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Computational Drug Repurposing and Natural Compound Discovery in Precision Medicine: Molecular Targeting Across Cancer, Neuroinflammation, and Antimicrobial Resistance

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Abstract: Computational drug repurposing and the search for natural compounds are changing the landscape of precision medicine. Instead of relying solely on the lengthy, expensive process of developing new drugs from scratch, these approaches leverage what we already know about existing drugs and the natural world. This means treatments can be discovered faster, more affordably, and with fewer risks. The focus is on how natural compounds that target multiple pathways, and on existing drugs used in new ways, can help address diseases with many causes. There is also growing interest in using new delivery methods, like nanotechnology, to make these compounds even more effective in real-world treatment. Even with all these advances, there are still some big challenges to overcome. Issues such as data quality, understanding how AI models make decisions, and addressing legal and ethical questions are important hurdles. To move forward, experts from different fields need to work together, create clearer rules, and improve how data is shared and understood. Looking ahead, combining data from many sources, improving AI models that predict how drugs work in the body, and building better ways for teams to collaborate will help push the field further. Overall, using computers to find new uses for drugs and discover helpful natural compounds offers a promising, flexible way to accelerate the development of new treatments and make medicine more personal for everyone.

Keywords: Computational Drug, Artificial Intelligence, Natural Compound Discovery, Precision Medicine, Machine Learning

1. Introduction

Computational drug repurposing and natural compound discovery have become essential pillars in advancing precision medicine, particularly for complex, multifactorial diseases such as cancer, neuroinflammatory disorders, and antimicrobial resistance [1]. Traditional drug development pipelines are often slow, expensive, and marked by high attrition rates, making them poorly suited to address urgent and evolving medical challenges. In contrast, computational repurposing strategies focus on uncovering new therapeutic roles for existing drugs and bioactive natural compounds. By building on existing pharmacological and toxicological knowledge, these approaches reduce development timelines and costs while substantially increasing the likelihood of clinical success [2]. The increasing adoption of artificial intelligence, machine learning, and bioinformatics has further accelerated this process by enabling large-scale analysis of molecular interactions, disease networks, and patient-specific biological signatures. One of the strongest advantages of drug repurposing lies in its practical efficiency. Drugs with established safety, dosing, and pharmacokinetic profiles can be rapidly evaluated for alternative clinical applications, allowing researchers to bypass many early-stage development barriers [3]. This flexibility is especially valuable in disease areas where traditional drug discovery is limited by financial constraints, biological complexity, or pressing clinical need. As a result, drug repurposing has gained increasing importance in oncology, neurodegenerative disorders, and the management of infectious diseases, where existing therapies may be inadequate or quickly compromised by resistance [4]. Importantly, repurposed drugs can often be incorporated into current treatment regimens, enhancing therapeutic efficacy while minimizing additional toxicity or patient burden. Alongside drug repurposing, natural compounds continue to play a critical role in therapeutic discovery due to their extraordinary chemical diversity and broad biological activity [5]. Compounds derived from plants, microorganisms, and marine organisms frequently exhibit anticancer, antimicrobial, and neuroprotective properties by acting on multiple molecular targets simultaneously. This multitarget nature is particularly beneficial for complex diseases driven by interconnected signaling pathways rather than single molecular defects [6].

