Research Summary:

Primary interest of my research group revolves around various application of two dimensional (2D) nanomaterial including, but not limited to, molecular recognition, sensing and catalytic applications. We developed laterally size controlled 2D single/thin-layer molecular assemblies by chemical synthesis/possessing (top-down/bottom-up method) from their corresponding precursors such as single molecular unit, single crystals etc. Followed by this we have functionalized those materials by using organic ligands to explore the supramolecular applications. The success of supramolecular application of various layered assemblies depends on the ability to fabricate surfaces with different functional groups by organic ligand synthesis which will be useful tools for molecular recognition. Following the synthesis, stabilization and surface functionalization of layered assemblies, my group is currently working on antibacterial activity, sensing, molecular recognition and catalytic applications. The highlight of some applications is as follows:

A. Development of various Nanoantibiotics

In view of the implications of inherent resistance of pathogenic bacteria, especially ESKAPE pathogens toward most of the commercially available antibiotics and the importance of these bacteria-induced biofilm formation leading to chronic infection, it is important to develop new-generation synthetic materials with greater efficacy toward antibacterial property. In this regard, it is expected that two-dimensional (2D) materials can be very useful because of their unique physical and chemical properties arising from their two dimensionality. In addressing this issue, at first, as a proof-of-principle study we have evaluated the potential of two-dimensional exfoliated MoS_2 (2D-MoS_2) toward inhibitory and bactericidal property against two representative ESKAPE pathogenic strain—a Gram-positive *Staphylococcus aureus* (MRSA) and a Gram-negative *Pseudomonas aeruginosa* (*ACS Appl. Mater. Interfaces* **2016**, 8, 31567-31573). 2D-MoS_2 exhibits metallic characteristic (1T) or semiconducting property (2H) depending on the crystal structure and preparation method. Along with physical and electronic properties surface functionalization also has been proven to be a great tool to tailor the nature of interaction of materials with biological systems. The functionalized TMDs show exceptionally high antibacterial activity with minimal toxicity, specifically for 2H phase of TMD (MoS_2) (*J. Am. Chem. Soc.* **2018**, *140*, 12634-12644). Based on that observations we have developed several nanoantibiotics which exhibit not only specific antibacterial activity, but also applied for *In vivo* wound healing application. Even though these broad-spectrum nano-antibiotics are remarkable towards combatting against multi-bacterial infections, but they are effective for a short time. Also, the prolonged expose of broad-spectrum antibiotics would disturb the balance of microbial flora at the site of infection, which may result in the development of drug-resistant bacteria and other health issues. Hence in comparison to broad spectrum antibiotics, selective antibacterial agents protect the host microbiome from collateral damage and avoid cross-resistance to non-targeted pathogens. In this regard, for the first time we have developed the nanomaterial-based antibiotics which show selective antibacterial activity for in vivo applications (*Angew. Chem. Int. Ed.* **2024**, *136*, e202314804, *ACS Biomater. Sci. Eng.* **2022**, *8*, 2932-2942, *J. Mater. Chem. B* **2022**, *10*, 4588-4594).

