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An explicative review of the pharmacological activities of 1,2,3-Triazole linked Benzimidazole derivatives.

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ABSTRACT

Benzimidazole and 1,2,3-triazole are two significant heterocyclic scaffolds widely explored in medicinal chemistry due to their diverse pharmacological properties. These structural motifs exhibit remarkable antimicrobial and antiviral activities, making them attractive candidates for drug design and development. Benzimidazole derivatives are known for their ability to target bacterial and fungal pathogens, while 1,2,3-triazole-linked compounds have demonstrated potent antiviral efficacy against a range of viruses, including influenza and coronaviruses. The combination of these pharmacophores in hybrid molecules has led to the development of novel therapeutic agents with enhanced bioactivity and selectivity. This review highlights the synergistic effects of combining these two pharmacophores in drug design, emphasizing their enhanced efficacy against a range of microbial and viral pathogens. The paper discusses the structural-activity relationship (SAR) of these hybrid molecules, their mechanisms of action, and their potential as novel therapeutic agents. The exploration of these conjugated systems offers promising insights into the future of antimicrobial and antiviral drug discovery, addressing the urgent need for novel treatments in an era of rising resistance and emerging viral threats. The review underscores the growing interest in these hybrid molecules as promising candidates for addressing the rising challenge of drug-resistant infections and emerging viral diseases, providing valuable insights for future drug discovery and development.

Keywords-1, 2, 3-Triazole, Benzimidazole, Synergistic effect, hybrid molecules, antiviral, antimicrobial activity.

INTRODUCTION

Medicinal chemistry heavily relies on heterocyclic compounds for the development of therapeutic agents against various diseases.[1,2] In the realm of pharmaceutical research, nitrogen-containing heterocycles play a vital role, exhibiting a wide array of biological activities.[3] 1,2,3-triazoles are

recognized for their therapeutic potential, finding applications in the treatment of microbial infections, tuberculosis, and hypertension, among other conditions.[4,5] 1,2,3-triazoles are gaining prominence as versatile linkers, enabling the creation of novel bifunctional drugs by connecting two pharmacophores. This capability has significantly increased their utility in the design of bioactive and functional compounds.[6,7] 1,2,3-triazoles demonstrate diverse biological activities, encompassing antimicrobial and antitubercular properties, as well as potential inhibition of SARS-CoV-2 and other viruses. [8,9] They also exhibit anti-inflammatory, antitumor, antihypertensive, antioxidant, and antiepileptic effects.[10,11] Furthermore, triazoles are utilized as α-glucosidase inhibitors, analgesics, anticonvulsants, and antimalarial agents. [12,13] Finally, triazole derivatives have shown efficacy in Alzheimer's disease and neuroprotection. [14,15] Benzimidazole is also a key player, functioning as a purine-analogue pharmacophores with a remarkably diverse therapeutic profile. Benzimidazole derivatives, for instance, are employed in the development of drugs targeting various conditions, including bacterial and fungal infections, viral diseases, cancer, diabetes, and neurological disorders.[16,17] The structural features of benzimidazole make them well-suited for interactions within biological systems,[18] leading to their classification as important therapeutic agents. This structural compatibility allows their derivatives to exhibit a variety of biological activities, such as antiviral, antifungal, antiproliferative, antihypertensive, analgesic, anti-inflammatory, antibacterial, and anthelmintic effects. [19,20] Benzimidazole derrivatives can exhibit diverse spectrum of biological activities and they are prominant structures against the cytomegalovirus.[21] They shows again antihistaminic[22] antimicrobial[23] antifungal[24] , and anti-herpes activity. [25] The combination of these pharmacophores Benzimidazole and 1,2,3-triazole in hybrid molecules has led to the development of novel therapeutics with enhanced efficacy, selectivity, and a lower risk of resistance. Given the importance of developing effective therapeutic agents and our contributions to this field, we aimed to find a new class of compounds. Specifically, we searched a novel set of hybrid derivatives that merge the pharmacologically relevant benzimidazole and triazole moieties. The combination of benzimidazole and triazole rings in hybrid molecules underscores their importance in designing new compounds with antiviral, antimicrobial and antiviral properties. Notably, research has highlighted benzimidazole-triazole hybrids with significant antimicrobial and antiviral activities as well as anti-SARS-CoV-2 agents.[26-30] The recent pandemic has intensified interest in these hybrids, driving research into their synthesis, antimicrobial properties, structure-activity relationships, and overall biological activities .The benefits of investigating benzimidazole-triazole hybrids include their expanded antimicrobial spectrum and increased potency, as evidenced by lower minimum inhibitory concentrations, alongside the requirement for specialized researchers.

This article provides the comprehensive literature review of the diverse biological activities of benzimidazole-1,2,3-triazole linked molecules, specifically focusing on their antimicrobial, antiviral, antifungal and antitubercular properties.

