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# Benzimidazole chemistry in oncology: recent developments in synthesis, activity, and SAR analysis

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A six-membered benzene ring is fused with a five-membered imidazole ring at positions four and five, generating benzimidazole, the benzo derivative of imidazole and a bicyclic aromatic chemical compound. Benzimidazole is a significant pharmacophore in a variety of physiologically active heterocyclic compounds due to its distinctive characteristics and structural framework. Because benzimidazole is both aromatic and heterocyclic, it interacts with a range of biological targets *via* metal ion interactions,  $\pi$ - $\pi$  stacking, and hydrogen bonding. Its broad range of medicinal chemistry applications, such as anti-inflammatory, antiviral, antifungal, and anticancer therapies, is based on these interactions. Its significance in the development of potentially novel therapeutic pharmaceuticals is highlighted by the fact that its structural flexibility permits the synthesis of derivatives with targeted bioactivity. Derivatives of benzimidazole have garnered significant research interest as potential anticancer medications. These heterocyclic compounds exhibit a wide range of biological activities, such as DNA interaction, enzyme inhibition, and modulation of cellular pathways crucial to cancer development. Thus, to optimize their therapeutic potential, recent studies have focused on evaluating the structure–activity relationships (SAR) of benzimidazole derivatives. The main topics of this review are the current developments in the synthesis, anticancer activity, and SAR studies of benzimidazole derivatives, which will shed light on the increasing role they play in cancer therapies.

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# 1 Introduction

According to WHO, deaths due to cancer are predicted to reach 13 million worldwide by 2030.<sup>1,2</sup> Most malignancies are characterized by the uncontrolled growth of undifferentiated cells. Current estimates indicate that one in every five people will develop cancer by the age of 75.<sup>3</sup> Cancer primarily results from the deregulation of key enzymes and proteins that regulate cell division and proliferation.<sup>4,5</sup> However, despite significant advancements in cancer diagnosis and treatment options, many patients do not respond well to therapy, and others relapse after an initial encouraging response. Although chemotherapy is still a crucial component of cancer treatment, the emergence of drug resistance significantly reduces its effectiveness.<sup>6</sup> To combat drug resistance, higher dosages of chemotherapeutic drugs are

sometimes necessary, which exacerbates drug-induced toxicities.<sup>7,8</sup> Therefore, there is a critical need to create and develop novel cancer therapies with potent activity while maintaining a high therapeutic index.<sup>9</sup>

Recently, O- and S-based heterocycles have been attracting increasing attention in the discovery of innovative anticancer drugs, following the extensive investigation of nitrogen-based heterocycles as anticancer agents.<sup>10</sup> While heterocyclic compounds with a sulfur atom account for the bulk of FDA-approved drugs, heterocyclic compounds with a nitrogen atom are regarded as the most common type of chemical material utilized in medicinal chemistry.<sup>11,12</sup> Benzimidazole and its derivatives are a family of bioactive compounds with important uses in the pharmaceutical sector.<sup>13</sup> Imidazole, also known as imidazoline, is a heterocyclic molecule<sup>14</sup> classified as



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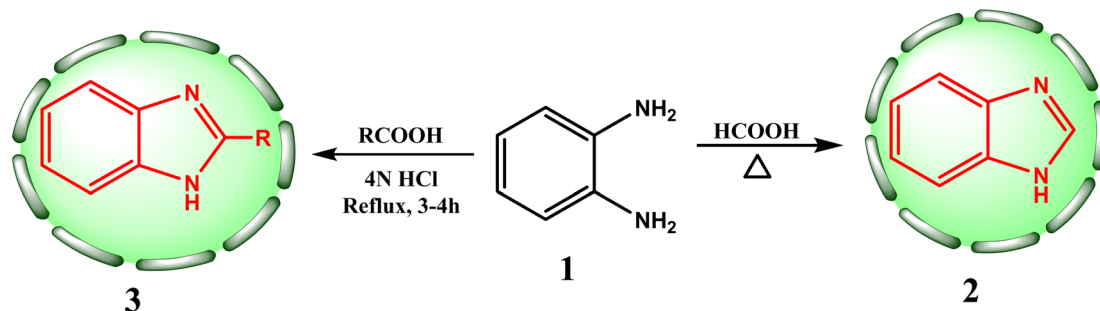


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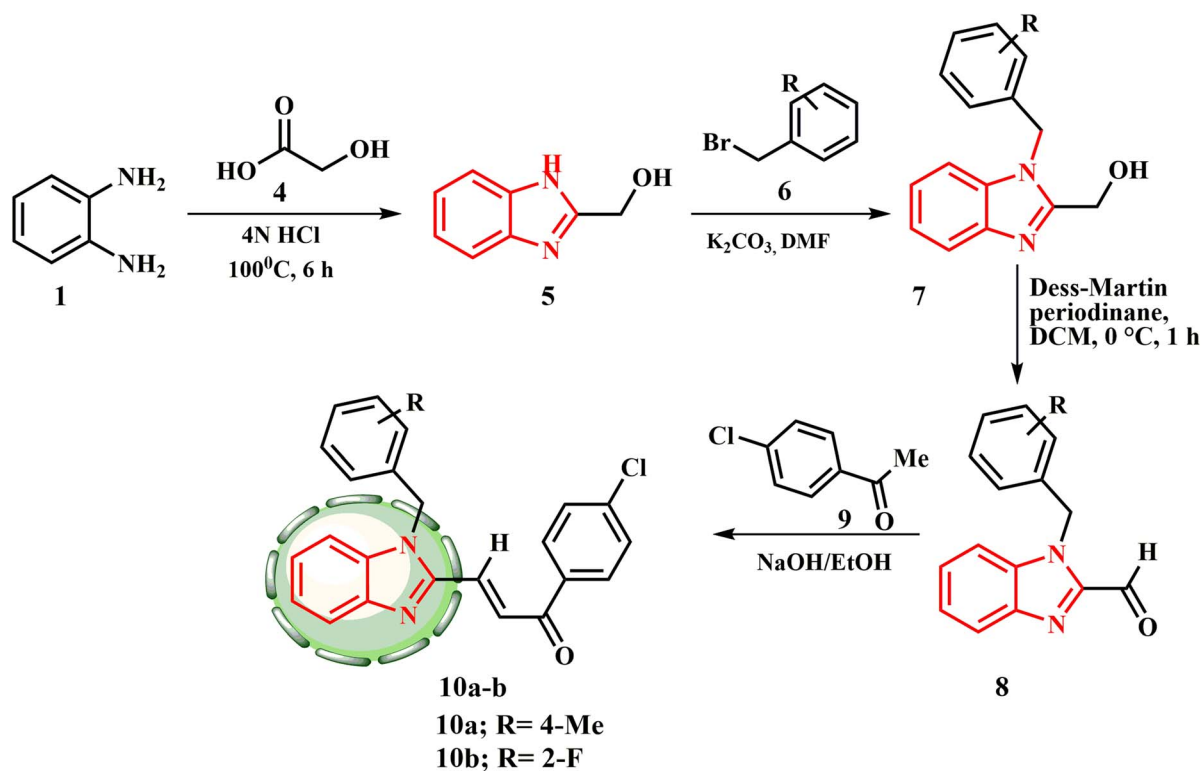
*Science, Islamic University of Madinah, Saudi Arabia. Between 2000 and March 2025, Prof. Gomha published 296 original research articles and 13 books, focusing on heterocyclic synthesis for medicinal, energy, environmental, and industrial applications. His research integrates green chemistry techniques such as microwave irradiation, ultrasound, mechanochemistry, and the use of ionic liquids. As of March 2025, his work has been cited approximately 8150 times, with an h-index of 52. He has supervised 18 MSc and 9 PhD theses, served on 43 journal editorial boards, reviewed for 176 journals, and contributed to faculty promotions and thesis evaluations. Prof. Gomha has received several national and international honors. He was awarded the Best Paper Prize from the Egyptian Heterocyclic Chemistry Society in 2015, and his work was recognized among the most downloaded by the Journal of Heterocyclic Chemistry in 2018–2019. From 2019 to 2024, he was listed among the World's Top 2% Scientists by Stanford University. The AD Scientific Index ranked him 2nd in Organic Chemistry at Cairo University (2020–2023) and 1st in 2024, as well as 1st at the Islamic University of Madinah. ScholarGPS ranked him 3rd globally in heterocyclic compounds and 112th in chemical synthesis. Cairo University honored him annually for research excellence (2008–2024) and named him a Top 10 Publisher (2015–2024). In 2024, he received the Best Researcher in Chemotherapy Award from Pencis for his contributions to sustainable chemotherapy research.*





In 1878, the parent benzimidazole (2)  
 was produced by heating (1) with formic acid  
 ↓ Modified  
 the synthesis of 2-alkylbenzimidazoles  
 (3, R = alkyl) was developed by Phillips

Scheme 1 Primary method for the synthesis of benzimidazole nucleus 2 and its derivative 3.

**Key observation:**

1) SAR indicated that chalcone moiety may have a significant role in the inhibition of antiproliferative action of these compounds.

2) The impact of diversification at the R position on the inhibitory activity was found to be inconclusive, as a methyl group or a fluorine atom was moderately tolerated.

