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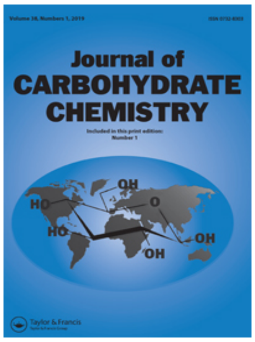

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Carbohydrate polymers as controlled release devices for pesticides

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ABSTRACT
Controlled release technology addresses problems associated with excessive use of toxic agricultural chemicals. This paper reviews the studies on the use of carbohydrate polymers as controlled release matrices for pesticides. Alginates, starch and its derivatives, chitosan, carboxymethylcellulose and ethylcellulose are some of the natural polymers discussed in this review. The advantages and disadvantages of these polymeric systems as well as the factors that affect pesticide release are presented. A discussion on the polymers' encapsulation efficiency and release profile is also included, which will aid future researchers in identifying the suitable formulation for controlled release of pesticides. Combination of two polymers, incorporation of sorbents into polymer matrices, and modification of polymer systems are some of the strategies also discussed herein. Recent trends in this area of research include nanoformulation, nanoencapsulation, and the development of polymeric systems with dual properties such as controlled release with photo-protective property and the attract-and-kill strategy. Cytotoxicity studies are being conducted to address safety issues of pesticide handlers as well as to determine the toxicity of the formulation to non-target organisms such as the plant itself.

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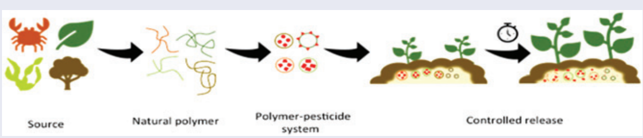
GRAPHICAL ABSTRACT



Introduction

Controlled release (CR) describes the delivery of a substance at a controlled rate for an extended period. This technology makes use of a matrix where the active constituent is incorporated. The matrix could be natural or synthetic polymers, sorbents and other synthetic materials, which can be specifically

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designed to suit an application. Use of natural and biodegradable polymers in CR systems has been extensively studied for drug delivery,[1–6] tissue engineering,[5,7–10] cosmetics, food and agricultural applications.[11–15] The release of attributes at controlled rate overcomes the problem of inefficient dosage regulation, rejection of foreign bodies, and loss of encapsulated materials.

CR in agriculture aims to address problems on overuse of pesticides and other agricultural chemicals. The contamination of water bodies by toxic pesticides and fertilizers causes aquatic environmental degradation. In addition, pesticide residues in agricultural produce and food products are concerns for human wellbeing. These environment and health issues resulted in banning and eradication of some extremely toxic chemical pesticides.[16–17] However, with the expanding population growth worldwide, the ban on pesticides may result in global hunger, hence alternative measures are to be considered. CR technology is one of the plausible solutions to this problem. This technology has been explored since the 1960s but only a few number of CR pesticide systems were granted patents to this day.[18–23, 51–53] Although some CR matrices failed in the marketing stage, scientists still continue to look for a polymer-based pesticide carrier.[24–25] In polymers, natural polysaccharides have the advantages of being biodegradable, abundant in nature, cost-effective, and environment-friendly.

Recently, Mattos et al. discussed green carriers for the delivery of biocides in their review on CR for crop and wood protection.[26] They discussed the driving force behind the interplay of carrier-biocide-environment through basic thermodynamics and how structures and shapes of carrier materials influence the release behavior of the active component. Natural polymers such as lignin, cellulose and cellulose esters were included in their article, discussing the carrier material and co-materials used, the biocides incorporated into the matrix, and the method of preparation.[26]

On the other hand, this review discusses the use of natural and biodegradable polymers including alginate, cyclodextrin and starch, chitosan, carboxymethylcellulose, and ethylcellulose as CR matrices for pesticides. Studies on CR systems using these natural polymers are discussed highlighting the advantages and disadvantages of these polymeric systems as well as the factors affecting the release of the pesticide. A discussion on the polymer's encapsulation efficiency and release profile is also included, which will aid future researchers in identifying the suitable formulation for CR chemical pesticides.

