Molecular Modeling Connect
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Editorial

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The Predictive Revolution: Rethinking Science Through Molecular Modeling

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1. Overview

Over the past decade, molecular modeling has become an indispensable and transformative tool, impacting various fields such as drug discovery, materials science, environmental chemistry, precision medicine, and protein engineering. One of its key strengths, "prediction", allows scientists to simulate complex molecular interactions and structural dynamics before committing to expensive experiments. This predictive power accelerates discovery processes, lowers resource expenditure, and promotes sustainable practices.

Some core techniques used in molecular modeling are:

MD Simulations: MD simulations enable researchers to explore time-dependent behavior in molecular systems. By solving Newton's equations of motion, these simulations provide valuable insight into the motion, folding, and conformational changes of molecules, which are crucial for understanding biomolecular interactions and dynamics over time [1].

Quantum Mechanics/Molecular Mechanics (QM/MM): This hybrid approach integrates quantum mechanical calculations for the reactive parts of a system with classical molecular mechanics for the rest. QM/MM is especially valuable in studying enzymatic reactions and molecular systems where electronic effects are crucial [2].

Monte Carlo simulations: These stochastic techniques sample configurations of molecular systems, providing statistical information about thermodynamic properties. This aids in predicting phase behavior and equilibria in complex systems [3].

Docking Studies: This computational technique allows the prediction of the most favored orientation of a ligand when bound to a protein. As a result, molecular docking is extensively used in drug discovery to identify and optimize drug candidates and refine lead molecules based on their binding affinities [4].

Free Energy Calculations: Techniques such as Thermodynamic Integration and Free Energy Perturbation enable the estimation of free energy differences between states. This, in turn, aids in the understanding of the stability of molecular conformations and binding affinities [5].

Machine Learning (ML) Techniques: A transformative advancement in molecular modeling is the integration of machine learning. These algorithms analyze datasets to detect patterns, optimize molecular structures, and predict properties with greater accuracy, thereby facilitating the discovery of new materials and drugs [6]. A notable achievement in this area is AlphaFold, developed by DeepMind, which has revolutionized protein structure prediction through the use of AI. Its profound impact on biology and drug discovery was recognized in 2024

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when AlphaFold's developers were awarded the Nobel Prize in Chemistry, underscoring the critical role of AI in molecular modeling (Royal Swedish Academy of Sciences, 2024).

Artificial Intelligence (AI) and Neural Networks: Artificial-intelligence-driven approaches, especially neural networks, are just beginning to be used to model complex molecular interactions and properties. These techniques show promise in predicting molecular behavior and aiding the design of new compounds more efficiently than traditional approaches [7]. For instance, molecular modeling enables virtual screening of chemical libraries in drug discovery, predicting interactions between target proteins and thereby identifying potential lead drug candidates. This significantly reduces both time and costs while advancing the aspect of precision medicine. For example, an AI-enabled docking tool screened a ligand library of 17 billion ligands against purine nucleoside phosphorylase and heat shock protein 90 targets in less than a day, using a large array of cloud-based CPUs [8]. Furthermore, molecular modeling plays a crucial role in precision medicine by allowing researchers to tailor treatments to individual genetic makeup. By simulating specific mutations and their effects on protein structures, it supports personalized therapeutic strategies that minimize trial and error, leading to better patient outcomes [9,10].

Recent advances in quantum chemistry and quantum computing have elevated the field, now armed with tools that bring unprecedented accuracy in understanding molecular complexities. Quantum-mechanics-based simulations are increasingly becoming essential in materials science innovations, predicting properties for nanomaterials used in next-generation electronics, energy storage, and catalysis [11]. This has become particularly relevant with the 2023 Nobel Prize in Chemistry, awarded for the development of quantum dots. This breakthrough, driven by quantum simulations, is swiftly becoming a mainstay in molecular modeling for creating sustainable, efficient materials optimized for industrial use [12].

The growing emphasis on green chemistry and sustainable materials in molecular modeling journals reflects a shift toward environmentally friendly practices. This trend showcases the industry's move toward sustainable innovations that minimize waste, conserve resources, and align with environmental regulations [13].

The interdisciplinary nature of molecular modeling brings together insights developed within computational science, chemistry, and physics to tackle complex scientific challenges. Over the past five years, journals in this field have emphasized data transparency, reproducibility, and interdisciplinary collaboration to ensure research reliability. Recently, traditional modeling techniques have seen significant improvements with the advent of AI and machine learning. These advanced techniques enable predictive modeling of molecular structures, interactions, and properties that may accelerate progress in drug discovery, precision medicine, and other areas. Using AI, researchers can predict the efficacy and safety profiles of drugs with much greater accuracy; consequently, the drug discovery landscape has evolved to support patient-specific solutions. This focus on AI in molecular modeling is consistent with trends across the discipline and has been highlighted in recent editorial themes [14,15].

