The present work is surface activity study of chitosan monomer and some of its derivatives. For this at first chitosan monomer has to be modeled. A monomer of chitosan was built up with Gauss view program. This geometry was optimized to minimum energy. Derivatives were constructed from the optimized minimum energy structure of chitosan monomer.

Schiff bases of chitosan including both aliphatic and aromatic substituents. Their N-reduced/alkylated forms also modeled and studied. Aliphatic Schiff bases: citral (CC), pyruvate (PyC) and glyoxylic acid (GC) derivatives. Aromatic Schiff bases: salicylaldehyde (SC), pyridoxal (PC) and pyridyl methyl (PMC) derivatives. Corresponding N-reduced forms are CCR, PyCR, GCR, SCR, PCR and PMCR respectively. The properties of these derivatives were studied and compared with that of chitosan. Properties such as polarizability, reactivity were examined. All of the derivatives show better reactivity than chitosan monomer. The variation in the properties depends on the groups attached to each derivative.

Citral is a natural open chain aldehyde found in the oil of lemon grass, orange, lemon etc. Citral has application in the field of cosmetics and scents. Adsorption behavior of Pb (II) and Hg (II) ions
onto CC were reported by Alikutty et al. [1]. Fig. 3.1 shows a monomer of CC.

![Molecular structure of CC](image)

**Fig. 3.1 Molecular structure of CC**

A long chain of aliphatic group is attached to chitosan monomer in CC. In CCR the imine group (-N=C-) will be reduced and we get an N-alkylated product.

Derivatives of Chitosan with ketoacids were effective for removal of Co$^{60}$ from nuclear plant wastewaters. It is also better for uranium removal from dilute solutions and from saline waters [2,3]. Another report shows that pyruvic acid—it is the simplest of α-keto acids—modified chitosan had higher adsorption capacities for metal ions of Cu, Zn and Co [4]. Second derivative of chitosan is from pyruvate. It can form imine with chitosan. The following figure depicts the structure of PyC.

![Structure of PyC](image)

**Fig. 3.2 Structure of PyC**
PyC has –COOH group attached to chitosan moiety. Alkaline reduction of this Schiff base also yields an N-alkylated product PyCR.

Glyoxylic acid or oxoacetic acid occurs naturally. It is widely used to introduce carboxymethyl group to chitosan. From glyoxylic acid, water soluble N-carboxymethyl chitosan can be prepared. N-carboxy methyl chitosan is a costly functional ingredient of cosmetic hydrating creams due to its durable moisturizing effect on the skin [5]. It is also a good adsorbent of metal ions. Adsorption capacity of N-carboxy methyl chitosan towards Au (III) ions was reported [6]. A review of carboxy methyl chitosan and its applications were reported by Mourya et.al [7]. Figure 3.3 shows the molecular structure of GC.

![GC structure](image)

**Fig.3.3 GC structure**

Salicylaldehyde is a key precursor to a variety of chelating agents. An aromatic group is introduced to chitosan when reacting with salicylaldehyde [4]. The structure of SC is depicted in fig.3.4.

![SC structure](image)

**Fig.3.4 Molecular structure of SC**
Pyridine derivatives were introduced into the polymer backbone of chitosan in order to improve the polymer properties including the solubility, physicochemical and biological properties. The introduction of pyridine derivatives into the chitosan backbone has recently gained interest because it can be applied in metal absorption antimicrobial activity, gene delivery sensor application and biomedical application [8]. Here 2-pyridinecarbaldehyde was introduced to chitosan to get pyridyl methyl chitosan (PMC) Schiff base and N-reduced (PMCR).

![Fig.3.5 Structure of PMC](image)

Chitosan–pyridoxal derivatives were synthesized by reacting chitosan with pyridoxal hydrochloride and then reducing the product formed with sodium cyanoborohydride [9]. The derivative showed enhanced adsorption capacities for Cu (II), Pb (II) and Fe (III) than chitosan.
An aromatic ring with more substituents is attached to chitosan in PC. The fig. 3.6 shows the molecular structure of PC.

Applications of chitosan and the above derivatives also studied. Metal chelation, corrosion inhibition and druggability of the derivatives were studied and compared with chitosan monomer.

3.1 Methods

3.1.1 Geometry optimization

The process of finding out the energy minimum structure (conformation) of the required molecule is known as geometry optimization. This can be achieved with a potential energy surface (PES) scanning process. PES is a plot of energy against some geometric parameters like bond lengths, bond angles, dihedral angles etc. If energy is plotted against only one variable then we get a 2D surface. And for a plot with energy against two variables the result will be 3D. So as the variables increased the plot become more and more complicated [10].