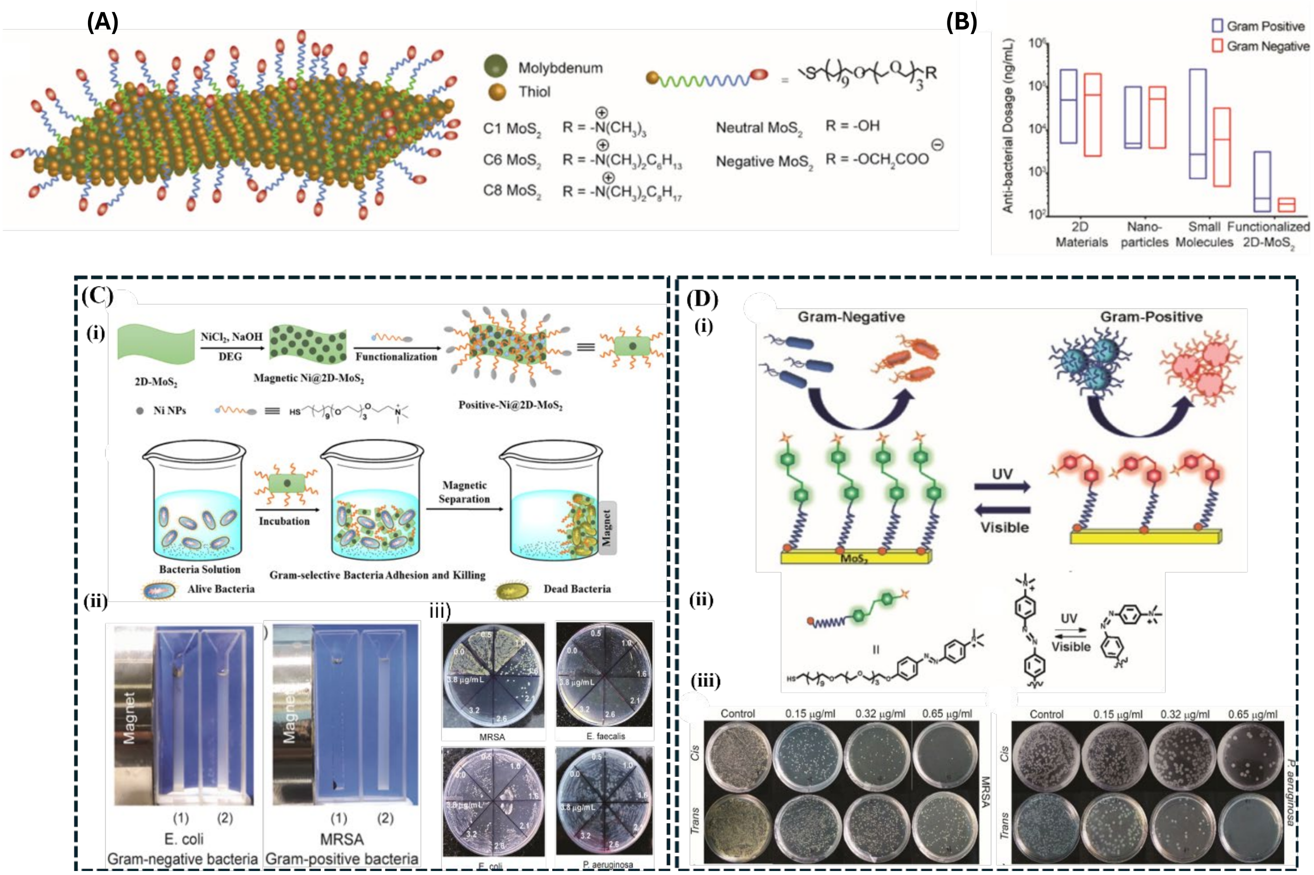

Figure 1. *(A) Functionalized 2D-TMDs with thiol ligands of varied charge and hydrophobicity used for antibacterial activity with better efficacy compared to small molecule and other nanomaterials (B). (C) and (D) Schematic illustrations for selective antibacterial activity based on stimuli responsive.*

B. Development of Nanozymes and their application in Antibacterial activity

Nanozymes are materials/macromolecules with inherent enzyme-like characteristics. Since the landmark paper on nanozymes was published in 2007 based on iron oxide nanoparticle, various types of nanozymes have been growing over the past decade because of their advantages compare to natural enzymes such as low stability, high cost, and difficult storage. Nanozymes were mainly conceptualized in interdisciplinary fields of material science, chemistry, biology and medicine. In our group, we mainly capitalize the nanozyme activity towards the development of antimicrobial agents. We have explored the peroxidase-like activity of transition metal dichalcogenides which was extended towards highly effective antimicrobial activity in presence of H_2O_2 (*ACS Appl. Nano Mater.,* **2021,** *4*, 12682-12689). We have also explored the role of functionalization, defects and doping in those materials for better understanding regarding the 2D-MoS_2 based nanozyme activity (*ACS Appl. Mater. Interfaces* **2022**, *14*, 42940-42949). Further, we explored the nanozyme activity in other materials such as graphene like system and macromolecular cages. We have also used self-assembled Pd-coordinated macromolecular cage as photoregulated oxidase-like nanozyme to kill pathogenic bacteria (*J. Am. Chem. Soc.* **2020,** *142*, 18981-18989, *Angew. Chem. Int. Ed.* **2023**, *135*, e202218226).

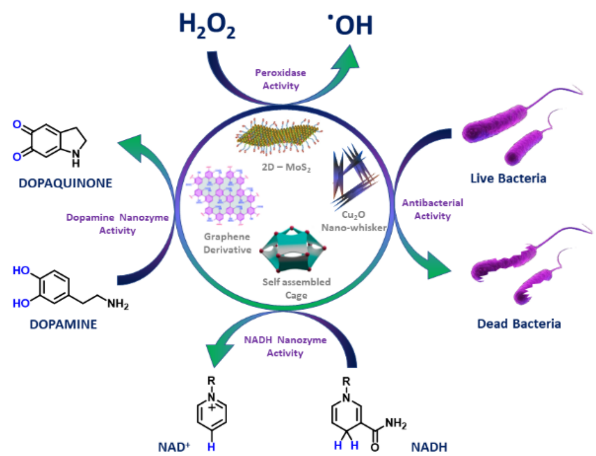

Figure 2. *Nanozyme activity of various nanomaterials/macromolecules as an antibiotic agent.*

C. Synthesis and Application of Carbon-Based Nanomaterials

Like TMDs, we have also developed carbon based functional nanomaterials for several biomedical. Depending on the size and shape of graphene oxide (GO) we altered the edge and surface ratio which control the interactions with the various molecules. In a similar approach we have selectively modified the edge and surface of varies GOs with L-amino acids and probe the effect on protein surface binding. The interaction of these functionalized GO with α-chymotrypsin (ChT) was investigated by activity assay, gel electrophoresis, zeta potential, circular dichroism and fluorescence spectroscopy. The results show that both electrostatic and hydrophobic interactions between the hydrophobic patches of receptors and the protein contribute to the stability of the protein-GO complex. Using this concept, several kinds of biomolecules are targeted such as enzymes, peptides, DNA and RNA, bacteria, cells etc. (*Nanoscale* **2022**, *14*, 7881-7890).

