

Controlled Release Study of Carbaryl Insecticide from Calcium Alginate and Nickel Alginate Hydrogel Beads

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ABSTRACT: In this study, controlled release formulations for reducing environmental impact of pesticides have been produced by encapsulating as a model pesticide carbaryl (Carb) in the alginate beads. The various hydrogel bead formulations were prepared by the ionotropic cross-linking of sodium alginate (NaAlg) with calcium and nickel ions. The surface morphology of prepared beads was characterized with scanning electron microscopy (SEM). SEM confirmed the spherical nature and surface morphology of the particles. Bead characteristics, such as carbaryl entrapment efficiency, particle size, equilibrium swelling degree, and carbaryl release kinetics, were determined. The effects of the bead preparation conditions such as crosslinker concentration and type, carbaryl/sodium alginate (Carb/NaAlg) ratio and percentage of NaAlg on the carbaryl release from the calcium alginate (Ca-Alg) and nickel alginate (Ni-Alg) beads were investigated in

distilled water at 25°C. It was observed that carbaryl release from the Ca-Alg beads was slower than that of Ni-Alg beads. The release results indicated that carbaryl release from both of the Ca-Alg and Ni-Alg beads decreases with the increasing crosslinker concentration, Carb/NaAlg ratio and percentage of NaAlg. The highest carbaryl release was found to be 100% for the Ni-Alg beads at 3 days whereas the lowest carbaryl release was found to be 67% for the Ca-Alg beads at 21 days. The swelling measurements of the beads were also in consistent with the carbaryl release results. The carbaryl release from most of the bead formulations followed Case II transport. © 2007 Wiley Periodicals, Inc. *J Appl Polym Sci* 105: 718–725, 2007

Key words: water soluble polymers; controlled release; carbaryl; pesticide; beads

INTRODUCTION

Over the past decades, hydrogel polymers have attracted a great deal of attention for use as potential carriers in the controlled release (CR) applications.^{1–5} Hydrogels are the hydrophilic, three-dimensional network structures having the natural propensity to absorb large quantity of water or biological fluids. The ability of hydrogels to swell in the presence of water or biological fluids regulates the release of the encapsulated bioactive agents. By controlling the degree of swelling because of crosslinking makes them potential carriers of drugs or pesticides for CR applications. The aims of controlled release formulations are to protect the supply of the agent to allow the automatic release of the agent to the target at a controlled rate and to maintain its concentration in the system within the optimum limits over a specified period of time, thereby providing great specificity and persistence.^{6,7}

The parameters that affect the properties of such CR formulations are depend upon the nature and type of the polymer used. Despite of several polymers used in the preparation of the CR formulations, natural polymers are often preferred to synthetic polymers because of their nontoxic, low cost, free availability, biodegradability.^{8,9}

Among such natural polymers alginates, which are naturally occurring polysaccharides obtained mainly from brown algae's belonging to the *Phaeophyceae* and composed of two monomeric units, β -D-mannuronic acid and α -L-guluronic acid.^{9,10} Alginate salts are known to form a three-dimensional network structure producing free volume for easy encapsulation of active agents when in contact with two valance ions such as calcium, copper, nickel ions, and this characteristic has been used to produce sustained release particulate systems for a variety of drugs, proteins, and pesticides.¹¹

Carbaryl (chemical name: α -naphthyl-*n*-methyl carbamate) is a wide spectrum insecticide used for 100 species of insects on citrus fruit, cotton, forests, lawns, nuts, ornamentals, shade trees, and other crops as on poultry, livestock, and pets.¹² It is formulated as wettable powder, which makes its handling very difficult, mainly because of the fast absorption by nasal, oral, and transdermal routes. It

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has also low chemical stability that is because of the rapid hydrolyzes to 1-naphthol in alkaline medium.¹³

One way to overcome these disadvantages of carbaryl is to produce controlled release formulations of it. In the previous studies, copper carboxymethyl cellulose, glutaraldehyde crosslinked sodium alginate/gelatin, and sodium alginate/sodium carboxymethyl cellulose blend beads were prepared and release characteristics of the carbaryl from these beads were researched.^{14,15} In this study, it was aimed to prepare hydrogel Ca-Alg and Ni-Alg beads containing carbaryl to achieve a controlled pesticide release profile suitable for agriculture application. The release characteristics in terms of entrapment efficiency, bead diameter, and equilibrium swelling degree (ESD) have been investigated. The effects of various processing parameters such as crosslinker concentration and type, carbaryl/sodium alginate ratio and percentage of NaAlg on the carbaryl release from the calcium alginate and nickel alginate beads were studied. Release properties were also supported by swelling measurements.