However, despite their promise, translating natural compounds into clinical use remains challenging. Poor aqueous solubility, low bioavailability, rapid metabolic degradation, and variability in activity outside their native biological context often limit their effectiveness. These challenges have fueled the development of advanced formulation and delivery strategies, including nanotechnology-based systems, lipid carriers, and polymeric nanoparticles, which aim to improve stability, absorption, and targeted delivery [7]. The integration of precision medicine into computational drug repurposing represents a meaningful shift toward more individualized therapeutic strategies. Precision medicine recognizes that patients differ widely in genetic makeup, molecular signaling, disease progression, and response to treatment. By incorporating this biological diversity, computational models can more accurately predict therapeutic outcomes and reduce the risk of adverse drug reactions [8]. Bioinformatics-driven analysis of large-scale datasets enables patient stratification, biomarker discovery, and rational drug selection tailored to specific disease subtypes. This personalized approach is particularly important in oncology and neurodegenerative diseases, where patients with similar clinical diagnoses often respond very differently to the same therapy [9]. Advances in artificial intelligence and machine learning have further reshaped the drug discovery landscape by enhancing predictive accuracy, refining candidate prioritization, and revealing therapeutic pathways that may not be apparent through conventional analytical methods. Modern AI systems can process vast, complex datasets far beyond human analytical capacity, allowing the identification of subtle patterns and non-obvious drug–disease relationships [10]. Deep learning models, in particular, have shown strong potential in simultaneously analyzing molecular structures, biological networks, and clinical data. These capabilities greatly improve the efficiency with which laboratory discoveries can be translated into clinically meaningful applications, helping to close the gap between computational prediction and patient care [11]. As computational approaches continue to mature, collaboration will become increasingly important. Partnerships among academic institutions, regulatory agencies, pharmaceutical companies, and computational scientists are essential for data sharing, methodological standardization, and clinical validation of AI-generated predictions. At the same time, ethical, regulatory, and technical challenges must be addressed to ensure responsible and equitable implementation [12]. Transparent model development, strong data governance practices, and adaptive regulatory frameworks will ultimately determine the long-term success of computational drug repurposing. Together, the integration of artificial intelligence, precision medicine, and natural compound discovery offers a powerful and forward-looking pathway toward more effective, personalized, and accessible therapeutic solutions across a wide range of medical disciplines.

2. Computational Drug Repurposing Methodologies

Computational drug repurposing, also known as in silico drug repurposing, systematically analyzes biological, chemical, and clinical data to uncover new therapeutic uses for existing drugs. Rather than treating drug discovery as a purely experimental process, this approach combines computational modeling, data mining, and artificial intelligence–driven techniques to identify new indications more efficiently and with greater targeting [13]. By leveraging large, diverse datasets, computational repurposing reduces experimental workload while improving the accuracy and reliability of predicted drug–disease relationships. Machine learning has become a cornerstone of modern drug repurposing strategies and is generally divided into supervised and unsupervised learning approaches. Supervised learning methods rely on labeled datasets to train models capable of predicting drug–target and drug–disease interactions, making them particularly effective when prior biological or clinical knowledge is available [14]. In contrast, unsupervised learning approaches analyze unlabeled data to uncover hidden structures and patterns in complex datasets. These methods are especially valuable for discovering novel repurposing opportunities without relying on predefined hypotheses. Techniques such as clustering and dimensionality reduction are commonly used to expose latent relationships among drugs, molecular targets, and disease phenotypes [15]. Beyond traditional machine learning frameworks, more advanced algorithms such as k-nearest neighbors, random forests, and support vector machines have shown strong performance in drug repurposing applications. In recent years, deep learning approaches have gained increasing attention due to their capacity to model high-dimensional, non-linear biological data with greater precision [16]. Convolutional neural networks are frequently applied to

analyze molecular structures and chemical fingerprints, while recurrent neural networks are used to capture sequential biological processes and dynamic drug-response behaviors. Together, these techniques enhance predictive accuracy and support more reliable identification of promising candidate compounds. Network-based approaches offer an additional and complementary perspective by representing biological systems as interconnected networks [17]. In these models, nodes represent entities such as drugs, genes, proteins, or diseases, while edges describe functional, regulatory, or mechanistic relationships between them (Figure 1). Graph-based analyses enable the identification of indirect or previously unrecognized associations that conventional analytical methods may miss. Incorporating multi-omics data, clinical outcomes, and molecular interaction networks further strengthens these models, enabling a system-level understanding of disease mechanisms and therapeutic intervention points [18]. High-throughput screening provides experimental support to computational strategies by allowing the rapid evaluation of large libraries of approved or investigational drugs against specific disease targets. When integrated with artificial intelligence and machine learning, high-throughput screening data can be analyzed efficiently to identify meaningful trends, prioritize high-potential compounds, and predict therapeutic relevance with greater confidence. This combined approach effectively bridges computational prediction and experimental validation, accelerating the transition from raw data to actionable insights. Despite substantial progress, several challenges continue to limit the full potential of computational drug repurposing [19]. Accurately modeling pharmacokinetic and pharmacodynamic behavior remains difficult, as does capturing patient heterogeneity and real-world biological variability. In addition, regulatory complexities associated with repositioning approved drugs can slow clinical translation. Addressing these limitations requires close collaboration among computational scientists, experimental researchers, clinicians, and regulatory experts [20]. As predictive models grow more sophisticated and multi-modal data integration improves, computational drug repurposing is expected to play an increasingly central role in precision medicine, supporting the development of more effective, personalized therapeutic strategies.