Emissive Carbon dots (C-Dots) are known for displaying versatile properties which have been widely utilized in many applications such as bioimaging, light-emitting devices and photocatalysis. Further functionalization can tune their physical and chemical properties which plays the key role in many biologically and chemically relevant applications. As evident from previous studies, amino acids provide an attractive means for introducing functionality with structural diversity. We have developed a method for water-soluble emissive C-Dots which were synthesized from pyrolysis of citric acid in presence of various amino acids under hydrothermal conditions. We have applied those C-Dots for various applications such as bioimaging, sensing etc (*J. Mater. Chem. B.* **2021,** *9*, 1432-1440).

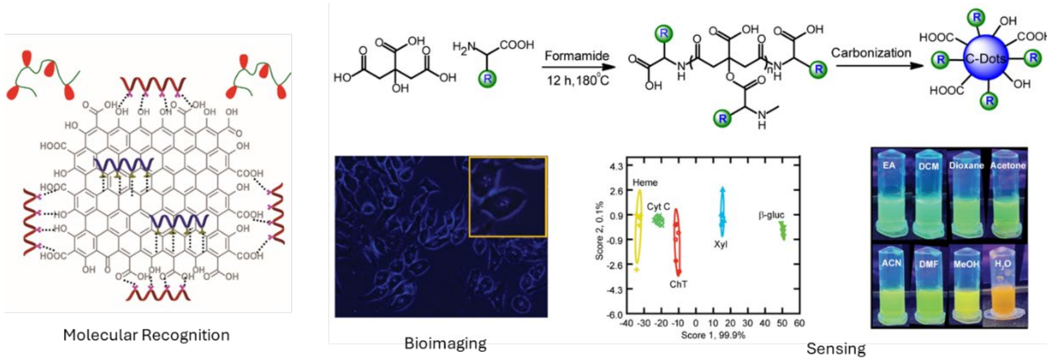

Figure 3. *Various carbon-based nanomaterials and their related applications.*

D. Array based Biosensing Using 2D nanomaterials as sensor platform

Most biomolecular sensing processes occur via specific as well as nonspecific interactions. The common examples of specific sensors are based on antigen-antibody interaction, enzyme-coenzyme interaction, aptamer based etc. Alternatively sensory processes such as taste and smell use "differential" binding where the receptors bind to their analytes by different binding characteristics that are selective rather than specific. The nonspecific array based sensor system provides highly versatile sensor platforms which have been used to sense a wide diversity of analytes and well-known as "chemical nose/tongue". We have used various 2D nanomaterials such as pristine and functionalized GO as well as 2D TMDs for array based sensing. We have developed several methodologies as well as able to identify various analytes ranging from small molecule to bacteria. In summery, we have developed, (i) Multichannel array-based discrimination of proteins by using nano graphene oxide as receptor (*Chem. Asian J.* **2019**, *14*, 553-560), (ii) Functionalized 2D-MoS_2 and fluorescence protein conjugates for detection of drug resistance bacteria (*Chem. Eur. J.* **2022**, *28*, e202201386), (iii) Application of sequential ON-OFF in array-based sensing for detection of nitroaromatics, protein and bacteria. (iv) Thiol-thiol exchange based array in TMDs to discrimination of various biologically related thiols and others (*ACS Nano* **2022**, *17*, 1000-1011).

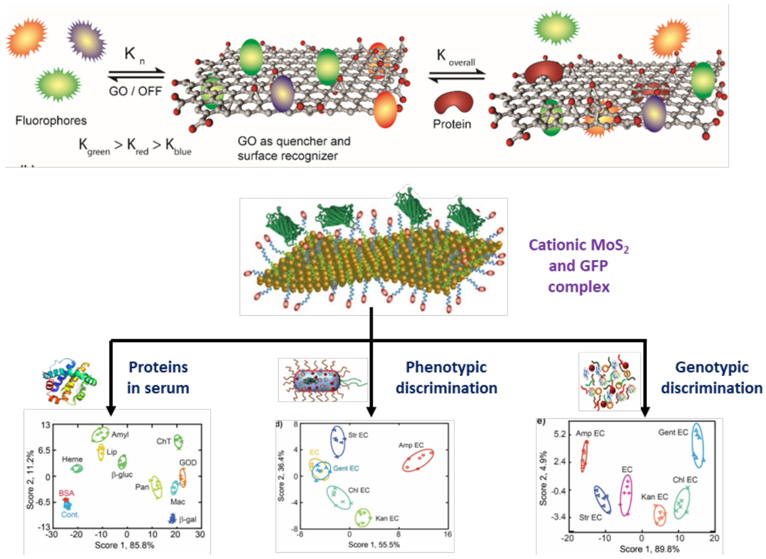

Figure 4. *Schematic representation of multichannel array based protein sensor by using functionalized 2D-materials as sensor and fluorophores as signal transducer and the detection of various bio-analytes.*

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