CHAPTER- IX

Self assembly inclusion of ionic liquid into hollow cylinder oligosaccharides

IX. 1. INTRODUCTION

Cyclodextrins are hollow cylinder cyclic oligosaccharides containing six (α-CD), seven (β-CD) and eight (γ-CD) glucopyranose units, which are bound by α-(1–4) linkages forming a truncated conical structure, which have a hydrophobic interior and hydrophilic rims having primary and secondary *–OH* groups [1]. Because of having unique structure, they can build up host-guest arrangement, *i.e.*, it can accommodate the hydrophobic moiety of a guest molecule into its hydrophobic cavity as well as the polar rims can stabilize the polar part of the guest, if any (e.g. ionic liquid) [2]. There has been an increasing attention in the use of cyclodextrins as a device for controlled liberation of active compounds due to their outstanding capability to form molecular inclusion complexes with hydrophobic guest molecules. It is well known that CDs are cyclic oligosaccharides of six to eight glucose units linked by α-1,4-linkages, which are known as α-, β- and γ-CD, respectively. Due to this special property, CDs have been used widely in pharmaceuticals, pesticides, foodstuffs, toilet articles, and textile processing [3,4]. In addition to these industrial applications, they are related to many interesting topics, such as molecular recognition, self assembly, selectivity, molecular encapsulation, chemical stabilization, and intermolecular interactions [4,5]. In an aqueous solution, the slightly apolar cavity of cyclodextrin is occupied by a small quantity of water molecules that are energetically unfavoured and therefore can be readily substituted by appropriate guest molecules that are less polar than water. The guest molecule prefers to penetrate the empty cavity, leading to the formation of an inclusion complex through host-guest interactions. In recent years, with increasing interest in macromolecular

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recognition, ICs of polymers with CDs have been investigated extensively [6-14]. So-called molecular necklaces may be formed through penetrating CD molecules by a polymeric chain [15,16]. Moreover, lots of organometallic compounds also can form inclusion compounds with CDs [17,18]. Based on the well-known representative structure of α-, *β*- and *γ*-CDs, many different derivatives have been synthesized, which possess different inclusion capabilities [19,20].

Ionic liquids (ILs) are nonvolatile, nonflammable and thermally stable solvents, and also very promising replacements for the traditional volatile organic solvents. Their quite rapid emergence as alternative solvents has involved a rapidly growing number of examples of the application such as organic synthesis, chemical reactions, chemical separations, and material preparations [21,22]. ILs are composed of sterically mismatched ions that hinder crystal formation, thus molecular structure can be used to tune physicochemical properties. The design and synthesis of functional ILs that incorporate structural or functional groups have been reported. For example, ILs was designed as oriented solvents which could impact selectivity in reactions by ordering reactants [23]. Furthermore, functional ILs were also used as templates for the synthesis of mesoporous and zeolitic materials [24] and in the formation of ordered thin films [25,26]. Recently, ILs having a long alkyl chain group exhibited surface active properties in their aqueous solutions. These IL surfactants have been investigated by surface tension measurements [27-30]. There have been few reports on the combination of CDs and ILs. Qi et al. have used ILs as running electrolytes in capillary zone electrophoresis and CDs as a modifier for the separation of anthraquinones extract of Chinese herb [31]. Moreover, CDs or their derivatives dissolved in IL can be used to prepare stationary phases in gas chromatography [32]. Considering the special structures and properties of IL surfactant (Zwitterionic detergent used for protein solubilization), it is of interest to investigate their complexation behaviour using different techniques.

In this work, we investigated the hydrophobic and hydrophilic interfaces between oligosaccharides such as *α*- and *β*-CD and IL surfactant viz. n-dodecyl-n n-dimethyl-3-ammonio-1-propanesulfonate.

IX. 2. EXPERIMENTAL

IX.2.1 Materials

The considered compounds i.e. IL and oligosaccharides such as α- and β-cyclodextrins of puriss grade were procured from Sigma-Aldrich, Germany and used as purchased. The mass fraction purity of IL, α- and β-cyclodextrins was ≥ 0.99, 0.98 and 0.98 respectively.