ANTIVIRAL ACTIVITY

Severe viral infections are emerging now a day and are the common causes of human illness and death. Presently, we have a limited availability of antiviral chemotherapeutic agents to prevent and treat these infections, so it is the need of an hour to develop potential antiviral drugs against various harmful and fatal viral infections. A large quantity of research has been performed on 1,2,3 triazole and their derivatives, which has proved the promising antiviral activity of this heterocyclic nucleus. [31-32]

Youssif et al studied the 1,2,3-triazole linked benzimidazole hybrids, including 2-(4-[(1-benzoylbenzimidazol-2-ylthio)methyl]-1H-1,2,3-triazol-1-yl)-N-(4-nitro-phenyl)-acetamide **(1)** and 2-(4-([1-(4-chlorobenzoyl)-benzimidazol-2-ylthio)methyl]-1H-1,2,3-triazol-1-yl)-N-(4-nitrophenyl)-acetamide **(2)**, which shown strong activity against the hepatitis C virus

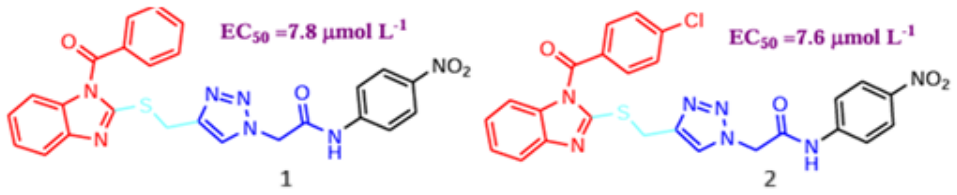


Figure 1 Structure of antiviral benzimidazole-1,2,3-triazole hybrids 1 and 2

Drugs **1** and **2** were active against the hepatitis C virus (HCV). The amount needed to reduce the virus by 50% (EC50) was 7.8 and 7.6 µmol/L, respectively. The amount that caused harm to 50% of cells (CC50) was 16.9 and 21.1 µmol/L. These findings showed that the chemical group at position 2 of benzimidazole plays an important role in stopping HCV.[33]

Pandey et al synthesised compounds 3a-3e and tested for their ability to fight two viruses: Japanese encephalitis virus (JEV) (P20778), a highly dangerous virus (RNA), and Herpes simplex virus type-I (HSV-I) (753166), a well-known virus found everywhere. Out of the five tested compounds, only one was inactive against the Japanese encephalitis virus (JEV). Compound 3b showed strong antiviral activity in lab tests, with a 90% reduction in virus effects at a concentration of 8 µg/ml. However, its effectiveness in living organisms was lower, providing only 16% protection and extending survival by 4 days. The researchers concluded that these compounds work better against JEV than against Herpes simplex virus type-I (HSV-I) because compounds 3b and 3e showed measurable activity against JEV in live tests. Compound 3c did not work against either virus. The effectiveness against HSV-I was recorded as 33% for 3a, 46% for 3b, 53% for 3d, and 64% for 3e. Since only compound 3e has a methyl group instead of hydrogen at position R1, the study suggests that R1 is not responsible for the antiviral activity.[34]

Tonelli et al prepared compounds of 1-substituted 2-[(benzotriazol-1/2-yl) methyl] benzimidazoles and evaluated them for antiviral activity against a wide range of viruses(DNA and RNA).

Nearby 12 compounds showed strong activity against Respiratory Syncytial Virus (RSV), with EC50 values mostly lower than HM. They performed better than the reference drug 6-azauridine, which was highly toxic to both MT-4 and Vero-76 cell lines (S.I. 16.7). The compounds also had moderate effect against Bovine Viral Diarrhoea Virus (BVDV), Yellow Fever Virus (YFV), and Coxsackie Virus B2 (CVB2), with EC50 values between 6 and 55 µM for the most effective ones. Although the activity against BVDV, YFV, and CVB2 is not very strong, it is still important because it could help identify targets for developing broad-spectrum antiviral drugs. Understanding how these compounds work is essential. Additionally, since their effectiveness depends on the type of chemical groups attached at position five of the benzimidazole nucleus, further research on different substitutions may help improve their activity and reduce toxicity. [35]

Al-Humaidi et al studied the formation of a series of 1,2,3-triazole-benzimidazole compounds Molecular docking studies and lab tests showed that many of the the compounds had strong binding affinities against SARS-CoV-2 and Omicron variant, performing better than the standard drugs.

Table 3 Antiviral activity of benzimidazole-1,2,3-triazole hybrids 24-26

Compound	CC_{50} (µg mL^{-1})	EC_{50} (µg mL^{-1})	Selectivity Index (SI)
Ceftazidime	1045.53	85.07	12.29
24	1065.51	155.05	6.87
25	1530.5	306.1	5.0
26	1028.28	80.4	12.78

The study showed that compound 140 had strong activity, with an IC50 of 75.98 nm against the Omicron variant and 74.51 nm against the SARS-CoV-2 variant. The 3D binding mode of compound is shown below.

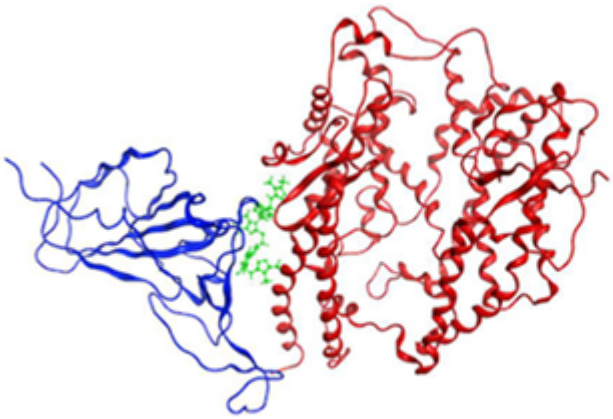


Figure: Three-dimensional binding mode of compound (green) at the binding interface between the Omicron S-RBD (red) and human ACE2 (blue)

