Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Impact of β-Cyclodextrin on Carbofuran Desorption in Soils with different Textural Properties

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Carbofuran is a carbamate insecticide that is used extensively. It is poisonous and has low mobility, so it stays in agricultural soils and causes environmental problems. The function of β-Cyclodextrin (β-CD), a cyclic oligosaccharide, in improving carbofuran desorption from sandy, loamy, and clayey soils is explored in this research. In order to measure the desorption efficiency, high-performance liquid chromatography (HPLC) was used in batch desorption tests with β-CD doses ranging from 0 to 20 mM. The desorption rates of carbofuran were shown to be much greater in sandy soils, which have little organic matter and cation exchange capacity, and to be significantly higher in soils with higher β-CD concentrations. The investigation of desorption kinetics showed that chemisorption was the major mechanism, with the pseudo-second-order model providing the best fit. This study presents a hopeful strategy for reducing the environmental hazards linked to carbofuran contamination by demonstrating the potential of β-CD to enhance pesticide cleanup in various types of soil.

Keywords: Carbofuran, Agriculture, β-Cyclodextrin, Soil, Desorption.

1. Introduction

There are serious ecological and environmental worries about contemporary agriculture's growing dependence on pesticides. Because of its efficacy in pest control and the dangers of soil and water pollution it poses, carbofuran, a very poisonous carbamate molecule, has garnered considerable attention among these pesticides. Carbofuran is extensively utilized in crop production for its insecticidal, nematicide, and acaricide properties. It is particularly useful for maize, sugarcane, rice, and potato crops. Its toxicity to non-target species, possibility of groundwater leaching, and persistence in soils make it imperative to comprehend how it behaves in soil systems. One important mechanism that determines the mobility, bioavailability, and environmental effect of carbofuran is its desorption from soil particles. The adsorption-desorption dynamics of carbofuran in soils with different textural qualities can be significantly influenced by cyclodextrins, especially β-cyclodextrin (β-CD), according to recent advances in soil remediation research.

Circular oligosaccharides called cyclodextrins are made from starch and consist of glucose units connected by α-1,4-glycosidic linkages. The capacity of β-cyclodextrin, which is composed of seven glucose units, to form inclusion complexes with a diverse array of hydrophobic molecules makes it stand out among the other cyclodextrins. The unique properties of β-cyclodextrin have been utilized in various industries, such as pharmaceuticals, food, and environmental remediation, due to its structure, which is defined by a hydrophilic exterior and a hydrophobic cavity. This structure allows it to encapsulate non-polar compounds, such as carbofuran, improving their solubility and changing their behavior in environmental matrices. The importance of finding long-term solutions to pesticide pollution has sparked significant interest in studying its possible effects on carbofuran desorption from soils.

The adsorption and desorption behavior of pesticides are greatly affected by the soil's textural qualities. Sand, silt, and clay are the three main types of mineral particles found in soils. Other components include organic materials, water, and air. The texture of the soil is impacted by these components, which in turn affect the soil's physical and chemical qualities, including its ability to store water, its cation exchange capacity, and its porosity. Soils with a coarse texture, like sand, have few adsorption sites, a high permeability, and a low organic matter concentration. Clayey soils and other fine-textured soils have a large surface area, great adsorption capacity, and a propensity to absorb pesticides more efficiently than other soil types. Because of their effects on adsorption strength and desorption ease, these textural qualities regulate the carbofuran-soil particle interaction.

Because of the lower adsorption capacity of sandy soils, carbofuran is more likely to be mobile and might potentially seep into groundwater supplies. Carbofuran may be heavily adsorbed in clayey soils, which reduces its bioavailability but might cause it to stay in the soil matrix for a long time. These dynamics might be drastically changed if β-cyclodextrin is introduced to these systems. The solubility of the pesticide can be improved and its desorption from soil particles accelerated when β-cyclodextrin forms inclusion complexes with carbofuran. When it comes to clayey soils, this action becomes even more important because carbofuran may be immobilized by high adsorption otherwise. One possible function of β-cyclodextrin in sandy soils is to slow down carbofuran's movement through the soil by adjusting how it interacts with water and soil particles.