The procedure starts with initial wave function and calculates energy then move to a new geometry having lower energy. This
process repeats until geometry with lowest energy which is close to the initial structure is obtained. In the energy minimization process some gradient points in the PES with respect to electronic energy will be found out. Gradient can be defined as a vector constituted by $3N-6$ first partial derivatives of energy with respect to the variables on which energy is dependent. The point on the PES where gradient is zero is called a stationary or critical point. These points may constitute a minimum, maximum or a saddle point.

Saddle point will be energy maximum in one direction and energy minimum in other directions. Saddle points are actually a transition state between two equilibrium states. The lowest energy point or trough in the PES corresponds to the global minimum structure. Other minima are called local minimum structures. A typical plot of PES is depicted in fig.3.7.

Fig.3.7 Schematic representation of PES
3.1.2 Frequency calculation

We have carried out frequency calculation along with every optimization process. A frequency calculation result has two benefits. First of all we can find out the infrared and Raman intensities. And the second is that it is possible to check whether the obtained geometry from the optimization is local or global minimum or a transition state. For a local or global minimum structure we get all the calculated frequencies are real and positive. But for transition state structure, the some of the frequencies will be complex and printed as negative values. This is called as imaginary frequency. Well behaved transition state structure of a reaction has one imaginary frequency.

3.1.3 Natural bond orbital (NBO) analysis

Natural bond orbital (NBO) method is a localization method that can closely describe the chemical concepts. The method was developed by Weinhold and co-workers [11]. Orbitals that are closely associated entirely with a single atom are termed as core orbitals. In NBO procedure these core orbitals and other orbitals associated with a single atom like lone pairs are at first localized and called as natural atomic orbitals (NAOs). Next, orbitals involving bonding or antibonding between pairs of atoms are localized by using only the basis set AOs of those atoms. Remaining Rydberg-like orbitals can be identified and all other orbitals are made orthogonal to one another. As a result, all NAOs and Rydberg orbitals are described using the basis-set AOs of a single atom and all NBOs are described using the basis-set AOs of two atoms. In cases where resonance or other delocalization effects exists, additional work is required. Therefore NBO analysis can
provide an orbital picture that is as close as possible to a classical Lewis structure for a molecule.

NBO method is very useful for the assignment of hybridization both to the atomic lone pairs and to each atom’s contributions to its bond orbitals. Hybridization is a widely accepted chemical concept even though it has no formal basis in the absence of high-symmetry constraints. The NBO localization analysis will give the percent s and p character (and d, f, etc.) from the coefficients of the AO basis functions from which the NAO or NBO is formed. The partial atomic charges also can be evaluated using NBOs with natural population analysis (NPA).

Hyperconjugation is a useful chemical concept that can rationalize certain chemical phenomena in terms of filled-orbital–empty-orbital interactions. NBO analysis can be used to quantify this phenomenon. Since the NBOs do not diagonalize the Fock operator (or the Kohn–Sham operator, if the analysis is carried out for DFT instead of HF), when the Fock matrix is formed in the NBO basis, off-diagonal elements will in general be non-zero. Second-order perturbation theory indicates that these off-diagonal elements between filled and empty NBOs can be interpreted as the stabilization energies. Thus NBO approach can be used to other analyses focusing on structural changes or changes in partial atomic charges in the investigation of hyperconjugative effects. Since NBO procedure is based on orbitals some limitations can be expected in cases where chemical species are poorly represented as Lewis structures.

Natural bond orbital (NBO) analysis is a technique introduced to understand chemical interaction of hyper conjugation and electron
density transfer (EDT) from filled lone pairs of electron (Lewis base) into the unfiled antibonds (Lewis acid) in hydrogen bonding systems[11]. A filled bonding or lone pair orbital can act as a donor and an empty or filled bonding, antibonding or lone pair orbital can act as an acceptor. These interactions may strengthen or weaken bonds. The NBO method demonstrates the bonding concepts like Lewis structure, bond type, atomic charge, hybridization, charge transfer, bond order, and resonance weights. This analysis is useful in understanding delocalization of electron density from occupied Lewis-type or donor NBOs to properly unoccupied non-Lewis type or acceptor NBOs within the molecule. The stabilization of orbital interaction is proportional to the energy difference between interacting orbits. Therefore, the interaction having strongest stabilization takes place between effective donor and effective acceptors.

