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Benzimidazole-Based Therapeutics: An Integrated Review of Chemistry, Green Synthesis, Pharmacological Activities, Approved Drugs and Emerging Therapeutic Perspectives

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Abstract : *Benzimidazole is an important nitrogen-containing heterocyclic scaffold that has occupied a prominent position in medicinal chemistry because of its distinctive structural characteristics and broad pharmacological potential. The fused benzene–imidazole framework provides opportunities for hydrogen bonding, π–π interactions, hydrophobic interactions, and diverse molecular recognition, allowing benzimidazole derivatives to interact with a wide range of biological targets. Over the past several decades, structural modification of the benzimidazole nucleus has resulted in therapeutically important compounds with applications in parasitic infections, acid-related gastrointestinal disorders, viral infections, cancer, cardiovascular diseases, and other pathological conditions.*

The present review provides an integrated overview of benzimidazole-based therapeutics, beginning with the fundamental chemistry and structural characteristics of the scaffold and extending to contemporary synthetic and pharmacological applications. Particular attention is given to conventional and green synthetic methodologies, including one-pot reactions, recyclable catalysts, plant-mediated synthesis, waste-derived catalysts, and nanoparticle-assisted approaches. The review further discusses important clinically used benzimidazole-containing drugs, including albendazole, mebendazole, thiabendazole, omeprazole, esomeprazole, lansoprazole, pantoprazole, rabeprazole, maribavir, bendamustine, candesartan, and telmisartan, with emphasis on their molecular targets and mechanisms of action.

The literature also demonstrates considerable interest in benzimidazole derivatives as antibacterial, antifungal, antiviral, anticancer, and antiparasitic agents. Particular emphasis is placed on β-tubulin inhibition, proton-pump inhibition, kinase modulation, DNA interaction, apoptosis induction, and receptor antagonism. The review additionally examines structure–activity relationships, drug resistance, pharmacokinetic limitations, safety concerns, environmental considerations, drug repurposing, nanotechnology-based delivery systems, and precision medicine. Recent green-synthesis studies involving plant-derived catalysts, zinc oxide and zinc sulfide nanoparticles, and waste materials demonstrate the potential of sustainable chemistry for the preparation of biologically important benzimidazole derivatives. Overall, the versatility of the benzimidazole nucleus, combined with advances in green chemistry, nanotechnology, computational drug discovery, and molecular pharmacology, continues to provide opportunities for the development of safer, more selective, and therapeutically effective next-generation drugs.

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Key Words: Benzimidazole; medicinal chemistry; heterocyclic compounds; anthelmintics; proton pump inhibitors; antiviral agents; anticancer agents; green synthesis; nanocatalysts; nanoparticles; drug resistance; structure–activity relationship; drug repurposing; precision medicine.

1. INTRODUCTION

The discovery and development of heterocyclic compounds have played a fundamental role in modern pharmaceutical research. Among the numerous heterocyclic systems investigated for biological applications, benzimidazole has emerged as one of the most versatile and extensively studied scaffolds. Benzimidazole consists of a benzene ring fused to an imidazole ring and possesses two nitrogen atoms capable of participating in hydrogen-bonding interactions with biological macromolecules. Its aromatic character, electronic properties, structural rigidity, and ease of functionalization make it particularly attractive for the design of pharmacologically active molecules.

The medicinal importance of benzimidazole became evident with the development of compounds exhibiting potent antiparasitic activity. Benzimidazole carbamates such as albendazole and mebendazole subsequently became important anthelmintic drugs. Their principal mechanism involves interaction with parasite β-tubulin and disruption of microtubule-dependent processes. This discovery established benzimidazole as an important pharmacophore in anti-infective drug development.

The therapeutic significance of the scaffold expanded considerably with the development of benzimidazole-derived proton pump inhibitors. Omeprazole and related compounds such as esomeprazole, lansoprazole, pantoprazole, and rabeprazole transformed the management of acid-related gastrointestinal disorders. These compounds demonstrate how relatively small structural modifications of the benzimidazole framework can produce a completely different biological mechanism, namely inhibition of the gastric H^+/K^+-ATPase.