It is mainly through its inclusion complexation that β-cyclodextrin affects carbofuran desorption. The non-polar portions of carbofuran molecules are encapsulated by the hydrophobic cavity of β-Cyclodextrin, which reduces their direct contact with soil particles. since of this interaction, carbofuran may be more easily released into the soil solution since the adsorption forces that bind it to the soil are less. In addition, β-cyclodextrin's hydrophilic surface improves carbofuran's solubility in water, which in turn increases its mobility in soil. Soil textural qualities affect the magnitude of these effects because soil composition affects the availability of adsorption sites and the intensity of soil-pesticide interactions.

There are important implications for tactics for environmental remediation related to the effect of β-cyclodextrin on carbofuran desorption. Improving carbofuran desorption in polluted soils can speed up its removal by increasing its bioavailability to soil microorganisms that can degrade it, or by leaching it out of the soil. To avoid accidental groundwater or nearby ecosystem pollution, it is crucial to properly regulate carbofuran's enhanced mobility. To maximize its effectiveness in soil remediation, it is crucial to comprehend how β-cyclodextrin interacts with the textural qualities of soil.

Several significant results have been brought to light by experimental investigations into the impact of β-cyclodextrin on carbofuran desorption. The presence of β-cyclodextrin in soils rich in clay greatly improves the desorption of carbofuran, counteracting the strong adsorption forces linked to clay minerals and organic substances. Because it interferes with carbofuran's interaction with soil particles, the inclusion complexation process is responsible for this impact. Research has demonstrated that β-cyclodextrin can enhance carbofuran's solubility in sandy soils, leading to its better dispersion throughout the soil solution. The impact of β-cyclodextrin on desorption is not as significant in sandy soils as in clayey soils due to the sandy soils' lesser adsorption capability.

Environmental parameters including pH, temperature, and the existence of competing ions also impact the effect of Ή-cyclodextrin on carbofuran desorption. To regulate the interaction between carbofuran, β-cyclodextrin, and soil particles, soil pH is very important. Carbofuran has a lower desorption potential in acidic soils because it binds to soil particles more firmly there. Under these circumstances, β-cyclodextrin may form stable inclusion complexes with carbofuran, which greatly improves desorption. Even though β-cyclodextrin's effect on desorption may be less noticeable in alkaline soils where carbofuran shows less adsorption, it can nevertheless enhance the pesticide's mobility and bioavailability.

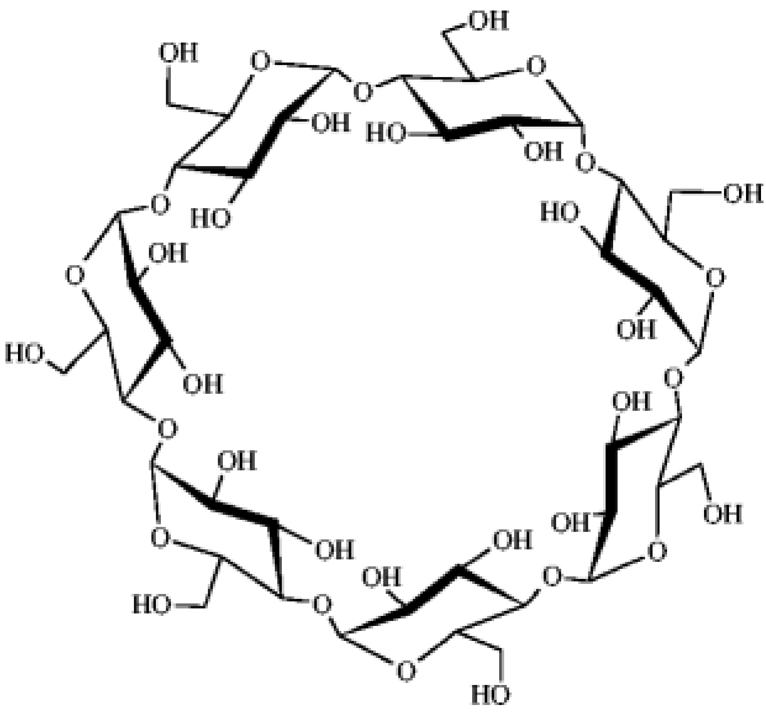
One more thing that affects desorption is temperature. Carbofuran and β-cyclodextrin can experience enhanced molecular mobility at higher temperatures, leading to better interaction and the promotion of inclusion complex formation. Especially in highly adsorbent soils, this action can cause desorption rates to spike. The desorption process can be impacted by competing ions in the soil solution, which disrupt the interaction between carbofuran and β-cyclodextrin. As an illustration, the availability of carbofuran for complexation with β-cyclodextrin might be affected by multivalent cations like magnesium and calcium, which can compete for adsorption sites on soil particles.

