

## CHAPTER IV

### SELF-ASSEMBLY INCLUSION OF GREEN SOLVENT WITH OLIGOSACCHARIDES

#### 4.1. Introduction

The formation of cyclodextrin (CD) based inclusion complexes with wide variety of guest molecules are of great interest because of their extensive application in fields of bio-sensing and bio-imaging, drug and gene delivery, electronics, energy production and regenerative medicine [1-7]. Cyclodextrins (CDs) are obtained from the enzymatic degradation of one of the most essential polysaccharides, starch. The core of their structures contains dimensionally stable cavities that can trap or encapsulate other molecules through non covalent interaction. The outer part of their cavities are hydrophilic in nature due to the large number of hydroxyl groups while the inner part of the cavities are lined with skeletal carbon and ethereal oxygen moieties of the glucose residues which make it relatively apolar and create a hydrophobic micro environment [8-10] (Scheme 1). On the other hand, Ionic liquids (ILs) (Scheme 2) with hydrophobic long chain have unique properties, such as "green" alternative to the conventional and environmentally detrimental volatile solvents, negligible vapour pressure, excellent thermal stability, strong ability to dissolve many chemicals, high electrical conductivity, large electrochemical window, and ability of repetitive utilization. All the unusual properties help IL to be broadly applied in material syntheses, chemical reactions, separations, electrochemistry and formation of ordered molecular assembly [11-12]. The term self-assembly refers to quite a fascinating phenomenon where unassociated, disorderly molecules come together in some fashion to form organized structures without any external stimuli [13].

In our previous work [14] we successfully addressed inclusion through hydrophilic-hydrophobic interaction of IL with  $\beta$ -CD. Herein, we present a physicochemical and spectroscopic investigation for inclusion of the IL with  $\alpha$ -CD and  $\beta$ -CD by easily available techniques.

## 4.2. Experimental Section

### 4.2.1. Materials

The investigated compounds e.g., IL,  $\alpha$ -CD and  $\beta$ -CD of puriss grade were procured from Sigma-Aldrich, Germany and used as purchased. The mass fraction purity of IL,  $\alpha$ -CD and  $\beta$ -CD were  $\geq 0.99$ , 0.99 and 0.98 respectively.

### 4.2.2. Apparatus and procedure

Solubility of the chosen compounds have been precisely checked and observed that the selected IL,  $\alpha$ -CD and  $\beta$ -CD are freely soluble in triply distilled and degassed water (with a specific conductance of  $1 \times 10^{-6} \text{S} \cdot \text{cm}^{-1}$ ). Experimental solution of IL was prepared by mass (Mettler Toledo AG-285 with uncertainty  $\pm 0.0003 \text{g}$ ), and then the working solutions were obtained by mass dilution at 298.15 K.

The surface tension experiments were done by platinum ring detachment method using a Tensiometer (K9, KRÚSS; Germany) at the studied temperature. The precision of the measurement was within  $\pm 0.1 \text{ mN} \cdot \text{m}^{-1}$ . Temperature of the system has been maintained 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  $\pm 0.01 \%$ ) using a dip-type immersion conductivity cell, CD-10, having a cell constant of approximately  $(0.1 \pm 0.001) \text{ cm}^{-1}$ . Measurements were completed in a water bath maintained within  $T = (298.15 \pm 0.01) \text{ K}$ .

The solution and solvent densities ( $\rho$ ) were measured by means of vibrating u-tube Anton Paar digital density meter (DMA 4500M) with accuracy of  $\pm 0.00005 \text{ g cm}^{-3}$  maintained at  $\pm 0.01 \text{ K}$  of the experimental temperature. It was calibrated by passing doubly distilled, deionized, degassed water and dry air.

The viscosities ( $\eta$ ) were measured using a Brookfield DV-III Ultra Programmable Rheometer with spindle size-42 fitted to a Brookfield digital bath TC-500.