EXPERIMENTAL

Materials

Sodium alginate, medium viscosity (viscosity of 2% solution at 25°C is ~ 3500 cps) was purchased from Sigma Chemical Company (Louis). Hektavin 85 (85% (w/w) in carbaryl) was supplied from Hektaş T. A. Ş. in Turkey and used after purification by recrystallization with ethyl alcohol. CaCl₂·2H₂O, BaCl₂·2H₂O and ethanol were obtained from Merck (Darmstadt, Germany).

Preparation of the carbaryl-loaded NaAlg beads

About 1–2% (w/v) NaAlg solution in distilled water was prepared by gentle heating. After complete cooling, different amount of carbaryl were added and mixed thoroughly using a magnetic stirrer (Corning PC 420). The polymer solution containing carbaryl was added dropwise into CaCl₂ or NiCl₂ solution using a 25 mL hypodermic syringe (1 mm diameter) with constant stirring. Experimental conditions, such as the distance between the syringe and crosslinking solution level, number of drops/min and temperature, were maintained constant. The beads formed were removed from crosslinking solution at a selected time (5 min). The beads were filtered, washed with water repeatedly to remove the crosslinking solution, and then allowed to dry in oven at 40°C.

To estimate the bead diameters, 10 samples of the completely dried beads from the different formula-

tions were selected and their diameters were measured by using electronic digital caliper (Mitutoyo IP.65, Japan).

Determination of carbaryl content of the beads

The known mass of beads was crushed in an agate mortar with a pestle and then polymeric powder was taken in a flask. Ethanol (50 mL) was added and refluxed at 25°C for 2 h to ensure the complete extraction of carbaryl from the beads. At the end of the 2 h, precipitate of NaAlg was filtrated and carbaryl was analyzed by using a UV-visible spectrophotometer (Ultrospec 2000, Cambridge, England) at a wavelength of 280 nm using pure ethanol as a blank. The percentage of entrapment efficiency was then calculated as:

$$\begin{aligned} \text{Entrapment efficiency (\%)} \\ = \frac{\text{Practical carbaryl loading}}{\text{Theoretical carbaryl loading}} \times 100 \end{aligned} \quad (1)$$

Swelling of the beads

Swelling property of the beads was studied by a measurement of ESD. ESD values for individual formulation of the beads were determined by measuring the extent of swelling of the beads in the distilled water at 25°C. To ensure complete equilibration, the bead samples were allowed to swell for 48 h. The excess surface-adhered liquid drops were removed by blotting and the swollen beads were weighed using electronic balance (Shimadzu AEG-120, Japan). The beads were then dried in oven (Nuve FN 120, Turkey) at 40°C until there was no change in the dried mass of samples. The percent ESD was calculated as follows:

$$\text{Equilibrium swelling degree (\%)} = \frac{(M_s - M_d)}{M_d} \times 100 \quad (2)$$

where M_s and M_d are mass of swollen beads and mass of dry beads, respectively.

SEM

SEM photographs were taken with JSM 5600 Scanning Microscope (Japan) to examine the morphology and surface structure of the beads at the required magnification at room temperature. The beads were deposited on brass hold and sputtered with a thin coat of gold under vacuum. Acceleration voltage used was 20 kV with the secondary electron image as a detector.

