# Review ofs Halyna Butovych’s PhD thesis

«Computer Simulations of Polymer-Enzyme Complexes and
Chelate Structures of Heavy Metal Ions»

The manuscript by Halyna Butovych is dedicated to the research of the formation of complexes in two distinct systems: polymer-enzyme mixtures and heavy metal chelates. For the polymer-enzyme system, the binding of enzymes to polymer chains – a process critical for biofuel production – was studied using a coarse-grained model and Langevin dynamics simulations. For the chelation of heavy metal ions, a process relevant to wastewater treatment, the research used a detailed atomistic approach, combining classical molecular dynamics (MD) with quantum-chemical modeling (DFT).

The thesis consists of an introduction, a chapter containing a review of the topic, three chapters with original research results, a conclusions section, a list of references, and appendices.

The first chapter provides a detailed theoretical background on complex formation, covering both polymer-enzyme complexes modeled with patchy particles and the chelation of heavy metal ions by different ligands in aqueous solutions.

The second chapter of the thesis introduces a new theoretical approach to modeling polymer-enzyme complexation, represented by patchy chains and monomers. The core of this model is a modified Wertheim’s first-order thermodynamic perturbation theory, which proves to be more accurate than the unmodified version in predicting the degree of binding. Computer simulations using Langevin dynamics validate the theory's predictions but also expose its weaknesses when functional groups on the chains are too close together. A central discovery of this research is the critical role of the arrangement of functional groups on the polymer chain, specifically whether they are at the intermediate or terminal monomers. Accounting for this factor is essential for an accurate description of the complex formation. Because of its computational efficiency and accuracy, this model has practical applications, such as optimizing industrial biofuel production, and is adaptable to a wide range of other macromolecular hybrids.

The third chapter is dedicated to a combined computational approach that was used to investigate the chelation of mercury ions (Hg2+) by linear polyethyleneimine (PEI). Molecular dynamics (MD) simulations were performed to study the formation of PEI-Hg complexes with PEI chains of varying lengths (4, 5, and 10 nitrogen units). The structures were then refined and validated using density functional theory (DFT) calculations. This methodology allowed for a detailed analysis of the complexes' atomic structures, including key distances between the mercury ions and the PEI's nitrogen atoms, as well as the ions' first hydration shell. The study also evaluated the polymer's conformational changes and investigated how chain length influences both single-ion and multi-ion binding. By calculating adsorption energies from both MD and DFT, the stability of the complexes was assessed. The findings confirm that linear PEI forms stable mercury complexes, with the five-unit PEI chain demonstrating the most stable binding. This research provides crucial insights into PEI's chelating properties, which are valuable for developing materials to remove mercury ions from contaminated water.

Finally, in the fourth chapter, the mechanisms of heavy metal chelation by EDTA are explored through a detailed computational study. Using MD simulations to observe complex formation and DFT calculations to refine structures and compute energies, the research compares how EDTA binds to highly toxic ions: mercury (Hg2+), cadmium (Cd2+), and lead (Pb2+). The central discovery is the strong correlation between EDTA's protonation state and its chelating effectiveness. The study shows that EDTA forms the most stable complexes with metal ions when it is fully deprotonated, a state achieved under alkaline conditions. As the solution becomes more acidic, protons attach to the EDTA molecule, significantly weakening its binding ability. This pH-dependent chelation mechanism is a critical finding, offering a powerful method for controlling the formation of metal-EDTA complexes. This principle has significant potential for use in wastewater treatment, industrial applications, and medicine.

The research presented in this work combines both analytical and numerical approaches chosen as best suited for each problem, indicating the authors' adaptability and thoroughness while conducting research. Overall results obtained in this work represent forefront research in the field of polymer physics. The reliability and novelty of these results are further corroborated by their publication in the Journal of Molecular Liquids and Physical Chemistry Chemical Physics – authoritative international scientific journals.

After reviewing the thesis, I found no shortcomings in the scientific concepts, methods, or calculations. Therefore, I have no fundamental objections to the work. In conclusion, I believe that **Halyna Butovych's** thesis completely fulfills the requirements for a Doctor of Philosophy degree. The author, **Halyna Butovych**, is deserving of this degree in natural sciences (104 - physics and astronomy).

12.09.2025

Researcher, Department of Computer Simulations of Many-Particle Systems, Yukhnovskii Institute for Condensed Matter Physics of the National Academy of Sciences of Ukraine

Dr. Sci. K. Haydukivska