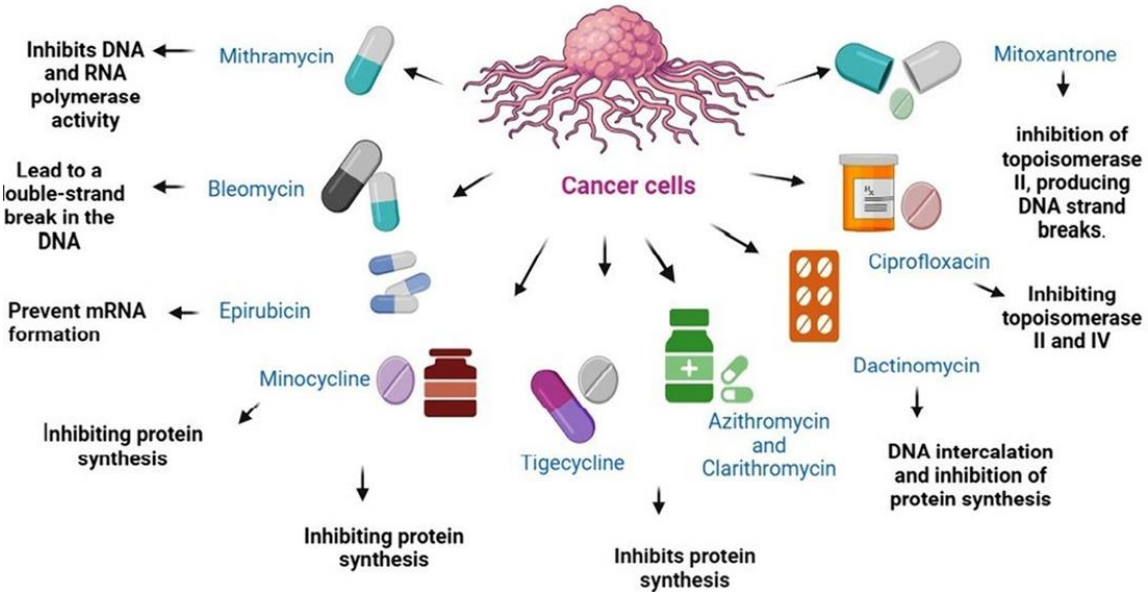

Figure 1. Antibiotics repurposed as anticancer agents and their mechanisms of action [51].

3. Applications of Computational Drug Repurposing and Natural Compounds

Computational drug repurposing and natural compound discovery have found wide-ranging applications across multiple disease areas, with particularly strong relevance in cancer, neurodegenerative disorders, and broader therapeutic development. By combining computational analysis with biological insight, these approaches enable the identification of effective treatment

strategies that address complex disease mechanisms while significantly reducing development time and cost [21]. This dual emphasis on efficiency and biological relevance has positioned computational repurposing as an increasingly practical tool in modern drug discovery. In cancer treatment, natural compounds have demonstrated considerable therapeutic potential, largely because of their ability to influence multiple signaling pathways involved in tumor initiation, progression, and metastasis [22]. Compounds such as curcumin and resveratrol have been widely studied for their ability to inhibit tumor growth, suppress metastasis, and induce programmed cell death in cancer cells (Table 1). However, despite these promising effects, their direct clinical application has been limited by practical challenges, including poor water solubility and low bioavailability. To address these barriers, advanced formulation strategies, such as nanoscale delivery systems, have been developed to improve compound stability, enhance absorption, and increase therapeutic efficacy [23]. These technological advances have renewed interest in incorporating natural compounds as supportive or adjunct therapies alongside conventional cancer treatments. Alongside natural products, drug repurposing has emerged as a powerful and flexible strategy in oncology. A growing number of drugs originally approved for non-cancer indications have been found to exhibit anticancer activity by modulating key molecular pathways linked to tumor growth, metabolism, and treatment resistance. For instance, certain metabolic drugs have been shown to influence cellular energy-sensing mechanisms, thereby increasing sensitivity to chemotherapy and limiting cancer cell proliferation [24]. These findings highlight how repurposed drugs can complement existing cancer therapies, offering new ways to overcome resistance while minimizing additional toxicity.