### 4.3. Results and Discussion

#### 4.3.1. Surface tension

Surface tension ( $\gamma$ ) measurements can be used to elucidate whether inclusion can happen or not but also to interpret the stoichiometry of inclusion complexes [15]. It was proved that no remarkable change occurs for the surface tension of pure water when  $\alpha$ - and  $\beta$ -CD are added in water, indicating that  $\alpha$ - and  $\beta$ -CD are almost surface inactive compounds in pure water mixtures [16].  $\gamma$  values increase with addition of CDs are due to the fact that surface activity decreases with increasing no. of CD molecules into the IL (Scheme 3 and 4) solution. Each curve, Fig.1 (a) and 1(b), clearly shows a single break point in surface tension at a certain concentration, i.e., the  $\gamma$  values increase with the increase in concentration, reach a certain point (break point), and then become approximately steady, which obviously indicates the formation of selective 1:1 inclusion complex. By examining the details of  $\gamma$ - values (Table-1) it is understood that  $\beta$ -CD is more efficient for the formation of inclusion complexes than  $\alpha$ -CD. This is evidently due to the fact that  $\beta$ -CD provides more workable feature (Scheme 1) for the formation of feasible inclusion complexes than  $\alpha$ -CD. Also, we envisage the non-polar tail group of the IL to be inserted via the wider rim through hydrophobic and hydrophilic interaction, so as to make maximum contact with the CD cavity (Scheme 3 & 4), while the charged polar head side remains either in the wider rim of CD or in the bulk solution through H-bonding.

#### 4.3.2. Conductivity study

The selected IL is freely soluble in water. The solution conductivity of IL is markedly altered by the addition of CDs. The dependence of specific conductivity of IL, as reported earlier [17-18], with both CD concentrations at 298.15K are depicted in Fig.1c & d. Through this method the stoichiometry of the inclusion complexes can be deduced from the breaks (Table 2) in the conductivity curves [19-20]. The remarkably decreasing specific conductivity with increasing CD concentrations indicates the Inclusion complex formation between CD and the hydrophobic part of the IL one by one and hence movement of the IL is restricted and the free ions per unit volume is decreased; as a result the conductivity decreases. At a certain

concentration of CDs, this linear decrease of specific conductance with IL concentration halted rather abruptly to show no or little further decrease with further CD additions and which represents the saturation point of inclusion. A distinct break in the conductivity curve occurred at a concentration of about 5.0 mmol L<sup>-1</sup> for CDs, suggesting that the stoichiometry of the Inclusion complex is equimolar [21]. This indicates that the principal inclusion complexes of CDs with IL in this range are of 1:1 ratio which indicates that the IL are almost totally in complexed form. This definitely illustrates that both the CDs have the favorable structures for the formation of selective inclusion complexes with the investigated IL. This is also supported by the above mentioned surface tension experiment.

#### 4.3.3. UV-Vis Spectroscopic study

Absorption spectra used to confirm the formation of inclusion complex. In this study, absorption spectrum of the studied compound was taken into consideration [21-22]. Since  $\alpha$ -CD and  $\beta$ -CD have almost no absorption throughout the wavelength; hence, their absorbance can be neglected [21]. Absorption spectra for IL found similar at most of the points along the wavelengths recorded which shows that the absorbance arises from IL only. Whereas, inclusion complexes show increased intensity at 224 nm due to the inclusion phenomena between CDs and IL (Fig. 1e and f). The same phenomenon has been observed by Wang *et al.* [23] in their interaction studies of  $\beta$ -CD and orange G. The UV-Visible spectra shows that the absorbance values increase with increasing CD concentrations while the concentration of IL remains the same. It indicates that the solubility of guest molecule (IL) increases upon forming the Inclusion complexes [24]. Since the alkyl part of IL more likely to enter the hydrophobic cavity of the CD in each case, stoichiometric ratio of inclusion complexes should be theoretically 1:1. A very good linear relationship was obtained for  $1/A$  vs.  $1/[CD]$  from the Hildebrand-Benesi Equation[25]. This reciprocal plot clearly indicates the stoichiometry ratio for the inclusion formation between IL and CDs are 1:1. The same phenomenon has been observed by Wang *et al.*[23]by using a derivative of sulphonated azo compound like orange G to form inclusion complex with  $\beta$ -CD. From the reciprocal plot (Fig.S1a and S1b) the apparent formation constant (K) were calculated 850 L.mol<sup>-1</sup> for  $\alpha$ -CD and 2553 L.mol<sup>-1</sup> for  $\beta$ -CD respectively. Thus, higher value of formation constant for  $\beta$ -