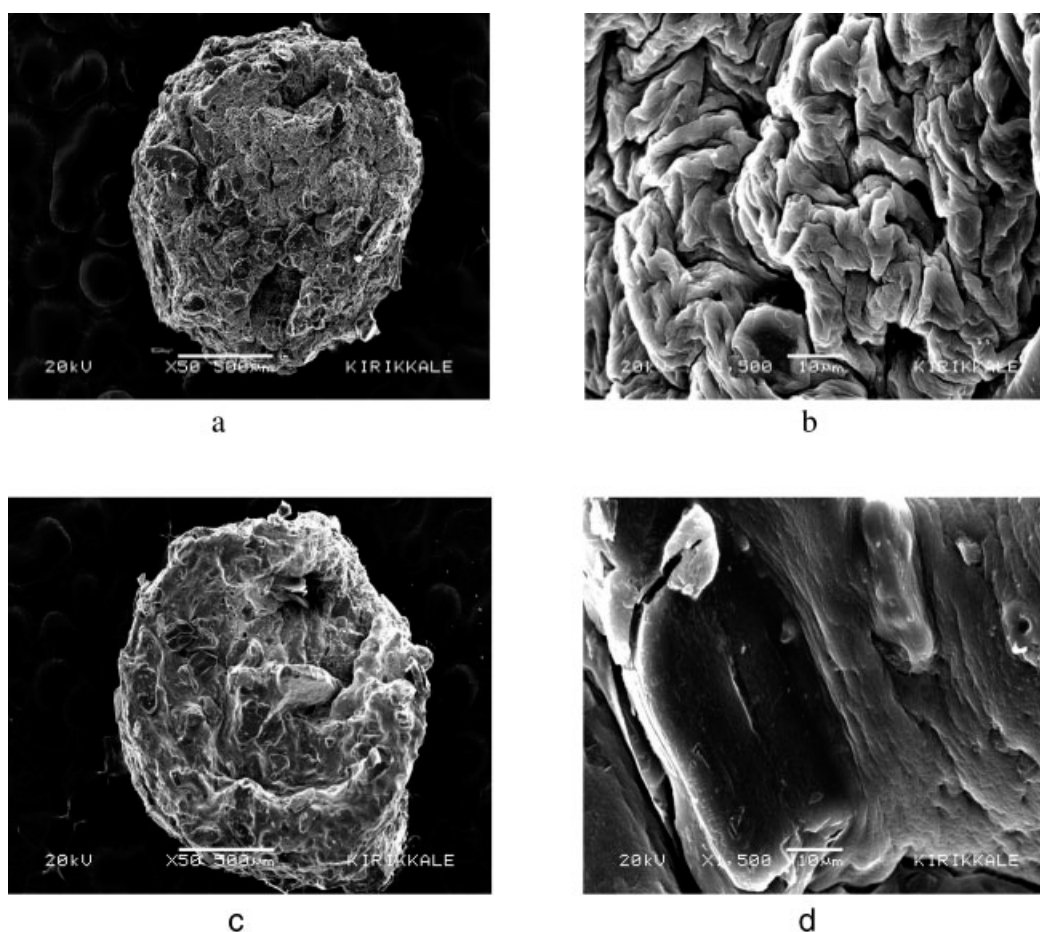


Figure 1 Scanning electron microscopic photographs of Ca-Alg bead (magnification, $\times 50$) (a), Surface morphology of Ca-Alg bead (magnification, $\times 1500$) (b), Ni-Alg bead (magnification, $\times 50$) (c), Surface morphology of Ni-Alg bead (magnification, $\times 1500$) (d).

Carbaryl release studies

About 50 mg of crosslinked beads was put in conical flasks containing 500 mL dissolution media (distilled water) and incubated in a shaking water bath (Nüve ST 402, Turkey) at 25°C with a speed of 50 rpm. At specific time intervals 4 mL solution was withdrawn and carbaryl content was determined by UV-visible spectrometer at 280 nm. Analyzed solution was added back to dissolution media to maintain a constant volume. From the absorbance values, the cumulative percent released was determined. All experiments were performed in triplicate to minimize the variational error. The average values were used for further data treatment and plotting.

RESULTS AND DISCUSSION

Bead formation and crosslinking

Carbaryl containing Ca-Alg and Ni-Alg hydrogel beads were prepared using CaCl_2 and NiCl_2 solutions as a crosslinker with sodium alginate. Ca-Alg and Ni-Alg beads formed have almost spherical

shape as revealed by the SEM photographs is shown in Figure 1(a–d). As it is seen from the Figure Ca-Alg and Ni-Alg beads have rough surface structure. However, as it is reflected from the Figure 1(b,d), Ni-Alg beads have more smooth surface structure than that of Ca-Alg beads due to differences between Ca and Ni ions.

The results of percentage entrapment efficiency and particle sizes are presented in Table I. The beads formed have particle sizes ranging from 1.34 ± 0.11 to 2.36 ± 0.37 mm in diameter. The Table illustrates that particle size of beads prepared using NiCl_2 solution are larger than that of prepared with CaCl_2 solution. The size of the beads changed with the bead preparation conditions such as crosslinker concentration, Carb/NaAlg ratio and percentage of NaAlg. Both of the Ca-Alg and Ni-Alg beads diameters decreased when crosslinker concentration was increased from 0.05M to 0.2M. This increase in crosslinker concentration causes increase in crosslink density of the bead. With an increase in crosslink density, the beads with smaller size were produced, probably due to the formation of a more rigid network as a result of

TABLE I
Particle Size and Percentage Entrapment Efficiency of the Beads Prepared by Using Different Cross-Linking Agents