1,2,3-triazole-benzimidazole hybrids have the potential to be strong anti-HSV (Herpes simplex virus) drug. These drugs were also tested against flaviviruses and pestiviruses. Among them, compound A showed very good effect against respiratory syncytial virus (RSV) with the EC50 value of 0.03 mm. [36]

Figure Structure of antiviral benzimidazole-1,2,3-triazole hybrid

Seliem et al reported quinolone-triazole compounds to target SARS-CoV-2. Their study shows that 4-((1-(2-chlorophenyl)-1H-1,2,3-triazol-4-yl)methoxy)-6-fluoro-2 (trifluoromethyl) quinoline and 6-fluoro-4-(2-(1-(4-methoxyphenyl)-1H-1,2,3-triazol-4-yl)ethoxy)-2-(trifluoromethyl) quinoline showed maximum antiviral activity and more selectivity index (SI) against SARS-CoV-2 compared to reference drugs. He concluded that the fluorine atoms in these drugs played a key role in their antiviral effects. [37]

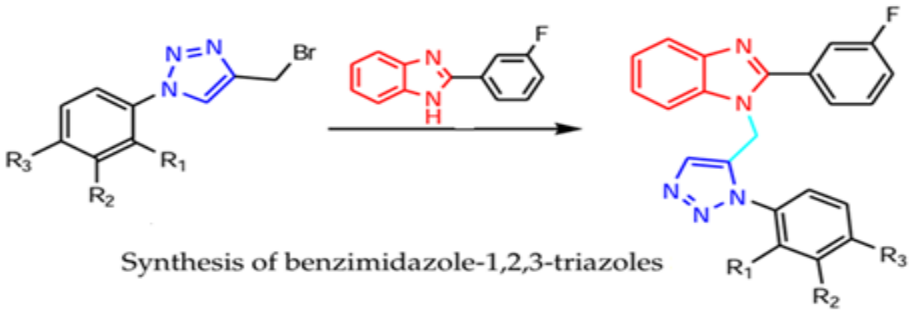
El-Sebaey reviewed the significance of the 1,2,3-triazole ring in antiviral compounds. He highlighted the importance of the chemical groups attached to the triazole core and the crucial role of other heterocyclic structures in the molecule. [38]

ANTITUBERCULAR ACTIVITY

Ashok et al reported that compound A was the most effective antitubercular drug candidate, inhibiting the growth of Mycobacterium tuberculosis (MTB) with a minimum inhibitory concentration (MIC) of 3.125 µg/mL (7.1 µM). For comparison, the control drugs Rifampicin and Isoniazid had MIC values of 0.04 µg/mL and 0.38 µg/mL respectively. The strong activity of 26h was likely due to the nitro group at the ortho position on the phenyl ring. Other compounds showed moderate antitubercular

activity: Compound A (MIC = 6.25 µg/mL, 14.7 µM) with a chlorine substituent, Compound B (MIC = 6.25 µg/mL, 14.2 µM) with a trifluoromethyl group and Compound C (MIC = 12.5 µg/mL, 28.4 µM) with a benzyl substituent. The study concluded that adding electron-withdrawing groups like nitro, chlorine, and trifluoromethyl to the phenyl ring significantly improved antitubercular activity. Additionally, theoretical calculations of physicochemical parameters showed that compounds 26a-26j had positive drug scores, indicating their potential as drug candidates. [39]

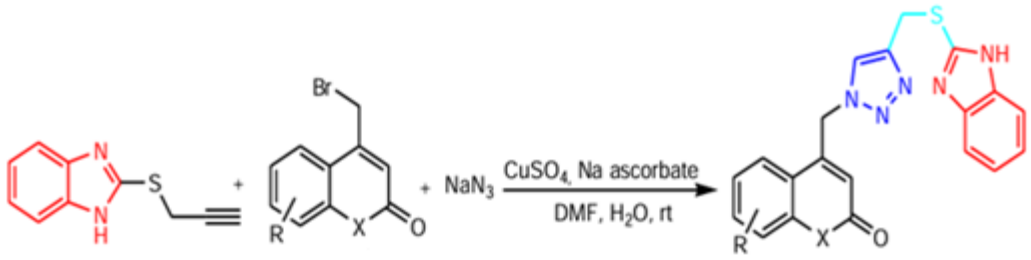
Gill et al. reported the synthesis of some hybrids by reacting 2-(3-fluorophenyl)-1H-benzo[d]imidazole with phenyl-substituted 4-(bromomethyl)-1-phenyl-1H-1,2,3-triazole in DMF at room temperature.



Synthesis of benzimidazole-1,2,3-triazoles

The trifluoro-substituted compound A showed strong anti-mycobacterial activity, inhibiting more than 96% of bacterial growth at a 6.25 µg concentration. Additionally, compounds B and C demonstrated better antimicrobial activity than the other tested compounds. These two were identified as the best candidates for developing new derivatives to enhance effectiveness against intracellular mycobacteria (macrophages) or in infected animals.[40]