Mechanism of incorporation and release of active components

The theory of incorporation of bioactive in polymers includes adsorption,[27–28] dispersion of the active component in the matrix, and encapsulation.[29–30] Moreover, the covalent bonding between functional groups of

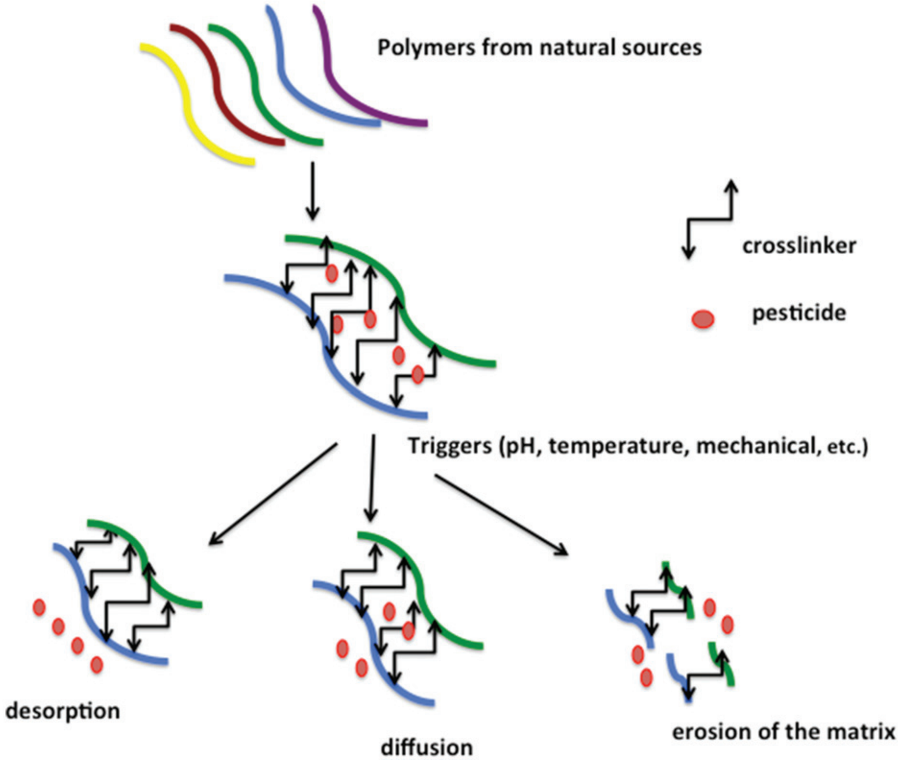

Figure 1. Mechanisms of pesticide release from polymer matrix [36].

the polymer and the active component also serve as a matrix. An important consideration in designing CR polymer matrix is its ability to release the active compound to the target site. Several release mechanisms were proposed and are largely dependent on the design of the CR device. Figure 1 shows the most common ones such as diffusion from pores, desorption from surface, and release due to erosion of the matrix.[31,36] The diffusion-controlled mechanism relies on the differences on the rates of diffusion of the active compound and the relaxation of the polymer chains. The former may be lower (Case I), higher (Case II) or similar to the latter as in anomalous diffusion (Case III). Surface desorption of the actives adsorbed on nanoparticles usually exhibits high initial release or burst release which can be modulated by increasing the crosslinking density or using a high molecular weight polymer.[36] Finally, the release of the active compound can also be controlled by the erosion of the matrix. The degradation of a polymer matrix can be brought about by influences of pH, temperature, pressure, enzyme and other environmental factors. Furthermore, mechanical triggers, such as shaking, sonication and vortexing, can also release pesticides that are physically bound to the polymer matrix.

Early works on controlled release of pesticides

CR of pesticides using strong sorbents such as mica, silica gel and activated charcoal have been explored since 1960.[31] At present, natural polymers are explored more favorably as CR systems for pesticides as they are abundant and relatively inexpensive.

Lowell et al. reported the first commercial microencapsulated pesticide PENNCAP-M® using crosslinked nylon-type polymers.[32] Early applications of CR of pesticides included mainly household insecticides such as the Hercon Lure and Kill™, Fly Tape and Roach Tape®, and Shell No-Pest Strip®.

Current trends in formulating controlled release matrices

Apart from existing encapsulation procedures, recent methods of formulating systems for CR include emulsion crosslinking methods, ionic gelation, and reverse micellar method.[33] Glutaraldehyde is the most common crosslinking agent used, but the use of formaldehyde as crosslinking agent has also been explored and found to have potential application in the CR of agricultural chemicals.[34] Ionic gelation method using natural polymers attracted attention due to its simple synthesis scheme;[35] however, gels obtained by this method lack mechanical strength.[36] Finally, reverse micellar method produces particles in the nanosize range.[37]

Natural polymers as controlled release devices for pesticides

A natural polymer when used alone is not very successful as a CR device. Addition of sorbents, pendant groups, cross-linker and grafting with another polymer are some of the strategies employed in CR formulations. Figure 2 shows the chemical structures of the polysaccharides included in this review. A brief description of each polymer as well as the studies conducted on them as CR devices for pesticides are herein presented.