Code	NaAlg (%) (w/v)	Carb/NaAlg ratio (w/w)	CaCl ₂ concentration (M)	NiCl ₂ concentration (M)	Bead diameter (mm)	Entrapment efficiency (%)
A ₁	1.5	1 : 1	0.1	–	1.58 ± 0.08	54
A ₂	1.5	1 : 2	0.1	–	1.53 ± 0.12	65
A ₃	1.5	1 : 4	0.1	–	1.41 ± 0.03	67
A ₄	1.5	1 : 2	0.05	–	1.59 ± 0.09	75
A ₅	1.5	1 : 2	0.2	–	1.34 ± 0.11	64
A ₆	1	1 : 2	0.1	–	1.39 ± 0.12	54
A ₇	2	1 : 2	0.1	–	1.59 ± 0.14	68
B ₁	1.5	1 : 1	–	0.1	1.88 ± 0.19	61
B ₂	1.5	1 : 2	–	0.1	2.02 ± 0.15	64
B ₃	1.5	1 : 4	–	0.1	2.09 ± 0.15	68
B ₄	1.5	1 : 2	–	0.05	2.36 ± 0.37	74
B ₅	1.5	1 : 2	–	0.2	1.75 ± 0.13	63
B ₆	1	1 : 2	–	0.1	1.71 ± 0.07	62
B ₇	2	1 : 2	–	0.1	2.02 ± 0.11	74

increased crosslink density. Agnihotri and Aminabhavi¹⁶ have found similar results with gellan gum and poly(vinyl alcohol) hydrogel microspheres. Also, the bead diameter increased with decrease in Carb/NaAlg ratio from 1/1 to 1/4. As the Carb/NaAlg ratio decreases the carbaryl content in the bead decreases. Hence, decrease in the carbaryl content cause the bead shape change from spherical to collapse form. Therefore, diameter of beads increased with decreasing Carb/NaAlg ratio. Similar observation was found in the previous study¹⁵ and another study in the literature.¹⁷ Moreover, it was observed that, in both of the formulations, with increasing percentage of NaAlg, diameter of the beads increases because of increasing amount of polymer in the bead preparation solution.

Entrapment efficiency of the beads is an important characteristics of the polymeric matrix. The percentage of entrapment efficiency may also change depending on the preparation conditions and the type of matrix material of the beads. The results of entrapment efficiency (%) are also included in Table I. These values increased slightly with decreasing both of the Carb/NaAlg ratio and crosslinker concentration for Ca-Alg and Ni-Alg beads. As the Carb/NaAlg ratio decreases, carbaryl loading decreases. Entrapment efficiency increases from 54% to 67% in the Ca-Alg beads while Carb/NaAlg ratio decreases from 1/1 to 1/4. On the other hand it increases from 51% to 68%, respectively, in the Ni-Alg beads. This phenomenon is explained as follows: when the Carb/NaAlg ratio decreases, NaAlg is bound to trap more carbaryl and thus, increase the entrapment efficiency. When the percentage of NaAlg solution is increased, entrapment efficiency also increases for both of the beads formulation because of increasing viscosity of bead preparation solution. Therefore, polymer traps more carbaryl molecules and entrapment efficiency increases. The highest entrapment

efficiency for the Ca-Alg and Ni-Alg beads were found to be 75 and 74%, respectively.

Effect of the crosslinker concentration on the carbaryl release

The release of carbaryl from the Ca-Alg and Ni-Alg beads were carried out at 25°C in distilled water and the amount of insecticide release within a given time was evaluated by UV spectroscopy. Effect of CaCl₂ and NiCl₂ concentration on the cumulative carbaryl release profile of beads is shown in Figure 2. Generally, it was found that as the concentration of CaCl₂ and NiCl₂ increases from 0.05M to 0.2M, release of carbaryl decreases. The maximum amount of carbaryl released from Ca-Alg bead prepared with 0.05M CaCl₂ was found to be 100% at 11 days whereas it was found to be 100% at 8 days for Ni-Alg bead. The observed decreases in the cumulative release are because of the fact that increasing concentration of crosslinker results in increase of the crosslink density, which gives rise to a compact network of the polymer. Consequently, the free volume reduces and penetration of water molecules and diffusion of carbaryl molecules become difficult.

Effect of crosslinker concentration on the cumulative release of carbaryl from beads was also supported by swelling measurements which are presented in Figure 3. As can be seen from the figure, ESD of beads decreases with the increase in crosslinker concentration. As the crosslinker concentration increases, number of bounded carboxyl groups increases, hence degree of crosslinking and rigidity of the polymer increase. Consequently, ESD of the beads and hence carbaryl release decrease. Similar results were reported by other workers.^{18–21}

Kulkarni et al.²¹ prepared glutaraldehyde cross-linked sodium alginate beads containing liquid