Scheme 2 Synthetic route for benzimidazole–chalcone hybrids 10a and b.



an azapyrrole, with two nitrogen atoms separated by a single carbon atom. Historically, this molecule was known as glyoxalin when it was initially synthesized in 1858 by German scientist Heinrich Debus using glyoxal, formaldehyde, and ammonia.<sup>15,16</sup> A six-membered benzene ring is fused with a five-membered imidazole ring at positions four and five to form benzimidazole, the benzo-fused imidazole derivative and a bicyclic aromatic molecule. These substances have antiviral, antifungal, antiparasitic, analgesic, anticancer, and antihistaminic properties, among other medicinal applications. Moreover, benzimidazole derivatives have demonstrated potential in the management of numerous conditions associated with neurology, endocrinology, ophthalmology, and cardiovascular disease.<sup>17</sup>

The benzimidazole nucleus has emerged as a key pharmacophore in cancer research due to its broad cytotoxic potential, adaptive tumor inhibitory mechanisms, and facile synthesis methods for producing a wide range of derivatives. Many bioactive chemicals and anticancer medicines have a benzimidazole motif.<sup>18</sup> The benzimidazole scaffold is crucial in the creation of anticancer medications such as bendamustine, carbendazim, nocodazole, and veliparip. It functions in a number of ways.<sup>19</sup> Benzimidazoles, a structurally distinct class of Topo I poisons that function as DNA minor groove binders, including Hoechst 33258 and Hoechst 33342.<sup>20–23</sup>

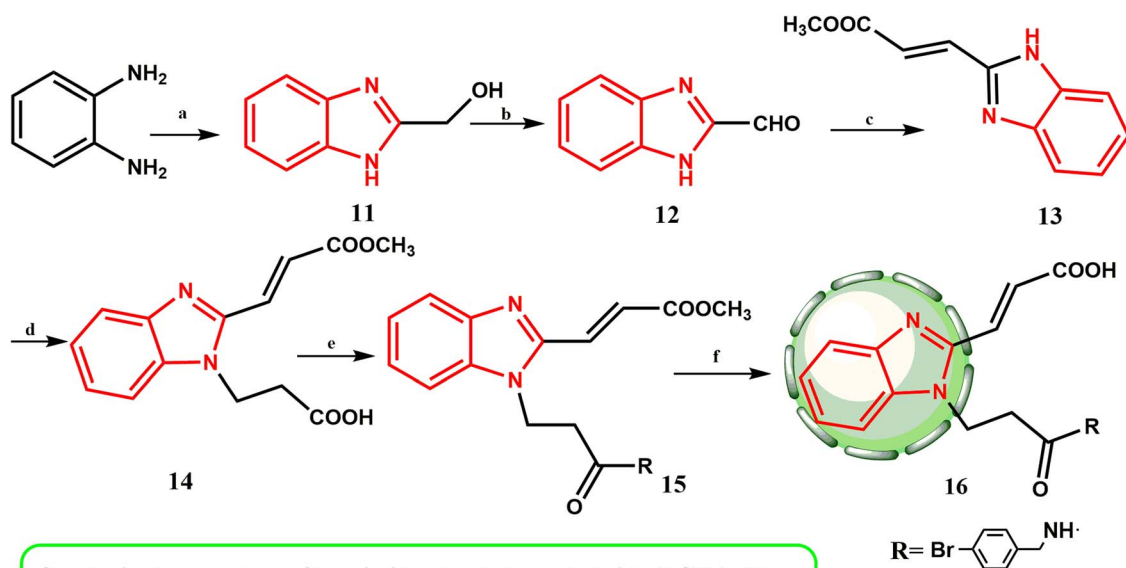
## 1.1 Techniques that yield benzimidazoles

The synthesis and chemistry of benzimidazoles have been well reviewed in the literature. In general, the majority of key ingredients mentioned previously may be utilized to develop benzimidazoles, as follows:

- (1) Phenylenediamines
- (2) Acidic compounds
- (3) *o*-(*N*-arylamino)arylamine
- (4) *o*-Nitro arylamines or *o*-dinitro arenes
- (5) *o*-Substituted-*N*-substituted
- (6) Imines
- (7) Amidines
- (8) Heterocyclic scaffolds
- (9) Four components

**1.1.1. Phenylenediamines.** In 1878, the parent benzimidazole (2) was produced by heating (1) with formic acid.<sup>24</sup> Since then, aliphatic acids have been used to produce a wide variety of benzimidazoles (2 and 3). Phillips established the most effective technique for producing 2-alkylbenzimidazoles (3, R = alkyl), which involves refluxing equimolar amounts of diamine and aliphatic carboxylic acid in 4 *N* hydrochloric acid for three to four hours (Scheme 1).<sup>24</sup>

As shown in Scheme 2, several benzimidazole–chalcone hybrids **10a** and **b** have been produced.<sup>25</sup> Refluxing *o*-phenylenediamine (1) with glycolic acid (4) in HCl produced (1*H*-benzo



Synthesized a new class of benzimidazole-chalcone hybrids (BCHs). These BCHs showed good inhibitory effect in the Topo II mediated DNA relaxation assay and anti-proliferative effect in tumor cell lines.

### Reagents and conditions

- (a)  $\text{CH}_2(\text{OH})\text{COOH}$ , 4N HCl/ $\text{H}_2\text{O}$  100 °C
- (b)  $\text{MnO}_2$ ,  $\text{CH}_2\text{Cl}_2$ , Reflux
- (c) Methyl diethyl phosphonoacetate,  $\text{K}_2\text{CO}_3$ , dry THF, Reflux
- (d) 3-bromopropionic acid,  $\text{K}_2\text{CO}_3$ , Acetone/DMF/ $\text{H}_2\text{O}$ =5/1/0.1, Reflux
- (e)  $\text{RNH}_2$ ,  $\text{CH}_2\text{Cl}_2$ , r.t
- (f) LiOH, THF,  $\text{H}_2\text{O}$ , r.t

Scheme 3 Synthesis of a new class of BCHs **15** and **16**.

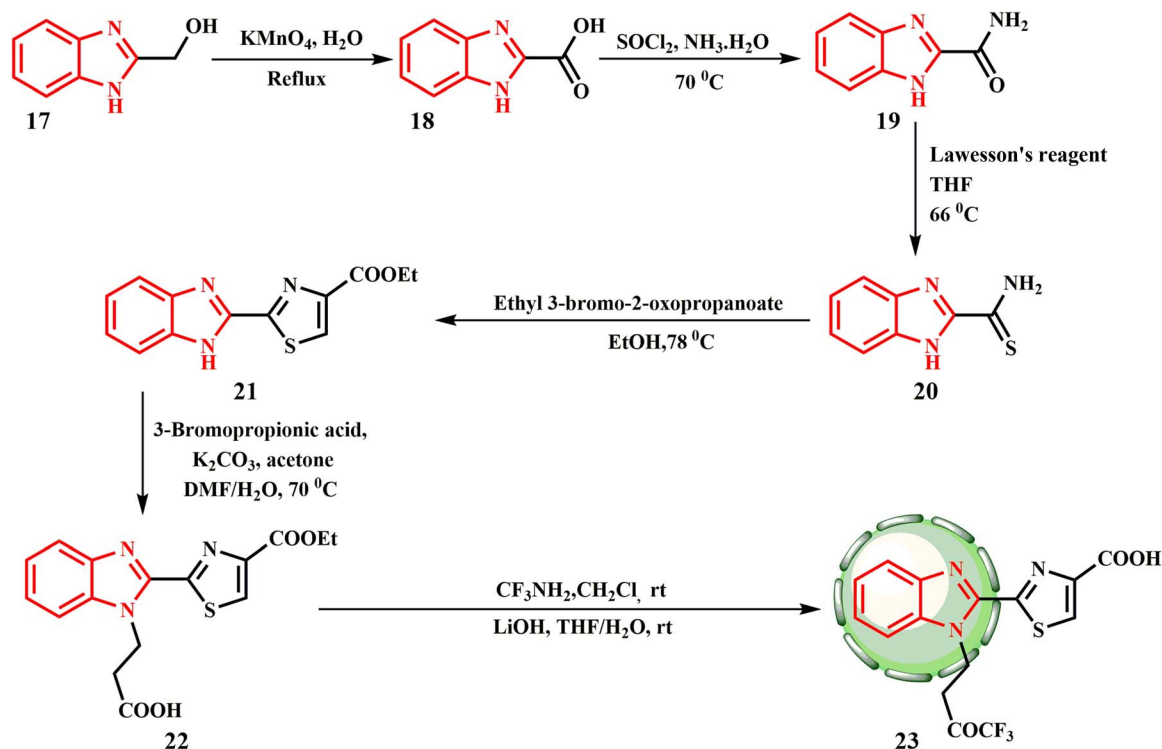


[*d*]imidazol-2-yl)methanol (5). 5 and suitable benzyl bromides 6 were used to produce the substituted (1-benzyl-1*H*-benzo[*d*]imidazol-2-yl)methanol (7) in the presence of  $K_2CO_3$ . Subsequently, the corresponding primary alcohols 7 were oxidized using Dess–Martin reagent to provide substituted-1-benzyl-1*H*-benzo[*d*]imidazole-2-carbaldehydes 8. Using the Claisen–Schmidt reaction with appropriate acetophenones 9, target compounds 10a and b were subsequently generated from 8.

Zhou *et al.*<sup>25</sup> established a novel class of benzimidazole-chalcone hybrids or BCHs. These BCHs demonstrated anti-proliferative effects in tumor cell lines and significant inhibitory effects in the Topo II-mediated DNA relaxation assay. One of the main enzymes involved in DNA replication, recombination, and repair is type II topoisomerase (Topo II).<sup>26,27</sup> Condensation and cyclization of *o*-phenylenediamine and glycolic acid produced compound 11 and the synthesis pathway for substances 16. The oxidation of the C2-hydroxymethyl of 11 with manganese dioxide produced aldehyde product 12. Intermediate 13 was prepared *via* the Wittig–Horner reaction of aldehydic compound 12 with methyl diethyl phosphonoacetate. Key intermediate 14 was developed by alkylation of 13 with 3-bromopropionic acid. The appropriate amides were produced by reacting carboxylic acid 14 with amines, and then the amides were treated with lithium hydroxide to produce 16. With an  $IC_{50}$

value of 0.64  $\mu M$ , compound 16 with a 4-Br substituent had the highest Pin1 inhibitory activity, indicating that the bromine atom is preferred, most likely to react with the residues of amino acid to establish an H-halogen link in this way (Scheme 3).