CD suggests inclusion is more favorable for  $\beta$ -CD in comparison to that of the  $\alpha$ -CD. The spectroscopic results also support surface tension and conductometric outcome.

#### 4.3.5. Thermodynamical aspects

Table 3 clearly depicts that the  $\Delta\mu_1^{0\#}$  (free energy of activation of viscous flow per mole of solvent) and  $\Delta\mu_2^{0\#}$  (free energy of activation of viscous flow per mole of the solute) values are positive and almost equal for all the solvent composition for each CDs [26-27]. This may be due to the fact that IL-co-solute (CD) interactions in the ground state are almost same as in the transition state. In other words, the solvation of IL in the transition state is also favorable in terms of free energy. As  $\Delta\mu_2^{0\#} \cong \Delta\mu_1^{0\#}$  then according to the Feakins model [25], the solutes (IL) behave as structure-makers. This indicates that the solvation of the IL in the ground state becomes increasingly favorable as the number of carbon atoms (hydrophobicity) of the side chain is appropriate for inclusion. The positive activation enthalpy ( $\Delta H^*$ ) values of the mixtures are suggesting that the formation of activated species for viscous flow becomes difficult as the amount of IL in the mixtures increases. The negative values of  $T\Delta S^*$ , which increase with increasing temperature of the system, for all the studied mixtures, suggests that the net order of the system decreases as the temperature of the solution increases. That is with increasing temperature of the system the total free energy of the system becomes smaller. Therefore the possibility of the inclusion is favorable with the rise in temperature as well as the mass fraction of CDs. The  $\Delta H^*$  and  $\Delta S^*$  quantities contain contributions from the following processes: (i) formation of the IL-CD complex due to non-covalent interactions (H-binding, van der Waals forces, hydrophobic and electrostatic interactions and steric effects), (ii) dehydration (release of water molecules) of the CDs during the molecular interactions, (iii) hydration of the Inclusion complex by the surrounding water molecules and (iv) conformation changes during formation of Complex (Liu et al. 2002). The entry (i) ,(ii) and (iii) signify that during these processes the values of entropy of interaction are always negative. Interestingly, the contribution from process (iv) cannot be considered because the CD molecule is not flexible and does not allow the change of its conformation upon binding with a guest

molecule and retain the same conformation before and after the inclusion with IL [14,28]. The more negative  $T\Delta S^*$  values in IL+ aq.  $\beta$ -CD than IL+ aq.  $\alpha$ -CD comprises inclusion is more appropriate in the former case than later.

#### 4.4. Conclusion

Thus from thermodynamical, structural and the experimental evidences it can generally be concluded that there are four energetically favorable interactions that shift the equilibrium towards the formation of inclusion complex: one, the displacement of existing polar water molecules from the apolar cavity of CDs. Two, the formation of extended hydrogen bonds by the primary and secondary hydroxyl (-OH) groups and rest of the water molecules that open a face for incoming the guest molecule. Three, a reduction of the repulsive interactions between the hydrophobic guest and the aqueous surroundings. And finally, there is an increased hydrophobic interaction as the guest inserts itself into the apolar cyclodextrin cavity. Also, the bindings of IL molecule with the CDs are not fixed or permanent but a dynamic equilibrium and the binding strength depend on the specific local interactions between surface atoms. The key factor that stabilises the inclusion complexes is the steric effect and it depends on the relative size of the CD to the size of the guest molecule or certain key functional groups within the guest molecule. Since, the IL molecule is the mark on size; it gets fitted properly into the CD cavity and form selectively stable 1:1 inclusion complex (scheme 5). Thus, in a word the inclusion of  $\alpha$ -CD is comparatively less effective (scheme 6) than that of the  $\beta$ -CD.