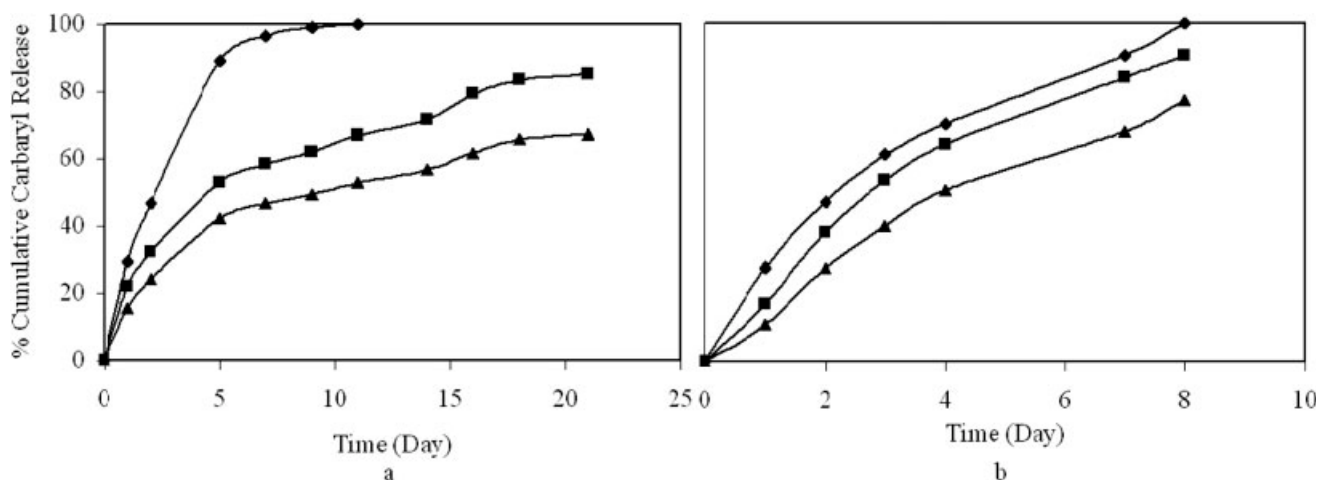


Figure 2 Effect of crosslinker concentration on the carbaryl release from Ca-Alg (a) and Ni-Alg (b) beads. Carb/NaAlg ratio: 1 : 2, crosslinker concentration: 0.05M (◆), 0.1M (■), 0.2M (▲).

pesticide in methanol medium and studied the effects of extent of crosslinking and amount of loading on pesticide release. They reported that swelling of the polymeric beads and pesticide release decrease with increasing exposure time to crosslinking agent.

In another previous study,²² release of the carbaryl from the copper alginate, barium alginate, and alginic acid beads were studied and same trends on this subject were also reported.

Effect of the crosslinker type on the carbaryl release

The effect of cation type in the crosslinking agents on the cumulative release of carbaryl is shown in Figure 4. It is reflected from the figure that, cumulative carbaryl release from the Ni-Alg beads is faster than that of Ca-Alg beads.

The explanation of this observation could be related to mechanism of the bonding of calcium and

nickel cations to alginate anions. Since calcium and nickel cations are divalent, their bonding to alginate is expected to occur in a planar two-dimensional manner, according to the egg-box model.^{22,23} The gelation and crosslinking of the polymers are mainly achieved by the exchange of sodium ions from the guluronic acid with the divalent cations, and the stacking of these guluronic groups to form the egg-box structure. On the other hand, carbaryl release of the beads crosslinked with CaCl_2 solution is slower than that of crosslinked with NiCl_2 solution. It is expected that divalent salts of CaCl_2 and NiCl_2 crosslink the alginate in a similar mechanism. The difference could be explained by noting that the degree of crosslinking depends on the ability of crosslinker ions to diffuse through the matrix. This diffusion ability is a function of the ionic size.²⁴ Since calcium ion has a radius of 1.00 Å compared with 0.69 Å for nickel ion, calcium ions are expected to fill larger space between the alginate chains pro-

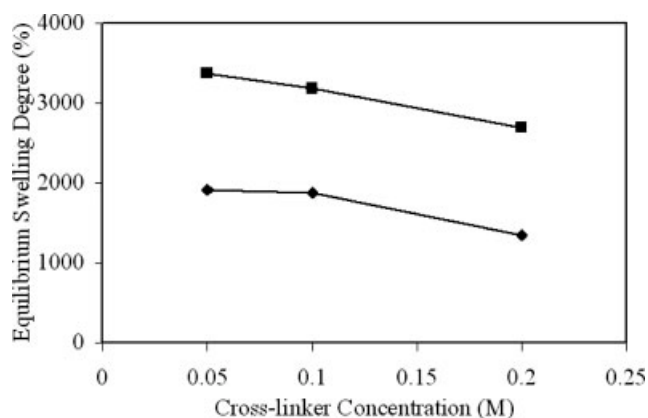


Figure 3 Effect of crosslinker concentration on the equilibrium swelling degree of Ca-Alg (◆) and Ni-Alg (■) beads.