Estimation of energetic importance of NBOs’ was done by second order Perturbation theory [12]. The interaction between bonding and anti bonding orbitals can be quantitatively described in terms of the NBO approach that is expressed by means of $E^{(2)}$ second-order perturbation interaction energy [13-15]. This energy represents the measure of the off-diagonal NBO Fock matrix element. The energy of stabilization $E^2$ is associated with $i$ (donor) and $j$ (acceptor). Delocalization can be calculated from the second order perturbation approach [16] as given below

$$E^{(2)} = -q_i \frac{(F_{i,j})^2}{\varepsilon_j - \varepsilon_i}$$

$E^{(2)}$ -- Energy of hyper conjugative interaction (stabilization energy).
\( \epsilon_j - \epsilon_i \) – Energy difference between donor and acceptor i and j NBO orbitals

\( (F_{i,j}) \) – Fock matrix element between i and j NBO orbitals.

### 3.1.4 Polarizability and hyper polarizability

The distribution of charge within the molecule affects properties like atomic charges, dipole moment and polarizability tensor. Quantum computation methods promise an inexpensive way to evaluate the NLO properties of materials by theoretical calculations based on the polarizability calculations. Electric dipole moment, the isotropic polarizability and the first hyperpolarizability can be used to understand the microscopic NLO mechanism of molecules. Polarizability is the measure of the change in electron distribution of a molecule in response to an applied electric field, or otherwise can be induced by electric interactions with solvents or ionic reagents. The charge density in a molecule can be measured from permanent electric dipole moment. The magnitude and direction of dipole moment is being sensitive to shape and molecular size. It acts as an indicator of physical, chemical and biological properties exhibited by molecule.

The molecule having polarizability values \( \alpha_{XX} = \alpha_{YY} = \alpha_{ZZ} \) said to be isotropic. If the molecule is anisotropic, then polarizability is \( \alpha_{XX} \neq \alpha_{YY} \neq \alpha_{ZZ} \). The intensity of Raman scattering may be proportional to the derived polarizability components. To express the scattering intensity in terms of the derived polarizability tensor, the quantities \((\alpha')\) and the anisotropy invariant \((\gamma)\) are necessary. The quantity \((\alpha')\) is the mean value of the three principle components of \((\alpha')\) and \((\gamma)\)
measures the anisotropy of the tensor. The definitions [17] for the isotropic polarizability are given as:

\[ \alpha' = \frac{1}{3}(\alpha_{xx} + \alpha_{yy} + \alpha_{zz}) \]

Hyper polarizability can be expressed as;

\[ \beta_{\text{total}} = \sqrt{\beta_x^2} + \sqrt{\beta_y^2} + \sqrt{\beta_z^2} \]

The polarizability anisotropic invariant is given as follows,

\[ \gamma^2 = \frac{1}{2}[(\alpha_{xx} - \alpha_{yy})^2 + (\alpha_{yy} - \alpha_{zz})^2 + (\alpha_{zz} - \alpha_{xx})^2 + 6(\alpha_{xy})^2 + \alpha_{yz}^2 + \alpha_{xz}^2] \]

### 3.1.5 Reactivity parameters

HOMO and LUMO analysis gives an idea into stability and hence reactivity of molecules. HOMO gives the electron donating capacity whereas LUMO energy represents electron acceptance of the molecules. The global reactivity parameters such as hardness (\(\eta\)), softness (\(S = \frac{1}{\eta}\)), chemical potential etc. can be evaluated from these two orbitals. The maximum hardness or absolute hardness (\(\eta\)) of a system having N electrons and total energy E is given as [18]:

\[ \eta = \left( \frac{\partial^2 E}{\partial N^2} \right)_{v(r)} \approx \frac{1}{2}(IE - EA) \approx \frac{1}{2}(E_{\text{LUMO}} - E_{\text{HOMO}}) \]

Where IE is the vertical ionization energy given as -E_{\text{HOMO}} and EA is vertical electron affinity as - E_{\text{LUMO}}[19]. Global softness is the reciprocal of hardness (\(S = \frac{1}{\eta}\)). As the harness value increase the
Electron affinity can be calculated from the equation;

\[ \chi = -\mu = \left( \frac{\partial E}{\partial N} \right)_{\nu(r)} \approx \frac{1}{2} (I_E + E_A) \approx -\frac{1}{2} (E_{\text{LUMO}} - E_{\text{HOMO}}) \]

The global electrophilicity index (\( \omega \)) is given as:

\[ \omega = \frac{\mu^2}{2\eta} \]

These reactivity descriptors are used to predict the reactivity of chitosan and derivatives in the present study.
References


4. Q. Ma, Z. Zou, Y. Gao, Xiandai Huagong. 2000, 20(10), 44.