Scheme 4 presents the synthesis of 23. Potassium permanganate oxidizes 17 to yield 1*H*-benzo[*d*]imidazole-2-carboxylic acid (18). The carboxylic acid group of 18 was changed to a carbamoyl group by creating the acyl chloride first, and then reacting it with ammonium hydroxide to produce compound 19. Using Lawesson's reagent, the carbonyl in chemical 19 was thiolated to produce compound 20. Compound 20 was condensed and cyclized with ethyl 3-bromo-2-oxopropanoate to produce an intermediate, 2-(1*H*-benzo[*d*]imidazol-2-yl)thiazole 21. The use of 3-bromopropionic acid to alkylate 21 produced the desired product 22. Carboxylic acid 22 was combined with amines to form the corresponding amides, which were then reacted with lithium hydroxide to produce the final product 23 (Scheme 4). Wang *et al.*<sup>28</sup> produced derivatives of 1*H*-benzimidazole and assessed their anticancer potential against the human prostate cancer cell line PC-3. With  $IC_{50}$  values of 0.64  $\mu M$  and 0.37  $\mu M$ , respectively, compounds 16 and 23 showed the greatest inhibitory effects. According to the SAR investigations, compounds 23 with thiazole rings as linkers exhibited

**Key observation:**

The SAR studies revealed that the compounds with the thiazole rings as linkers 23 showed better inhibition than the compounds bearing a double bond between terminal carboxyl group and 1*H*-benzimidazole ring 16.

Scheme 4 Synthesis of derivatives of benzimidazole thiazole 22 and 23.



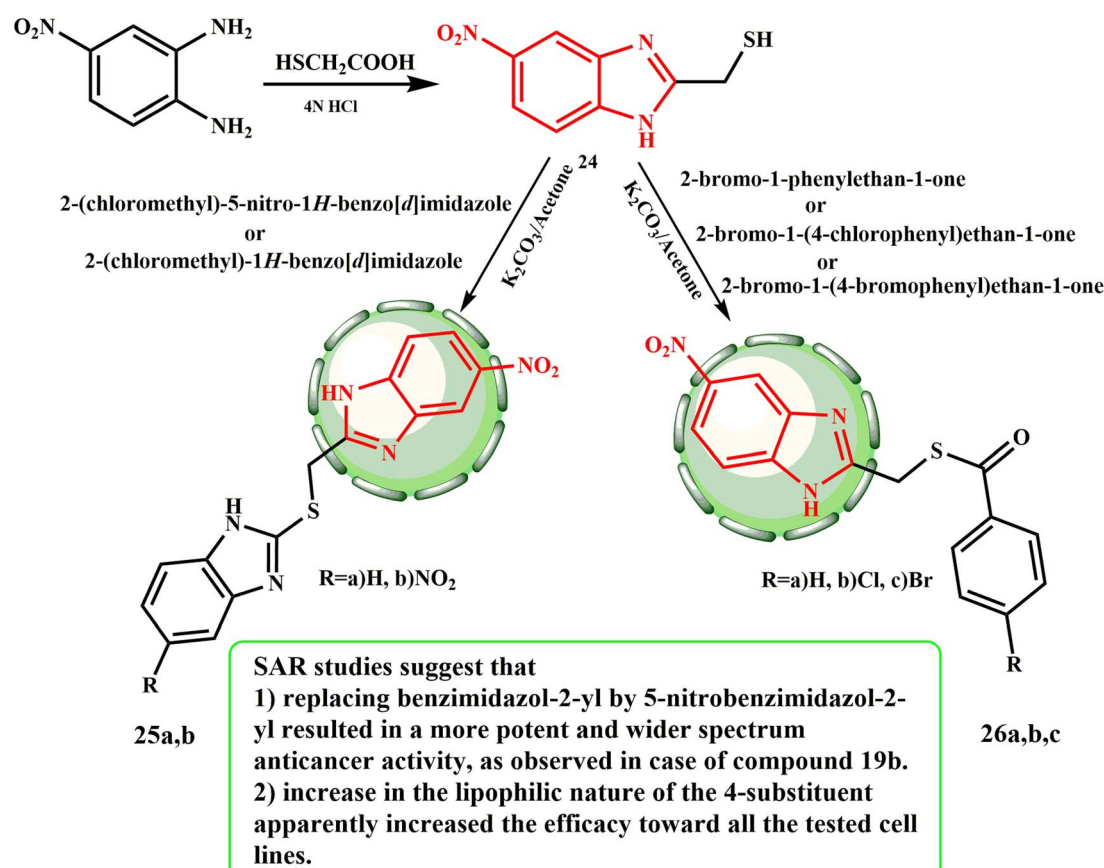
greater inhibition than **16** with a double bond between the 1*H*-benzimidazole ring and the terminal carboxyl group.

An effective method for creating novel benzimidazoles **25a** and **b** and **26a–c** was accomplished, which began with 2-mercaptomethyl-5-nitro-1*H*-benzimidazole (**24**)<sup>29</sup> (Scheme 5). El-Gohary *et al.*<sup>30</sup> produced new 1*H*-benzimidazole compounds and tested them against human cancer cell lines, including HepG-2 (liver), HCT-116 (colon), and MCF-7 (breast), to determine their anticancer potential. The most promising analogues were determined to be compounds **25b**, **26b**, and **26c**. According to the SAR evaluations, compound **25b** exhibited a more powerful and broad-spectrum anticancer action when 5-nitrobenzimidazol-2-yl was substituted for benzimidazol-2-yl. Furthermore, the improved lipophilicity of the 4-substituent appeared to enhance its effectiveness against all the examined cell lines. Compound **25b**, the 5-nitrobenzimidazol-2-yl homologue, had strong and comprehensive anticancer action. For compounds **26b** and **c** to have anticancer action, the substituent at the 4-position of the phenacyl moiety must be lipophilic. The compounds appeared to be more active against the three examined cell lines as the lipophilicity of the 4-substituent was increased, which the activity following the order of 4-bromophenacyl analog **26c** > 4-chlorophenacyl analog **26b**.

The present study used 2-chloromethyl-1*H*-benzimidazole **27** (ref. 31) as the starting materials to produce novel

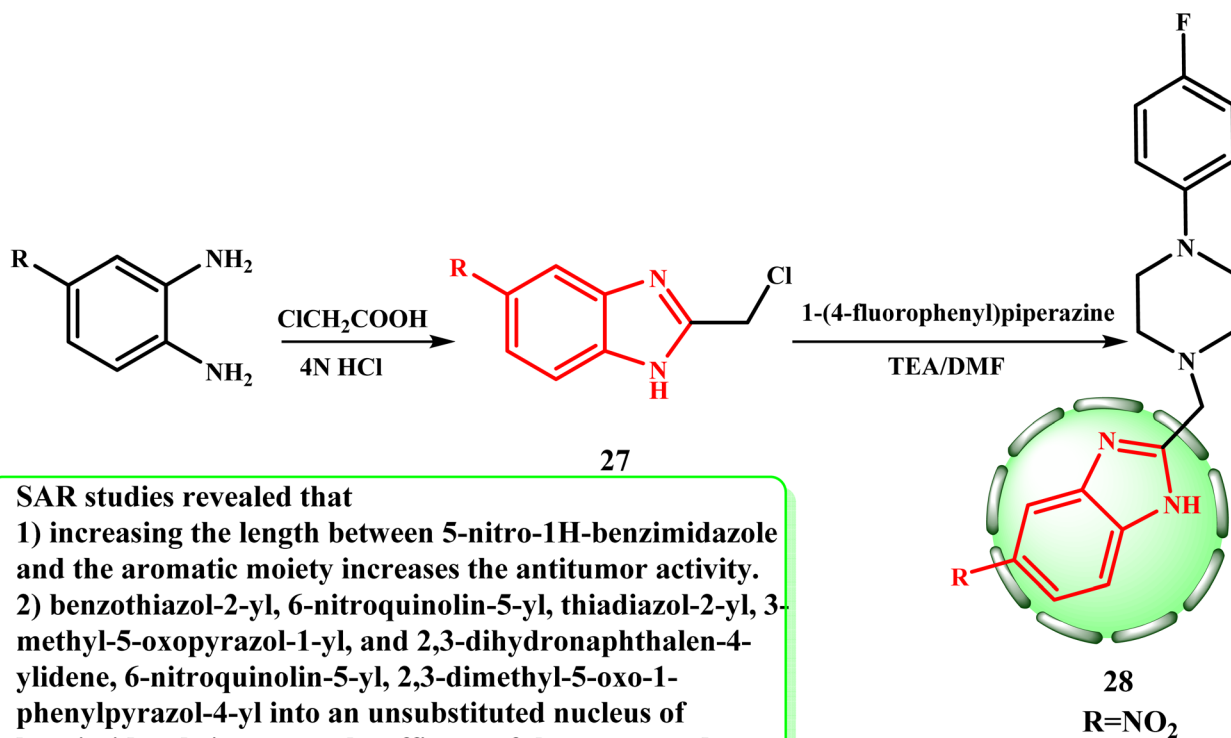
benzimidazoles **28** employing a straightforward, effective, and repeatable approach with a simple work-up procedure (Scheme 6). In the following way, the appropriate **27** reacts with 1-(4-fluorophenyl)piperazine in DMF when triethylamine is present to produce 2-(aryl amino)methyl-benzimidazole **28**. El-Gohary *et al.*<sup>32</sup> developed and evaluated a variety of 1*H*-benzimidazole derivatives for their anticancer characteristics. The MTT assay was used to screen the derivatives against the HepG-2 (liver), HCT-116 (colon), and MCF-7 (breast) cancer cell lines. Compound **28** exhibited the strongest activity against all the cell lines, in accordance with the results. The cytotoxic tests of the compounds revealed that they were less active than the reference medication, 5-fluorouracil. According to SAR investigations, the anticancer activity increased with the length of the contact between the aromatic moiety and 5-nitro-1*H*-benzimidazole.<sup>32</sup>