IX.2.1 Apparatus and procedure

Solubility of the chosen cyclodextrin in water (deionized, triply distilled, degassed water with a specific conductance of 1×10^{-6} S·cm^{-1}) and IL in aqueous α- and β-cyclodextrin, have been precisely checked to prior of the start of the experimental work, and seen that the selected IL soluble in all proportion of aq. α- and β-cyclodextrin. Aqueous binary solution of IL was prepared by mass (Mettler Toledo AG-285 with uncertainty ±0.0003g), and then the working solutions were obtained by mass dilution at 298.15 K. The conversion of molarity into molality was accomplished using experimental density values. All solutions were prepared afresh before use. The uncertainty in molality of the solutions is evaluated to ±0.0001 mol kg^{-3}.

The surface tension experiments were done by platinum ring detachment method using a Tensiometer (K9, KRŰSS; Germany) at the experimental temperature. The accuracy of the measurement was within ±0.1 mN·m^{-1}. Temperature of the system has been maintained by circulating auto-thermostated water through a double-wall glass vessel containing the solution.

The conductance measurements were carried out in a Systronic-308 conductivity meter (accuracy ± 0.01 %) using a dip-type immersion conductivity cell, CD-10, having a cell constant of approximately (0.1 ± 0.001) cm^{-1}. Measurements were made in a

water bath maintained within T = (298.15 ± 0.01) K and the cell were calibrated by the method proposed by Lind et al [33]. The conductance data were reported at a frequency of 1 kHz and the accuracy was ±0.3%.

IX.3. RESULTS AND DISCUSSION

IX.3.1. Surface tension:

It was reported that the IL with a long alkyl chain was surface active in aqueous solutions [34]. Then, if long alkyl chain IL can form inclusion complexes (ICs) with α- and β-CD, the surface tensions of their solutions would be distinctly affected by the addition of α- and β-CD. Therefore, surface tension measurements can be used to elucidate not only whether inclusion can happen or not but also the stoichiometry of inclusion complexes. The surface tension of aqueous solution of IL surfactant with various α- and β-CD concentrations were measured respectively, and the dependence of the surface tensions on α- and β-CD concentrations is shown in Figure IX.1 respectively. It is found that no remarkable change happens for the surface tensions of pure water when α- and β-CD is added (not shown here), indicating that α- and β-CD have no effect on the surface tensions of pure water. Thus, one may presume that the remarkable changes of surface tensions of aqueous solutions of IL surfactant are ascribed to the formation of the ICs. For aqueous solution of surface active ionic liquid (SAIL) the surface tensions increase remarkably with increasing concentration of α- and β-CD, indicating the formation of inclusion complexes between α- and β-CD and the IL surfactant.

The surface tensions (γ) with corresponding concentration of IL in different mass fraction [0.001, 0.003 and 0.005(M) respectively] of aq. α- and β-CD have been made at the temperature 298.15K. Each curve clearly shows a break point in surface tension at a certain concentration, that is, the γ values increase with corresponding concentration, reach a certain point (break point), and then become approximately steady, which obviously indicates the formation of inclusion complex. The formation of inclusion complexes is accountable for insertion of the hydrophobic (aliphatic) group of chosen

ionic liquid insight into the cavity of α- and β-CD. Single break, double break, and so on in the curve of surface tension indicate inclusion complex may have in different stoichiometries, like 1:1, 1:2, and so on (Scheme IX.2) ratios of CD and IL respectively. Since we noted in Figure XI.1, each curve shows a single break point, which further suggests that 1:1 inclusion complexes are formed.