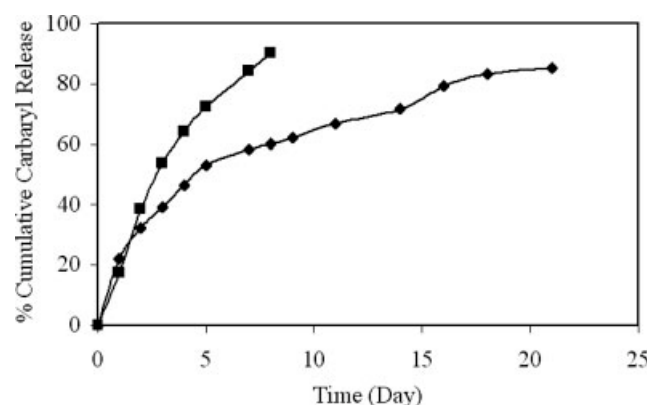


Figure 4 Effect of cation type on release of carbaryl. Carb/NaAlg ratio: 1 : 2, crosslinker type: 0.1M CaCl_2 (◆), 0.1M NiCl_2 (■).

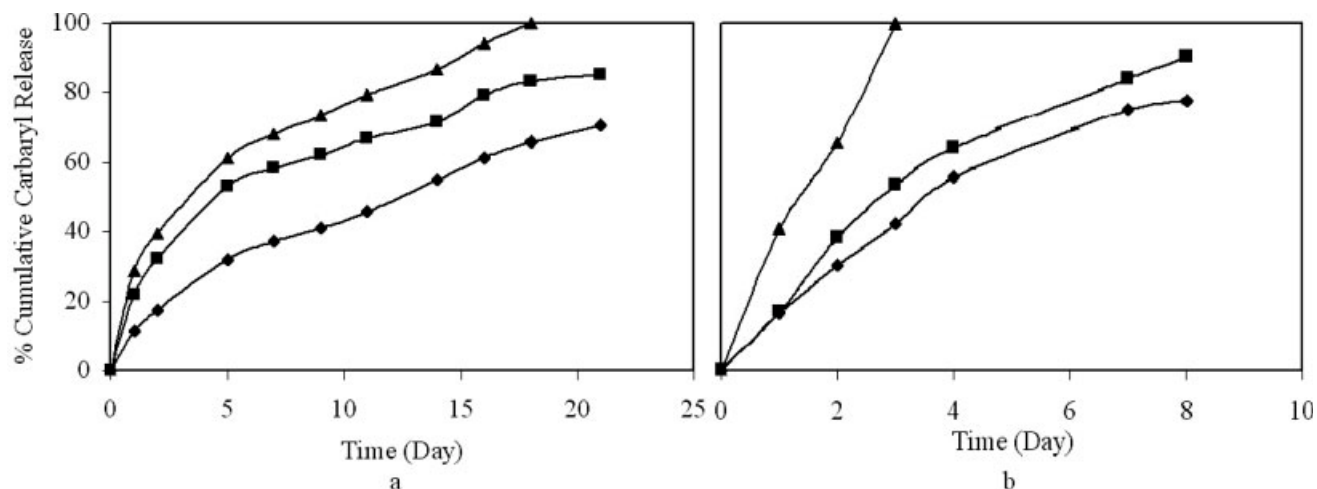


Figure 5 Effect of Carb/NaAlg ratio on the carbaryl release from Ca-Alg (a) and Ni-Alg (b) beads. Crosslinker concentration: 0.1M, Carb/NaAlg Ratio: 1 : 1 (◆), 1 : 2 (■), 1 : 4 (▲).

ducing a tight arrangement, leading to slow release. Similar observation was found in the literature. Bajpai and Sharma²⁵ have investigated swelling and degradation behavior of alginate beads crosslinked with Ca^{2+} and Ba^{2+} ions. They reported that equilibrium water uptake values of calcium alginate beads are greater than that of barium alginate beads because of ionic size.

Effect of carbaryl/sodium alginate ratio on the carbaryl release

Another parameter that affects the carbaryl release from the beads is Carb/NaAlg ratio. For this purpose Carb/NaAlg ratio was changed from 1/1 to 1/4 for Ca-Alg and Ni-Alg beads prepared with crosslinker concentration of 0.1M. The effect of Carb/NaAlg ratio on the carbaryl release is shown in Figure 5. The figure illustrates that carbaryl release from the Ca-Alg and Ni-Alg beads increases with the decrease in Carb/NaAlg ratio of the beads. The cumulative release of 1/1 Carb/NaAlg ratio beads have shown 71% at 21 days for Ca-Alg beads whereas that of 1/4 Carb/NaAlg ratio beads have shown 100% release at 18 days. Same trends were observed for the Ni-Alg beads in the Figure 5(b). When the Carb/NaAlg ratio decreases from 1/1 to 1/4, carbaryl content of the beads decreases. Lower carbaryl content might lead to the easier penetrating of liquid through beads and then faster carbaryl diffusion occurs from the beads. Similar observation was also obtained in the study of diclofenac sodium release from glutaraldehyde crosslinked NaAlg beads.²⁶

Carbaryl release data are also in agreement with the ESD values presented in Figure 6. As the Carb/

NaAlg ratio decreases from 1/1 to 1/4, ESD increases from 1489% to 2274% for Ca-Alg beads and from 2817% to 3524% for Ni-Alg beads, respectively.