Benzimidazole chemistry has subsequently entered several other therapeutic areas. Benzimidazole-containing molecules have been investigated as antiviral, anticancer, antibacterial, antifungal, anti-inflammatory, antihypertensive, and enzyme-inhibitory agents. Maribavir represents an important antiviral example, whereas bendamustine demonstrates the incorporation of the benzimidazole framework into an established anticancer drug. Candesartan and telmisartan further illustrate the utility of benzimidazole-containing structures in cardiovascular pharmacotherapy.

The biological versatility of the scaffold is closely related to its capacity for structural modification. Substitution at N-1, C-2, C-5, C-6, and other positions can alter electronic distribution, lipophilicity, aqueous solubility, metabolic stability, target affinity, and biological selectivity. Consequently, systematic structural modification has become an important strategy for generating new benzimidazole derivatives with improved pharmacological profiles.

In parallel with medicinal chemistry, considerable attention has been directed toward environmentally sustainable methods for synthesizing benzimidazole derivatives. Conventional synthetic methods may require organic solvents, elevated temperatures, toxic reagents, and lengthy purification procedures. Green chemistry approaches attempt to overcome these limitations through the use of safer solvents, renewable feedstocks, recyclable catalysts, one-pot reactions, solvent-free conditions, microwave irradiation, and plant-assisted nanoparticles.

Recent contributions by Wadhawa and co-workers have demonstrated the applicability of environmentally benign catalysts and plant- or waste-assisted nanomaterials in benzimidazole synthesis. These studies include the use of lemon juice as a catalyst, waste magnesium oxide, plant-derived nanocatalysts, Montmorillonite K10-supported nanoparticles, and zinc sulfide nanoparticles generated through plant-assisted approaches. Such work establishes an important connection between sustainable synthesis, nanotechnology, and heterocyclic medicinal chemistry.

Therefore, the objective of the present review is to provide an integrated account of the chemistry, synthesis, green approaches, pharmacological activities, clinically relevant drugs, mechanisms of action, limitations, and future therapeutic opportunities associated with the benzimidazole scaffold.

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II. LITERATURE REVIEW

2.1 Benzimidazole as a Privileged Medicinal Chemistry Scaffold

The concept of a privileged scaffold refers to a structural framework capable of interacting with multiple classes of biological targets following appropriate substitution. Benzimidazole satisfies many characteristics associated with privileged structures. The fused aromatic system provides structural rigidity, while the two nitrogen atoms contribute hydrogen-bond donor/acceptor characteristics and facilitate interactions with enzymes, receptors, and nucleic acids.

The electronic nature of the ring system permits extensive substitution without destroying the fundamental heteroaromatic framework. Consequently, medicinal chemists have been able to introduce alkyl, aryl, heteroaryl, halogen, alkoxy, amino, nitro, carbonyl, and other substituents to modify biological activity.

2.2 Structural Features and Structure–Activity Relationships

The biological properties of benzimidazole derivatives are strongly influenced by the nature and position of substituents.

N-1 substitution

Modification of the N-1 position can influence molecular lipophilicity, hydrogen-bonding characteristics, membrane permeability, and metabolic stability. Appropriate N-substitution may improve pharmacokinetic characteristics and target interaction.

C-2 substitution

The C-2 position is particularly important for medicinal chemistry because introduction of alkyl, aryl, heteroaryl, carbonyl, or other groups can substantially modify biological activity. C-2 substitution has been widely employed in the design of antimicrobial, antiviral, anticancer, and antiparasitic derivatives.

C-5 and C-6 substitution

Substituents at C-5 and C-6 can influence electronic properties, aqueous solubility, lipophilicity, metabolic stability, and receptor or enzyme affinity. Halogenated and electron-withdrawing derivatives are frequently explored in antimicrobial and anticancer research.