The proposed mechanistic route for the formation of benzimidazoles by reacting a derivative of *o*-phenylene diamine with an organic acid has already been studied.<sup>24,33</sup> Furthermore, the role of hydrochloric acid in the reaction has also been investigated.<sup>24,34</sup> The catalytic action of hydrochloric acid is explained by the protonation of oxygen, which activates the carboxyl group. The reaction intermediate is an addition product, which is produced when the carbonyl group of the protonated acid is attacked by the shared electron pair of a nitrogen. Nevertheless, the researchers concluded that the generation of the monoacyl

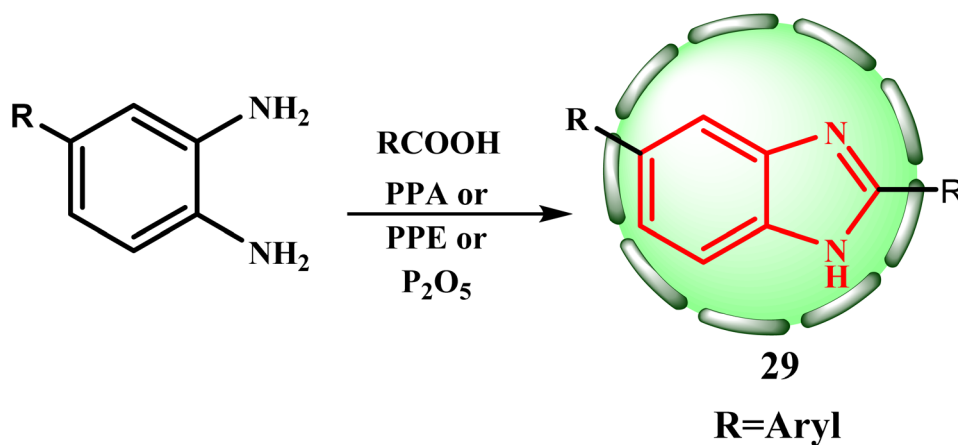


Scheme 5 Synthesis of novel benzimidazoles **25a** and **b** and **26a–c**.





Scheme 6 Synthesis of target 2-(aryl amino)methyl-benzimidazole 28.

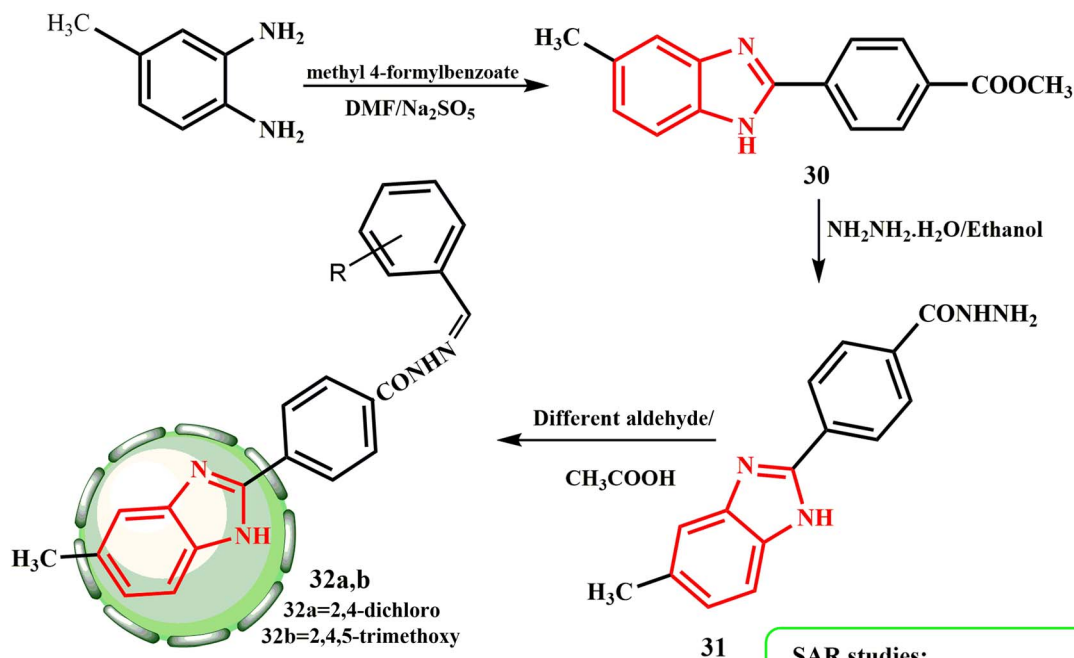


Scheme 7 Synthetic route for the formation of 2-arylbenzimidazole 29.

derivative was a necessary step in the benzimidazole ring building process.<sup>24,34</sup> It has been reported that heating aromatic carboxylic acids with *o*-phenylene diamine in a sealed tube at 180–190 °C produces good yields of 2-arylbenzimidazoles (29, R = Ar). An improved method for producing 2-arylbenzimidazoles 29 from aromatic carboxylic acid uses polyphosphate ester (PPE) or polyphosphoric acid (PPA) as a dehydrator. As an alternative, phosphorus pentoxide has also been documented to function as a dehydrator in the process of producing a derivative of 2-arylbenzimidazole (Scheme 7).<sup>34</sup>

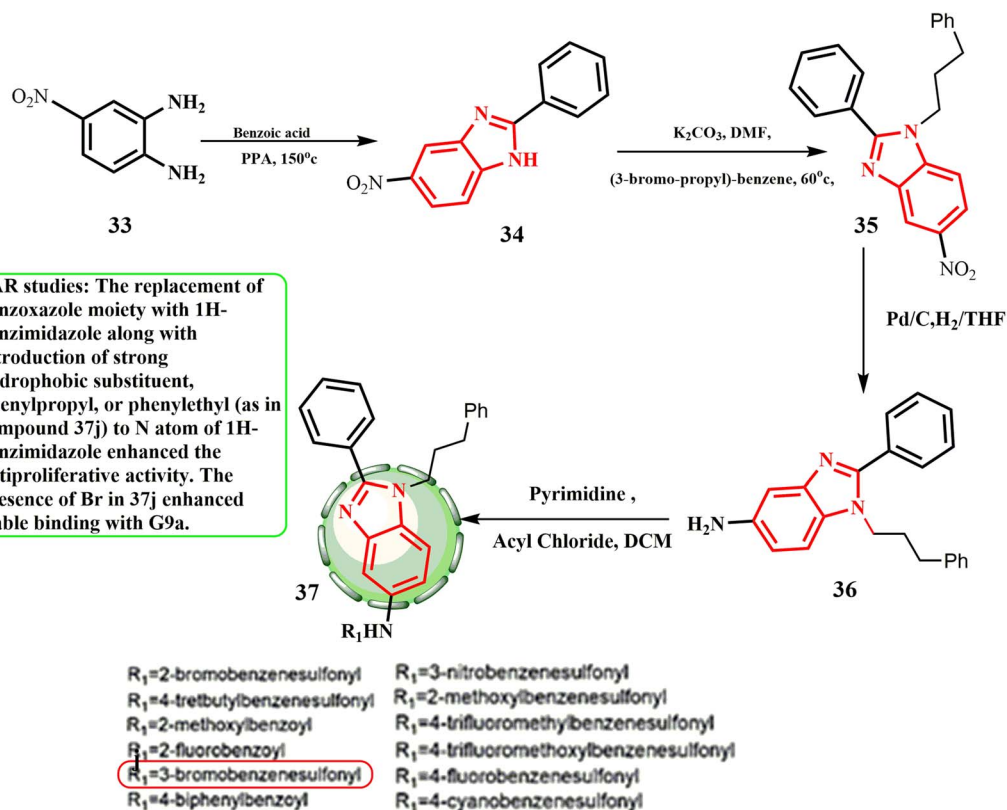
Scheme 8 shows the preparation of certain *N'*-(substituted-benzylidene)-4-(5-methyl-1*H*-benzimidazol-2-yl)benzohydrazide derivatives 32a and b for the analysis. Three steps were used to get the targeted synthetic substances. Firstly, methyl-4-formylbenzoate and 5-methyl-1,2 phenylenediamine were mixed equimolarly in DMF with Na<sub>2</sub>S<sub>2</sub>O<sub>5</sub> to yield 30. Compound 31 was produced by refluxing a mixture of ethanolic solution of hydrazine hydrate and 30, which occurred in approximately seven hours. The desired compounds 32a and b were obtained *via* condensation of hydrazide with different substituted





**SAR studies:**  
electron donating tri-methoxy group on the hydrazone moiety (as in compound 32b) when compared to the electron withdrawing di-chloro substitution (as in compound 32a) enhanced the antiproliferative action of the compound.

Scheme 8 Preparation of certain *N'*-(substituted-benzylidene)-4-(5-methyl-1*H*-benzimidazol-2-yl)benzohydrazide derivatives 32a and b.