Effect sodium alginate percentage on the carbaryl release

The effect of NaAlg percentage in the loaded hydrogel beads on its release behavior is shown in Figure 7. This figure reveals that the released amount of carbaryl decreases when the NaAlg percentage increases in the bead preparation solution in the range of 1–2%. The results are quite obvious and can be explained on the basis of the swelling behavior of the beads, which also obey the same pattern as it is seen in Figure 8. NaAlg is a polysaccharide that contains different type of hydrophilic functional groups. As there is increase in the percentage of the NaAlg, hydrophilic functional groups increase in the bead formation solution. Therefore, more functional groups

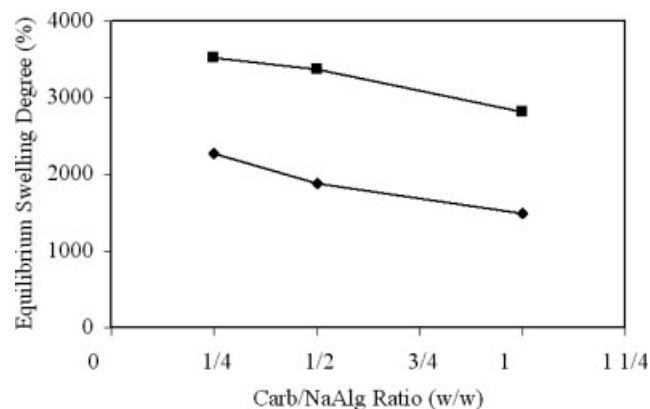


Figure 6 Effect of Carb/NaAlg ratio on the equilibrium swelling degree of Ca-Alg (◆) and Ni-Alg (■) beads.

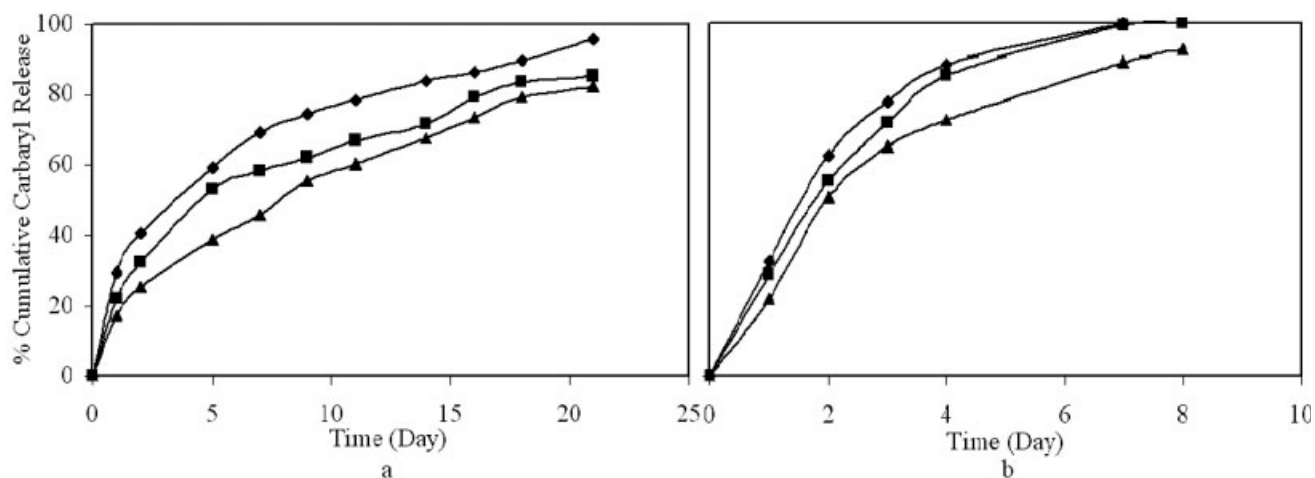


Figure 7 Effect of NaAlg percentage on the carbaryl release from Ca-Alg (a) and Ni-Alg (b) beads. Crosslinker concentration: 0.1M, percentage of NaAlg: 1% (◆), 1.5% (■), 2% (▲).