Thus, rational substitution of the benzimidazole nucleus provides an effective approach for tuning pharmacological activity.

2.3 Conventional Synthetic Approaches

A major synthetic route to benzimidazole derivatives involves condensation of o-phenylenediamines with aldehydes, ketones, carboxylic acids, or their derivatives. Depending on the starting materials and reaction conditions, cyclization may proceed through imine formation followed by oxidative or dehydrative ring closure.

Other approaches involve oxidative cyclization, transition-metal catalysis, photocatalysis, microwave-assisted synthesis, and one-pot multicomponent reactions. Although these methods can provide good yields, conventional procedures may involve hazardous reagents, volatile organic solvents, prolonged reaction times, and difficult purification.

These limitations have encouraged researchers to explore environmentally sustainable synthetic alternatives.

2.4 Green Synthesis of Benzimidazole Derivatives

Green chemistry has become increasingly important in heterocyclic synthesis. The principal objectives include reducing waste, avoiding toxic reagents, lowering energy consumption, using renewable materials, and developing recyclable catalytic systems.

Important green approaches include:

- solvent-free synthesis;
- aqueous-phase reactions;
- microwave-assisted reactions;
- ultrasound-assisted synthesis;
- use of natural acids and bases;
- reusable solid catalysts;

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- plant-extract-assisted nanoparticles;
- waste-derived catalysts;
- heterogeneous nanocatalysts; and
- one-pot synthetic procedures.

These methods can provide advantages such as shorter reaction times, improved yields, simple work-up, reduced solvent consumption, and catalyst recyclability.

2.5 Contributions of Wadhawa and Co-workers to Green Benzimidazole Chemistry

Research by Wadhawa and co-workers has contributed to the development of sustainable approaches for benzimidazole synthesis. One study reported one-pot synthesis of benzimidazoles using lemon juice as a readily available and environmentally friendly catalyst. The work demonstrated that naturally derived catalytic systems can provide alternatives to conventional synthetic conditions.

Another study investigated waste magnesium oxide as a catalyst for benzimidazole synthesis, demonstrating the potential of waste-derived materials for heterogeneous catalysis.

Plant-assisted nanotechnology has also been employed in subsequent studies. Plant-derived materials have been used in the preparation of nanoparticles that function as catalysts for benzimidazole synthesis. Zinc sulfide and other nanoparticle systems have been investigated as reusable solid catalysts, while Montmorillonite K10-supported nanoparticle systems provide another approach for heterogeneous catalysis.

These studies are particularly significant because they combine three major concepts: green chemistry, nanotechnology, and heterocyclic synthesis. The use of renewable plant materials and waste-derived substances can reduce dependence on conventional chemical catalysts while simultaneously providing functional nanomaterials.

2.6 Anthelmintic Benzimidazoles

Benzimidazole anthelmintics constitute one of the earliest and most successful therapeutic applications of the scaffold. Albendazole, mebendazole, and thiabendazole are representative compounds.

The principal molecular target is parasite β-tubulin. Binding to tubulin interferes with microtubule assembly and consequently disrupts essential cellular processes, including nutrient uptake, intracellular transport, and cell division. Energy depletion and impaired cellular function ultimately lead to parasite death.

Albendazole possesses broad-spectrum activity and is used in the treatment of several intestinal and tissue helminth infections. Mebendazole is widely used against intestinal nematodes, whereas thiabendazole has historically been used against selected nematode infections.

The success of these drugs has stimulated extensive research into related compounds, including flubendazole and oxfendazole. Some compounds primarily remain veterinary or investigational agents and should therefore be distinguished from approved human medicines.

2.7 Anthelmintic Resistance

Resistance represents an important challenge to the continued effectiveness of benzimidazole anthelmintics. Genetic alterations in parasite β-tubulin can decrease the affinity of the drug for its molecular target.