For the aqueous solution of DDAPS, the surface tension values increase gradually with increasing the concentration of α- and β-CD (Figure IX.1), indicating the formation of inclusion complexes between α- and β-CD and DDAPS. For the SAIL the change in γ is suppressed with the increasing mass fraction of aq. α- and β-CD compared to aq. ionic liquid, i.e., the break point comes at the lower concentration of respective ionic liquid as well as the γ values come closer to that of aq. CDs, suggesting that inclusion becomes feasible with increasing amount of CD in solution. If we compare between aq. α-CD and β-CD, both the values of γ and concentration at the break point are lower in case of aq. β-CD than that of aq. α-CD (Table IX.1). This is evidently due to the fact that β-CD provides more viable attribute (either size or cavity diameter and volume) for formation of feasible inclusion complex than α-CD. The study ionic liquid, thus, form soluble 1:1 complexes with both the cyclodextrin in which we visualize the nonpolar tail group of the ionic liquid to be inserted via the wider rim, so as to make maximum contact with the cyclodextrin cavity (Scheme IX.3), while the charged polar head residue remains in the wider rim of cyclodextrin or in bulk solution. This is due to the fact that DDAPS has a long hydrophobic tail, thus a larger steric inhibition for penetrating into the cavity of α- and β-CD. Then after the addition of aqueous α- and β-CD, the number of α- and β-CD molecules increase with respect to the fixed number of ionic liquids, can pull or attract partially encapsulated hydrophobic tail of cationic part of IL; therefore, at the break point the hydrophobic tail group of DDAPS molecule is included into the apolar cavity of α- and β-CD molecule (Scheme IX.4) and finally form equimolar 1:1 inclusion. In consequence, it can be deduced that hydrophobicity plays an important role in the formation of inclusion complexes. Thus, the surface tension measurements indicate that the long chain tail of IL was included in the α- and β-CD

molecules. The studied IL, thus, form soluble 1:1 complexes with the cyclodextrin in which we visualize the nonpolar tail group of the IL to be inserted via the wider rim, make more contact with the cyclodextrin cavity, while the charged polar head residue remains in the wider rim of cyclodextrin or in bulk solution (Scheme IX.4). The hydrophilic part of the IL remains outside and can make H-bonds with the hydrophilic rim of cyclodextrin and also surrounded by water molecules.

If we compare between aq. α-CD and β-CD, both the values of γ and concentration at the break point are lower in case of aq. β-CD than that of aq. α-CD for SAIL (Scheme IX.5). This is obviously due to the fact that β- CD are provided more viable feature (either size or cavity diameter and volume) for formation of feasible inclusion complex than α-CD. Therefore, it can be deduced that hydrophobicity plays an important role in the formation of inclusion complexes. It has been reported that the choice of anion determines water miscibility and has the most dramatic effect on the properties of IL*s* [35]. IL*s* containing the sulphonate anion is very soluble in water, exhibiting a hydrophilic character and in the aqueous solution it pull the movable water molecules towards itself, as a result the cation of studied IL and α- and β-CD molecules are become free to interact each other in the solution which form the inclusion complex. It is suggested that the nature of the anion has significant influence on the inclusion complexes.

In general, therefore, there are four energetically favourable interactions that help shift the equilibrium towards the forward (Scheme IX.2) to form the inclusion complex:

- The displacement of exits polar water molecules from the apolar cavity of cyclodextrin.
- The formation of extended hydrogen bonds by the primary and secondary hydroxyl (-OH) groups and rest water molecules that open a face for enter the guest molecule.
- A reduction of the repulsive interactions between the hydrophobic guest and the aqueous environment.

- An increase in the hydrophobic interactions as the guest inserts itself into the apolar cyclodextrin cavity.

Association of the inclusion complex is not a rapid process because large number of water molecules in the surrounding environment is trapped by anionic part of the IL and it has the high charge surface density. The resulting concentration gradient shifts the equilibrium towards the right. (Scheme IX.2)