## Tables

**Table 1. Values of surface tension at the break point ( $\gamma$ ) with corresponding concentration of IL in different mass fraction of aq.  $\alpha$ -CD and aq.  $\beta$ -CD at 298.15K<sup>a</sup>.**

| mass fraction<br>( $w$ ) | IL in $\alpha$ -CD |                                | IL in $\beta$ -CD |                             |
|--------------------------|--------------------|--------------------------------|-------------------|-----------------------------|
|                          | conc<br>( $m$ )    | $\gamma$<br>/mNm <sup>-1</sup> | conc<br>( $m$ )   | $\gamma$ /mNm <sup>-1</sup> |
| $w_1=0.001$              | 0.05               | 54.95                          | 0.05              | 55.14                       |
| $w_1=0.003$              | 0.05               | 57.46                          | 0.05              | 57.35                       |
| $w_1=0.005$              | 0.05               | 59.98                          | 0.05              | 59.13                       |

<sup>a</sup>Standard uncertainties  $u$  are:  $u(T) = 0.01\text{K}$ , <sup>b</sup> $w_1$  and  $w_2$  are mass fractions of  $\alpha$ - and  $\beta$ -cyclodextrin in aqueous mixture respective

**Table 2. Values of Specific conductance at the break point ( $\kappa$ ) with corresponding concentration of IL in different mass fraction of aq.  $\alpha$ -CD and aq.  $\beta$ -CD at 298.15K<sup>a</sup>.**

| mass fraction ( $w$ ) | IL in $\alpha$ -CD |                             | IL in $\beta$ -CD |                             |
|-----------------------|--------------------|-----------------------------|-------------------|-----------------------------|
|                       | conc ( $m$ )       | $\kappa$ /S.m <sup>-1</sup> | conc ( $m$ )      | $\kappa$ /S.m <sup>-1</sup> |
| $w_1=0.001$           | 0.05               | 2.79                        | 0.05              | 2.78                        |
| $w_1=0.003$           | 0.05               | 2.36                        | 0.05              | 2.31                        |
| $w_1=0.005$           | 0.05               | 2.10                        | 0.05              | 2.04                        |