Frequently investigated resistance-associated substitutions include F167Y, E198A, and F200Y. Such alterations can reduce drug binding and contribute to treatment failure.

The emergence of resistance highlights the importance of molecular surveillance, appropriate treatment strategies, combination therapy where appropriate, and development of compounds capable of retaining activity against resistant parasite populations.

2.8 Benzimidazole-Derived Proton Pump Inhibitors

The discovery of omeprazole established an important new therapeutic application of benzimidazole chemistry. Proton pump inhibitors contain a substituted benzimidazole system linked to a pyridine moiety and are designed as acid-activated prodrugs.

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After absorption, these drugs reach the acidic secretory canaliculi of gastric parietal cells. Acid-mediated activation generates reactive intermediates that form covalent bonds with cysteine residues of the H^+/K^+-ATPase. Inhibition of this final stage of gastric acid secretion produces prolonged suppression of acid production.

Important clinically used compounds include omeprazole, esomeprazole, lansoprazole, pantoprazole, and rabeprazole.

Table 1. Representative benzimidazole-derived proton pump inhibitors

Drug	Major target	Principal action	Important applications
Omeprazole	H^+/K^+-ATPase	Irreversible acid suppression	GERD, peptic ulcer disease
Esomeprazole	H^+/K^+-ATPase	Proton-pump inhibition	GERD, erosive esophagitis
Lansoprazole	H^+/K^+-ATPase	Gastric acid suppression	GERD, ulcer disease
Pantoprazole	H^+/K^+-ATPase	Irreversible inhibition	Acid-related disorders
Rabeprazole	H^+/K^+-ATPase	Rapid acid suppression	GERD, acid-peptic disorders

2.9 Antiviral Applications

The structural flexibility of benzimidazole has encouraged its investigation against several viral targets. Substituted derivatives have been reported to interact with viral enzymes involved in replication, maturation, and protein processing.

Maribavir provides an important clinically relevant example. It is a benzimidazole riboside antiviral agent that inhibits the CMV pUL97 protein kinase. Inhibition of this viral kinase interferes with essential stages of CMV replication.

Beyond maribavir, experimental benzimidazole derivatives have been investigated against influenza viruses, HIV, herpesviruses, and coronaviruses. These studies demonstrate the potential of the scaffold for developing target-specific antiviral compounds.

2.10 Anticancer Applications

Benzimidazole derivatives have attracted extensive attention in oncology because they can interfere with multiple pathways associated with malignant transformation and tumor progression.

Tubulin inhibition

Some benzimidazole compounds interfere with tubulin polymerization. Because microtubules are essential for mitotic spindle formation, their disruption can cause cell-cycle arrest and tumor-cell death.

Protein kinase inhibition

Benzimidazole derivatives have been designed as inhibitors of kinases involved in cellular proliferation and angiogenesis, including EGFR and VEGFR-associated pathways.

DNA interaction

Planar benzimidazole systems may interact with DNA through intercalation or groove binding. Such interactions can interfere with replication and transcription.

Topoisomerase inhibition

Some derivatives have demonstrated the ability to interfere with DNA topoisomerases, enzymes required for maintaining DNA topology during replication.

Apoptosis induction

Benzimidazole derivatives have been reported to activate apoptosis through mitochondrial pathways, caspase activation, oxidative stress, and modulation of pro- and anti-apoptotic proteins.

Antiangiogenic activity

Inhibition of angiogenic signaling can restrict tumor blood-vessel formation and thereby suppress tumor progression.

Albendazole and mebendazole have been investigated as repurposed anticancer agents in preclinical models. However, their experimental anticancer activity should not be confused with established clinical approval for cancer treatment.

2.11 Clinically Relevant Benzimidazole-Containing Drugs

The broad pharmacological diversity of the scaffold is illustrated by the compounds summarized below.