In the context of neurodegenerative diseases, natural compounds have gained attention for their potential neuroprotective and disease-modifying effects. Conditions such as Alzheimer's and Parkinson's disease are characterized by complex, multifactorial pathologies that are difficult to address with single-target therapeutic approaches. Natural compounds, by contrast, often act on multiple biological processes simultaneously, including oxidative stress, inflammation, apoptosis, and neuronal survival [25]. Network-based and systems pharmacology approaches have been particularly valuable for clarifying these interactions, revealing how individual compounds can simultaneously influence multiple disease-related pathways. This multitarget activity makes natural compounds particularly appealing candidates for managing neurodegenerative conditions, where broad modulation of disease mechanisms is often required [26]. Beyond oncology and neurodegeneration, computational drug repurposing has demonstrated broad applicability across diverse medical fields. Specialized platforms and computational pipelines have been developed to systematically explore new therapeutic indications for approved drugs by integrating chemical properties, molecular structures, and biological data [27]. These approaches not only speed up the identification of promising candidates but also support the optimization of dosage, formulation, and routes of administration to align treatments with patient needs better. As a result, drug repurposing continues to expand therapeutic options for diseases with limited, ineffective, or unavailable current treatments [28]. Overall, the application of computational drug repurposing and natural compound discovery represents a versatile and impactful strategy in contemporary medicine. By effectively linking computational prediction with biological validation, these approaches support the development of therapies that are not only more efficient to discover but also more accessible and personalized. As computational tools and biological data continue to advance, this integrated strategy is likely to play an increasingly important role in addressing complex diseases across a wide spectrum of clinical settings.

Table 1. Computational Drug Repurposing and AI-Driven Precision Medicine Studies

Study Focus	Disease Area	Key Contribution	Ref. No.
Targeted drug repurposing using computational modeling	Hepatocellular carcinoma	Identified celecoxib as a GSK-3β inhibitor with therapeutic relevance	[22], [38]
In silico repurposing of	Liver cancer	Targeted Keap1–NRF2 axis for	[26],

FDA-approved drugs		precision oncology	[44]
Machine learning applications in cancer biology	Oncology	Demonstrated AI-driven improvements in diagnosis, prognosis, and treatment	[35]
AI and machine learning in laboratory medicine	Clinical diagnostics	Improved pre-analytical and post-analytical processes	[32]
Clinical data + molecular profiling	Drug hypersensitivity	Predicted antibiotic-induced anaphylaxis using integrated datasets	[33], [42]
CRISPR and NGS integration	Personalized cancer care	Combined genomic editing and sequencing for precision medicine	[14]
Artificial intelligence in healthcare	Multidisciplinary	Reviewed AI applications, challenges, and clinical impact	[13], [15]
Biomarker-based precision analysis	Hepatocellular carcinoma	Gender-specific biomarker insights in Bangladeshi patients	[19]

