50% of the dry weight of agricultural wastes [147]. The crystalline [148] and insoluble nature of cellulose is a formidable challenge for hydrolysis [149]. Cellulose degrading microorganisms convert cellulose into soluble sugars either by acid or enzymatic hydrolysis; this is one of the largest material flows in the biosphere [150]. Cellulose is completely degraded by a three enzyme system consisting of exo-β-1,4-glucanase, endo-β-1,4-glucanase and β-glucosidase. Endoglucanases act internally on the chain, cleaving β-linked bonds and liberating non reducing ends. Exoglucanases remove cellobiose from this non-reducing chain end. Finally, β-glucosidase splits cellobiose and small oligosaccharides to glucose [151].

- Pectin has a complex structure. Preparations consist of fragments that depend on their source and extraction methodology. Commercial extraction causes extensive degradation of the neutral sugar-containing side chains. Most of the structure is a 'smooth' homopolymer of partially methylated poly-α-(1⟶4)-D-galacturonic acid residues, but there are substantial 'hairy' non-gelling areas of alternating α -(1⟶2)-L-rhamnosyl-α -(1⟶4)-D-galacturonosyl sections. These contain branch points with mostly neutral side chains (1 - 20 residues) of mainly L-arabinose and D-galactose (rhamnogalacturonan I) [152-154]. Divalent calcium cations fit into negative cavities like eggs in an egg crate. A model is shown in Fig. 7.

Polymers supporting agrochemicals have recently been developed by Pizzaro [155] to overcome the environmental problems of conventional agrochemicals. Gradual bioactive agent release was achieved by hydrolytic or enzymatic cleavage. Their success resulted from the choice of polymer support.

The EVA-150 - starch controlled-release matrix of imazethapyr [114] noted in section 3.3 may also be noted here.

5. Encapsulation in biopolymer matrices

Encapsulation is the packaging of sensitive ingredients within a coating [156,157]. Surrounding particles, droplets, or gases by polymers gives capsules many useful properties. They have been widely used in release and transfer control. The wall protects the

core against adverse reactions, prevents the loss of volatile ingredients, and can control release. In addition, microencapsulation can convert liquids into easily handled free-flowing powders. Controlled release strongly depends on wall thickness and porosity [158].

6. Microcapsule manufacture

Microcapsules are manufactured by physical, physical-chemical, and chemical methods.

6.1. Physical methods

6.1.1. Pan coating

Pan coating is widely used. Core particles are tumbled in a pan or other device while the coating material is slowly applied. Fertilizers may be coated with degradable polymers by pan coating.

6.1.2. Fluidized bed

Micro encapsulation by fluidized bed coating disperses particulate cores in a supporting air stream and spray coats them with solutions or melts. Fluidized bed technology gives control and flexibility. Its thorough mixing reduces agglomeration. The high heat and mass transfer rates and uniform temperature distribution have led to widespread use in the petrochemical, pharmaceutical, and food industries [159,160].

6.1.3. Spray drying

An active material suspended in a melt or polymer solution is trapped in the dried particle. The operation is economical. The short dryer contact time allows labile materials to be handled but some degradation may occur [161]. The main factors affecting effectiveness are the wall material, the core (concentration, volatility), the infeed emulsion (total solids, viscosity, droplet size) and the process conditions including atomization type, inlet air temperature, air flow, and humidity.

6.2. Physical-chemical method

A coacervate is a 1 to 100 μm spherical droplet of polymer molecules held together by hydrophobic forces from a surrounding liquid. They form spontaneously from dilute organic solutions.

6.3. Chemical methods

6.3.1. Interfacial polycondensation

Interfacial polycondensation is a widely applicable encapsulation method. It offers rapid polymer production in an almost ready-to-use form at ambient temperature and pressure. An organic solution of pesticide and diacid chloride is emulsified in water and an aqueous solution containing an amine and polyfunctional isocyanate is added. Base neutralizes the acid formed. Condensed polymer walls form instantaneously at the interface of the emulsion droplets. The product properties depend on the monomer concentration and diffusion and interfacial reaction rates. However, the mechanism is not well understood because of the fast kinetics and the need to include several equilibrium and rate processes in a model. Among these are (i) monomer ionization equilibria, (ii) aqueous and organic phase monomer transport from the bulk to the reaction site, (iii) the reaction rate between the monomers, and (iv) oligomer phase separation [162].