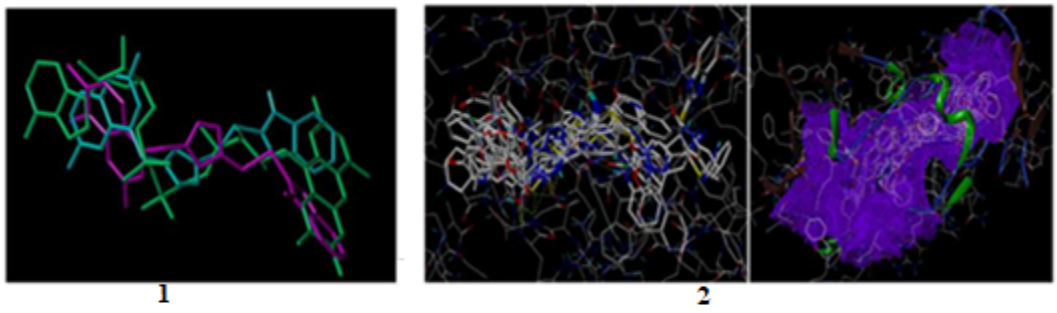
Anand et al. given a reaction involving 2-propargyl benzimidazole, 4-bromo methyl coumarins / 1-aza-coumarins, and sodium azide under dipolar cycloaddition reaction conditions. This reaction selectively produced 1,4-disubstituted triazoles



Scheme –Synthesis of benzimidazole-1,2,3-triazoles

Antitubercular tests for M. tuberculosis along with docking simulation studies, showed that methyl substituted compounds A1 and A2 had promising activity with a MIC of 3.8 µM and high C-score values. The Surf Lex-Dock tool performed analysis intermolecular interactions within the ligands and the receptor protein. The three-dimensional structure of the target protein was obtained from PDB entry 4FDO. The protein was processed by removing the co-crystallized ligand and water molecules

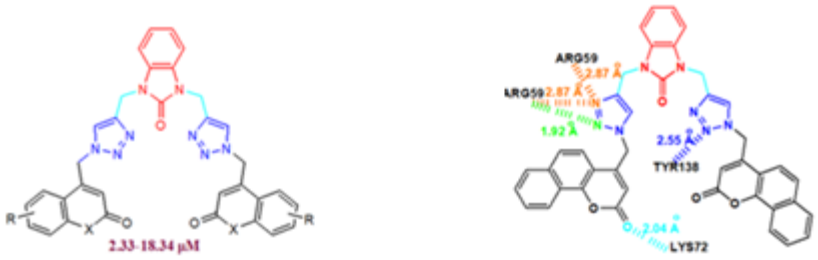
and adding essential hydrogen atoms. All fourteen inhibitors (A1- A14) were kept into the ENR active binding site using docking analysis. Below image 1 illustrates the docking results, while image 2 presents the overlay of compounds with the reference ligand.[41]



1 2

Image 1 Superimposition of compounds **A1** (Cyan color), **A2** (Magenta color) with ligand (Green–blue color). **2** All 14 compounds docked into the active site of the enzyme 4FDO.

Khanapurmath et al prepared 1,2,3 triazoles using a dipolar reaction. Among them, benzimidazolone linked triazoles showed good antitubercular activity, with MIC values ranging from 2.33 to 18.34 µM. Two compounds were most effective. All compounds had very low cytotoxicity, with IC50 values in human embryonic kidney cells ranging from 943 to 12,294 µM. None of the 14 compounds showed significant toxicity, indicating their strength for antitubercular activity. Insillico studies showed strong interaction of the benzimidazole oxygen, which may contribute to their biological activity. [42]

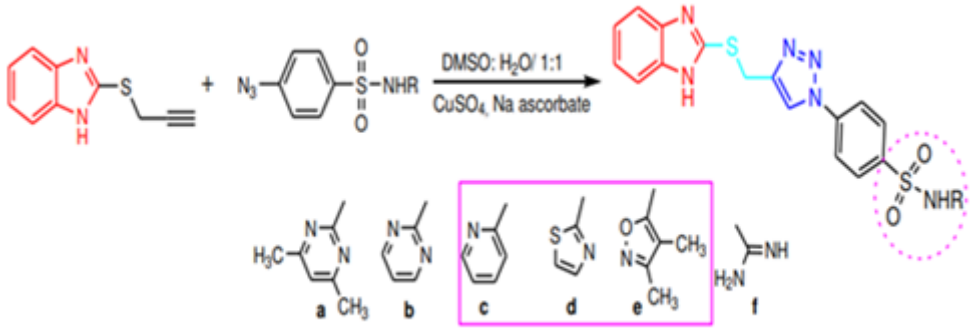


structures of benzimidazole bis triazoles

Sharma et al. provided a summary of benzimidazole linked 1,2,3-triazoles as antitubercular compounds, highlighting various hybrids with quinolines coumarin, isoniazid, , benzimidazole and other structures. [43]

ANTIBACTERIAL ACTIVITY

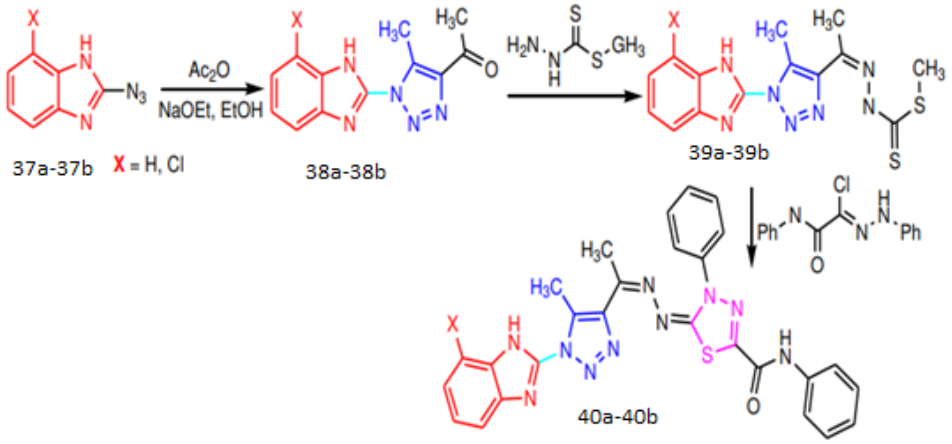
Al-Blewi et al. reported an azide–alkyne reaction by taking thio propargyl benzimidazole with sulphazides, in DMSO. This reaction produced benzimidazole-sulphonamide conjugates in 92% yield after 7 hours of heating at 75°C.