4. Challenges and Limitations of AI-Driven Drug Repurposing

Despite its considerable promise, integrating artificial intelligence into drug repurposing poses several important challenges and limitations that must be carefully addressed to ensure reliable, ethical, and clinically meaningful translation. These challenges broadly relate to data quality and integration, model interpretability and generalizability, ethical considerations, and regulatory and intellectual property constraints [29]. Together, they shape both the opportunities and the limitations of AI-driven drug repurposing in real-world healthcare settings. One of the most critical obstacles in AI-driven drug repurposing is the quality and accessibility of data. Artificial intelligence models depend heavily on large, accurate, and well-curated datasets to generate meaningful and reproducible predictions. In practice, however, biomedical data are frequently fragmented across multiple platforms, stored in incompatible formats, and affected by missing values, inconsistencies, and systematic biases. Integrating heterogeneous data sources, including genomic, clinical, chemical, and pharmacological information, remains a substantial technical challenge [30]. Without standardized data frameworks, harmonized annotation practices, and robust governance structures, AI models risk being trained on incomplete or flawed datasets. This can compromise predictive accuracy, limit reproducibility, and reduce the applicability of computational findings in real clinical environments.

Model interpretability represents another major concern, particularly for deep learning–based systems. Many advanced AI models operate as opaque "black boxes," providing limited insight into how specific predictions or recommendations are generated. This lack of transparency poses a significant barrier to clinical adoption, as clinicians and regulatory authorities require clear mechanistic explanations to evaluate safety, efficacy, and clinical relevance. Trust in AI-supported decision-making depends not only on predictive performance but also on the ability to understand and validate model behavior. Furthermore, achieving reliable generalization across diverse patient populations remains challenging [31]. Biases embedded in training datasets can lead to skewed or inconsistent predictions when models are applied to underrepresented populations, different disease subtypes, or varied healthcare settings, thereby limiting their broader clinical utility. Ethical considerations further complicate the application of artificial intelligence in drug repurposing. Clinical equipoise is a central ethical issue, as trials involving repurposed drugs must maintain genuine uncertainty regarding the comparative effectiveness of proposed treatments. When repurposed candidates lack sufficient supporting evidence relative to established therapies, difficult ethical questions arise regarding patient safety, trial design, and informed consent. Equitable access to repurposed therapies also remains a pressing concern. Although drug repurposing can lower development costs, high pricing strategies, market exclusivity, and limited availability of certain repurposed or orphan drugs may still restrict patient

access [32]. These challenges risk undermining the broader public health benefits that drug repurposing is intended to deliver.

Regulatory and intellectual property considerations add a layer of complexity to AI-driven drug repurposing efforts. While regulatory pathways designed to accelerate approval of repurposed drugs can reduce development barriers, navigating these frameworks requires specialized regulatory expertise and careful strategic planning. Securing intellectual property protection for repurposed compounds is often difficult, as demonstrating novelty and non-obviousness can be challenging when working with previously approved drugs (Figure 2) [33]. Although artificial intelligence can assist in generating mechanistic insights and hypothesis-driven evidence to support patent claims, these claims must still meet rigorous legal and regulatory standards to ensure commercial viability and long-term sustainability. Addressing these challenges will require coordinated, interdisciplinary collaboration among computational scientists, experimental researchers, clinicians, ethicists, regulatory authorities, and industry stakeholders. Advances in data standardization, transparent and interpretable model design, ethical oversight, and regulatory alignment are essential for translating AI-driven drug repurposing from computational prediction into safe, effective, and equitable clinical application. By confronting these limitations directly, the field can move closer to realizing the full potential of artificial intelligence as a transformative tool in precision medicine.