Alginates and alginate mixtures

Alginate (Alg), one of the most abundant polymers in nature, is an anionic polysaccharide, which can be extracted as a gum from brown algae. It is a block copolymer consisting of (1,4)-linked-β-D-mannuronic acid and α-L-glucuronic acid in varying proportions (Figure 2).

Several studies on CR of pesticides using alginates were conducted by various authors. Standard Alg-herbicide-water formulation was modified by adding different sorbents, such as bentonite and activated carbon, to determine the CR of diuron,[38] carbofuran,[39] atrazine,[40] isoproturon,

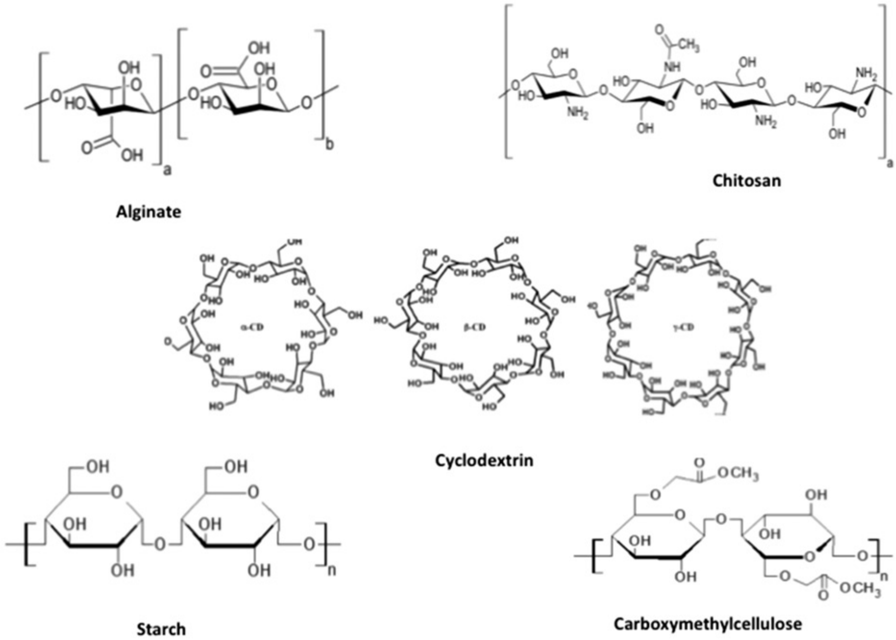

Figure 2. Chemical structures of the natural polysaccharides used for controlled release of pesticides.

imidacloprid, cyromazine,[41] chloridazon, and metribuzin.[42] High encapsulation efficiency (EE) of 83–98% was reported for all sorbent-modified formulations and the release mechanism of pesticides was reportedly being diffusion-controlled. Reduction of pesticide leaching in soil by 50% and 75% (for natural and acid-treated bentonite, respectively) was also reported.[39] Meanwhile, solubility plays a key role in the release of the pesticides in water. It was reported that water-soluble pesticides had lower EE and higher release rates in water. In reverse, hydrophobic pesticides tend to adsorb more on the sorbent, resulting their higher EE and slower release in water.[42] Incorporation of lignin to the Alg-sorbent formulations enhanced the release of pesticides such as chloridazon, metribuzin,[43] isoproturon, imidacloprid, and cyromazine[44] in water.

Natural polymer in tandem with another polymer such as alginate-gelatin beads crosslinked by $CaCl_2$ was reported as CR matrix for cypermethrin. Loading concentration of the pesticide in the matrix was found to affect its release behavior.[45]