Scheme– Synthesis of benzimidazole-1,2,3-triazole hybrids

synthesised analogues were tested for their antibacteriall activity against 4 bacteria Bacillus cereus, Staphylococcus aureus, Escherichia coli, Pseudomonas aeruginosa and two fungi Candida albicans, Aspergillus brasiliensis. One of the compounds had the best activity against Bacillus cereus and Staphylococcus aureus. Similarly, other three compounds were the most effective against Escherichia coli.[44]

Rashdan et al. created hybrids using 2-azido-1H-benzo[d]imidazole derivatives. These compounds reacted with acetylacetone in the presence of sodium ethoxide, forming hybrid molecules. These key molecules were then used to produce new carbazone derivatives), which were further reacted with 2-oxo-N-phenyl-2-(phenyl amino) aceto hydrazine chloride to produce the final analogue.



Scheme 4 Synthesis of benzimidazole-1,2,3-triazole hybrids 38a-38b,39a-39b and 40a-40b

The derivatives were tested for their antimicrobial activity against Staphylococcus aureus and Candida fungal albicans. The proved as drugs 1 and 2 had strong antimicrobial activity against all microorganisms. Compounds 3 and 4 were active only with Gram-positive and Gram-negative bacteria but not on fungi. Additionally, both in silico and in vitro studies confirmed that compounds 1 and 2 were the most active against bacterial strains and can be strong antimicrobial agents. The hybrid molecules underwent molecular docking studies with DNA gyrase B and showed binding energy

ranging from -9.8 to -6.4 kcal/mol, confirming their high potency. Among them, compounds 1 and 2 had the lowest binding energy (-9.8 and -9.7 kcal/mol), indicating stronger binding compared to the standard drug Ciprofloxacin (-7.4 kcal/mol) against DNA gyrase B, as shown below [45]

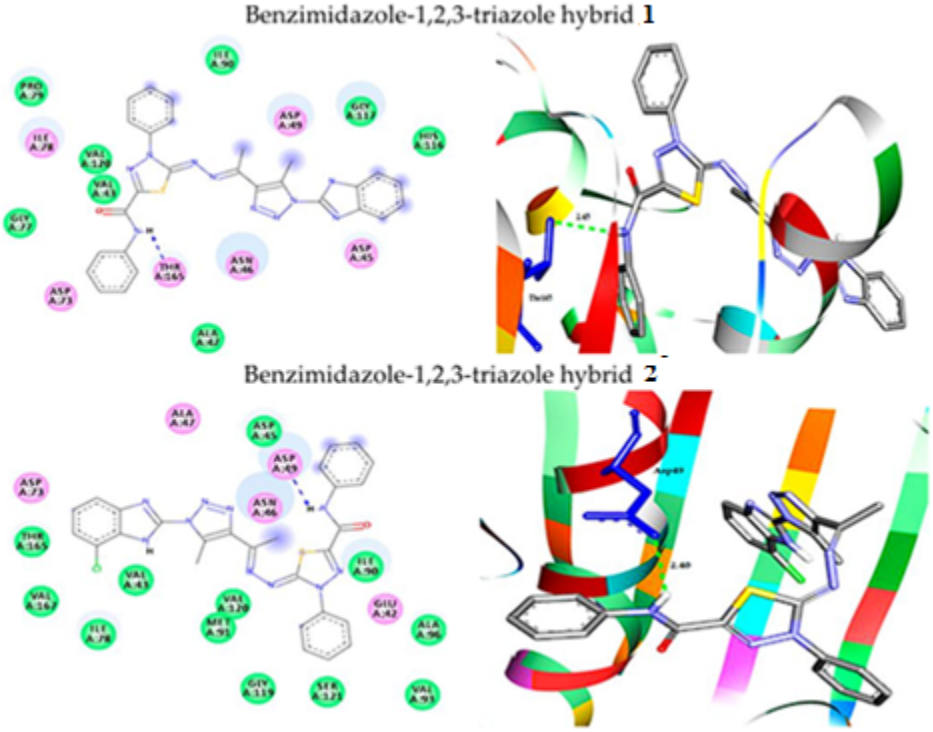
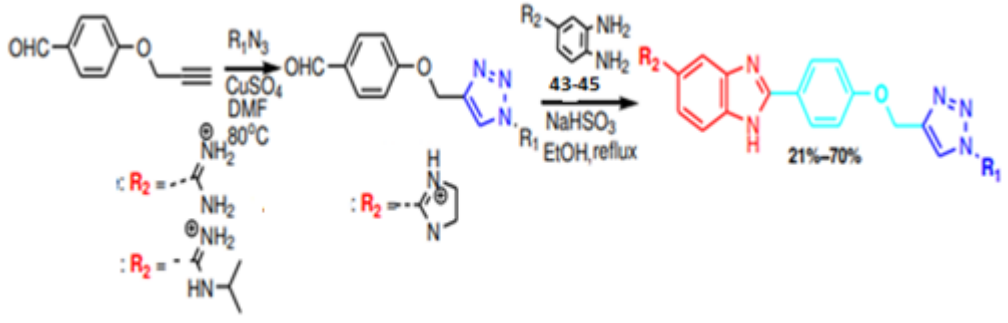


Figure depicts molecular mechanism of the best-docked compounds (1 and 2) with the target enzyme DNA gyrase B.