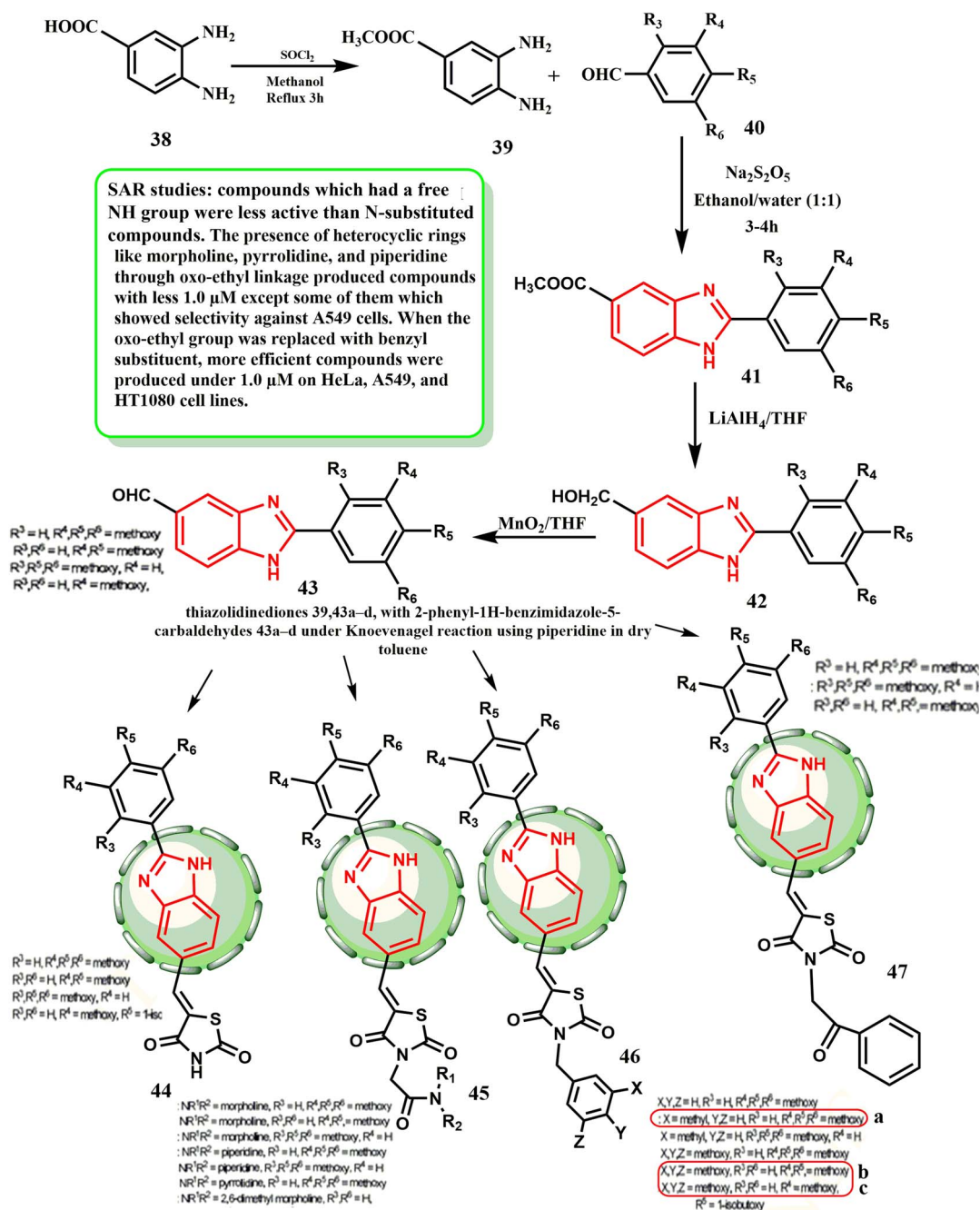
Scheme 9 Synthesis of benzimidazole derivatives 37.



benzaldehydes. Compounds **32a** and **b** were discovered to exhibit significant effectiveness against a number of cancer cell lines, preventing their proliferation by 50–84%.<sup>35</sup> SAR studies revealed that the antiproliferative action of compound **32b** was enhanced by the presence of tri-methoxy as an electron-donating group on hydrazone, as opposed to the electron-drawing di-chloro substitution in **32a**.

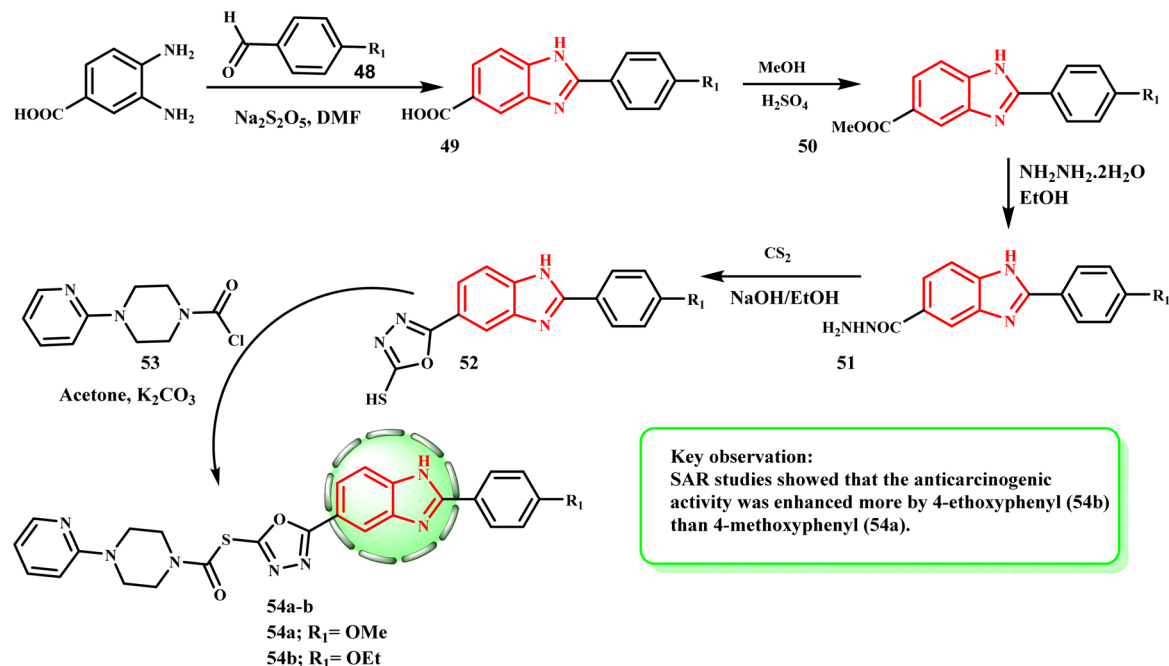
Scheme 9 shows that commercially produced 4-nitrobenzene-1,2-diamine (**33**) was employed as the starting material for the synthesis of benzimidazole derivatives **37**. In

polyphosphoric acid (PPA), **33** first interacted with benzoic acid to produce **34**, which then combined with (3-bromo-propyl)-benzene to produce intermediate **35** in the presence of  $K_2CO_3$ . Amino intermediate **36** was produced by reducing intermediate **35** with Pd/C in THF. Essential compounds **37** were obtained by treating amine **36** with suitable acyl chlorides or sulfonyl chlorides and triethylamine in dichloromethane. After various screening rounds, **37j** was shown to be an effective G9a antagonist ( $IC_{50} = 1.32 \mu M$ ), which caused the MCF-7 cancer cell line to undergo autophagy ( $IC_{50} = 5.73 \mu M$ ), where increased



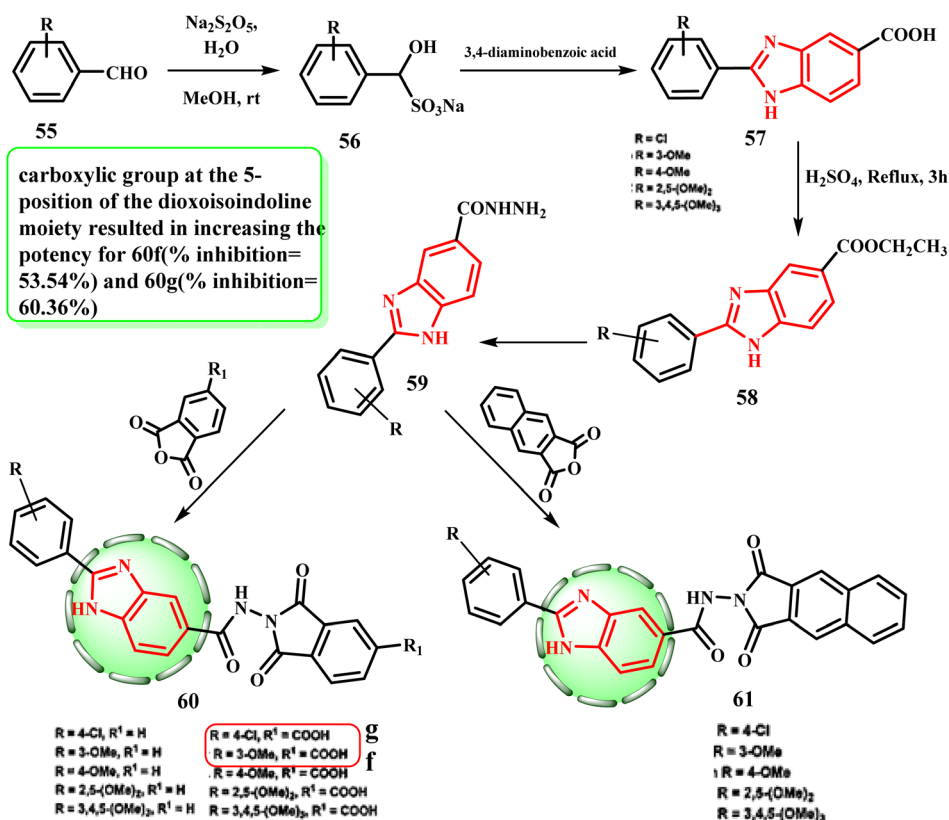
Scheme 10 Approach for the synthesis of benzimidazole-thiazolidinediones 46a–c.