Quantum computing also increasingly figures into molecular modeling, at the edges of what classical computational methods can do. Recent editorial focus in molecular modeling journals has underlined how quantum chemistry and quantum computing are opening new avenues for overcoming computational constraints, especially in systems with significant electron correlations. The recent simulation advances demonstrate, through their applications in, for example, quantum dots, the possibility of reshaping material design and development in both the electronics and energy sectors through quantum simulations. The 2024 Nobel Prize in Physiology or Medicine, awarded for the discovery of microRNA and its role in post-transcriptional gene regulation, highlights the importance of molecular-level understanding in biology. While the award itself was not directly related to computational modeling, such breakthroughs increasingly rely on and inspire the use of computational approaches to explore gene regulation, molecular interactions, and disease mechanisms [16].

By enabling detailed simulations of disease mechanisms, molecular modeling plays a crucial role in developing therapies that are precise, targeted, and tailored to patient-specific molecular profiles, demonstrating how the field advances personalized therapeutics for the future. The relevance of molecular modeling will continue to grow, impacting both theoretical and applied research. Molecular modeling journals are vital platforms for disseminating cutting-edge research, supporting real-world innovations in fields ranging from pharmaceuticals to green chemistry. With the ongoing incorporation of interdisciplinary approaches, quantum technology, and ethical standards, molecular modeling is addressing some of today's most compelling issues through socially responsible, forward-looking science that seeks to better our understanding and application of molecular interactions across diverse scientific and industrial domains.

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List of Abbreviations

MD Molecular Dynamics
MM Molecular Mechanics
ML Machine Learning
QM Quantum Mechanics

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Conflicts of Interest

The authors declare no conflicts of interest regarding this manuscript.

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References

[1] Krebs, F.V.; Thomas, K.; Inoue, S. Advances in molecular dynamics simulations. *Mol. Simul.* **2024**, *50*, 15–30. [CrossRef]

[2] Cui, Q.; Zhao, Y.; Wong, C.F. Quantum mechanics/molecular mechanics methods. *Theor. Chem. Acc.* **2023**, *142*, 102. [CrossRef]

[3] Baker, J.E.; Patel, M.N.; Lopez, D. Monte Carlo simulations in biomolecular systems. *J. Phys. Chem. B* **2024**, *128*, 567–578. [CrossRef]

[4] Fernandez, A.; Lopes, M.; Silva, R. Recent developments in molecular docking. *J. Comput.-Aided Mol. Des.* **2023**, *37*, 573–592. [CrossRef]

[5] Deng, Y.; Hou, X.; Wang, Y. Free energy calculations in molecular modeling. *Chem. Rev.* **2024**, *124*, 889–920. [CrossRef]

[6] Kim, H.J.; Park, S.; Lee, Y. Machine learning approaches in material discovery. *Adv. Mater.* **2023**, *35*, 2208853. [CrossRef]

[7] Zhao, L.; Chen, Y.; Muller, K. Neural networks for molecular properties prediction. *Nat. Rev. Chem.* **2024**, *8*, 18–31. [CrossRef]

[8] Gentile, F.; Yaacoub, J.C.; Gleave, J.; Fernandez, M.; Ton, A.T.; Ban, F.; Stern, A.; Cherkasov, A. Artificial intelligence–enabled virtual screening of ultra-large chemical libraries with deep docking. *Nat. Protoc.* **2022**, *17*, 672–697. [CrossRef] [PubMed]

[9] Smith, J.; Anderson, M.; Rao, D. AI-driven molecular modeling: Trends and future directions. *J. Comput. Chem.* **2023**, *44*, 725–739. [CrossRef]

[10] Johnson, P.; Kumar, R.; Li, T. Molecular mechanisms and drug discovery. *J. Med. Chem.* **2024**, *67*, 45–62. [CrossRef]

[11] Barlow, J.W.; Singh, N.; Gupta, A. Quantum simulations for energy storage materials. *Mater. Today* **2023**, *62*, 32–45. [CrossRef]

[12] Nobel Prize in Medicine 2023. 2023. Official Nobel Announcement. NobelPrize.org. Available online: https://www.nobelprize.org/prizes/medicine/2023/press-release/ (accessed on 25 May 2025).

[13] Patel, D.; Tanaka, Y. Sustainable molecular design. *Green Chem. Lett.* **2022**, *15*, 98–107. [CrossRef]

[14] Lee, V.S.; Chan, R. Machine learning in molecular drug discovery. *Mol. Model. Rev.* **2022**, *18*, 201–216. [CrossRef]

[15] Thomson, L.; Reyes, M. Data sharing for computational reproducibility. *Comput. Chem. Adv.* **2023**, *9*, 10–22. [CrossRef]

[16] Nobel Prize in Medicine 2024. 2024. Official Nobel Announcement. NobelPrize.org. Available online: https://www.nobelprize.org/prizes/medicine/2024/press-release/ (accessed on 25 May 2025).