A detailed comprehension of these interactions and their effects on the environment is necessary for the use of β-cyclodextrin in soil systems that have different textural characteristics. Aside from aiding carbofuran desorption, β-cyclodextrin has the ability to affect the pesticide's breakdown processes. The persistence of carbofuran in the soil can be decreased by making it more susceptible to microbial breakdown, which β-cyclodextrin achieves by making it more soluble and bioavailable. Groundwater and non-target habitats might be contaminated due to the higher mobility of carbofuran when β-cyclodextrin is present. To effectively establish remediation techniques that take advantage of β-cyclodextrin's advantages while reducing its hazards, it is crucial to balance these factors.

2. STRUCTURE OF β-CYCLODEXTRIN

Of the several cyclic oligosaccharides called cyclodextrins, β-Cyclodextrin (β-CD) is among the most significant. The glucose units that make up these starch-derived natural chemicals are linked together by α-1,4-glycosidic linkages. One important thing about β-cyclodextrin is that it can form inclusion complexes with many different types of guest molecules. This makes chemicals that aren't very soluble or stable better able to dissolve in water and increase their bioavailability. The remarkable capacity of β-cyclodextrin to trap hydrophobic molecules in its hydrophobic cavity renders it indispensable in a wide range of industries, including cosmetics, medicines, food, agriculture, and environmental remediation. Gaining knowledge about the structure of β-cyclodextrin is essential for its practical use, as its unique ability to serve as a molecular host is influenced by its conical shape, which is hydrophilic on the outside and hydrophobic on the inside.

Central to β-cyclodextrin is a cyclic structure that is made up of seven D-glucose units. Like starch and other polysaccharides, these glucose units are connected by α-1,4-glycosidic linkages. The stability of the link between the glucose monomers is ensured by this sort of bond, which provides the foundation for the cyclodextrin ring. The β-cyclodextrin takes on a truncated cone-like shape due to the cyclic arrangement of the glucose residues, which leads each glucose unit to assume a chair conformation. The hydrophobic cavity of β-CD, which may contain guest molecules with sizes between 4 and 7 Å, is formed by this ring structure, which is essential. At the C-2, C-3, and C-6 locations, β-cyclodextrin has several hydroxyl (-OH) groups connected to the glucose units, making its external surface hydrophilic. Many of β-CD's uses, especially in medicine administration and food preservation, rely on its solubility in water, which is made easier by these hydroxyl groups.



Thanks to its unique arrangement of hydroxyl groups and the way glucose units are arranged in β-cyclodextrin, this molecule is very water-soluble, which makes it a useful component for improving the solubility and stability of other substances. But since it is non-polar and hydrophobic, the interior cavity enables β-cyclodextrin to encase molecules that are either hydrophobic or lipophilic. The inclusion complexation process is the foundation of several β-CD uses, since the cavity of β-CD may efficiently encase guest molecules such medicinal medicines, tastes, perfumes, and environmental contaminants. The dynamic and reversible system may be used for many applications due to the non-covalent interactions, such as hydrogen bonding, van der Waals forces, and hydrophobic contacts, that allow β-CD and guest molecules to interact.

Many guest molecules find the β-CD cavity to be an appropriate host because to its size and structure. Specifically, molecules with poor water solubility may be accommodated in the hydrophobic cavity of β-CD, including aromatic chemicals, steroids, vitamins, and certain medicines. One of the reasons β-cyclodextrin has been used extensively in the pharmaceutical business is its capacity to improve the solubility of compounds that are not very soluble. Oral administration reduces the bioavailability of many medicines, especially hydrophobic ones, due to their poor solubility in the GI tract. Nevertheless, the solubility of these medications may be greatly increased and their absorption in the body improved by encasing them in the β-CD cavity. The food and cosmetics industries also make use of this phenomena; β-cyclodextrin is used to stabilize volatile substances, enhance the delivery of tastes, perfumes, and nutrients, among other uses.