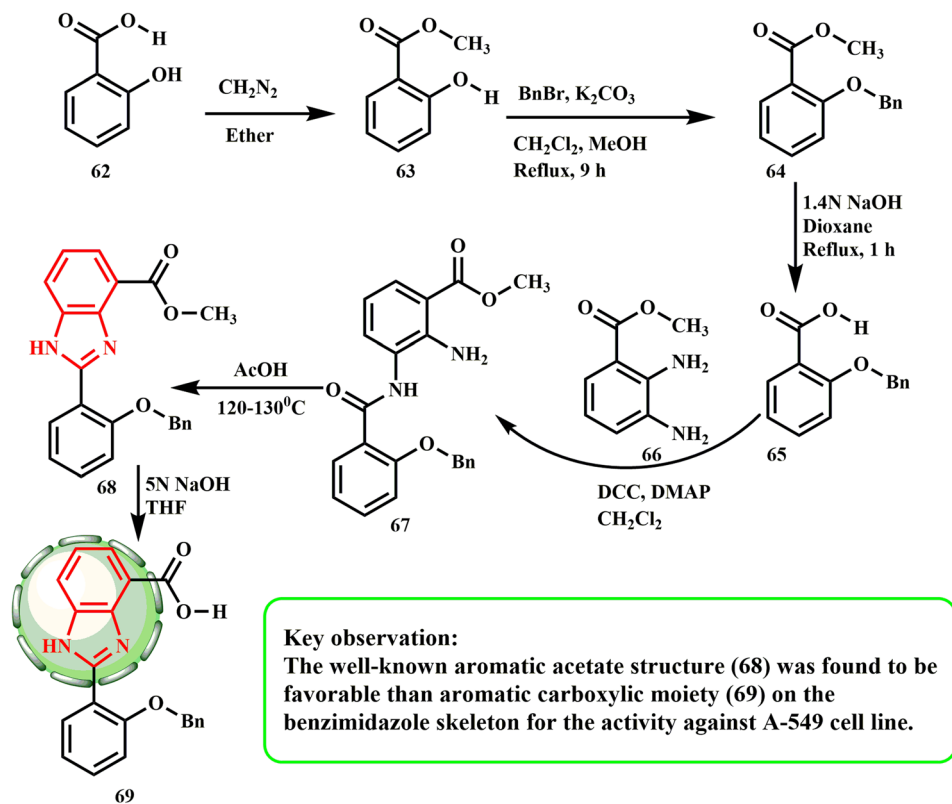




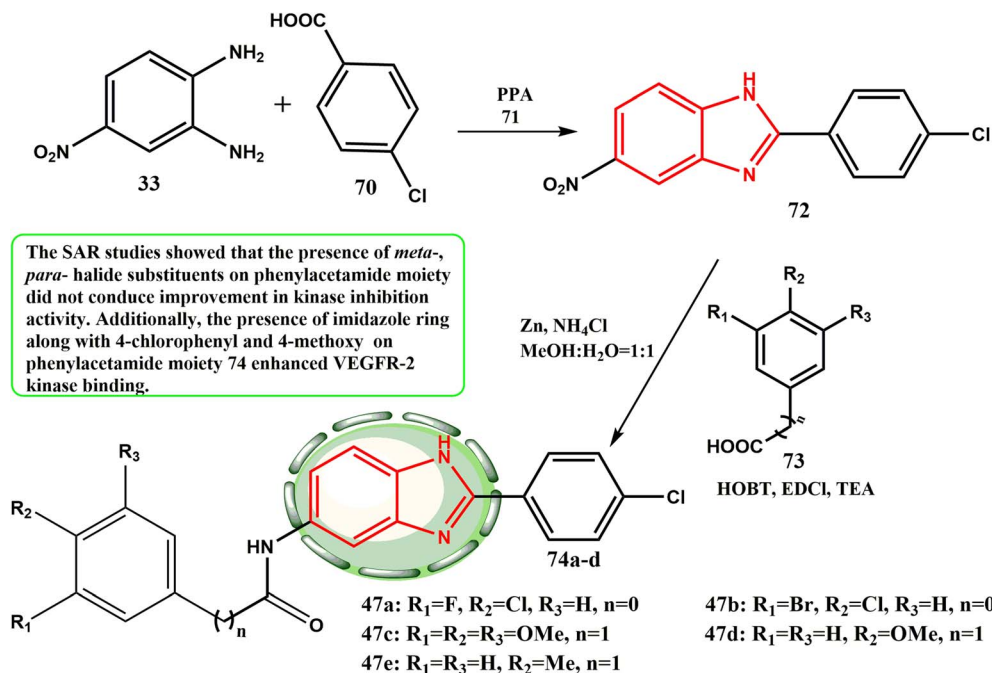
Scheme 11 Synthesis of compounds 54a and b.

concentrations caused the MCF-7 cells to undergo apoptosis.<sup>36</sup> The antiproliferative action was increased by the addition of a moiety containing 1*H*-benzimidazole and a potent hydrophobic substituent, phenylpropyl (found in compound 37j), to the *N* atom of 1*H*-benzimidazole. Stable binding with G9a was improved by the presence of Br in 37j.

Scheme 12 Synthesis of *N*-(1,3-dioxo-isoindol-2-yl)-2-phenyl-1*H*-benzo[d]imidazole derivatives 60 and 61.



Scheme 13 Synthesis of benzimidazole analogues 68 and 69.



Scheme 14 Procedure for the preparation of 2-arylbenzimidazole derivatives 74a-d.

Scheme 10 describes the approach for the synthesis of benzimidazole-thiazolidinediones **46a-c**. The Knoevenagel condensation reaction was used to produce the final products **46a-c** in a convergent manner. In the presence of sodium

metabisulfite, 3,4-diaminobenzoic acid (**38**) was natively altered to its methyl ester **39**, which subsequently interacted with various substituted benzaldehydes **40** to yield 1*H*-benzo[d]imidazole-5-carboxylates **41**. Lithium aluminum hydride was



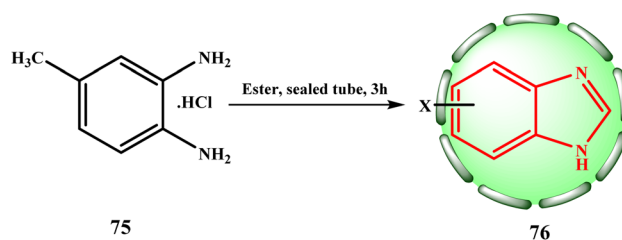
used to decrease the ester functionalities in **41**, resulting in alcohols **42**, which were subsequently oxidized to their respective aldehydes **43**. Compounds **46a–c** were created by employing the Knoevenagel reaction to react different thiazolidinediones with 2-phenyl-1*H*-benzimidazole-5-carbaldehydes **43** in dry toluene containing piperidine. Both conventional and microwave-assisted synthesis were used to carry out the Knoevenagel condensation reaction for the synthesis of compounds **46a–c**. Compounds **46a–c** exhibited satisfactory cytotoxicity to prostate, cervical, bone, and lung cell lines ( $IC_{50} = 0.096–0.63 \mu\text{M}$ ).<sup>37</sup> According to SAR evaluations, with the exception of a few that demonstrated selectivity against A549 cells, compounds with  $IC_{50}$  values less than  $1.0 \mu\text{M}$  were generated when heterocyclic rings such as morpholine, pyrrolidine, and piperidine were present *via* an oxo-ethyl linkage. On the HeLa, A549, and HT1080 cell lines, more effective compounds were generated at  $1.0 \mu\text{M}$  when the oxo-ethyl group was substituted out for a benzyl substituent. On almost all the screened cancer cell lines, derivatives such as **46b** that had 3,4,5-trimethoxybenzyl substitution at the tail produced higher active molecules at concentrations below  $1.0 \mu\text{M}$ . By contrast, derivative **46a**, which included a 3-methyl benzyl moiety on the thiazolidinedione tail, was more effective against all cancer cell lines at  $1.78 \mu\text{M}$ . The most powerful derivative, **46c**, has benzimidazole replaced with 4-isobutoxy-3-methoxy.

Scheme 11 displays the procedure used to synthesize compounds **54a** and **b**. Using sodium bisulphite in DMF, 4-substituted benzaldehyde **48** reacted with 3,4-diaminobenzoic acid (**38**) to produce 2-(4-substituted-phenyl)-1*H*-benzo[*d*]imidazole-6-carboxylic acid (**49**) derivatives in the first step. A simple esterification procedure transformed molecule **49** into methyl ester **50**, which was then reacted with hydrated-hydrazine to yield 2-(4-substituted-phenyl-6-carbohydrazide)-1*H*-benzo[*d*]imidazole (**51**). Hydrazide derivative **51** was converted to 2-(4-substituted-phenyl)-6-(5-mercapto-1,3,4-oxadiazol-2-yl)-1*H*-benzo[*d*]imidazole derivative (**52**) by reacting with carbon disulfide in boiling basic medium of ethanol and NaOH. Compound **52** and acetylated piperazine derivative **53** reacted in acetone at the last reaction step to yield 2-((5-(2-(4-substituted-phenyl)-1*H*-benzo[*d*]imidazol-6-yl)-1,3,4-oxadiazol-2-yl)thio)-1-(4-substituted-piperazin-1-yl) derivatives of ethane-1-on (**54a** and **b**). Çevik *et al.*<sup>38</sup> produced a variety of 1*H*-benzimidazole-oxadiazole compounds and tested them against HeLa, MCF-7, A549, HepG-2, and C6 human cancer cell lines *in vitro* to determine their anticancer properties. By inhibiting topoisomerase I, compounds **54a** ( $IC_{50} = 0.224 \pm 0.011 \mu\text{M}$ ) and **54b** ( $IC_{50} = 0.205 \pm 0.010 \mu\text{M}$ ) demonstrated the strongest antiproliferative action against the HeLa cancer cell line when doxorubicin ( $14.280 \text{ mM}$ ) was used as the standard medication. However, the majority of the derivatives demonstrated effective antiproliferative activity. The above-mentioned MTT experiment results supported our hypothesis that compounds **54a** and **b** would be more potent than Hoechst 33342 ( $0.306 \text{ mM}$ ) due to their potential for effective activity and reduced toxicity.