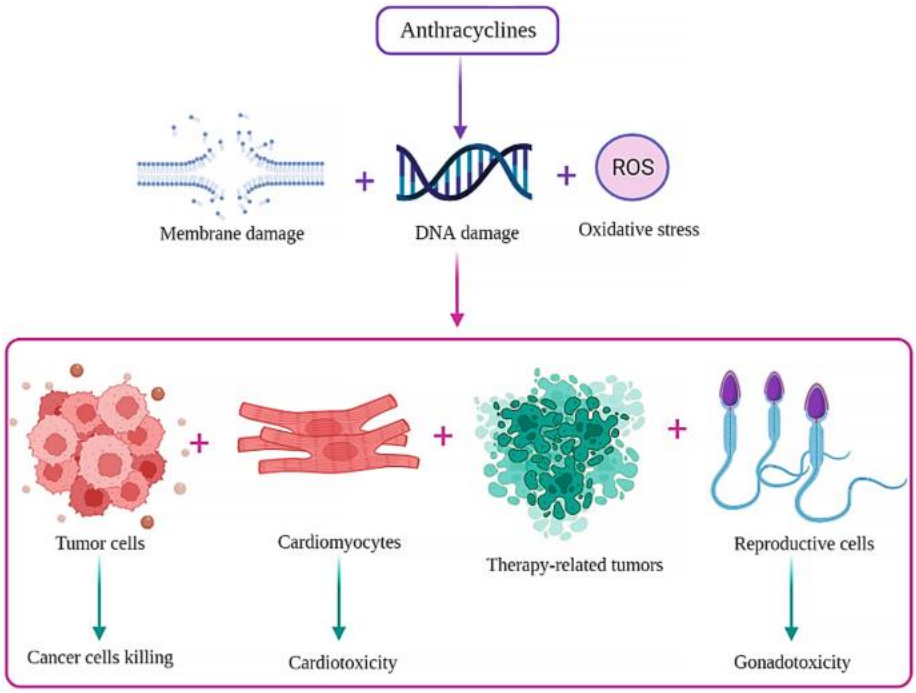

Figure 2. Mechanisms of action and biological effects of anthracyclines [52].

5. Future Directions in Computational Drug Repurposing and AI-Driven Discovery

Future research in computational drug repurposing is expected to place greater emphasis on integrating multi-omics data, including genomics, transcriptomics, proteomics, and metabolomics. Bringing these data layers together offers a more complete view of disease biology by capturing molecular interactions across multiple biological scales. Such integrated analyses can reveal complex disease networks, identify novel therapeutic targets, and strengthen drug repurposing efforts by linking molecular signatures to existing drugs with well-characterized safety and pharmacological profiles [34]. At the same time, continued advancements in computational methodologies are set to reshape the drug repurposing landscape further. Machine learning and artificial intelligence are evolving toward more efficient, scalable, and biologically informed models capable of detecting subtle and non-obvious drug–

disease relationships. Improvements in deep learning architectures, algorithm optimization, and data-processing efficiency will enable the analysis of high-dimensional biological data more rapidly and accurately (Table 2**)**. As a result, the time required to generate actionable therapeutic hypotheses will continue to decrease, accelerating the transition from computational prediction to clinical evaluation [35].

Collaborative frameworks will play an increasingly critical role in advancing drug repurposing research. Strong partnerships among academic institutions, regulatory agencies, pharmaceutical companies, and patient advocacy groups can promote data sharing, improve access to resources, and support large-scale validation studies. In parallel, the development of regulatory pathways specifically tailored to repurposed drugs will be essential for streamlining approval processes without compromising safety or efficacy standards. Greater regulatory alignment can help ensure that validated therapies move more efficiently from discovery to patient care. The future of drug discovery will also rely heavily on AI-driven modeling of pharmacokinetics and pharmacodynamics [36]. In silico prediction of drug absorption, distribution, metabolism, excretion, and therapeutic response has the potential to improve dose optimization and refine predictions of therapeutic windows. As precision medicine continues to advance, AI-based analytical frameworks will become increasingly important for interpreting complex biological interactions, clarifying mechanisms of action, and anticipating potential adverse effects across diverse patient populations. Despite these promising developments, financial and technical barriers remain important considerations. The development and implementation of advanced AI platforms require substantial investment in computational infrastructure, access to high-quality data, and specialized interdisciplinary expertise. Collaborative investment strategies and shared technological platforms will be necessary to distribute costs and expand access to AI-driven drug repurposing tools [37]. By addressing these challenges proactively, future research can more fully realize the potential of computational drug repurposing as a foundational component of precision medicine.