There is room for substantial alteration in the molecular structure of β-cyclodextrin to accommodate certain uses. One way to change the complex's solubility, stability, and selectivity is to tweak the hydroxyl groups on the β-CD molecule's outer surface. The process of derivatizing β-CD may result in the production of derivatives that are either more soluble in water or exhibit greater selectivity for certain guest molecules. This paves the way for novel uses in fields as diverse as medicine delivery and environmental cleaning. In addition, the versatile β-CD compound is further enhanced by the fact that its cavity is not rigid and may be shaped and size-controlled by the surrounding environment and the kind of guest molecule being contained.

The techniques of synthesis and preparation may impact the physical and chemical characteristics of β-CD, along with its intrinsic structure. In most cases, β-Cyclodextrin is made by converting starch into smaller oligosaccharides by the action of cyclodextrin glycosyltransferase (CGTase). This enzyme then facilitates the creation of cyclodextrin rings. Enzymatic synthesis is still the most popular technique for synthesizing β-CD because of its specificity and the moderate reaction conditions, however alternative approaches include chemical procedures or the modification of other kinds of cyclodextrins. Purifying β-CD after synthesis eliminates contaminants and allows for further modification to improve its functional characteristics.

Due to its structural flexibility, β-cyclodextrin may be combined with other chemicals to enhance its performance in certain uses. To illustrate, β-CD may be combined with other materials, grafted onto polymer chains, or added to nanoparticles to produce novel materials with distinct characteristics. These changes may make the material more biodegradable for environmental uses, make the inclusion complexes more stable, or improve the controlled release profiles for medication administration. Many diverse industries have been motivated to innovate by the capacity to adjust the structure of β-CD while keeping its distinctive properties.

β-cyclodextrin may form inclusion complexes with several guest molecules due to its distinctive chemical structure, which makes it an intriguing substance. Numerous uses in the pharmaceutical, culinary, cosmetic, and environmental sectors stem from its conical form, hydrophilic exterior, and hydrophobic interior, which effectively enhance the solubility and stability of hydrophobic substances. Because of its malleable structure, β-cyclodextrin may have its features customized to suit many applications, making it a very useful and flexible molecule. It is probable that additional uses may arise as studies on β-CD's modification and functionalization progress, increasing its potential and influence in many sectors. Understanding the behavior of β-cyclodextrin and finding ways to optimize its application in many scientific and technical domains requires research into its structure and how it interacts with guest molecules.

3. REVIEW OF LITERATURE

Kaur, Paawan & Kaur, Pervinder. (2019). In order to remove imazethapyr and imazamox from soils in an eco-friendly manner, this study aims to create and investigate the potential of chitosan-β-cyclodextrin biocomposites. A UV-Visible spectrophotometer was used for characterization after the biocomposites were synthesized with an ultrasonic aided method. We used liquid chromatography tandem mass spectrometry to quantify imazethapyr and imazamox. The examined soils showed a significant influence of soil parameters on adsorption, as indicated by the adsorption capacities of imazethapyr and imazamox, which varied from 0.12 to 1.22 and 0.02 to 1.01 μg1-ng-1mLn, respectively ($p < .05$). At high quantities (1.0 and 10 μg mL-1), distilled water was only able to desorb 1.23 to 5.48 and 3.11 to 8.63% of adsorbed imazethapyr and imazamox, respectively. As with herbicides, at low concentrations (0.01 and 0.1 μg mL-1) they were not desorbed. The sequential extraction cycle, type and concentration of extractant, contact time, liquid to soil ratio, temperature, and biocomposites of β-cyclodextrin and chitosan were some of the factors studied in an effort to remove imazethapyr and imazamox from soils. The removal rate of herbicides from the soils under study ranged from 59.42% to 99.44% at an initial herbicide concentration of 0.01 to 10 μg mL-1, while utilizing a low molecular weight chitosan-β-cyclodextrin biocomposite (LCD) under ideal conditions. Inceptisol 3 had the greatest imazethapyr and imazamox removal rate, followed by entisol, inceptisol 2, aridisol, inceptisol 1, vertisol, and alfisol. This is likely because the herbicide-soil interactions were influenced by the varied physico-chemical properties of the soil. In light of these findings, LCD can be considered a safe and effective in situ green extracting agent for cleaning up soils polluted with imazethapyr and imazamox.