IX. 3.2. Conductance study:

Conductivity is a constructive method for studying the hydrophobic and hydrophilic interfaces and also inclusion phenomenon. So, it can be used to elucidate not only whether inclusion can occur but also the stoichiometry of the inclusion complexes (ICs) formed. If it forms an inclusion complex with α- and β-CD, the solution conductivity will be specifically affected by the accumulation of α- and β-CD. The conductivity of various α- and β-CD concentrations in aqueous IL are measured at 25^0C, and the dependence of the conductivity on α- and β-CD concentration are shown in Figure IX.2. At a certain concentration in α- and β-CD, the linear decrease of molar conductance with ionic liquid concentration halted rather abruptly to show no or little further decrease with further addition of α- and β-CD, has been treated as the saturation point of the inclusion. From the perusal of Figure IX.2 it is seen that the conductivity of the ionic liquid decreased remarkably with increasing the concentration of α- and β-CD due to inclusion-complex formation between α- and β-CD and the hydrophobic part of IL. The decreasing tendency of the conductance-concentration curve clearly indicating that the α- and β-CD molecule attract or rapture the SAIL molecules one by one, as a results movement of the ionic liquid is restricted and which diminish the conductivity of overall solution system. If we compare between aq. α-CD and β-CD, both the values of conductance and concentration at the break point are lower in case of aq. β-CD than that of aq. α-CD for SAIL (Table IX.2). A discernible break in the conductivity curve occurred at a concentration of about 0.015 $molL^{-1}$ β-CD, suggesting that the stoichiometry of the β-CD–DDAPS ionic compound is equimolar. A

discernible break in the conductivity curve occurred at a concentration of about 0.016 $molL^{-1}$ α-CD, suggesting that the stoichiometry of α-CD–DDAPS ionic compound is equimolar [36]. This indicates that the chief inclusion complex of β-CD and α-CD with IL in this range is 1:1 which indicates that the IL has been almost totally complex. This is also in correlation with the data from surface tension measurement discussing underway, undoubtedly establish that both the CDs have the favorable structure for the formation of inclusion complexes with the above selected IL and also β- CD is more efficient than α-CD in the formation of inclusion complexes with the above selected IL.

Structural influence of Cyclodextrins

Inclusion complex formation is a dimensional fit between host cavity of CD and SAIL molecule (Scheme IX.1). The most notable feature of cyclodextrin molecules (lipophilic cavity diameter of α- and β-CD is 4.7-5.3Å and 6.0-6.5Å respectively) provides a microenvironment into which appropriately sized non-polar moiety enters and form strong inclusion complexes [37] (Scheme IX.4). But, no covalent bonds are broken or formed during formation of the inclusion complex [38]. The main driving force is in aqueous solution the slightly apolar cyclodextrin cavity is occupied by water molecules which are energetically unfavoured (polar-apolar interaction), therefore can be readily substituted by more hydrophobic side chain group of IL molecules less polar than water, to attain an apolar–apolar association and decrease of cyclodextrin ring strain resulting in a more stable lower energy state [39]. One or two cyclodextrin molecules can entrap one or more IL molecules; therefore, the plausible host:guest ratio of the inclusion is 1:1, 1:2, 2:1, and 2:2, or even more complicated association complex, and higher order equilibria exist, approximately always simultaneous (Scheme IX.2). However, the simplest and most frequent case of host:guest ratio is 1:1 and 1:2 by the spirit of molecular encapsulation by α- and β-CD has been observed from surface tension and conductance study. Thus, after inclusion of an ionic liquid molecule, second molecule can trap by the cavity of the cyclodextrin. This is because, the cavity size (Scheme IX.1) and volume, allow two molecules accommodation through the wider or

secondary rim and both the narrow and wider rims are blocked (Scheme IX.3). The inclusion result state that the binding strength of IL- β-CD complex is well fits together on specific local interactions between surface atoms and form strong inclusion than IL-α-CD complex.

Based on these dimensions, the oligosaccharides such as α- and β-cyclodextrins and the selected SAIL can typically form complex with aliphatic side chain. Hence, the positive interfaces occurred to form the inclusion complex by

• The displacement of polar water molecules from the apolar cavity of cyclodextrin.

• Increased number of hydrogen bonds formed as the substituted water, returns to the larger pool.

• A reduction of the repulsive interactions between the hydrophobic group of surface active ionic liquid and the aqueous environment.

• An increase in the hydrophobic-hydrophobic interfaces as the inclusion of surface active ionic liquid itself into the apolar cavity of oligosaccharides.