Starch-alginate beads crosslinked by $BaCl_2$ and $AlCl_3$ were used as CR matrix for thiram. $BaCl_2$ was found to be the more efficient crosslinker with high EE of above 95% for all its formulations and exhibited a better CR behavior compared to $AlCl_3$-crosslinked beads.[46] Incorporation of kaolin and bentonite,[47] Neem Leaf Powder (NLP)[48] and optimization of starch-alginate weight ratio[49] was reported to improve the CR property of $CaCl_2$–crosslinked starch-alginate beads. Bentonite-based formulation showed better CR of thiram than kaolin-based formulation; however, the EE was reported to be above 97% for all polymer-sorbent formulations.[47] It was reported that NLP, a natural biopesticide, increased the release rate of thiram to a maximum of 16.58 ± 0.42 mg after 300 h, which was reduced to 11.82 ± 0.34 mg and 11.02 ± 0.16 mg for formulations added with kaolin and bentonite, respectively.[48] On the other hand, optimizing the percent weight ratio (42.7% starch: 57.3% alginate) of the formulation released 50% of chlorpyrifos in 5 days compared to the commercial chlorpyrifos that released the pesticide in just 1 day.[49]

Sodium alginate (NaAlg) nanoparticles (nps) prepared by emulsion crosslinking method using dioctyl sodium sulfosuccinate (AOT) as primary emulsifier and polyvinyl alcohol as secondary emulsifier was characterized and evaluated as CR device for imidacloprid (IMI). Its EE was 98.66% and the formulation was found to be less toxic to non-target organisms compared to the plain pesticide.[50]

Patents for alginate-pesticide formulations include an alginate gel beads prepared by adding dropwise a mixture of water-soluble salt of alginic acid, pesticide and water into a gellant bath containing di- or trivalent metal salt such as calcium chloride to form Alg gel. The gel beads, formulated to either float or sink, released the pesticide, e.g., larvicide, herbicide, insecticide, and so on, usually in water to control mosquito larvae.[51] Another patent for CR pesticide (fungicide, nematocide or insecticide) consists of a spray-based alginate treatment for seed coating. The seed is sprayed with a solution of alginate salt containing one or two pesticides, then crosslinking the alginate by spraying with calcium chloride solution. CR of the coated pesticide protected the seed from pest infestation.[52] Another patent for alginate gel discs used for the CR of juvenile hormones in aqueous environment has been published. Juvenile hormones in this invention act as insecticides to control the proliferation of mosquitoes, horn flies, bean beetles, potato beetles, and other insects that are harmful in the adult stage.[53] Table 1 lists the alginate-based CR pesticide formulations.

Cyclodextrins and starch derivatives

Cyclodextrins (CDs) are cyclic oligosaccharides containing 6 (α-CD), 7 (β-CD) or 8 (γ-CD) (1,4)-α-linked glucose units (Figure 2). It is formed by bacterial enzymatic degradation of starch. The most important structural feature of these compounds is their truncated cone shape, with a hydrophobic interior cavity and hydrophilic surfaces, which makes them well known for forming inclusion compounds, both in solution and in solid state, with various molecules placed in their hydrophobic interior cavity.

Table 1. List of controlled release pesticide formulations based on alginates.

Formulation	Factors affecting CR	Advantage/s	Disadvantage/s	Reference
Sorbent-modified alginate-herbicide-water	Sorbent used and nature of herbicide i.e. solubility	High EE and CR behavior for herbicides	lacking mechanical stability	38–44 84
$CaCl_2$-crosslinked Alg-gelatin beads loaded with Cypermethrin	Pesticide concentration; crosslinker	Low pesticide conc. showed CR	Inorganic salts decrease swelling of polymer matrix	45
Starch-alginate beads using $BaCl_2$, & $AlCl_3$ crosslinkers encapsulating thiram	Type of crosslinker	$BaCl_2$, was found to be the better crosslinker	Inorganic salt reduced swelling of the polymer matrix	46
NLP-$CaCl_2$-crosslinked sodium alginate-starch as CR matrix for thiram	Non-Fickian diffusion, swelling	Bentonite-based showed more CR behavior than kaolin-based formulation	Inorganic salts affect swelling of the matrix	47
		NLP enhanced pesticidal action		48
Chlorpyrifos-loaded $CaCl_2$-crosslinked sodium alginate-starch microspheres	pH & temp-dependent swelling; erosion	system is a promising CR device for chlorpyrifos	Unstable matrix formed; anomalous release mechanism	49
NaAlg Nps with AOT & PVA as CR device for imidacloprid	Solubility of pesticide	Effective on leafhoppers & less toxic to non-target organisms	A little expensive than the usual alginate formulation	50