Flaherty, Ryan et al., (2013) The affinity capillary electrophoresis was used to measure the binding constants of seven commonly used pesticides (2,4-D, acetochlor, alachlor, dicamba, dimethenamid, metolachlor, and propanil) with native and derivatized cyclodextrins (α-CD, β-CD, γ-CD, hydroxypropyl-β-CD, methyl-β-CD, sulfated-β-CD, and carboxymethyl-β-CD). With the exception of sulfated-β-CD, which had very weak binding to acetochlor, alachlor, and metolachlor, all seven pesticides studied shown substantial binding interactions with the cyclodextrins. The cyclodextrins showed the strongest binding of propanil in this investigation. It was also determined if cyclodextrins could remove these herbicides from polluted soil. There was a general relationship discovered between the percent extraction improvements and the pesticide-cyclodextrin binding constants. Soluble pesticide-cyclodextrin complexes with a Type AL solubility diagram were often the result of aqueous cyclodextrin extraction of soil pesticides. In general, hydroxypropyl-β-CD and methyl-ŗ-CD showed the highest degrees of enhancement in extraction. Type BS solubility diagrams were created in these soil extraction tests due to the relatively intractable pesticide-cyclodextrin complexes formed by most pesticides with γ-CD (and a few instances with α-CD and β-CD). This means that compared to the control (1.0 mM phosphate at pH=7.0), the observed aqueous extraction level for the pesticide-cyclodextrin combinations was lower. Future innovative approaches to remediating polluted soil might benefit from this study's findings by avoiding the drawbacks of using organic solvents and surfactants. Furthermore, research into binding might be useful in creating pesticide-cyclodextrin combinations.

Singh, R.P et al., (2011) The purpose of the laboratory investigations was to use a batch equilibrium approach to find the carbofuran adsorption/desorption equilibrium between four soils with different textures and distilled water or an aqueous solution of $0.01\,mol\,L^{-1}$ β-cyclodextrin. Isotherms for adsorption were found to be L-shaped for silt loam soils and S-shaped for sandy loam soils, which coincide with Freundlich isotherms. Carbofuran adsorption to the four soils was reduced when β-cyclodextrin was present compared to pure water. The use of distilled water resulted in positive hysteresis in all soils, whereas a solution of β-cyclodextrin as a desorbent produced negative hysteresis. The findings suggest that β-cyclodextrin might be useful in cleaning up soils that have been polluted by pesticides.

Singh, R. et al., (2009) Researchers in India used batch equilibrium and soil thin layer chromatography (soil TLC) to study the adsorption and mobility of carbofuran on four different textured soils at a constant volume fraction (fs = 0.1) of methanol/water mixtures. The Freundlich isotherm matched the observed equilibrium adsorption isotherms for all three types of soils: silt loam (FSL and ASL), loam (KL) and sandy loam (BSL). According to the values of the Freundlich constant (KF) and partition coefficient (KD), the order of carbofuran adsorption was as follows: FSL, ASL, KL, and BSL soils. Soil TLC experiments showed that KF and KD values were inversely related to the Frontal Retardation factor (FRf) values. The KOC, KOM, and KC values were used to assess the carbofuran's affinity for the soil's organic carbon, organic matter, and clay content. Adsorption of carbofuran onto the soils investigated was found to be spontaneous, as evidenced by the negative magnitude of the Gibbs'free energy (ΔG°). Carbofuran has a high LI for soils that might seep into shallow aquifers and groundwater, according to the soils that were tested. A very significant link was seen when Pearson's correlations were computed for KF and KD against the soil characteristics and the soil's clay + silt concentration. Soil pH was the second most important factor in determining carbofuran adsorption, after the mineral composition of the soil (clay and clay + silt), according to multiple regression of KF and KD against the soil parameters. Using carbofuran's aqueous solubility, the 1-octanol/water partition coefficient (KOW), the adsorbability index (AI), and the first-order molecular connectivity index (1χ), the predicted log KOM values were also assessed. The amount of adsorption could be more accurately predicted by using the adsorbability index (AI) and the first-order molecular connectivity index (1χ) of carbofuran, as opposed to relying on the aqueous solubility and the 1-octanol/water partition coefficient (KOW), which produced significantly off-base results when compared to experimental measurements.

