INTRODUCTION

Osteoarthritis (OA), the most common of joint diseases, is characterized by a progressive loss of articular cartilage and inflammation of synovium. Chondrocytes, the resident cells in articular cartilage, play an important role in cartilage degradation in OA [1]. Previous studies showed that inflammatory cytokines were involved in the pathogenesis of OA. Stimulating of chondrocytes by interleukin (IL)-1β leads to the production of matrix metalloproteinases (MMPs) and other inflammatory mediators such as nitric oxide and prostaglandin (PGE)2 [2,3]. Nuclear factor kappa B (NFκB) in synovial lining cells, in fibroblast-like synoviocytes and also in chondrocytes of subjects affected by OA, NFκB is responsible for the induction of the transcription of genes encoding pro-inflammatory cytokines such as IL1β and tumor necrosis factor (TNF)α, enzymes such as cyclo-oxygenase-2 that generate pro-inflammatory mediators such as PGE2 as well as cartilage-degrading enzymes, e.g., the metalloproteinase (MMP-1, 3, and 13). These cytokines stimulate the production of degradative enzymes such as MMPs in cartilage, which is responsible for excessive cartilage matrix degradation in arthritis [4].

The nuclear transcription factor NFκB has a central role in the autoimmune, inflammatory, and destructive mechanisms that drive the progression of OA. Normally, NFκB is held in an inactive state in the cytoplasm by IκB inhibitory proteins. In response to specific external stimuli, including TNFα and IL-1, the inhibitor of κB (IκB) component of the complex is phosphorylated and degraded, resulting in the translocation of NFκB into the nucleus and induction of gene transcription. The signal-induced phosphorylation of IκB involves two IκB kinases, IκB kinase subunit (IKK)α and IKKβ. Various studies indicate that IKKβ plays the dominant role in the pro-inflammatory signal-induced phosphorylation of the IκB protein. On the other hand, IKKα is dispensable for these functions but is essential for developing the epidermis and its derivatives. IKKβ has been found to be responsible for some of the observed anti-inflammatory properties of marketed drugs such as aspirin and salicylates. Nowadays, the drugs used for the treatment of OA such as nonsteroidal anti-inflammatory drugs have numerous side effects. Therefore, it is urgently needed to seek safe and effective drugs to treat OA [5-7].

These target strategies only to affected cartilage and joints to avoid other undesirable systemic effects. In this paper, docking the IKKβ has been described as a targeted by herbal compounds and inhibitors, evaluate its anti-osteoarthritis properties (OA) and anti-inflammatory potential under in silico conditions.

METHODS

Docking studies were performed to find out the maximum interaction between design ligands and selected five proteins using Schrödinger Software NY. Structures of selected proteins were downloaded from protein data bank.

Results: Morin, salubrinal, icariin, and chondroitin sulfate, and sesamol have higher binding energy than other compounds. Based on these properties out of 9 compounds we have selected 5 best docked and compounds selected were molecular dynamics simulation with inhibitor of κB kinase subunit (IKK) β, Arg20, Leu21, Thr23, Lys99, Lys106, Asp145, Asn150, and Asp166 were actively involved in H-bond interaction with ligands. Each compound has different binding modes, which reflects the difference of interacting residues with different functional groups. Morin has better interaction than other compounds. Either Cys99 or Lys44 found predominantly in most of the complex except in β-ecdysterone whereas both found interacting with morin.

Conclusion: The results revealed out that the herbal compounds can inhibit the IKKβ protein. The virtual screening yielded five potential IKKβ inhibitors: Morin, salubrinal, icariin, and chondroitin sulfate, and sesamol. This inhibitor shows good interaction, energy, and pharmacophoric activity and will be suitable for further experiments of an anti-OA target.

Keywords: Docking studies, Nuclear factor kappa B, Herbal medicine, Osteoarthritis, Inhibitor of κB kinase subunit β.
typical structure file from the PDB is not suitable for immediate use in molecular modeling calculations, and so the crystal structure of IKKβ was prepared through protein preparation wizard, implemented in Maestro 10.4 [18]. Missing residues were added using the prime loop modeling, which is also embedded in protein preparation wizard. First, the bond orders were assigned, hydrogen atoms were added, and all the crystallographic waters molecules were removed. The processing script optimizes the hydrogen-bonding network, rotating hydroxyl and thiol hydrogen, generating appropriate protonation and tautomeration states of His, and performing chi flips in Asn, Gln, and His residues. Optimized structure of IKKβ was minimized using optimized potentials for liquid simulations (OPLS)-2005 force field until the average root-mean-square deviation (RMSD) of the non-hydrogen atoms reached 0.3Å.