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Table 2. Representative clinically relevant benzimidazole-containing drugs

Drug	Therapeutic area	Major molecular target	Principal pharmacological action
Albendazole	Antiparasitic	Parasite β-tubulin	Microtubule disruption
Mebendazole	Antiparasitic	Parasite β-tubulin	Inhibition of microtubule assembly
Thiabendazole	Antiparasitic	Parasite cellular targets	Anthelmintic activity
Omeprazole	Gastroenterology	H^+/K^+-ATPase	Gastric acid suppression
Esomeprazole	Gastroenterology	H^+/K^+-ATPase	Gastric acid suppression
Lansoprazole	Gastroenterology	H^+/K^+-ATPase	Gastric acid suppression
Pantoprazole	Gastroenterology	H^+/K^+-ATPase	Gastric acid suppression
Rabeprazole	Gastroenterology	H^+/K^+-ATPase	Gastric acid suppression
Maribavir	Antiviral	CMV pUL97 kinase	Inhibition of CMV replication
Bendamustine	Oncology	DNA	DNA alkylation/crosslinking
Candesartan	Cardiovascular	AT1 receptor	Angiotensin II receptor blockade
Telmisartan	Cardiovascular	AT1 receptor	Angiotensin II receptor blockade

2.12 Cardiovascular Applications

Benzimidazole-containing structures have also contributed to cardiovascular pharmacotherapy. Candesartan and telmisartan are angiotensin II receptor blockers that contain benzimidazole-related structural elements.

These agents selectively antagonize the angiotensin II type-1 receptor, reducing vasoconstriction and aldosterone-mediated effects. Their success illustrates the ability of benzimidazole-containing molecules to function as receptor-directed therapeutic agents rather than being restricted to anti-infective applications.

2.13 Antimicrobial and Antifungal Activities

Numerous synthetic benzimidazole derivatives have demonstrated antibacterial and antifungal properties. Activity may arise through interference with microbial enzymes, DNA processes, membrane-associated functions, or cytoskeletal components.

Agricultural compounds such as carbendazim and benomyl have historically been important benzimidazole-related fungicides. However, these should be discussed separately from clinically approved human antifungal medicines because their principal applications are agricultural.

The study of such compounds has nevertheless contributed to understanding the interaction between benzimidazole structures and fungal cellular targets.

2.14 Pharmacokinetic and Safety Considerations

Although benzimidazole-containing drugs have considerable therapeutic value, their pharmacological profiles vary substantially.

Important considerations include absorption, aqueous solubility, metabolic stability, protein binding, hepatic metabolism, drug interactions, and tissue distribution. Some benzimidazole derivatives exhibit limited aqueous solubility, which may restrict systemic bioavailability.

Albendazole can produce hepatic and hematological adverse effects, particularly during prolonged systemic treatment. Proton pump inhibitors are generally well tolerated but prolonged use has been associated with potential electrolyte, renal, nutritional, and infection-related concerns.

Drug interactions may also occur through cytochrome P450-mediated metabolism. Omeprazole and esomeprazole, for example, can inhibit CYP2C19 and may affect the pharmacological activation of clopidogrel.

Consequently, therapeutic application of benzimidazole-containing drugs requires consideration of dose, duration, patient characteristics, concomitant medication, and indication.

2.15 Drug Repurposing

Drug repurposing has become an attractive strategy for identifying additional applications of established benzimidazole compounds. Albendazole and mebendazole have been extensively investigated for potential anticancer applications based on their effects on microtubules and cellular metabolism.

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Veterinary benzimidazoles such as fenbendazole and oxfendazole have also attracted research interest. Nevertheless, experimental observations must be distinguished from clinically demonstrated efficacy. Repurposing requires appropriate pharmacokinetic, toxicological, pharmacodynamic, and controlled clinical evaluation.

2.16 Nanotechnology-Based Drug Delivery

Nanotechnology provides opportunities to overcome several limitations associated with benzimidazole compounds, particularly poor aqueous solubility and limited bioavailability.

Potential delivery platforms include polymeric nanoparticles, liposomes, solid lipid nanoparticles, nanostructured lipid carriers, and other nanoscale systems.