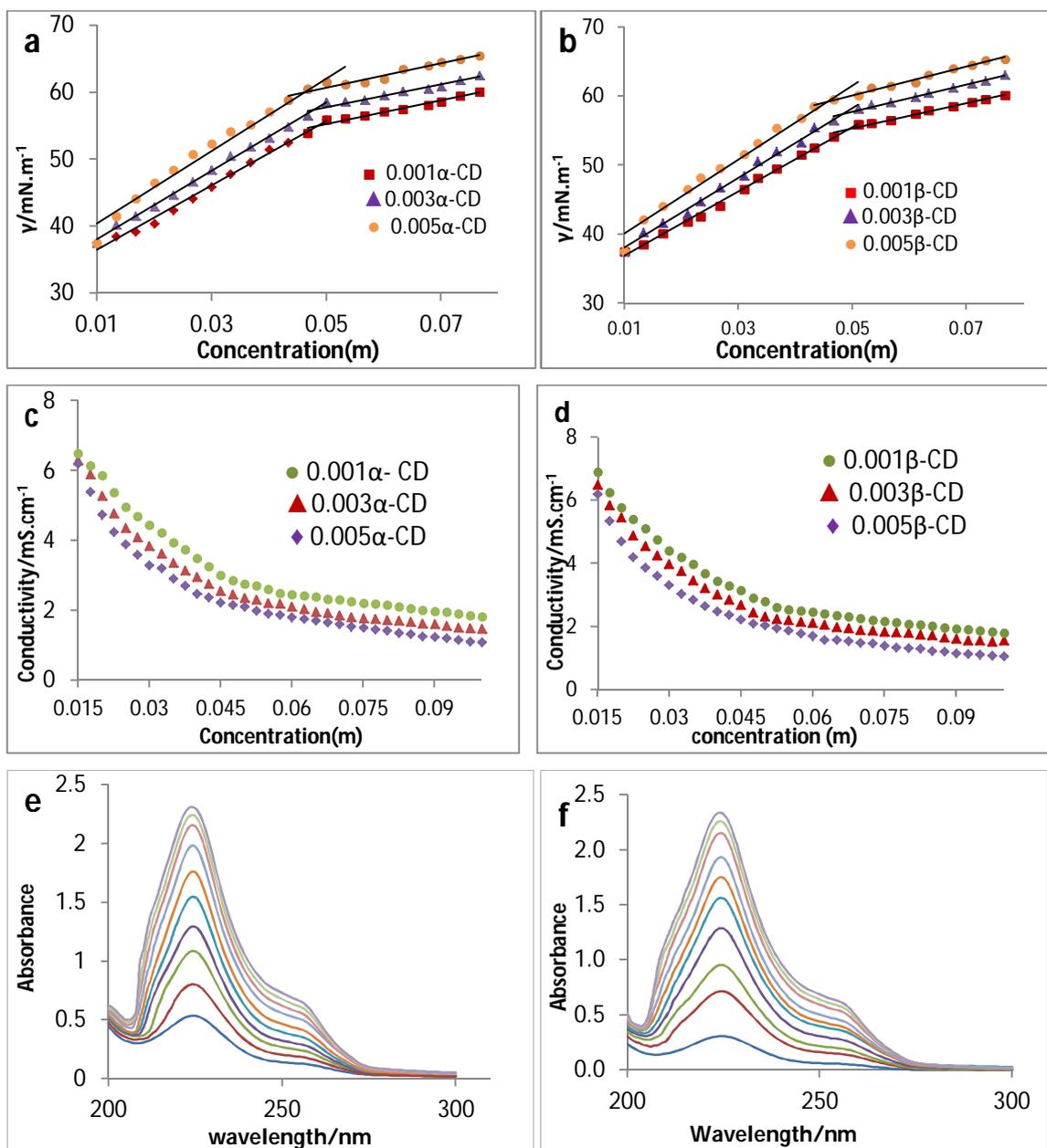
<sup>a</sup>Standard uncertainties  $u$  are:  $u(T) = 0.01\text{K}$

**Table 3. Values of  $\phi_1^0, \phi_v^0$ (aqueous),  $\mu^{0\#}$ ,  $T\Delta S^\#$ ,  $\Delta H^\#$ , for IL in different mass fraction of aq.  $\alpha$ -CD and aq.  $\beta$ -CD at 293.15 to 313.15K respectively.**

| Thermodynamic<br>Parameters | $\phi_1^0 \cdot 10^6$<br>/m <sup>3</sup> .mol <sup>-1</sup> | $\Delta\mu_1^{0\#}$<br>kJ.mol <sup>-1</sup> | $\Delta\mu_2^{0\#}$<br>kJ.mol <sup>-1</sup> | $\Delta\mu^{0\#}$<br>kJ.mol <sup>-1</sup> | $T\Delta S^\#$<br>kJ.mol <sup>-1</sup> | $\Delta H^\#$<br>kJ.mol <sup>-1</sup> |
|-----------------------------|---|---|---|---|--|---------------------------------------|
| $w_1 = 0.001$               |   |   |   |   |  |                                       |
| 293.15K IL+ $\alpha$ -CD    | 17.026  | 58.86                                       | 58.87                                       | 58.86                                     | -12.36                                 | 46.50                                 |