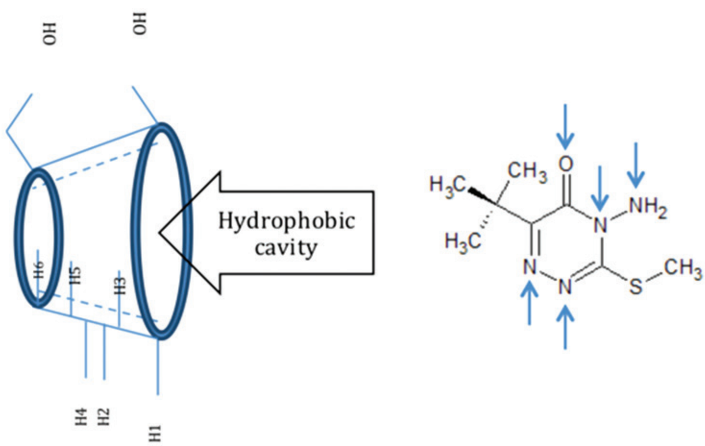

Figure 3. Cyclodextrin structure showing the hydrogen atoms that will possibly interact with the N and O atoms (see the blue arrows) in metribuzin.

Cyclodextrin complexes of herbicides such as atrazine, simazine, metribuzin, alachlor and metolachlor were reported.[54] β-CD inclusion complexes of atrazine, metribuzin and simazine and γ- CD complexes of alachlor and metolachlor were successfully prepared. Metribuzin could form β-CD complex (Figure 3) relatively easily owing to its higher water solubility. β-CD-pesticide complex when formed is stable and crystalline with high water solubility.[54] Szente reported that molecular inclusion of volatile organophosphorus pesticides such as Malathion, Dichlorvos, Sumithion, Chlorpyriphos, and Sulprofos in β-CD resulted in solid formulations with low vapor pressure, having improved the physical stability and even masked the odor of pesticides. The cyclodextrin-entrapped pesticides were reported to be stable even at high temperatures and the formulation was deemed more acceptable with CR property suitable for use indoors.[55]

Doane, Shasha, and Russel reviewed pesticides encapsulation within starch matrix.[56] Starch attracted considerable attention as polymeric material for CR because aside from it being renewable, abundant, and inexpensive, it can be readily modified chemically, physically and biologically into low MW or high MW compounds for specific applications.[56]

Riley reported about the safety of parathion encapsulated in starch-xanthate matrix in comparison to parathion adsorbed on attapulgus clay granules. Encapsulation prevents the loss of pesticide by volatilization and avoids generation of finely dispersed particles during preparation, mixing or application and thus, reduces inhalation risks.[57]

McGuire and Shasha studied the encapsulation of microbial pesticides using starch. Starch or flour matrices are reported to be more efficient and have longer residual activity than commercial formulations.[58] The CR of sugar and dimethoate to fight against apple maggot fly *Rhagoletis pomonella* and other insects has also been reported. The biodegradable CR device provides effective release of sugar (insect feeding stimulant) and dimethoate (toxicant) and showed greater than 70% insecticidal activity for at least 11 weeks.[59] A uniform starch microcapsules prepared by premix membrane emulsion was used for CR of avermectin. The pesticide was reported to release via non-Fickian and Case-II transport, achieved by varying the size of the microcapsules and the concentration of pesticide loaded onto the polymer matrix.[60] Trimnell and Shasha entrapped pesticides within native or pregelatinized starch. They reported up to 90% EE of trifluralin depending on spraying and drying procedure. One month exposure of the composite to an airflow of 200 ft/min under a hood released only 16% of trifluralin.[61]

Vemmer and Patel reviewed encapsulation methods designed to entrap living biological control agents such as microorganisms and entomopathogenic nematodes. The so-called smart polymers, such as starch, chitosan, etc., were well studied for their responses to changes in pH, temperature, and so on in vitro, while not enough studies were done on how these polymers will interact in soil or with the agro-ecosystem.[62] Recently, Vemmer et al. developed a CO_2-releasing co-formulation. In this study, CO_2 was made as bait to make an attract-and-kill strategy for the control of soil-dwelling pests. Addition of starch to the Ca-alginate beads containing *Saccharomyces cerevisiae* resulted to a significantly higher CO_2 concentration in soil for 4 weeks.[63] Table 2 enumerates some of the starch and cyclodextrin-based CR pesticide formulations.

Table 2. Cyclodextrin and Starch-based controlled release formulations for pesticides.