Table 2. Natural Compounds, Molecular Docking, and Resistance Mechanisms

Compound	Disease	Key Findings	Ref. No.
Tanshinone IIA – STING pathway	Neuroinflammation	Identified as a natural inhibitor via computational exploration	[21], [41]
Withaferin A – mutant p53 (R248Q)	Cancer	Demonstrated multi-faceted inhibitory activity	[31], [39]
Tinosporaside – COX-2	Inflammation / Cancer	Proposed as a safer natural alternative to celecoxib	[40], [29]
Xanthohumol – estrogen receptor	Breast cancer	Suggested as a natural substitute for tamoxifen	[46]
TEM-1 β-lactamase	Antimicrobial resistance	Explained ceftriaxone resistance via molecular docking	[36], [43]
VEGFR2 mutations	Hepatocellular carcinoma	Revealed sorafenib resistance through signaling crosstalk	[45]
Probiotics	Neuro-trauma	Identified neurotherapeutic potential in spinal cord injury	[37]
Nanotechnology-based delivery	Environmental & health systems	Improved stability and application of bioactive compounds	[48]

6. Discussion

The increasing integration of computational drug repurposing and natural compound discovery represents a meaningful shift in how modern therapeutics are identified, refined, and translated into

clinical practice. Traditional de novo drug discovery remains costly, time-consuming, and burdened by high failure rates, making it an inefficient response to many urgent medical challenges. Computational approaches offer a more practical alternative by building on existing drugs and bioactive compounds with known properties [38]. When combined with artificial intelligence, machine learning, and systems-level biological data, these strategies align closely with the goals of precision medicine, supporting the development of therapies that are more targeted, adaptive, and patient-specific. One of the most compelling strengths of computational drug repurposing is its ability to leverage existing pharmacological and safety data. This advantage allows researchers to bypass early-stage toxicity testing and focus directly on identifying new disease indications or therapeutic contexts [39]. In oncology, for example, repurposed drugs have shown encouraging potential by modulating metabolic, inflammatory, and signaling pathways that drive tumor growth and therapeutic resistance. At the same time, natural compounds offer chemically diverse scaffolds that can interact with multiple molecular targets, making them especially relevant for diseases with complex, overlapping mechanisms [40]. Together, the convergence of drug repurposing and natural compound exploration creates a flexible and powerful framework for therapeutic innovation. From a methodological perspective, advances in computational techniques have been central to expanding both the scope and reliability of drug repurposing efforts. Machine learning models, ranging from traditional algorithms to advanced deep learning architectures, have proven effective in identifying complex, non-linear relationships within high-dimensional biological data [41]. Supervised learning approaches perform particularly well when high-quality labeled datasets are available, enabling accurate prediction of drug–target and drug–disease interactions. In contrast, unsupervised learning methods allow the discovery of latent patterns and previously unrecognized associations without predefined assumptions, supporting hypothesis generation in underexplored disease areas [42]. Network-based and graph-theoretical approaches further strengthen predictive capacity by modeling biological systems as interconnected entities, offering system-level insight that extends beyond single-target perspectives. The application of these computational methodologies across diverse disease domains highlights their strong translational relevance. In cancer therapy, both repurposed drugs and natural compounds have demonstrated the ability to disrupt oncogenic signaling, promote apoptosis, and enhance tumor sensitivity to existing treatments [43]. However, the clinical impact of many natural compounds is limited by challenges related to solubility, bioavailability, and pharmacokinetics. Advances in formulation science, including nanocarrier-based delivery systems, have begun to address these barriers by improving compound stability, tissue targeting, and therapeutic effectiveness. In neurodegenerative diseases, where disease mechanisms are particularly complex and remain poorly understood, multitarget compounds and network-based repurposing strategies offer distinct advantages. Computational tools enable the identification of compounds that simultaneously modulate oxidative stress, neuroinflammation, protein aggregation, and apoptotic pathways, reflecting the multifaceted nature of neurodegeneration [44].

Beyond specific disease categories, computational drug repurposing offers a scalable and adaptable solution for addressing unmet medical needs across a wide range of therapeutic areas. By systematically analyzing large drug libraries and integrating chemical, biological, and clinical data, these approaches facilitate the identification of new indications, optimized dosing regimens, and alternative routes of administration. This flexibility is especially valuable in areas such as antimicrobial resistance and rare diseases, where traditional drug development is often limited by economic constraints or scientific uncertainty. Despite these clear advantages, several challenges continue to limit the widespread clinical adoption of AI-driven drug repurposing. Data quality remains a persistent concern, as biomedical datasets are often fragmented, heterogeneous, and incomplete [45]. Integrating diverse data sources, including genomic profiles, clinical records, and chemical descriptors, requires robust standardization, harmonization, and governance frameworks. Without these safeguards, predictive models risk being trained on biased or noisy data, reducing reproducibility and increasing the likelihood of translational failure. Addressing these limitations will require coordinated efforts to improve data sharing, curation, and interoperability across institutions and platforms.