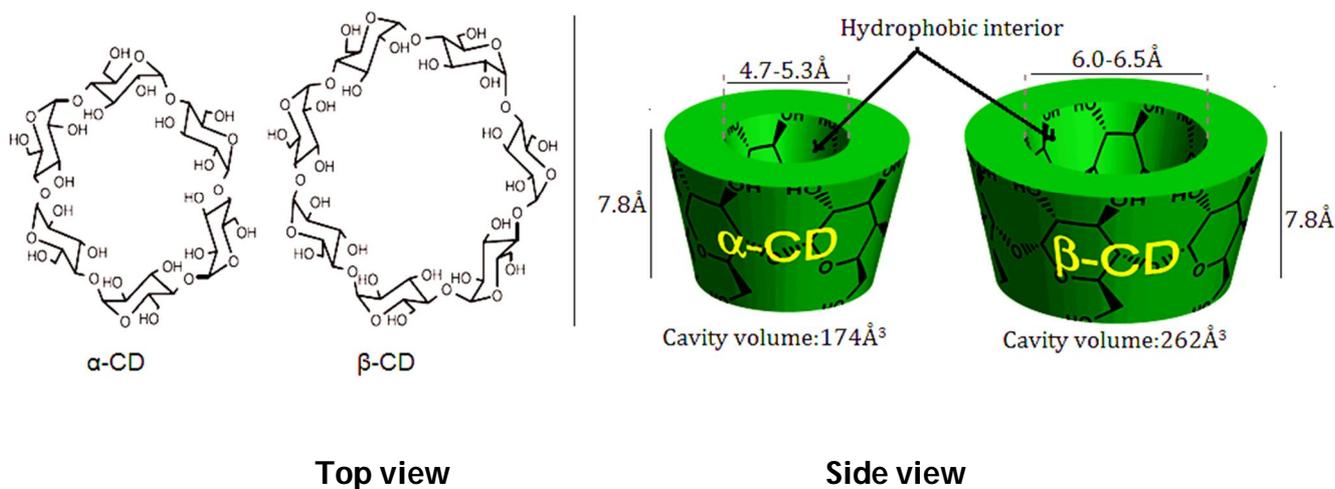
|               |                  |        |       |       |       |        |       |
|---------------|------------------|--------|-------|-------|-------|--------|-------|
|               | IL+ $\beta$ -CD  | 18.038 | 60.43 | 60.44 | 60.43 | -13.66 | 46.77 |
| 303.15K       | IL+ $\alpha$ -CD | 17.045 | 58.48 | 58.49 | 58.48 | -14.19 | 44.29 |
|               | IL+ $\beta$ -CD  | 18.061 | 60.21 | 60.22 | 60.21 | -15.16 | 45.05 |
| 308.15K       | IL+ $\alpha$ -CD | 17.074 | 58.26 | 28.27 | 58.26 | -14.89 | 43.37 |
|               | IL+ $\beta$ -CD  | 18.085 | 60.11 | 60.10 | 60.10 | -15.95 | 44.15 |
| <hr/>         |                  |        |       |       |       |        |       |
| $w_I = 0.003$ |                  |        |       |       |       |        |       |
| 293.15K       | IL+ $\alpha$ -CD | 17.026 | 58.86 | 58.87 | 58.86 | -13.78 | 45.08 |
|               | IL+ $\beta$ -CD  | 18.038 | 60.43 | 60.44 | 60.43 | -14.81 | 45.62 |
| 303.15K       | IL+ $\alpha$ -CD | 17.045 | 58.49 | 58.50 | 58.49 | -14.65 | 43.84 |
|               | IL+ $\beta$ -CD  | 18.061 | 60.22 | 60.23 | 60.22 | -15.67 | 44.55 |
| 313.15K       | IL+ $\alpha$ -CD | 17.074 | 58.86 | 58.87 | 58.86 | -15.38 | 42.48 |
|               | IL+ $\beta$ -CD  | 18.085 | 60.11 | 60.12 | 60.11 | -16.16 | 43.95 |
| <hr/>         |                  |        |       |       |       |        |       |
| $w_I = 0.005$ |                  |        |       |       |       |        |       |
| 293.15K       | IL+ $\alpha$ -CD | 17.026 | 58.27 | 58.28 | 58.27 | -15.11 | 43.16 |
|               | IL+ $\beta$ -CD  | 18.038 | 60.44 | 62.45 | 60.44 | -16.09 | 44.35 |
| 303.15K       | IL+ $\alpha$ -CD | 17.045 | 58.49 | 58.50 | 58.49 | -15.97 | 43.52 |
|               | IL+ $\beta$ -CD  | 18.061 | 60.24 | 60.23 | 60.23 | -16.93 | 43.30 |
| 313.15K       | IL+ $\alpha$ -CD | 17.074 | 58.87 | 58.88 | 58.87 | -16.25 | 42.62 |
|               | IL+ $\beta$ -CD  | 18.085 | 60.12 | 60.13 | 60.12 | -17.30 | 42.82 |