Bistrović et al. prepared some hybrids using 4-(prop-2-ynyloxy) benzaldehyde as the starting material. The compounds were checked for their antimicrobial activity against Gram-positive bacteria (S. aureus ATCC 25923, methicillin-sensitive S. aureus, E. faecalis, vancomycin-resistant E. faecium) and Gram-negative bacteria (E. coli ATCC 25925, P. aeruginosa ATCC 27853, A. baumannii ATCC 19606, ESBL-producing K. pneumoniae.



Scheme —Synthesis of benzimidazole-1,2,3-triazole hybrids

It is found that the compounds were generally more effective against Gram-positive bacteria than Gram-negative bacteria. Compounds 1 and 2 showed strong activity against S. aureus (MIC = 8–32 μg/mL) due to their better binding affinity compared to other amidines. Compound 3 was the most promising against ESBL-producing E. coli (MIC = 4 μg/mL). Anti-trypanosome studies revealed that the p-methoxyphenyl group in two compound with improved activity, with 20b (IC50 = 1.1 mM, IC90 = 3.5 mM) being more potent than Nifurtimox. Interestingly, while there was a relation between activity and DNA binding, the antiprotozoal effects of 2 did not match with its DNA interaction.[46]
Rao et al. prepared some derrivatives using the 1,2,3 triazole click chemistry scheme. However, these compounds showed l;east activity against Mycobacterium bovis strain.[47].

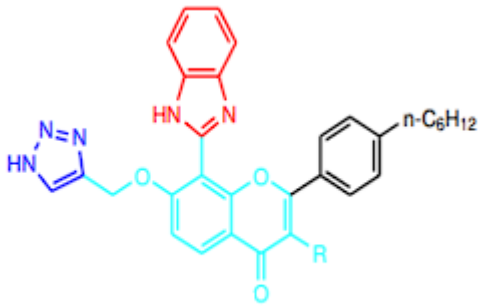
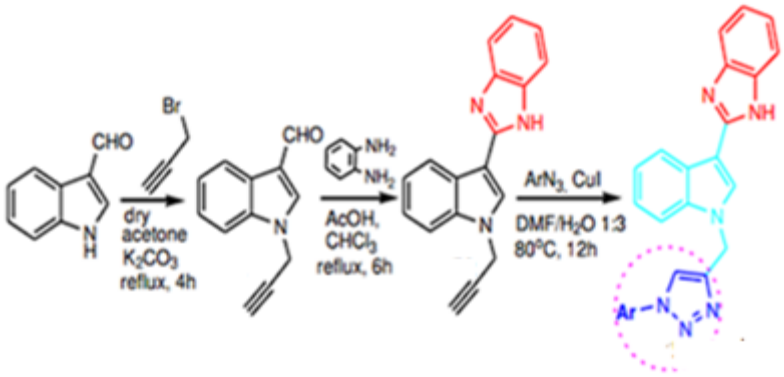


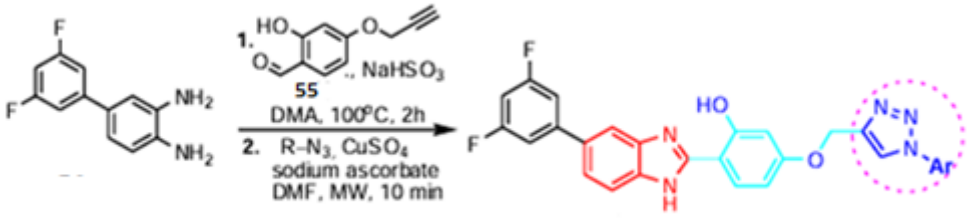
Figure – Structure of benzimidazole-1,2,3-triazole hybrids

Ashok et al. reported some hybrids starting from 1H-indole-3-carbaldehyde. The compounds were tested for their antimicrobial activity against Gram-positive bacteria (Staphylococcus aureus, Bacillus subtilis and Gram-negative bacteria using Gentamicin as the reference standerd drug. Their antifungal activity was evaluated against Candida albicans ATCC 10231 and Aspergillus Niger ATCC 9029 using Fluconazole as the standard drug. It is found that three Compounds were the most promising antimicrobial agents, with a MIC of 3.125–6.25 μg/mL. [48]



Scheme –Synthesis of benzimidazole-1,2,3-triazole hybrids

Mallikanti et al. reported benzimidazole-linked 1,2,3-triazole derrivatives which include Formation of benzimidazole intermediate by reacting 3',5'-difluorobiphenyl-3,4-diamine with 2-hydroxy-4-(prop-2-ynyloxy) benzaldehyde. Again it involves Microwave-assisted copper-catalysed click reaction to obtain the final compounds