IX.4. CONCLUSION

The extensive study of surface tension and conductance measurements concludes the hydrophobic interfaces of DDAPS in the apolar cavity of the oligosaccharides such as α and β-cyclodextrins favours the inclusion complex formation. The results point out that the oligosaccharides such as α and β-CD and the selected IL are finally form stable inclusion complexes (ICs) with a 1:1 stoichiometry. They both are promoting to each other due to the soluble nature by the formation of ICs, where α and β-CD molecules adopting a symmetrical conformation, and each glucose unit of α and β-CD being in a similar environment. The inclusion complex formation is more all-embracing in case of β-CD than in α-CD.

Hence, the generous culmination discussed and explained in this exertion exigent the exclusivity of the work and pertinent to the design for sundry applications.

TABLES:

Table IX.1. Values of surface tension at the break point (γ) with corresponding concentration of IL (n-dodecyl-n n-dimethyl-3-ammonio-1-propanesulfonate) in different mass fraction of aqueous α and β-cyclodextrin respectively at 298.15K[a].

mass fraction (w)	conc (m)	γ /mNm^{-1}
n-dodecyl-n, n-dimethyl-3-ammonio-1-propanesulfonate		
w_1=0.001[b]	0.0441	77.81
w_1=0.003[b]	0.0427	77.11
w_1=0.005[b]	0.0421	76.26
w_2=0.001[b]	0.0413	77.67
w_2=0.003[b]	0.0405	77.06
w_2=0.005[b]	0.0381	76.15

[a] Standard uncertainty u is: $u(T)$ =0.01K

[b] w_1 and w_2 are mass fractions of α- and β-cyclodextrin in aqueous mixture respectively

Table IX.2. Values of conductance at the break point (Λ) with corresponding concentration of IL (n-dodecyl-n n-dimethyl-3-ammonio-1-propanesulfonate) in different mass fraction of aqueous α and β-cyclodextrin respectively at 298.15K[a]

mass fraction (w)	conc (m)	Λ (S m^2/mol)
n-dodecyl-n, n-dimethyl-3-ammonio-1-propanesulfonate		
w_1=0.001[b]	0.01615	12.89
w_1=0.003[b]	0.01546	14.89
w_1=0.005[b]	0.01518	17.56
w_2=0.001[b]	0.01892	13.16
w_2=0.003[b]	0.01635	19.52
w_2=0.005[b]	0.01486	19.83

[a] Standard uncertainty u is: $u(T)$ =0.01K

[b] w_1 and w_2 are mass fractions of α- and β-cyclodextrin in aqueous mixture respectively