Formulation	Factors affecting CR	Advantage/s	Disadvantage/s	Reference
β-CD inclusion complexes of atrazine, metribuzin and simazine and γ- CD complexes of alachlor and metolachlor; β-CD complexes of volatile organophosphates	Biodegradation of matrix in natural environment	Stability, crystallinity and high water solubility of CD complexes formed; ideal for volatile pesticides; for use indoors	Matrix not very stable in natural environment	54 55
Starch-xanthate granules encapsulating parathion	Microcapsule size, conc. of pesticide	Encapsulation prevents loss of pesticide by volatilization, reduce inhalation risks	Starch may coat & adhere strongly to the skin along with encapsulated pesticide	57
Bt-encapsulated starch matrices	Porous structure, swelling	Longer Bt activity	Starch is prone to degradation	58
Starch/flour matrices fruit-mimicking sphere	Coating of the formulation	Attract and kill strategy	Use of paint as coating material	59
Avermectin-encapsulated starch microcapsules	Size of microparticles	Tunable microparticle size to achieve suitable release	Starch is prone to degradation	60
Starch-borate and native or pregelatinized starch as wall material and matrix for trifluralin, respectively	Spraying and drying time	Relatively high pesticide incorporation and CR property	Pesticide may evaporate before spraying with water	61
CO_2-releasing formulation for soil dwelling pests	Swelling of matrix	Attract and kill strategy	Limited effectivity of up to 4 h only	63

Chitosan and derivatives

Chitosan has been widely explored as CR matrix for drug delivery. In the agrichemical industry, the use of chitosan in CR formulation of pesticides has been explored owing to its biodegradability, biocompatibility and its inherent pesticidal, antibacterial[83] and antifungal activities.[64,82]

A novel photodegradable formulation of Imidacloprid (IMI) with CR property was prepared by directly incorporating the insecticide via layer-by-layer (LbL) self-assembly of alginate and chitosan, with the polymers added alternately during preparation. Release pattern of IMI was studied in vitro using a diffusion cell assembly at pH 7.4. Toxicity was evaluated against the adult stage of the insect *Martianus dermestoides*. Among the photocatalysts (TiO_2, SDS/TiO_2, Ag/TiO_2, and SDS/Ag/TiO_2) being studied, SDS/Ag/TiO_2 was identified as the best formulation with the potential to degrade easily in the natural environment.[65]

Yin and co-workers prepared a water-soluble carboxymethyl chitosan (Az-CMCS) by simple one-step mixing of azidobenzaldehyde (Az) and carboxymethyl chitosan (CMCS) in aqueous solution at room temperature.[66] In another study, the synthesized Az-CMCS polymer system was used as matrix for diuron.[67] The pesticide was dispersed in about 10% polymer solution, irradiated at 253.7 nm using a 20W UV lamp to induce gelation. Results showed that all formulations exhibited CR behavior with the UV irradiated polymer matrix showing a faster release rate than formulations prepared under solar-simulated irradiation. Release study for diuron at pH 6.0 revealed a diffusion–controlled mechanism, which was attributed to the formation of porous structure in the hydrogels upon swelling.[67]

Silva et al. developed alginate-chitosan nanoparticles as a carrier for the herbicide paraquat. Association efficiency of 74.2% was reported and almost 100% of the herbicide was released from the polymer matrix after 8 h as compared to the complete release of the unformulated herbicide after 6 h.[68]

Tripolyphosphate-crosslinked chitosan (Chi-TPP) nanoparticles was evaluated as CR matrix for paraquat. EE of the herbicide in the matrix was $62.6 \pm 0.7\%$ and the system exhibited CR of the pesticide. The polymer matrix was found to be stable for 60 days.[12] Chitosan nanocapsule prepared by ionic gelation using TPP as crosslinker was evaluated as matrix for hexaconazole.[69] EE for the fungicide was 73% with its CR behavior more evident at pH 10. Fungicidal activity of the nanoformulation was assessed using *R. solani* and was compared with commercial formulation. The prepared chitosan nanocapsule showed CR behavior as compared to the commercial formulation and was found to be best for alkaline soil.[69]

Li and co-workers utilized carboxymethyl-chitosan (CM-chit) and bentonite (H-ben) composite as CR matrix for atrazine and imidacloprid. The matrix has a dual advantage of encapsulating the herbicides in the dense polymer gel (CM-chit) and sorption by H-ben. This caused the reduced release rates of the pesticides in water. T_{50} for atrazine was extended up to 572 h while that of imidacloprid was 24 h.[13]