Fenyvesi, Éva et al., (2009) The article discusses soil-remediation methods that can improve the transport and availability of contaminants by using cyclodextrins. Because of problems in effecting the movement of the pollutants, soil-remediation procedures are not very effective. Solubilizing chemicals, such as cyclodextrins and surfactants, promote desorption of pollutants from soil, allowing them to concentrate in the aqueous phase and facilitate transport. Due to the enhanced water solubility, the KoCD values used to describe the octanol/aqueous cyclodextrin partition are consistently lower than the Kow values. Using cyclodextrins as a solubilizer can enhance several processes, including soil washing, electrokinetic remediation, permeable reactive barrier technology, phytoremediation, and microbial degradation, among others. Cyclodextrins are more advantageous to soil biota than synthetic surfactants since they are non-toxic and biodegradable. In addition to pollutants (which serve as microbial substrates), they have the ability to dissolve co-metabolites and organic nutrients. On the other hand, non-target species may potentially be exposed to pollutants to a greater extent when solubilizers raise the bioavailability of contaminants.

Villaverde, Jaime & Maqueda et al., (2006) Researchers looked at how applying beta-cyclodextrin (BCD) at the same time as herbicide norflurazon (NFL) affected the sorption-desorption and transport processes in soils with various properties. Using a batch equilibration approach, NFL was adsorption-desorption tested on six diverse soils with BCD, and its mobility in uniformly packed soil columns was associated with the results. The NFL measurements were carried out using high-performance liquid chromatography (HPLC) with a 220 nm diode array detector. Fluorimetric detection employing a postcolumn reaction was also used for BCD analysis in HPLC. A solution-based inclusion complex was produced by NFL's interaction with BCD. Soil applications of this combination resulted in a significant reduction in NFL adsorption capacity and an increase in desorption, likely as a result of the increased solubility of NFL-BCD complexes. Adsorption and soil column tests showed that BCD's effect on NFL availability and mobility is concentration and property dependent, with varying affinities for sorbed BCD on various types of soils. Soil particles are coated with BCD molecules, which bind to the soil more firmly at lower concentrations. This coating connects the soil surface to the NFL, which functions as an adsorbent and slows down the herbicide's movement. In soils with little adsorption or at greater concentrations of BCD, the majority of the BCD molecules are in the aqueous phase, and NFL molecules form complexes with BCD in solution, which helps to dissolve it.

Jozefaciuk, Grzegorz et al., (2003) Although cyclodextrins are being used in more and more soil remediation methods, very little is known about how they affect the physical qualities of soil. Research has shown that RAMEB, a well-liked addition for soil remediation, may drastically change the surface and pore characteristics of clay minerals in soil. Soil samples were chosen to reflect a broad range of clay contents (3-49%), and the impact of different RAMEB dosages on physical attributes was investigated in this work. Rameb treatment significantly altered the soil's physical qualities, according to the findings. Results from water vapor adsorption isotherm analyses showed that RAMEB enhanced water adsorption and surface area on sandy soils while decreasing them on clayey soils. Soils treated with RAMEB showed an increase in water adsorption energy, suggesting that nonpolar contaminants may be removed more effectively. At concentrations of 1% RAMEB and higher, water vapor desorption isotherms revealed an increase in micropore volumes and radii in the nanometer range. A rise in fractal dimensions indicates that the micropores become rougher and more complex after RAMEB therapy. As the concentration of RAMEB grew, the volume of soil mesopores as assessed by mercury intrusion porosimetry (micrometers range) reduced in most soils, but the average mesopore radius increased. This suggests that RAMEB was blocking smaller mesopores. Soil granulometric composition measurements using sedimentation analysis revealed an increase in coarse-size soil fractions at the expense of finer fractions as a result of particle aggregation; the clay content and dosage of cyclodextrin influenced the behavior of the studied soils following RAMEB treatment. Strong interactions between cyclodextrins and the solid phase of clay-rich soils dictated the soil's subsequent characteristics. The overabundance of cyclodextrin, which did not interact with clays, was the most important factor in soils that were low in clay. Soil remediation methods may be greatly impacted by RAMEB's ability to modify surface, pore, and aggregation soil characteristics.