Model interpretability presents another significant barrier. Many advanced AI systems,

particularly deep learning models, offer limited transparency in their decision-making processes. While high predictive accuracy is valuable, the "black-box" nature of these models undermines clinical trust and complicates regulatory evaluation. Clinicians and policymakers need mechanistic explanations to assess therapeutic relevance, patient safety, and clinical feasibility [46]. Improving explainability through interpretable AI methods and hybrid modeling approaches will be critical for bridging the gap between computational prediction and real-world clinical decision-making. Ethical considerations further shape the implementation of AI-driven drug repurposing. Clinical trials involving repurposed drugs must strike a careful balance between innovation and patient safety, particularly when evidence supporting new indications is still emerging. Informed consent, clinical equipoise, and fair patient selection require rigorous attention [47]. Equitable access also remains a pressing issue. Although drug repurposing can lower development costs, pricing strategies, intellectual property protections, and market exclusivity can still restrict access, especially in low-resource settings. Ensuring that the benefits of computational drug repurposing extend across populations will require sustained ethical oversight and supportive policy frameworks. Regulatory and intellectual property challenges further influence the success of repurposed therapies. While accelerated regulatory pathways can reduce development timelines, navigating these systems demands specialized expertise and careful strategic planning. Demonstrating novelty and therapeutic value for existing compounds remains difficult, particularly when intellectual property protection is limited [48]. Although artificial intelligence can support the generation of mechanistic insights to strengthen regulatory submissions and patent applications, these claims must still satisfy stringent legal and scientific standards. Aligning regulatory innovation with technological progress remains a key priority for the field. Looking ahead, future progress in computational drug repurposing will increasingly depend on integrating multi-omics data. Combining genomic, transcriptomic, proteomic, and metabolomic information will enable a deeper understanding of disease heterogeneity and therapeutic response. This systems-level perspective supports biomarker discovery, improves patient stratification, and enhances the precision of repurposing strategies, moving the field closer to truly personalized treatment design [49]. Advances in AI-driven pharmacokinetic and pharmacodynamic modeling are also expected to play a major role in shaping future developments. In silico prediction of drug behavior in the human body can inform dose optimization, therapeutic windows, and safety assessments, reducing reliance on costly, time-intensive experimental testing. These capabilities are especially important in precision medicine, where individual variability in drug response can significantly influence outcomes. Finally, overcoming financial and technical barriers will require shared infrastructure and collaborative investment. High-performance computing platforms, access to high-quality datasets, and the development of interdisciplinary expertise demand substantial resources [50]. Collaborative models involving academia, industry, regulatory agencies, and patient organizations will be essential for distributing costs, accelerating innovation, and promoting transparency and standardization. Together, computational drug repurposing and natural compound discovery represent powerful and complementary strategies for advancing precision medicine. While methodological, ethical, and regulatory challenges remain, continued innovation in computational tools, data integration, and collaborative frameworks offers a sustainable pathway toward more effective, personalized, and accessible treatments across a broad spectrum of diseases.

7. Conclusion

Computational drug repurposing and natural compound discovery are powerful, complementary strategies for advancing precision medicine. By integrating artificial intelligence, machine learning, and systems-level biological data, these approaches enable faster, more cost-effective identification of therapeutic candidates with improved translational potential. Although challenges related to data quality, model interpretability, ethical considerations, and regulatory frameworks remain, continued methodological innovation and interdisciplinary collaboration are steadily addressing these barriers. As multi-omics integration and AI-driven modeling continue to evolve, computational drug repurposing is poised to play a critical role in delivering more effective, personalized, and accessible treatments across diverse disease landscapes.

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