Encapsulation of methomyl in the photocrosslinked azidobenzaldehyde (Az)– carboxymethyl chitosan (CMCS) nanocapsules was studied. EE was reported to be 90% in aqueous medium at pH 4.0. Diffusion-controlled release of the pesticide was carried out at pH 6.0 with a half release time ($t_{1/2}$) of 36.3–69.5 h from different samples.[70]

Kumar et al. explored the CR property of a nanocapsule prepared from chitosan and alginate by polyelectrolyte complexation. They reported 62% encapsulation of acetamiprid. CR behavior was observed when the matrix was immersed in buffers of different pH. It was reported that 50% of the insecticide was released after 24 h at pH 10 and after 36 h at pH 7 and 4 while the plain formulation released approximately half of the pesticide in just about 6 h.[71]

Ye et al. prepared a novel amphiphilic system by grafting 2-nitrobenzyl succinate (NBS) onto the amino group of carboxymethyl chitosan in a

Table 3. List of Chitosan-based controlled release pesticide formulations.

Formulation	Factors affecting CR	Advantage/s	Disadvantage/s	Reference
Layer-by-layer (LbL) self assembly of Alg & CS incorporating IMI	Photocatalyst	biodegradability of formulation in natural environment	Use of photocatalyst makes CRF more expensive	65
Photocrosslinkable-water soluble Az -CMC CS matrix for diuron	Irradiation method	Photodegradable, solar-simulated irradiation showing better CR property	More costly to prepare	67
Paraquat-loaded TPP-crosslinked CS Nps	Size of nanoparticles	Moderately high EE and CR property	Ionic interaction between TPP and paraquat; limited stability	12
Paraquat-loaded Alg-CS Nps	Size of nanoparticles	Moderately high EE and CR property	CRF is not very different from unformulated paraquat in terms of release time	68
Hexaconazole-encapsulated CS nanocapsule	Size of polymer matrix	Moderately high EE with CR property in alkaline soils	Not very useful in usual soil environment with neutral to slightly alkaline soil pH	69
CMCS-bentonite composite encapsulated with atrazine & imidacloprid	Sorbents	Dual advantage of encapsulating the herbicides & sorption by bentonite	Use of sorbents may result in extremely slow release of pesticide	13
Methomyl encapsulated photocrosslinked Az-CMCS nanocapsules	pH of release media	High EE at pH 4.0	More costly to prepare	70
Acetamiprid-loaded CS-Alg polyelectrolyte complex	pH of release media	CR behavior greater in pH 7 and 4	Not very effective in alkaline soils	71
Diuron-loaded p-Nitrobenzyl succinate grafted CMCS	pH, sunlight	High EE	Cannot be used without light	72

method described elsewhere. The hydrophilic carboxymethyl chitosan and hydrophobic photosensitive 2-nitrobenzyl groups could self-assemble to form polymeric micelles in deionized water, crosslinked with glutaraldehyde to serve as matrix for pesticide. The formulation showed high diuron EE (91.9%). Release rate of up to 96.8% over an 8-h period using a buffer at pH 7 under solar initiated irradiation was observed.[72] Table 3 enumerates the CR formulations based on chitosan and its derivatives.

Carboxymethylcellulose or ethylcellulose

Carboxymethylcellulose, CMC (Figure 2) is a cellulose derivative obtained by base-catalyzed reaction of cellulose with chloroacetic acid. It is often found and used as its salt sodium carboxymethylcellulose. Its main use is in food science as food thickener and stabilizer and has recently been explored as CR system for pesticides.

CMC gel was used as matrix for CR of the anionic herbicide 2,4-D, with EE ranging from 55 to 90%. Results showed that unformulated 2,4-D is released in water within 1 h while it took 48 h to release 90% of the pesticide from the gel formulations. The T_{50} of the pesticide in water varied from 8.8 to 19.8 h for the formulations, maximum value obtained for the one added with hydroxy-iron intercalated bentonite that also showed highest sorption for 2,4-D. The formulations were also reported to exhibit CR of the pesticide in a thin soil layer; thus, minimizing the leaching of the herbicide in soil[73] by desorption and diffusion mechanisms.