Molecular docking
The docking protocol was carried out using glide [19-21]. It performs grid-based ligand docking with energetic and searches for favorable interactions between one or more typically small ligand molecules and a typically larger receptor molecule, usually a protein. After ensuring that the protein and ligands were in the correct form for docking, the receptor-grid files were generated using a grid-receptor generation program. In this study, the grid was generated by using the predicted active site through the sitemap. The receptor grid generated file was uploaded, and the precision extra precision (XP) was selected. Glide score was generated based on the following formula.

GScore = vDW + Coul + Lip + HBond + Bury + Rot + Site. (1)

Where, vDW = van der Waals energy, Coul = Coulomb energy, Lip = lipophilic contact term, HBond = hydrogen-bonding term, Bury = metal-binding term, Bury = penalty for buried polar groups, Rot = penalty for freezing rotatable bonds, and Site = polar interactions at the active site.

Binding free energy calculation
The free energy of binding was calculated using prime MM-GB/SA approach [22]. In this approach, the docked poses were minimized using the local optimization feature in Prime, and the energies of the complex were calculated using the OPLS-AA (2005) force field and generalized-born/surface area (GB/SA) continuum solvent model. The free energy of binding, ΔGbind, is calculated as [23,24].

ΔGbind = ΔE + ΔGsolv + ΔGSA

ΔE = Ecomplex - Eprotein - Eligand

Where, Ecomplex, Eprotein, and Eligand are the minimized energies of the protein-ligand complex, protein, and ligand, respectively. Prime uses a surface generalized born model employing a Gaussian surface instead of a van der Waals surface for better representation of the solvent-accessible SA.

ΔGsolv = Gsolv(complex) - Gsolv(protein) - Gsolv(ligand)

Where, Gsolv(complex), Gsolv(protein), and Gsolv(ligand) are the solvation free energies of the complex, protein, and ligand, respectively. Prime uses a surface generalized born model employing a Gaussian surface instead of a van der Waals surface for better representation of the solvent-accessible SA.

ΔGSA = GSA(complex) - GSA(protein) - GSA(ligand)

Where, GSA(complex), GSA(protein), and GSA(ligand) are the SA energies for the complex, protein, and ligand, respectively. The rational criteria for selection of best compounds based on scoring and interaction parameters shown in XP docking with different charge model of ligands.

Molecular dynamics (MD) simulation
MD simulations were performed using Desmond with OPLS 2005 force field [25]. Prepared structures were imported in Desmond setup wizard, and they were solvated in the orthorhombic periodic box of TIP3P water molecules and neutralized using an appropriate number of counter ions and 0.15M of salt concentration. A distance of 10 Å was set between the box wall and protein complex to avoid direct interaction with its own periodic image. Steepest descent method was used to minimize the energy of prepared systems with a maximum of 5000 steps until a gradient threshold (25 kcal/mol Å) is reached. The systems were equilibrated using the default protocol provided in Desmond. The equilibrated systems were further carried to perform MD simulations for 20000 ps at a constant temperature of 300 K and the constant pressure of 1 atm with a time step of 2 fs.

RESULTS AND DISCUSSION
Molecular docking and binding free energy calculation
The prepared protein structure of IKKβ was docked using glide with nine compounds taken for the study. The results of the docking studies were provided in Table 1, and it is revealed that Morin as better compound based on docking score. All docking results are monitored by scoring functions that predict how well the ligand binds in a particular docking pose. This scoring function will give the ranking of the ligands. In the present study, docking score was taken into consideration for the selection of best ligand. It is an empirical scoring function that approximates the ligand binding free energy. It includes various force field interactions such as electrostatic and van der Waals contributions which influence ligand binding [26-28]. Subsequently, the docked structures were carried for binding free energy calculation. The results of binding free energy calculation were provided in Table 2. It is found that binding energy values were well supporting the docking result. Morin, salubrinal, icariin, and chondroitin sulfate have higher binding energy than other compounds. All the other values contribute to the ΔGbind, thereby reflects the total binding energy of the protein-ligand complex.

Binding pose analysis
The binding mode of the compounds with IKKβ showed that H-bonds and salt bridges along with other non-bonded interactions were found to influence the interaction between the proteins and ligands. The two-dimensional diagram of protein-ligand interaction was shown in Fig. 1 whereas the three-dimensional view of the active site of protein-ligand interaction was shown in Fig. 2. It is found from Table 3 that Arg20, Leu21, Thr23, Lys44, Glu61, Gln97, Cys99, Lys106, Asp145, Asn150, and Asp166 were actively involved in H-bond interaction with ligands. Each compound has different binding modes, which reflects the difference of interacting residues with different functional groups. Morin has better interaction than other compounds. Either Cys99 or Lys44 found predominantly in most of the complex except in β-ecdysterone whereas both found interacting with Morin. The results obtained from the molecular docking reveals the key interacting residues required for IKKβ inhibition.