6.3.2. Interfacial crosslinking

Interfacial cross-linking avoids the use of toxic diamines. The small bifunctional monomer containing active hydrogen atoms is replaced by a protein. When reaction occurs at the emulsion interface the acid chloride reacts with the protein forming a membrane. The cross-linked microcapsules are biocompatible and biodegradable, and the protein backbone renders the membrane more resistant and elastic than those obtained by interfacial polycondensation. The method is very versatile, and the microcapsule properties (size, porosity, degradability, mechanical and resistance) can be tuned by varying the preparation. A carbohydrate can be added to modulate biodegradability. Temperature response is imparted by *N*-isopropylacrylamide with additional co-monomers pentaerythritol diacrylate monostearate, acrylamide and hydroxyethyl acrylate [163]. The latter contains hydroxyl groups that can be converted to acrylate or methacrylate and covalently cross-linked by a water soluble thermal free radical initiator. Increased stability and higher viscosity were achieved when the hydrogels were physically and chemically gelled compared to thermally gelled controls.

6.3.3. In situ polymerization

In a few microencapsulation processes, direct polymerization of a single monomer is carried out on the particle surface. Usual deposition rates are about 0.5 μm min^{-1}. Coating thickness ranges 0.2–75 μm. The coating is uniform, even over sharp projections. For example, aluminum pigment was encapsulated with styrene–maleic acid copolymer by *in situ* polymerization [164]. Poly (trimethylolpropane triacrylate)/aluminum flake composite particles (PTMPTA/Al) were also prepared by *in situ* polymerization to improve aluminum pigment corrosion resistance and adhesion [165,166].

Pesticide microencapsulation aims at maintaining a target concentration to minimize disadvantages and maximize effectiveness. Polymers for their

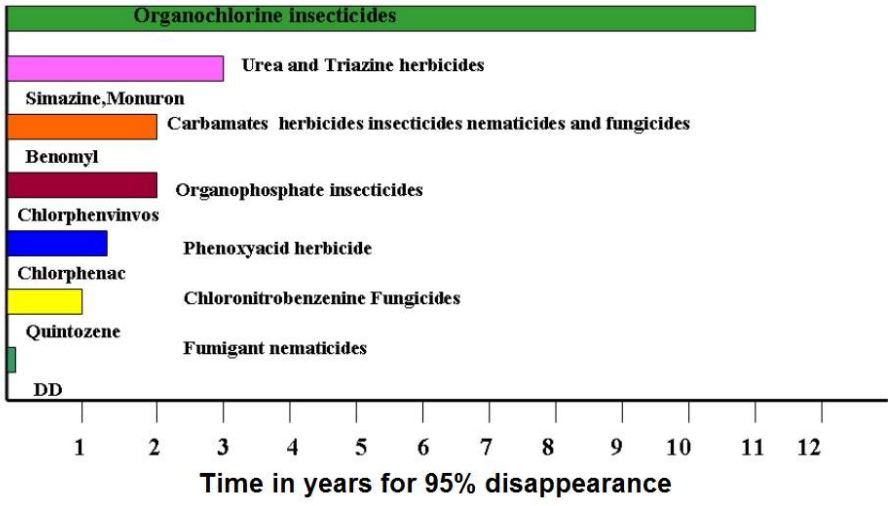

Figure 8. Pesticide disappearance (95%) from soil (time in years).

microencapsulation should meet the criteria: (a) the molecular weight, vitreous transition temperature and structure must allow sufficient liberation; (b) they must not react with the pesticide; (c) the polymer and its degradation products must not cause environmental contamination; (d) they must be stable during use and storage; and (e) they must be easily produced at low cost. Recently, Green and Beestman [167] reviewed patented and commercialized agrochemical formulations; they pointed out that most of the controlled liberation products are based on micro and nano-encapsulation because these improve persistence and reduce active ingredient losses [168-176]. Among the first studies evaluating the effectiveness of microencapsulated pesticides, Perez *et al.* [177] and Taverdet [178] concluded that micro-encapsulation reduces contamination of underground waters. Atmospheric pesticide is also reduced [179,180]. Reduced crop phytoxicity has been attributed to controlled slow pesticide liberation allowing longer weed control [181,182]. However, in some cases micro-encapsulation requires the use of toxic substances and/or processes of long duration [183-185].