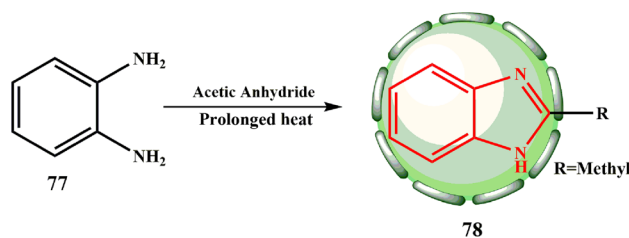
Several aryl aldehyde sodium bisulfates adduct **56** were reacted with the benzoic acid derivative to produce the initial document 2-substituted-benzimidazole-5-carboxylic acids **57**.

Then, benzimidazole derivatives **57** were converted into the ester congeners **58** by a reaction with ethanol in the presence of sulphuric acid. Hydrazide derivatives **59** were generated when **58** reacted with hydrazine hydrate. Lastly, the target hybrids **60** were generated by allowing hydrazides **59** and acid anhydrides to react in acetic acid (Scheme 12).<sup>39</sup> Series **60** was produced by adding a carboxylic group to the dioxoisindoline moiety at position 5, which increased the potency of **60f** (% inhibition = 53.54%) and **60g** (% inhibition = 60.36%).

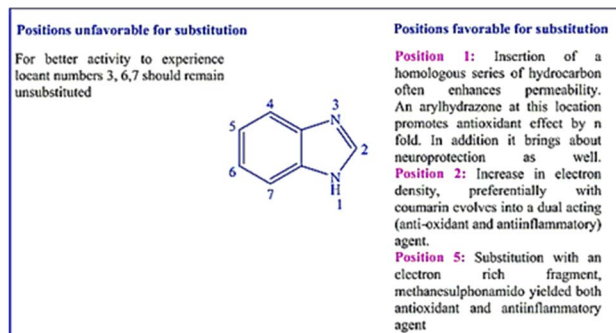
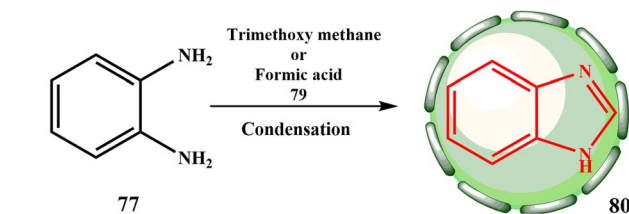
Derivatives of benzimidazoles were synthesized and reported by Huang *et al.* Salicylic acid (**62**) was first esterified by diazomethane to produce methyl salicylate **63**, which allowed the



Scheme 15 Method for the preparation of 5-methyl benzimidazole (76).



Scheme 16 Synthesis of 2-methylbenzimidazole (78).

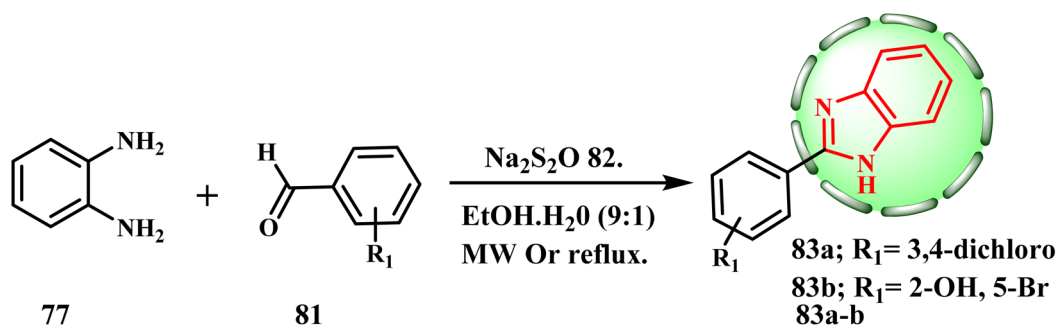


Scheme 17 Synthesis of BZ 80.

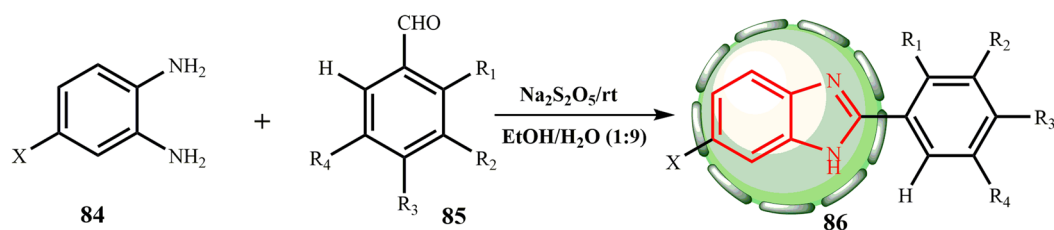


production of the desired derivatives. After being treated with benzyl bromide and potassium carbonate, the hydroxyl group of **63** was protected with benzyl ether to yield **64**.<sup>40</sup> The saponification reaction then changed component **64** into carboxylic acid **65**. After treating compound **65** with dicyclohexylcarbodiimide, amide **67** was produced, which was further transformed into benzimidazole **68** through cyclization–dehydration by refluxing in acetic acid.<sup>41</sup> Lastly, 5 M NaOH was used to saponify compound **68**, yielding compound **69** (Scheme 13). Benzoimidazole-4-methylacetate, **68** (A549, IC<sub>50</sub> 70 μM), was found to be more effective than benzoimidazole-4-carboxylic acid, **69** (A549, IC<sub>50</sub> 87 μM) in the anticancer screening tests.<sup>42,43</sup>

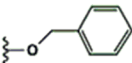
Scheme 14 shows the main procedure for the preparation of 2-arylbenzimidazole derivatives. The readily available starting material **33** was reacted with substituted benzoic acid **70** in polyphosphoric acid (PPA) (**71**) at 150 °C for 10–15 h to yield the 2-arylbenzimidazole intermediate **72**.<sup>44</sup> The nitro group was reduced to generate an amino intermediate, which was then reacted with substituted aromatic carboxylic acids **73** at 20 °C for 2–4 h with 1-ethyl-3-(3-dimethylaminopropyl) carbodiimide (EDCI) and hydroxy benzotriazole (HOBT) as a condensing agent and triethanolamine<sup>45</sup> as a base to obtain **74a–d**. According to the CAM experiment, compound **74d** demonstrated a great level of angiogenesis inhibition (79% inhibition per 10 nM per egg),

**Key observation:**

Target engagement with electron-withdrawing substituents chloro and bromo on the phenyl ring substituent of the 1*H*-benzimidazole scaffold may be responsible for its anticancer activity.

Scheme 18 Synthesis of substituted 1*H*-benzimidazole derivatives **83a** and **b**.**The SAR studies revealed that:**

- 1) the antitumor activity was enhanced by substitution of methyl group at the 5(6)-position of 1*H*-benzimidazole moiety.
- 2) it was found that EDGs like OCH<sub>3</sub> and N(CH<sub>3</sub>)<sub>2</sub>, increased the cytotoxic activity, at the phenyl group present on 1*H*-benzimidazole scaffold at position.

X = H, CH<sub>3</sub>R<sub>1</sub> = H, OH, CF<sub>3</sub>, NO<sub>2</sub>, OCH<sub>3</sub>R<sub>2</sub> = H, OH, OCH<sub>3</sub>R<sub>3</sub> = H, OH, OCH<sub>3</sub>, N(CH<sub>3</sub>)<sub>2</sub>, R<sub>4</sub> = H, OCH<sub>3</sub>, I

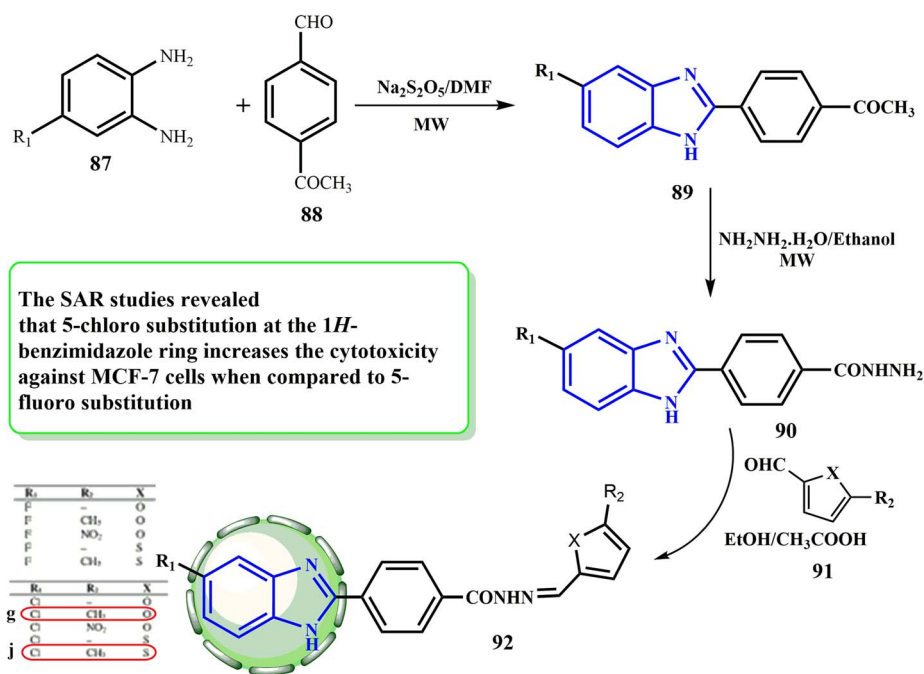
Compound	X	R <sub>1</sub>	R <sub>2</sub>	R <sub>3</sub>	R <sub>4</sub>
<b>86a</b>	H	H	OH	H	H
<b>86b</b>	H	H	H	OH	H
<b>86c</b>	H	OCH <sub>3</sub>	H	H	OCH <sub>3</sub>
<b>86e</b>	H	H	OCH <sub>3</sub>	OCH <sub>3</sub>	OCH <sub>3</sub>
<b>86f</b>	H	H	H	N(CH <sub>3</sub> ) <sub>2</sub>	H
<b>86g</b>	H	NO <sub>2</sub>	H	H	H
<b>86h</b>	H	H	OCH <sub>3</sub>	OH	H
<b>86i</b>	H	H	H	-OCH <sub>2</sub> -C <sub>6</sub> H <sub>5</sub>	H

Scheme 19 Synthesis of 2-(substituted-phenyl) benzimidazole derivatives **86**.