4. MATERIAL AND METHODS

Soil Collection and Characterization

The purpose of collecting soil samples from three different agricultural sites, which included sandy, loamy, and clayey soil types, was to assess the impact of β-cyclodextrin (β-CD) on carbofuran desorption. In order to guarantee that the study included a wide range of soil physicochemical qualities often seen in agricultural environments, these locations were chosen. To maintain the integrity of the samples and keep them true to their original state, they were treated with extreme care during collection.

To reduce moisture content while preserving the integrity of organic matter and mineral components, the soils were air-dried at room temperature after collection. Following drying, the samples were passed through a 2 mm mesh filter to exclude larger soil aggregates, rocks, and trash. The materials were sieved to achieve a constant particle size, which led to more reliable experimental results. Analysis was conducted on important soil parameters like pH, organic matter content, cation exchange capacity (CEC), and texture, which includes percentages of sand, silt, and clay. These factors are essential for comprehending how carbofuran and β-CD interact with soil. For example, hydrophobic chemicals tend to be poorly retained in sandy soils (high sand content, low organic matter) compared to clayey soils (high clay content, organic matter).

Desorption Studies

The influence of β-CD on the release of carbofuran from the soils was investigated by batch desorption tests. In each experiment, a specific kind of soil was mixed with 50 mL of a carbofuran solution (10 mg/L) in a clean, inert container to prevent contamination or unwanted responses. To ensure applicability to real-world circumstances, the carbofuran concentration was chosen based on its average application rates in agricultural activities.

A range of β-CD concentrations (0, 5, 10, 15, and 20 mM) were introduced to the mixture in order to assess its effect on carbofuran desorption. To comprehend the influence of β-CD on desorption efficiency that is dose-dependent, these concentrations were selected. The mixes were mechanically mixed thoroughly after the addition of β-CD to make sure that carbofuran and β-CD were distributed evenly throughout the soil. After the ingredients were combined, the containers were tightly sealed and shook at a steady 25°C for a whole day. In order to keep things consistent between tests, we chose this temperature to reflect the ambient temperatures found in agricultural settings.

To isolate the soil particles from the liquid phase, the mixtures were centrifuged at the correct speed for the specified amount of time after the shaking phase. Careful extraction of the water-based supernatant containing the adsorbed carbofuran was followed by HPLC analysis of the carbofuran content. The selectivity, specificity, and accuracy of HPLC in quantifying carbofuran at low concentrations led to its selection. By comparing the concentration of carbofuran in the supernatant to the original concentration, the desorption percentage was obtained.

Data Analysis

A thorough study was performed on the data collected from desorption investigations in order to measure the effectiveness of carbofuran desorption and to comprehend the processes involved. To evaluate the correlation between β-CD levels and desorption efficiency, desorption percentages were computed for every soil type and β-CD concentration group. Moreover, in order to assess the binding affinity of carbofuran for the soil matrix when β-CD was present, distribution coefficients (Kd) were calculated, which characterize the equilibrium partitioning of carbofuran between the soil and inert phases.

Fitting the experimental data to pseudo-first-order and pseudo-second-order kinetic models helped to clarify the kinetics of carbofuran desorption. These models explain the stages that determine the rate of desorption, whether those steps are controlled by chemical interactions between β-CD and carbofuran molecules (pseudo-second-order) or by diffusion processes (pseudo-first-order). The coefficient of determination (R^2) was used to evaluate the quality of fit for each model. A more robust identification of the primary desorption process is possible with higher R^2 values, which show that the model and experimental data are more in accord.

5. RESULTS AND DISCUSSION

Table 1: Properties of soil

Soil Type	pH	Organic Matter (%)	CEC (cmol/kg)	Sand (%)	Silt (%)	Clay (%)
Sandy	6.5	0.8	3.1	85.2	10.3	4.5
Loamy	6.8	1.4	12.6	43.5	38.0	18.5
Clayey	7.2	2.5	25.7	20.1	34.8	45.1

Sandy soil has a minimum cation exchange capacity (CEC) of 3.1 cmol/kg, a low organic matter concentration of 0.8%, and a slightly acidic pH of 6.5, according to the data in Table 1. The coarse texture is caused by the composition, which is mostly sand (85.2% of the total) with trace quantities of silt (10.3%) and clay (4.5%). Sandy soil is more suited for desorption because of its low organic matter and CEC, which together show a decreased capacity to hold carbofuran. Loamy soil, on the other hand, has a greater CEC of 12.6 cmol/kg due to its modest organic matter level (1.4%) and near-neutral pH of 6.8.