Singh and co-workers [6] developed a starch and poly(methacrylic acid)-based delivery system for pesticide/fungicide controlled and sustained release. It used N, N′-methylene bis acrylamide crosslinker. The product was characterized by FTIR and TGA.

Chitosan microcapsules containing the water-soluble herbicide 3-hydroxy-5-methylisoxazole were fabricated by Yeom and coworkers [186] by an advanced microencapsulation method. The effects of fabrication variables on capsule size and release properties were discussed.

7. Environmental challenges

Direct pesticide application can cause severe threat, but controlled release significantly reduces risks to both environment and human health [187]. The polymer and its biodegradation products may also produce toxicity, although that is less probable when natural polymers are used [188].

When a pesticide is applied it enters a dynamic ecosystem and immediately begins to move from one part to another, degrades *in situ* or moves into other systems. Pesticide disappearance (95%) from soil by evaporation, leaching, surface runoff, plant uptake or the in the bodies of migrating animals is depicted in Fig. 8. Plants lose pesticides by evaporation into the soil, in root exudates, and removal when harvested. Only residues in the plant or soil are metabolized. For persistent pesticides these are often only a small proportion of the whole. Many metabolic pathways are similar in plants, microorganisms, insects and mammals [189,190].

A polymer's ultimate fate depends on its structure, polymer-active agent interaction, functional groups, end products, soil and environmental conditions, enzyme presence, *etc*. Synthetic polymers may degrade over several days to months and may adversely affect the environment and soil fertility. However, the degradation products of natural polymers are generally nontoxic and do not damage fertility. Thus controlled release formulations usually contain biopolymers or other biodegradable polymers.

Degradation of the crosslinker may also cause contamination. Epichlorohydrin, glutaraldehyde, and N,

N'-methylene bis acrylamide are common crosslinking agents in hydrogels, the key material behind controlled release formulations. Unreacted monomers or depolymerized product may damage fertility.

8. Future prospects and challenges

Care is required before CR is widely commercialized. The following points deserve attention:

1. Soil fertility, ground water purity, and crop quality may not be compromised. Naturally occurring and biodegradable polymers like polysaccharides and proteins are favored, as their decomposition may enhance fertility.

2. Economic viability is essential. In undeveloped and developing countries cost is especially important. Thus, materials which are cheaper as well as effective are required.

3. Naturally occurring pesticides and herbicides of reduced toxicity should be considered. Encapsulation should further reduce their toxicity.

4. Systems which can respond to the local soil, environment and climate are desirable. The polymers may be functionalized or derivatized to yield a large change in physico-chemical properties in response to a minor change in external conditions.

5. The products must provide a constant flux of active agent for the necessary time span.

6. Integration of pesticide, fertilizer, micronutrients, and water into a single formulation would make it more effective and economic.

A variety of polymer systems may be devised by careful consideration of chemical strategy, economics and the ecology. These may contribute to the green revolution and improve prosperity.

Abbreviations

AI-Active Ingredients;
CPA- Crop Protection Agents;
CR-Controlled Release;
CRF-Controlled Release Formulation;
DCBA- Dichlorobenzaldehyde;
DSC-Differential scanning calorimetry;
EU-European Union;
EVA-Ethylene vinyl acetate;
FTIR-Fourier Transform Infrared;
MBA-N,N methylene bis acrylamide;
PMMA- Poly methyl methacrylate;
PSMA- Poly (styrene-*co*-maleic anhydride);
SEM-Scanning Electron Microscopy;
UF-Urea Formaldehyde.

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