CR of acephate was determined using commercially available polyvinyl chloride, CMC, and CMC with kaolinite. EE was reported to be greater than 93% for all formulations, CR behavior was further enhanced with the addition of clay. Diffusion of acephate was reported with half release time ($T_{1/2}$) of 2.97–52.41 days in water and 2.98–76.38 days in soil from the different formulations.[74]

Volatilization of alachlor from microcapsules formed by combining the pesticide with cellulose acetate butyrate (CAB), EC and EC with emulsifier was studied. The three microcapsule formulations released alachlor at a significantly slower rate compared to traditional formulation, the slowest rate was observed for CAB.[75]

EC matrices encapsulated nearly 100% of chlorsulfuron.[76] In its traditional form, chlorsulfuron was released in less than 1 h while it took a minimum of 50 days to release 90% of chlorsulfuron from the formulation coated with 20% EC plus plasticizer.[76]

EC and lignin (together as one formulation) were studied as CR matrix for chloridazon. CR of the pesticide was reportedly controlled by the granule size of CR lignin matrices, the thickness of the coating film (EC) and the surface properties of the formulation by adding a plasticizer such as Dibutyl sebacate or DBS.[77] A similar study was conducted to determine CR of imidacloprid. EE for the pesticide was reported to be higher than 87% in all cases. The T_{50} ranged from 3.02 to 168.6 h, enhanced by changing the thickness of the EC coating film and modifying the surface properties by addition of plasticizer.[78]

Sopeña et al. studied the CR of alachlor[79] using EC microencapsulated formulations (MEFs). Alachlor's total leaching losses in soil columns was reduced from 98% (commercial form) to 59% in MEFs, with 66.3–81.3% of the herbicide reportedly found in the first 12 cm of the soil column, in comparison to the 20.4% of alachlor remaining in the entire soil column using the commercial formulation.[79] In another study, Sopeña's group performed the same experiment this time using another herbicide (norflurazon).[80] Similarly, the group concluded that the herbicide's release in water was controlled and its leaching in sandy soil was greatly diminished

Table 4. CMC and EC-based controlled release pesticide formulations

Formulation	Factors affecting CR	Advantage/s	Disadvantage/s	Reference
2,4-D—loaded CMC crosslinked w/$AlCl_3$	Addition of sorbent, solubility of pesticide	High EE & CR in soil	Use of modified sorbents which adds to the cost	73
Acephate-loaded CMC gel with clay	Sorbent added	High EE, CR property	Additional cost incurred by using sorbent	74
Microcapsules of CAB, EC and EC with emulsifier as CR matrix for alachlor	Nature of polymer & pesticide	CR of pesticide highly evident in CAB	CAB is quite expensive	75
Chlorsulfuron-EC + plasticizer	Plasticizer	Very high EE & CR property	Use of toxic plasticizer	76
EC & lignin granules inc. chloridazon & imidacloprid	Granule size, EC film, plasticizer	High EE & enhanced T_{50} of the pesticides	DBS is a skin and eye irritant	77, 78
EC-MEFs encapsulating alachlor & norflurazon	Polymer:herbicide ratio, stirring, emulsifiers	Avoids contamination of groundwater	More costly to prepare	79, 80

with 50% remaining (mostly in the upper ring) in MEFs as compared to only 2% of norflurazon remaining in the entire soil column using the commercial formulation.[80] Table 4 summarizes the CR pesticide formulation using CMC and EC as polymer matrices.

Summary and future directions

Pesticides are considered as harmful but important substances in agriculture. They will still be in use to address issues such as global food security and the economy of nations dependent on agriculture. As can be seen from the trend above, natural and biodegradable polymers have been continually studied and manipulated in order to design CR devices for agrichemicals.

In the coming years, research efforts will still focus on the continuous search for more benign additives and crosslinkers. Incorporation of sorbents enhances CR of the bioactive from the polymer matrix while combination of two natural polymers explored the synergistic effect of the polymers in the formulation. Other recent studies focused on the combination of natural polymers known to possess controlled release and photoprotective properties such as the study conducted by Wang & Zhao.[81] Addition of groups with photoprotective property avoids the unnecessary release of the pesticide via photodegradation or volatilization whereas some photosensitive components are sometimes added to trigger release of the pesticide to the target site. The recent trend on designing systems for nanoencapsulation will continue to grow as nanomaterials are identified to be more efficient CR vehicles because they are more water-soluble and tunable to release the actives at specific conditions of pH and temperature. Some recent nano- and micro-formulations are added with components such as metal ion[82] and essential oil[83] to come up with systems that have enhanced antifungal and antibacterial activities against specific target organisms. Safety of the pesticide handlers is of paramount concern to the formulators. Hence, CR formulations must not only be effective, but must also be harmless to the farmers and non-target organisms. CR technology is a trend widely explored in the delivery of pesticides. This trend parallels current pressing issues such as human health, environmental degradation and agricultural economics.

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