FIGURES

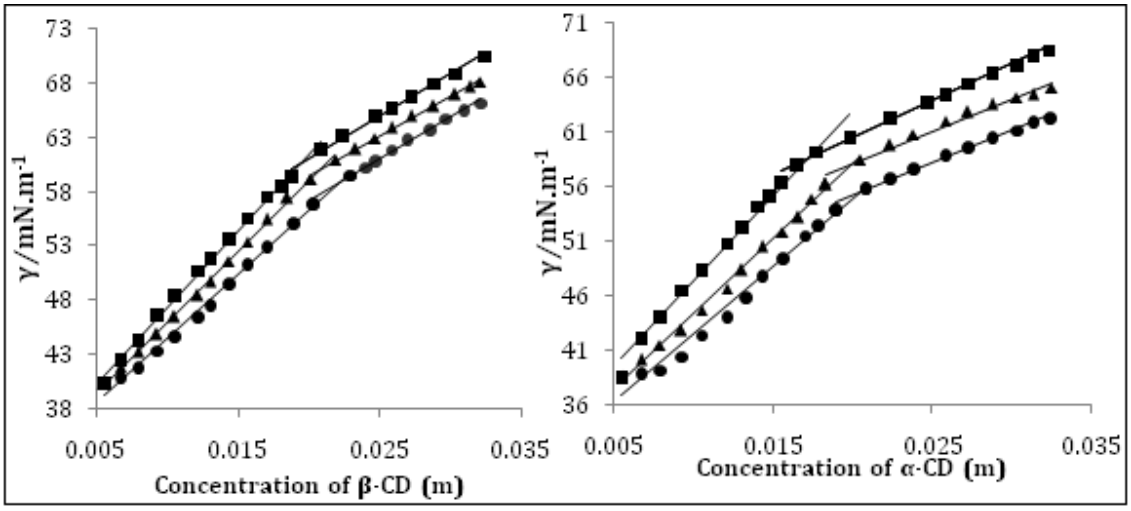


Figure IX.1. **Plot of surface tension (γ) of ionic liquid corresponding to the added conc. of aq. β-CD (*m*) and aq. α-CD (*m*) in w_1=0.001(♦), w_1=0.003(▲), w_1=0.005(●) mass fraction of α-CD.**

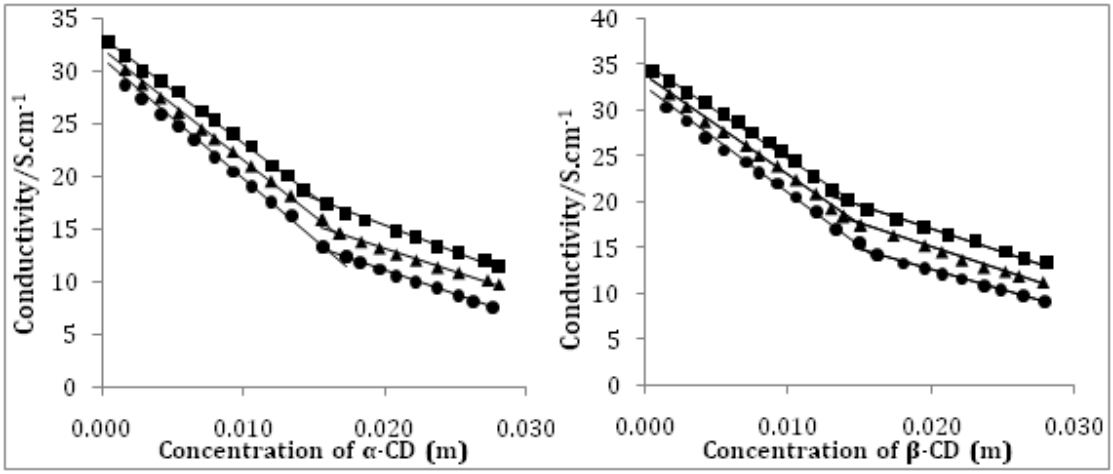
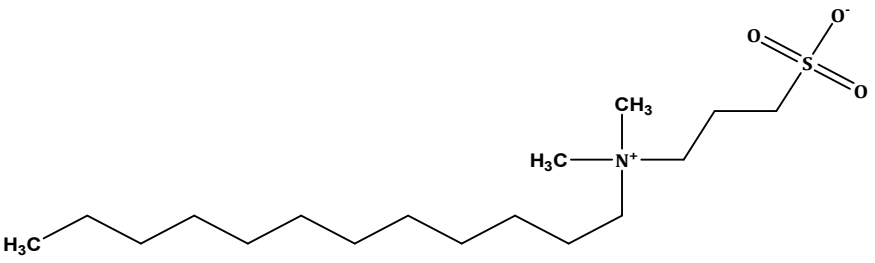
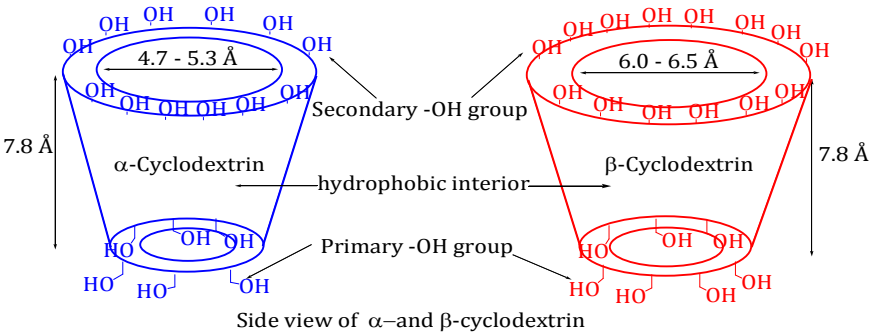