MD simulation
MD simulations were performed to procure a better understanding of the dynamic behavior and stability of the protein-ligand complex. All the MD simulations were performed for 20000 ps. The change in the structural integrity was analyzed by calculating the RMSD and root mean square fluctuation (RMSF) of all the residues in the protein-ligand complex.

Table 1: Glide XP result of compounds under study

<table>
<thead>
<tr>
<th>Compound CID</th>
<th>Compound name</th>
<th>Docking score</th>
<th>Glide score</th>
<th>Glide energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>5281670</td>
<td>Morin</td>
<td>-11.043</td>
<td>-65.769</td>
<td>-44.611</td>
</tr>
<tr>
<td>5717801</td>
<td>Salubrinal</td>
<td>-7.687</td>
<td>-75.464</td>
<td>-58.085</td>
</tr>
<tr>
<td>5318997</td>
<td>Icariin</td>
<td>-7.671</td>
<td>-81.167</td>
<td>-57.511</td>
</tr>
<tr>
<td>24766</td>
<td>Chondroitin</td>
<td>-7.531</td>
<td>-58.703</td>
<td>-47.349</td>
</tr>
<tr>
<td>68289</td>
<td>Sesamol</td>
<td>-7.171</td>
<td>-31.674</td>
<td>-24.597</td>
</tr>
<tr>
<td>68245</td>
<td>Delphinidin</td>
<td>-7.078</td>
<td>-60.993</td>
<td>-40.615</td>
</tr>
<tr>
<td>6919837</td>
<td>LBHS09</td>
<td>-6.981</td>
<td>-65.362</td>
<td>-41.171</td>
</tr>
<tr>
<td>10281</td>
<td>Thymoquinone</td>
<td>-6.794</td>
<td>-31.482</td>
<td>-25.06</td>
</tr>
<tr>
<td>101778163</td>
<td>β-Ecdysterone</td>
<td>-6.387</td>
<td>-52.778</td>
<td>-40.423</td>
</tr>
</tbody>
</table>

CID: Compound identifier; XP: Extra precision
mean square fluctuations (RMSF) over backbone atoms. Fig. 3 shows all the complexes have even deviations around 3 Å and sometimes cross above 4 Å. Fig. 4 shows RMSF of all residues in the protein on binding with five complexes. It shows salubrinal and chondroitin sulfate fluctuates higher than the rest of the complexes, whereas Morin and icariin fluctuate higher than sesamol. Highest fluctuation of 25 Å was reached by the residues from 450 to 550 which were found to be the elongated chains. It was concluded from the trajectory analysis of all the protein-ligand complexes over 20000 ps time period of simulation that the ligand was stable in the binding pocket and did not dissociate.
Fig. 2: Three-dimensional view of the active site of an inhibitor of κβ kinase subunit β and its ligand complexes

Fig. 3: Root mean square deviation of best five complexes over 20000 ps time period of simulation

Fig. 4: Root mean square fluctuation of best five complexes over 20000 ps time period of simulation
Further, the radius of gyration was calculated to predict the compactness of the protein-ligand complexes over the simulation time period, and the results were shown in Fig. 5. It was revealed that all the protein-ligand complexes did not lose the compactness as the graph shows all the complexes were even with not many fluctuations. Fig. 6 shows the number of hydrogen bonds between the top 5 protein-ligand complexes which reveals that all the complexes have stable interaction except in case of chondroitin sulfate where both loss and gain of more interaction happens during the simulation time period. Thus, the result obtained here confirms the structure and interaction stability of the protein-ligand complexes taken under study.

CONCLUSION

This *in silico* study revealed that NFκβ is suppressing medicinal herbal phytochemicals by inhibiting the MMP-13 production in chondrocytes through downregulation of NFκβ signaling pathways. In this study, the best five compounds are Morin, salubrinal, icariin, and chondroitin sulfate, and sesamol. An *in vitro* study must be conducted to explore the IKKβ inhibitory potential of these five compounds. In addition, five bioactive compounds have been mentioned that may serve as promising therapeutic agents for the treatment of OA.

AUTHORS CONTRIBUTION

Since there is only one author for this manuscript, author contribution need not be mentioned.

CONFLICTS OF INTEREST

The authors have no conflict of interest.

REFERENCES

3. Marcu KB, Otero M, Olivotto E, Borzi RM, Goldring MB. NF-