These approaches may improve dissolution, protect drugs from premature degradation, enhance tissue distribution, provide controlled release, and facilitate targeted delivery.

The application of nanoparticles is particularly relevant to the research direction involving green synthesis. Plant-mediated preparation of metal and metal-oxide nanoparticles provides an opportunity to combine sustainable nanomaterial synthesis with catalytic and pharmaceutical applications.

2.17 Precision Medicine and Computational Drug Discovery

The future development of benzimidazole therapeutics is increasingly connected with precision medicine and computational technologies.

Pharmacogenomic differences in drug-metabolizing enzymes may influence systemic exposure and treatment response. Similarly, molecular surveillance of β-tubulin mutations can assist in understanding anthelmintic resistance.

Computational approaches such as molecular docking, molecular dynamics, QSAR, virtual screening, and machine learning can accelerate identification of promising benzimidazole derivatives. These methods allow researchers to predict target binding, optimize substituent patterns, identify potential toxicity, and prioritize compounds for experimental testing.

2.18 Future Research Opportunities

Several areas offer substantial opportunities for future benzimidazole research:

1. Development of selective derivatives against resistant parasites.
2. Design of benzimidazole-based anticancer agents with improved tumor selectivity.
3. Discovery of novel viral targets.
4. Development of multifunctional hybrid molecules.
5. Application of plant-based and waste-derived catalysts.
6. Development of recyclable nanocatalysts.
7. Nanotechnology-based drug-delivery systems.
8. AI-assisted molecular design.
9. Pharmacogenomic optimization.
10. Integration of green chemistry with pharmaceutical manufacturing.

The combination of sustainable synthesis and modern drug-discovery technologies may be particularly valuable. Green catalytic systems reported by Wadhawa and co-workers demonstrate how renewable biological resources and waste materials can be incorporated into the preparation of pharmacologically relevant heterocycles.

III. CONCLUSION

Benzimidazole has evolved from a simple heteroaromatic ring system into one of the most versatile scaffolds in medicinal chemistry. Its ability to undergo extensive structural modification and establish diverse molecular interactions has enabled the development of therapeutically important compounds across several pharmacological fields.

Classical benzimidazole anthelmintics such as albendazole, mebendazole, and thiabendazole demonstrate the importance of β-tubulin as a pharmacological target, whereas omeprazole and related proton pump inhibitors demonstrate the successful adaptation of the scaffold for gastric H^+/K^+-ATPase inhibition. Maribavir illustrates its

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potential in antiviral therapy, while bendamustine and several experimental derivatives demonstrate the growing relevance of benzimidazole chemistry in oncology. Benzimidazole-containing cardiovascular agents further emphasize the broad target diversity achievable through structural modification.

At the same time, the field is progressing beyond conventional medicinal chemistry. Green synthesis using natural catalysts, waste-derived materials, plant-assisted nanoparticles, and recyclable heterogeneous systems provides a more sustainable route to benzimidazole derivatives. Research involving lemon juice, waste magnesium oxide, plant-derived nanocatalysts, zinc sulfide nanoparticles, and supported nanocatalysts demonstrates the potential of combining green chemistry with modern heterocyclic synthesis.

Despite these advances, challenges including drug resistance, limited bioavailability, adverse effects, drug interactions, environmental concerns, and insufficient clinical translation of experimental compounds remain. Addressing these limitations will require multidisciplinary approaches involving medicinal chemistry, pharmacology, nanotechnology, computational chemistry, molecular biology, and green chemistry.

Future research should therefore focus on rational scaffold optimization, pharmacophore hybridization, drug repurposing, advanced drug-delivery systems, resistance-guided drug design, and AI-assisted discovery. The integration of these approaches with sustainable synthetic methodologies is likely to expand the therapeutic potential of benzimidazole and facilitate the development of safer, more selective, environmentally responsible, and clinically effective next-generation therapeutics.

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