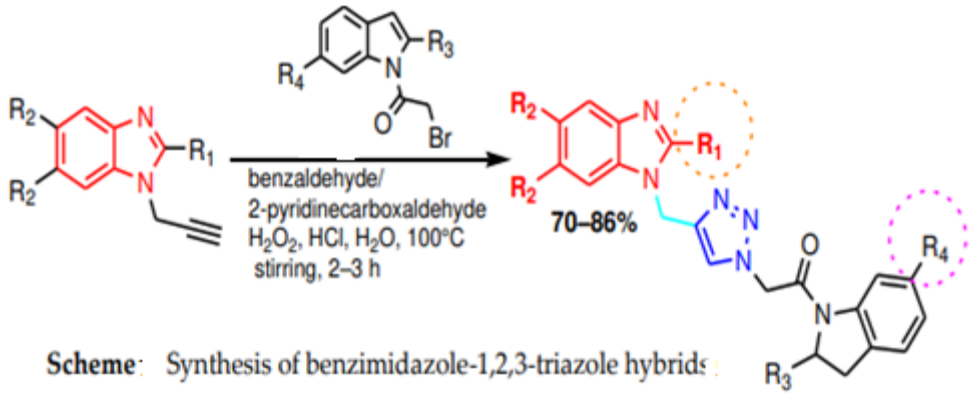


Scheme — Synthesis of benzimidazole-1,2,3-triazole hybrids

Compounds A1-A8 were tested for antibacterial activity against Gram-positive bacteria (S. aureus, B. subtilis) and Gram-negative bacteria (E. coli, P. aeruginosa) using Ampicillin as the standard drug. It is found that Most compounds showed optimum zones of inhibition against all tested bacterial strains. Two Compounds exhibited greater activity against P. aeruginosa, S. aureus, and B. subtilis than the standard reference drug. All Compounds displayed moderate antibacterial activity. Three Compounds showed potent antifungal activity against C. albicans and A. Niger , outperforming the standard drug Griseofulvin.[49]

Chandrika et al. synthesised two analogues with diverse antifungal action with C. albicans: and Against C. parapsilosis additionally, these compounds showed strong activity against C. albicans biofilms.[50]

Deswal et al. reported a new series of 1,2,3-triazole- benzimidazole--indoline analogues witrh cycloaddition combining N-propargylated benzimidazole derivatives and substituted 2-azido-1-(indolin-1-yl)ethanone derivatives giving the final compounds in moderate to good yields

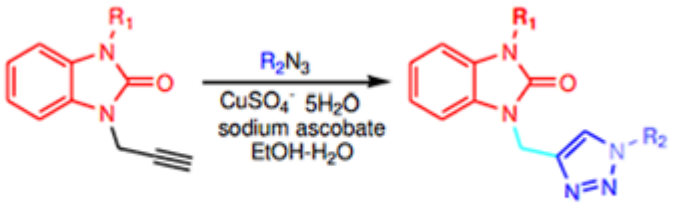


Scheme: Synthesis of benzimidazole-1,2,3-triazole hybrids

Outcomes show that compound 1 has a stronger inhibitory effect on E. coli, while compound 2 effectively inhibits all tested bacteria. The strong antibacterial effectr of these compounds is concerned to at position two of benzimidazole in the pyridine nucleus and the nitro group on the indole heterocycle. again, inhibition of glycosidase invitro of all synthesized compounds found that 1 (IC_{50} = 0.015 ± 0.0003 mol/mL) and 2 (IC_{50} = 0.018 ± 0.0008 mol/mL) are strong inhibitors of α-glucosidase, showing even more good than the reference drug. [51]

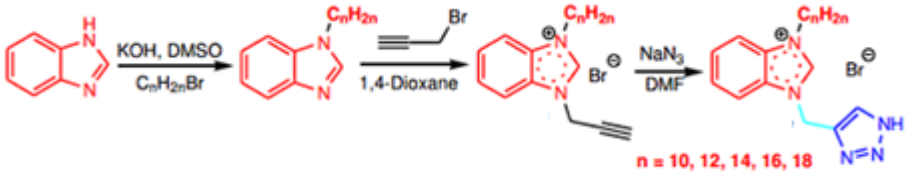
Saber et al. created some benzimidazolone derivatives with 1,4-disubstituted-1,2,3-triazole, using only click chemistry. All analogues showed antibacterial activity against S. aureus, E. coli, and P.

aeruginosa. However, compounds A1 and A2 were more powerful with the Gram-positive bacterium S. aureus, while A3 had better activity against the Gram-negative bacterium E. coli, using Chloramphenicol as the standard drug.[52]



Scheme—Synthesis of benzimidazole-1,2,3-triazole hybrids

Mohsen et al. reported 1,2,3-triazole analogues in 3 steps using benzimidazole. This involves two alkylation reactions followed by a alkyne azide cycloaddition reaction.

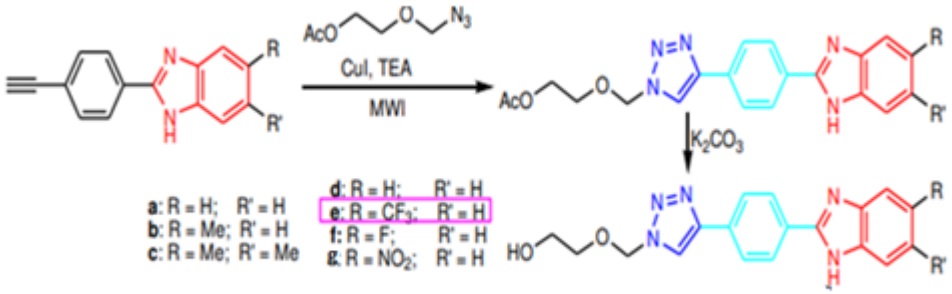


Scheme— Synthesis of benzimidazole-1,2,3-triazole hybrids

The repored derivatives depicted better zones of inhibition S. aureus and against E. coli. This suggests that the 1,2,3-triazole core played a key role in antimicrobial action. Ciprofloxacin is used as an internal reference standerd drug. [53]

ANTIFUNGAL ACTIVITY

Ouahrouch et al reported compounds containing acetylenes and 2-(azido methoxy) ethyl acetate, were reacted using Copper Iodide as a catalyst and triethylamine under microwave oven treatment. This process formed the 1,2,3-triazole hybrids, which are linked via a benzene ring to the benzimidazole ring, alongwith high yields.