The proportions of sand, silt, and clay are evenly distributed, making for a well-balanced texture. Because of these features, loamy soil has intermediate properties for adsorption and desorption. Soil rich in clay has a high CEC (25.7 cmol/kg), organic matter concentration of

2.5 percent, and pH of 7.2, all of which attest to its powerful adsorption ability. Due to its tiny particles and excellent retention qualities, clayey soil is the most resistant to carbofuran desorption. Its texture is mostly composed of clay and silt, with minor sand content.

Table 2: Desorption Efficiency

β-CD Concentration (mM)	Sandy Soil (% Desorption)	Loamy Soil (% Desorption)	Clayey Soil (% Desorption)
0	12.3 ± 1.5	9.8 ± 1.2	6.5 ± 1.0
5	25.6 ± 2.0	21.3 ± 1.8	15.8 ± 1.4
10	38.7 ± 2.3	34.2 ± 2.1	27.5 ± 2.0
15	52.1 ± 2.5	47.9 ± 2.4	40.8 ± 2.3
20	64.8 ± 2.8	59.6 ± 2.5	52.3 ± 2.6

Table 2 shows that carbofuran desorption was negligible in the absence of β-CD (0 mM). Desorption efficiency was greatest in sandy soil at 12.3%, followed by loamy soil at 9.8%, and clayey soil at 6.5%. All kinds of soil showed a significant improvement in desorption as the β-CD content rose, although sandy soil showed the most noticeable benefit. Desorption efficiency for sandy soil increased to 25.6%, for loamy soil to 21.3%, and for clayey soil to 15.8% at 5 mM β-CD. In contrast to sandy soil, which attained 64.8% desorption efficiency at the highest β-CD concentration of 20 mM, loamy soil reached 59.6%, and clayey soil 52.3%.

Table 3: Desorption Kinetics

Soil Type	Pseudo-First-Order (R^2)	Pseudo-Second-Order (R^2)
Sandy	0.89	0.95
Loamy	0.85	0.93
Clayey	0.82	0.91

Table 3's data offers valuable information. With R^2 values of 0.89 for pseudo-first-order and 0.95 for pseudo-second-order, sandy soil stood out among the other soil types. This indicates that its desorption dynamics are reasonably uncomplicated, perhaps because it has a low adsorption potential. The pseudo-second-order model showed a moderate adsorption-desorption behavior with a R^2 value of 0.93 while the pseudo-first-order model had a R^2 value of 0.85 for loamy soil. Based on its finer texture, greater organic matter content, and stronger adsorption capability, clayey soil has a more complicated desorption process, as shown by its lowest R^2 values of 0.82 for pseudo-first-order and 0.91 for pseudo-second-order.

6. CONCLUSION

β-cyclodextrin (β-CD) is an impressive molecule with many uses in many fields because of its one-of-a-kind chemical structure and ability to form inclusion complexes. Its adaptability is demonstrated by its capacity to encapsulate various guest molecules in its hydrophobic cavity while maintaining solubility in water-based settings. The pharmaceutical sector has utilized β-CD to enhance the bioavailability, stability, and solubility of pharmaceuticals that are not very water-soluble. This has allowed for the creation of more potent therapeutic agents with controlled release mechanisms. In novel food formulations, β-CD helps improve flavor, stability, and shelf life, while also hiding off-putting smells and cutting down on fat. By stabilizing and limiting the release of pesticides, β-CD helps agricultural activities, which in turn reduces pollution and improves crop protection efficiency. In addition, β-CD is a sustainable tool for environmental remediation due to its non-toxic and biodegradable properties, which help remove organic contaminants and improve biodegradation.

The enormous potential of β-CD isn't without its obstacles, such the fact that it doesn't dissolve well in water and that stable complex formation relies on guest molecule compatibility. These constraints are being addressed by advancements in the synthesis of β-CD derivatives with improved solubility and functionality, which is leading to more efficient and focused uses. The future path of β-CD development is its incorporation into innovative disciplines including nanotechnology, customized medicine, and sustainable environmental practices. With the continuous research into its applications, β-CD is set to continue playing a crucial role in solving some of the biggest scientific and industrial problems of our day, solidifying its position as a foundational material for innovation and sustainability.

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