## Figures

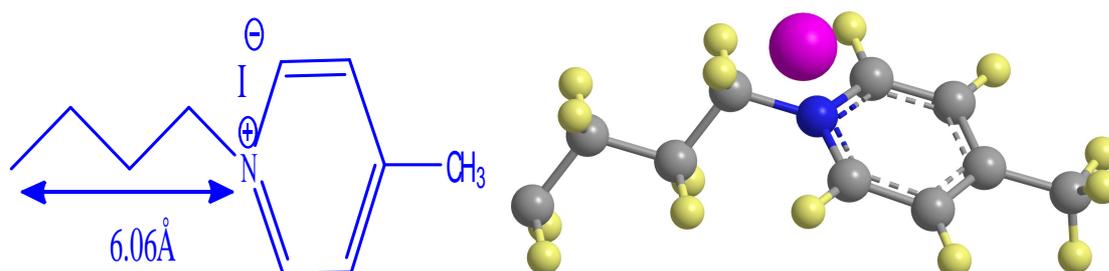


**Fig.1 (a) Curve of  $\gamma/mN.m^{-1}$  vs. Concentration (m) of IL and  $\alpha$ -CD solution. (b) Curve of  $\gamma/mN.m^{-1}$  vs. Concentration(m) of IL and  $\beta$ -CD soln. (c)The Curve of Conductivity vs. Concentration of IL and  $\alpha$ -CD Solution.(d) Curve of Conductivity vs. Concentration of IL and  $\beta$ -CD solution. (e) Absorbance vs. Wavelength of IL and  $\alpha$ -CD solution. (f)Absorbance vs. Wavelength of IL and  $\beta$ -CD solution**