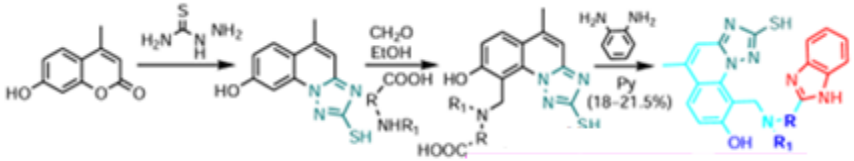


Scheme 26 Synthesis of benzimidazole-1,2,3-triazole hybrids

Acetyl group in triazole hybrids was removed using K_2CO and methanol, releasing the OH group and forming the corresponding triazoles with almost complete yields. Compounds were checked for in

vitro antifungal activity against two phytopathogenic fungi i. e. Verticillium dahliae Kleb and Fusarium oxysporum f. sp. Albedinis. The mycelial linear growth rate results showed that most compounds had weak inhibition against both fungi. However, one compound exhibited a significantly higher inhibition rate of 29.76% against Verticillium dahlia.[54]

Pandey et al reported 1 2 3 triazole hybrids through a 3-step process. 1st step include reaction of 7-hydroxy-4-methyl coumarin with thiosemicarbazide, forming the triazole intermediate. second step include Mannich reaction of intermediate with formaldehyde and an amino acid, yielding intermediates. Third step include Reaction of intermediates with o-phenylenediamine in pyridine, producing benzimidazole-1,2,4-triazole hybrids with low yields**.**



Scheme — Synthesis of benzimidazole-1,2,4-triazoles

Compound 1A showed strong antifungal activity against Candida albicans and Cryptococcus himalayensis, with a MIC value of 3.5 µg/mL for both fungi. Compound 1B exhibited low to moderate antifungal activity against all five fungal species.[55]

Jiang et al. reported that hybrid 1A showed antifungal activity against Candida albicans, Candida tropicalis, Cryptococcus neoformans, Trichophyton rubrum, Aspergillus fumigatus. The MIC_{50} values ranged from 1 to 64 µg/mL, with Fluconazole used as the standard reference drug.

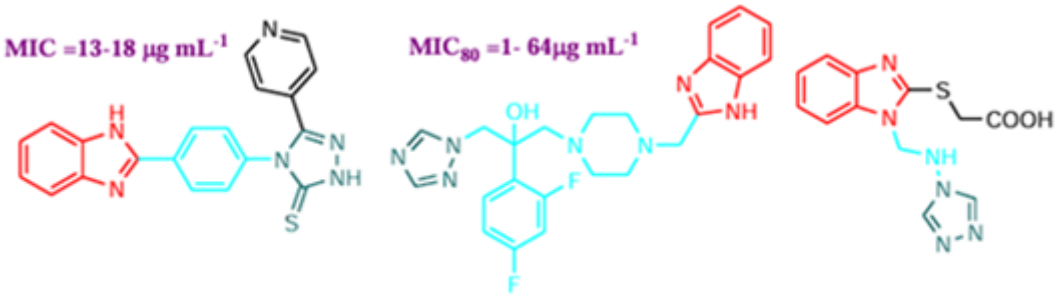


Figure —Structure of benzimidazole hybrids

Antifungal activity data proposed a preliminary structure-activity relationship (SAR) that The amine linker played a crucial role in antifungal activity and Substituted piperazine derivatives showed comparable or better activity than the corresponding N-methyl derivatives. [56]

CONCLUSION

This review compiles the synthesis of benzimidazole-triazole compounds documented for their biological effects. The research indicates that specific chemical modifications—such as attaching fluorine, chlorine, bromine, trifluoromethyl, nitro, cyano, amide, aldehyde, hydroxyl, methoxy, dimethylamino, or ester groups, or incorporating other heterocycles like pyridine, pyrimidine, thiazole,

indole, isoxazole, thiadiazole, or coumarin—significantly alters the biological activity of these compounds. Key structure-activity relationships (SARs) emerged from the analyzed data. As observed, the combined presence of benzimidazole and triazole rings in a single molecule significantly enhances antimicrobial activity. Recent ADME and SAR studies are essential for guiding the synthesis of new, property-optimized benzimidazole-triazole hybrids. The dual antimicrobial and antiviral activity of these compounds is highly beneficial from both a therapeutic and economic perspective, meeting current medical demands, particularly in combating SARS-CoV-2. ADME studies confirm these hybrids' potential as effective antimicrobials and antivirals, opening avenues for developing compounds with superior biological properties. Although current research describes fundamental molecular characteristics like lipophilicity/hydrophilicity, it primarily focuses on liquid formulations. This review aims to serve as a valuable resource for designing and synthesizing novel benzimidazole-triazole hybrids to address the increasing challenge of microbial and viral infections and drug resistance.

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