Figure IX.2. **Plot of conductance of ionic liquid corresponding to the added conc of aq. α-CD (*m*) and aq. β-CD (*m*) in w_1=0.001(●), w_1=0.003(▲), w_1=0.005(■) mass fraction of β -CD respectively.**

SCHEMES

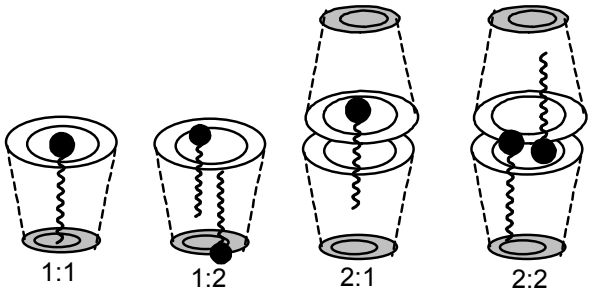


N-dodecyl-N,N-dimethyl-3-ammonio-1-propanesulphonate

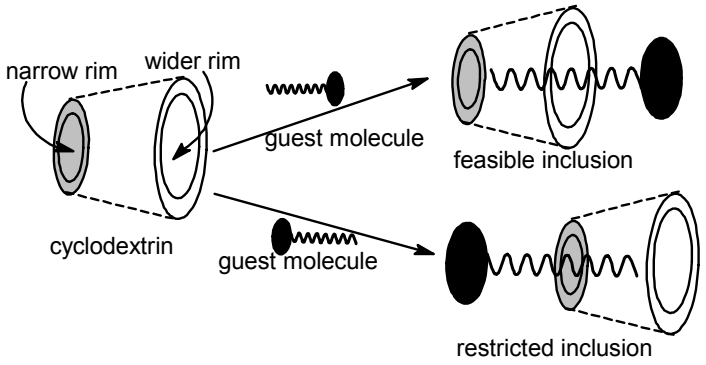


Side view of α–and β-cyclodextrin

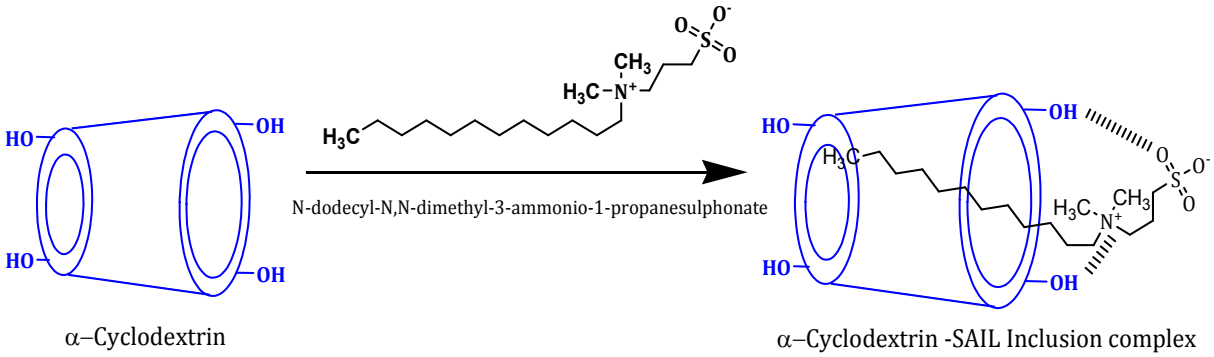
Scheme IX.1: The molecular structure of chosen ionic liquid and α- and β-cyclodextrin (α- CD 6 membered and β-CD 7 membered sugar ring molecules).