bound with Ca or Ni ions, which result in decrease of ESD and carbaryl release. Similar type of results have also been obtained by Bajpai and Giri in the study of carboxymethyl cellulose hydrogels containing KNO_3 .²

Carbaryl release kinetics

The release data of all the systems have been further substantiated by fitting the fraction release data M_t/M_∞ to an empirical equation proposed by Peppas²⁷

$$\frac{M_t}{M_\infty} = kt^n \quad (3)$$

where M_t is the amount of carbaryl released at time t and M_∞ is the drug released at equilibrium time; k , a constant characteristic of the pesticide-polymer system; and n , the diffusional exponent, which suggests the nature of the release mechanism. Fickian release is defined by an initial $t^{1/2}$ time dependence

of the fractional release for slabs, cylinders, and spheres. Analogously, Case-II transport is defined by an initial linear time dependence of the fractional release for all geometries.²⁸ A value of $n = 0.5$ indicates the Fickian transport (mechanism), while $n = 1$ is of Case II or non-Fickian transport (swelling-controlled).²⁹ The intermediary values ranging between 0.5 and 1.0 are indicative of the anomalous transport.^{8,15,27} The least-squares estimations of the fractional release data along with the estimated correlation coefficient values, r , are presented in Table II. From these data, the n value ranged between 0.51 and 1.12, with correlation coefficient values of 0.99, indicating the carbaryl release from most of beads have indicated Case II transport, but some of them have indicated non-Fickian transport. Moreover, it is seen from the table that carbaryl release from Ni-Alg beads almost display Case II transport while that of Ca-Alg beads display non-Fickian transport.

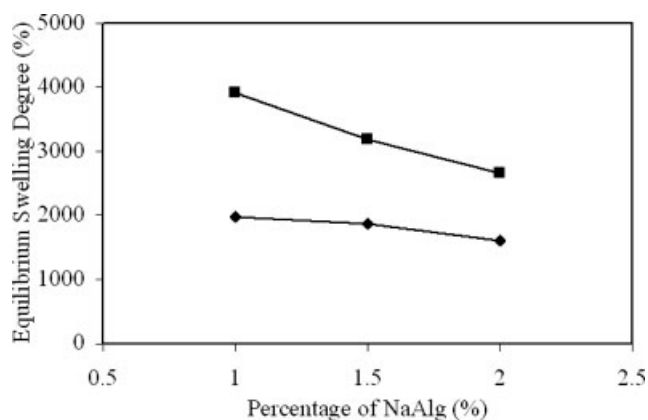


Figure 8 Effect of NaAlg percentage on the equilibrium swelling degree of Ca-Alg (◆) and Ni-Alg (■) beads.

TABLE II
The Results of k , n and r Calculated from eq. (3)

Code	$k \times 10^{-2}$	n	r	Diffusion mechanism
A ₁	0.12	0.58	0.998	Non-Fickian
A ₂	0.22	0.51	0.997	Non-Fickian
A ₃	0.02	0.89	1.000	Case II
A ₄	0.02	0.93	1.000	Case II
A ₅	0.17	0.51	0.987	Non-Fickian
A ₆	0.30	0.54	0.999	Non-Fickian
A ₇	0.17	0.52	0.999	Non-Fickian
B ₁	0.17	0.86	1.00	Case II
B ₂	0.18	1.05	0.996	Case II
B ₃	0.02	0.94	1.000	Case II
B ₄	0.28	0.72	0.999	Non-Fickian
B ₅	0.12	1.12	0.993	Case II
B ₆	0.02	0.99	1.000	Case II
B ₇	0.02	1.05	1.000	Case II

CONCLUSIONS

Pesticide carbaryl was successfully encapsulated in the alginate polymer. Bead size, entrapment efficiency, and ESD of the Ca-Alg and Ni-Alg beads were determined and it is observed that these parameters effected various processing parameters such as crosslinker concentration and type, Carb/NaAlg ratio, and percentage of NaAlg. It was observed that diameter of Ni-Alg beads was found larger than that of Ca-Alg beads. Carbaryl release studies indicate that for the beads prepared with high concentration of crosslinker cumulative carbaryl release was found to be slower than the other beads. It is also observed that carbaryl release from the Ni-Alg beads was much higher than that of Ca-Alg beads. Swelling measurement results of the beads also supported the release studies. The n values calculated for the release of carbaryl from Ca-Alg beads indicate that carbaryl release has almost shown non-Fickian transport whereas release from Ni-Alg has almost shown Case II transport. Finally, carbaryl release from the beads is changed to depend on crosslinking agent used and preparation conditions. The effective controlled release formulations can be obtained varying of them. From these results hydrogel alginate beads appear to be interesting as a controlled released system for agrochemical applications to improve pesticide stability, and to reduce the risks both to people who handle the product and to groundwater.

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