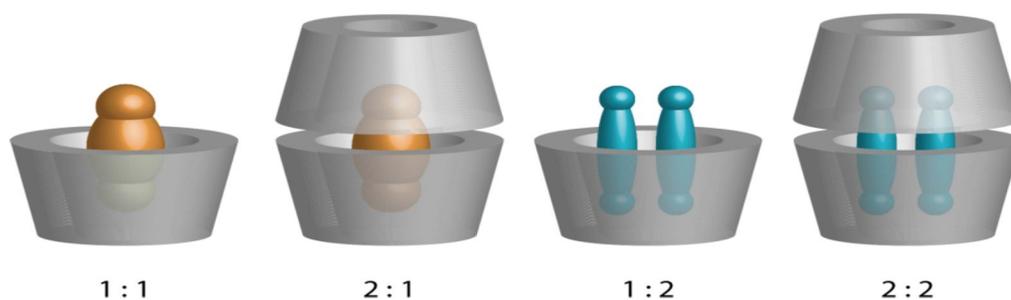
## Schemes



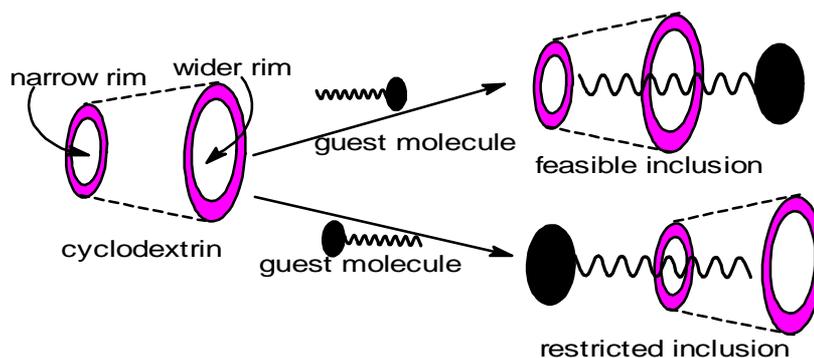
**Scheme 1. Molecular structure and approximate geometric dimension of  $\alpha$ -CD and  $\beta$ -CD.**



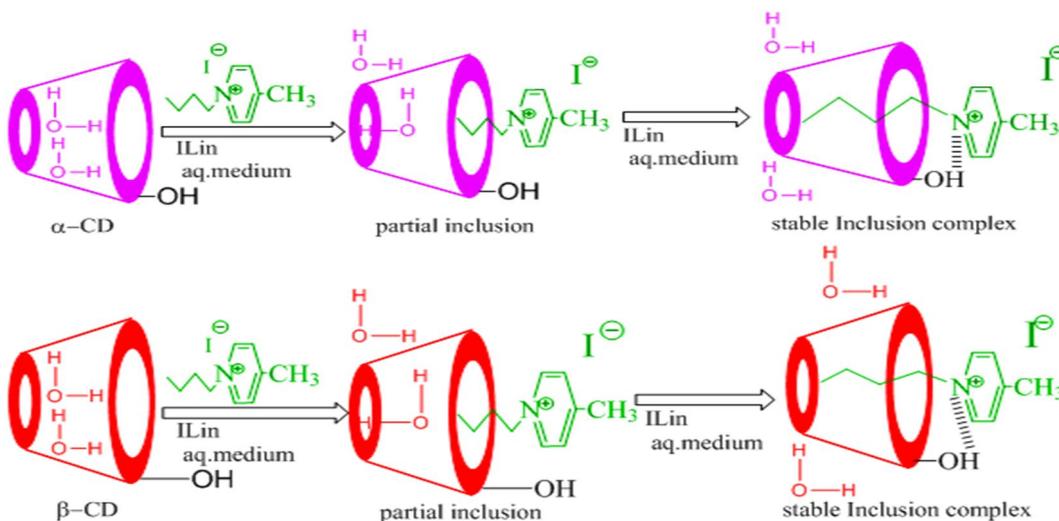
**Scheme 2. The molecular structure of 1-butyl-4-methylpyridinium iodide**



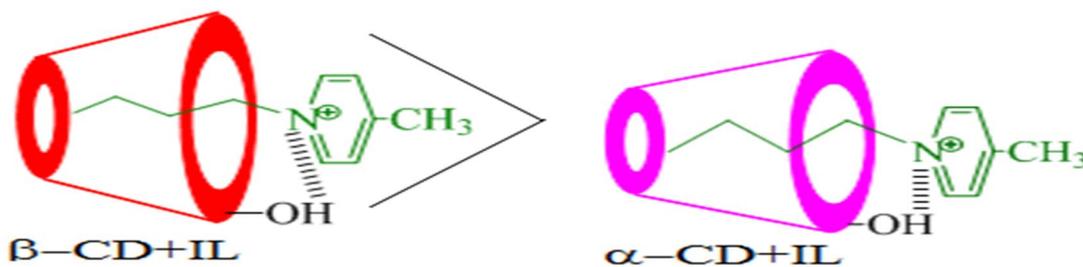
**Scheme 3. The plausible stoichiometries inclusion ratio of host:guest molecules.**



Scheme 4. The feasible and restricted inclusion.



Scheme 5. Schematic representation of convincing mechanism of 1 : 1 inclusion complexes' insight into  $\beta$ -cyclodextrin with the titled ionic liquid.



Scheme 6. The efficiency of inclusion with increase in mass fraction of CD.