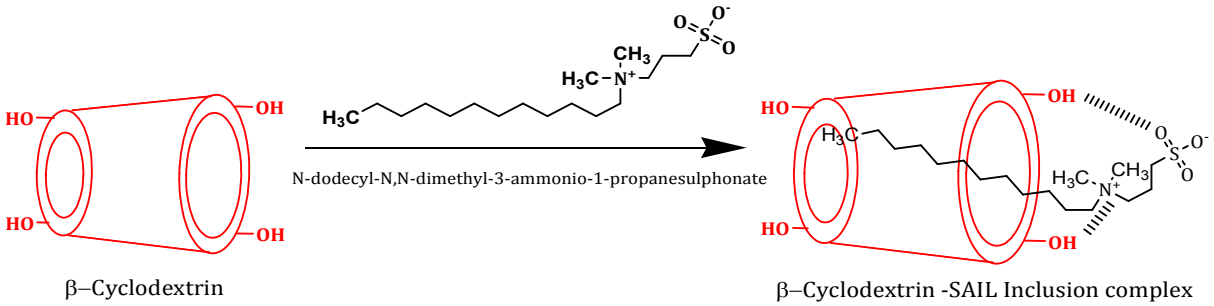


Scheme IX.2: The plausible stoichiometries inclusion ratio of host:guest molecule.

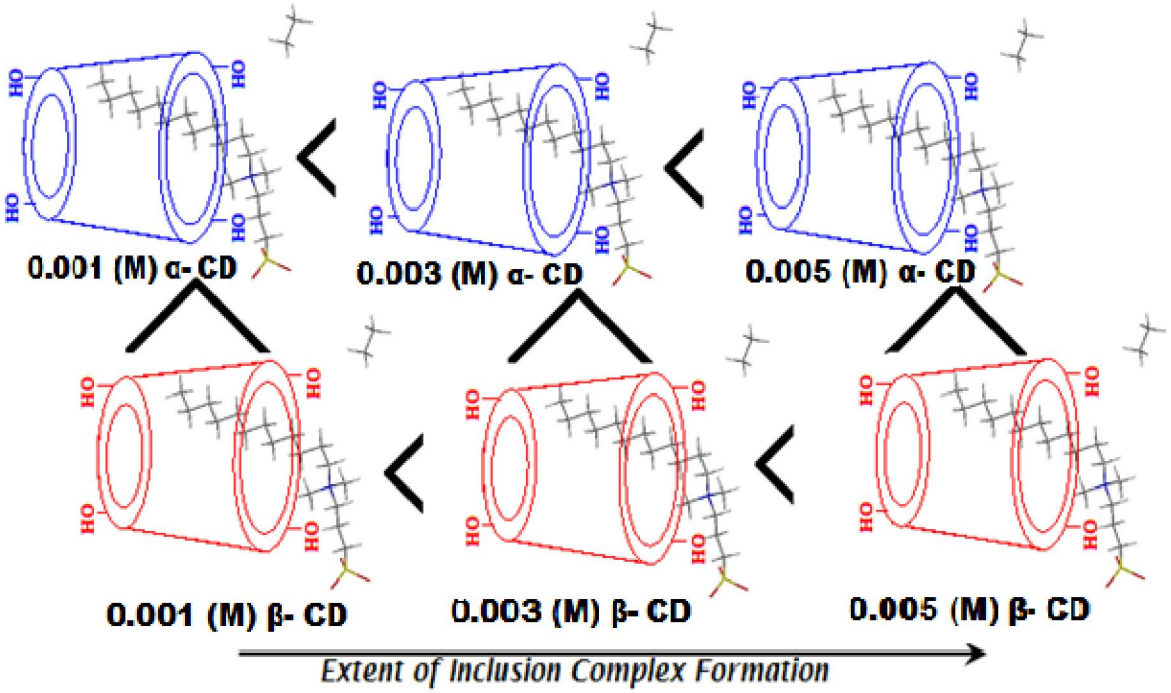


Scheme IX.3: The feasible and restricted inclusion of host:guest molecule.





Scheme IX.4: Schemetic representation of convincing mechanism of 1:1 inclusion complexes insight into α- and β-cyclodextrin with the titled ionic liquid.



Scheme IX.5: Extent of inclusion complex formation insight into α- and β- CD with the titled ionic liquid.