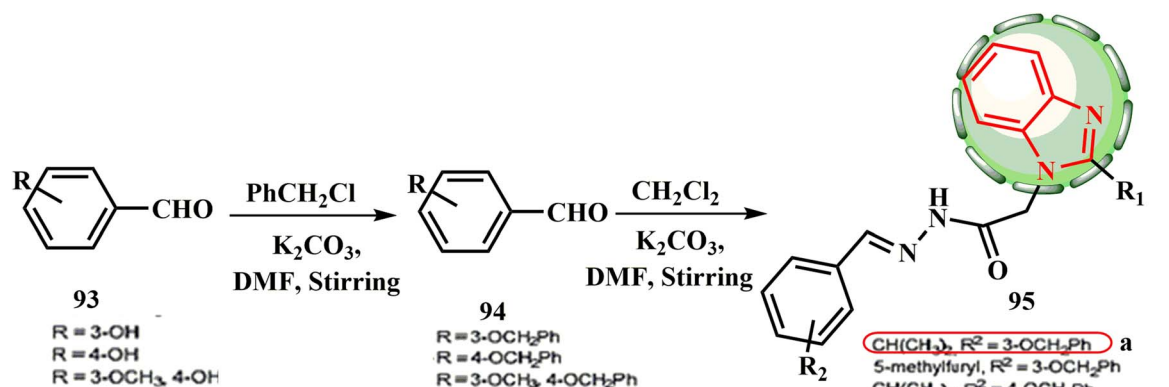
demonstrating the highest level of VEGFR-2 kinase inhibitory activity (51.4 nM IC<sub>50</sub>), and effective anti-proliferative potencies against HepG-2 and HUVEC cells (1.47 μM and 2.57 μM, respectively).<sup>46</sup> According to the SAR investigations, the phenylacetamide moiety *meta*- and *para*-halide substitutes did not increase the kinase inhibitory activity. Furthermore, the imidazole ring and 4-chlorophenyl together with the 4-methoxyphenylacetamide moiety in compound **74d** improved VEGFR-2 kinase binding.

Other benzimidazoles were synthesized similarly. Niemientowski started by producing 5-methyl benzimidazole (**76**, X = 5-methyl) by the condensation of equimolar amounts of **75** and ethyl formate at 225 °C in a sealed tube for three hours to investigate the reaction between 4-methyl-*o*-phenylenediaminehydrochloride (**75**) and esters (Scheme 15).<sup>24,34</sup>

Although a shorter treatment only produced *N,N'*-diacetylphenylenediamine (Scheme 16), the further treatment of **77** with acetic anhydride produced 2-methyl benzimidazole (**78**, R



Scheme 20 Synthesis of target compounds **92**.



Scheme 21 Synthetic protocol for benzimidazole hybrids **95**.



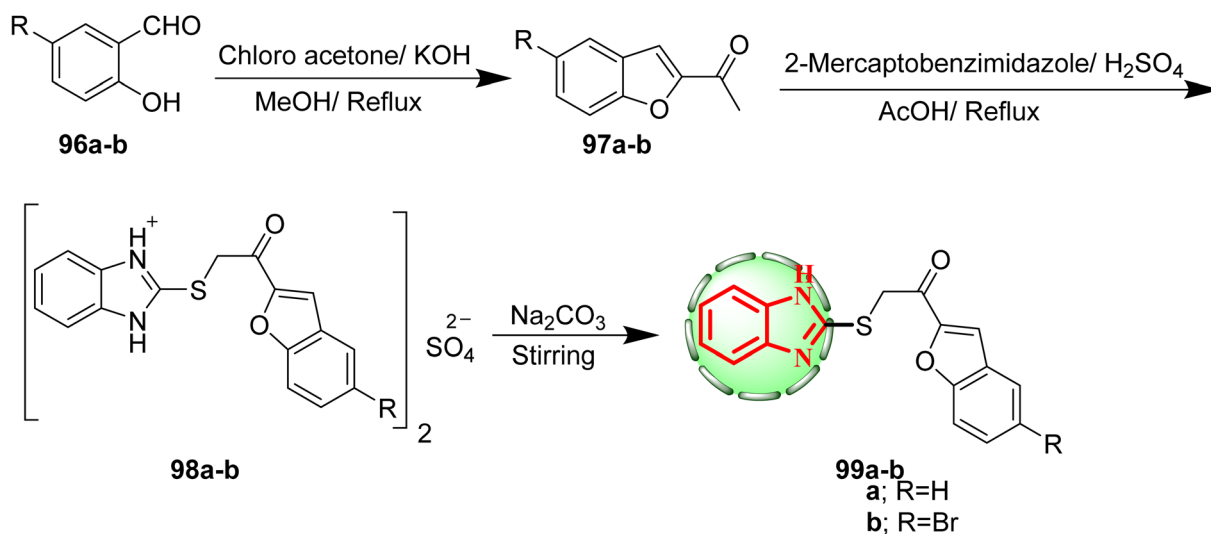
= CH<sub>3</sub>). Reinhardt found that the 2-methylbenzimidazole yields from 1% and 2% acetic anhydride were increased using diluted hydrochloric acid.<sup>24,34,47</sup>

With the help of the scientific research by Hoebrecker<sup>48</sup> in a six year period, scientists Banerjee<sup>49</sup> set the foundation for existing medical chemistry research by discovering a novel heterocyclic molecule (basic structure and synthesis shown in Scheme 17). BZ is the name of this substance.

The synthesis and cytotoxic potential of 1*H*-benzimidazole scaffolds were examined by Pham *et al.* *N*,2,6-trisubstituted 1*H*-benzimidazole derivatives **83a** and **b** were prepared from benzene-1,2-diamine derivative **77**. There are two steps in the synthetic process (Scheme 18). Firstly, using microwave assistance for the heating requirement, benzene-1,2-diamine derivative **77** was condensed with substituted aromatic aldehyde **81** to produce 2,6-disubstituted 1*H*-benzimidazole derivatives **83a** and **b**. Then, using the non-selective (positive) control involved in paclitaxel (PTX) in the MTT assay, we evaluated the anticancer activity of compounds **83a** and **b** on five cancer cell lines

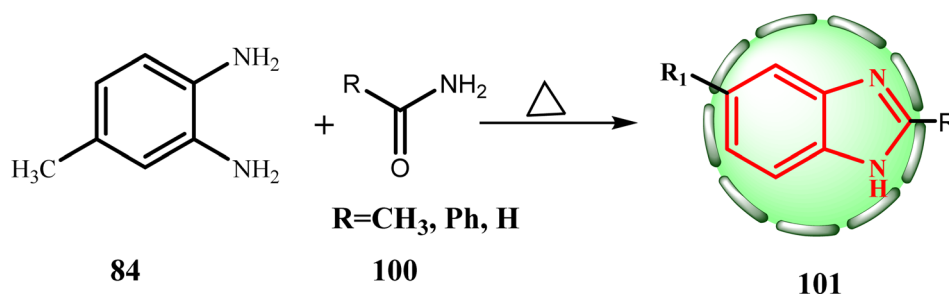
including hepatocellular carcinoma cell line (HepG-2), human breast cancer cell lines (MDA-MB-231 and MCF-7), the aggressive and highly malignant rhabdomyosarcoma cell line (RMS), and colon carcinoma cell line (C-26). Among the synthesized compounds, compounds **83a** (3,4-dichloro) and **83b** (5-bromo-2-hydroxy) demonstrated the greatest anticancer activity against all the tested cell lines.<sup>50</sup>

Given that Na<sub>2</sub>S<sub>2</sub>O<sub>5</sub> dissolves readily in an EtOH-H<sub>2</sub>O mixture (9 : 1 v/v) as the medium for the manufacture of benzimidazole derivatives, the oxidation reaction to yield 2-phenyl benzimidazole derivatives **86** can occur at room temperature, as illustrated in Scheme 19. Huynh *et al.*<sup>51</sup> produced 2-(substituted-phenyl)benzimidazole derivatives by reacting *ortho* phenylenediamines with benzaldehydes and using sodium metabisulphite as an oxidant. Three human cancer cell lines, A549, MDA-MB-231, and PC-3, were used to test these substances for their anticancer activities. The functioning of the phenyl ring system at 2-position, the biochemical properties of the cell lines, and electron-withdrawing and -donating groups



The SAR studies revealed that combining 2-thiobenzimidazole with 2-acetylbenzofuran and 4-aminoacetophenone, resulted in maximum cytotoxic action. It was observed that benzo fused heterocyclic acetyl derivatives exhibited maximum anticancer activity whereas the addition of 5-bromo substituent suppressed its activity.

Scheme 22 Synthesis of benzimidazole-linked 2-acetylbenzofuran derivatives **99a** and **b**.



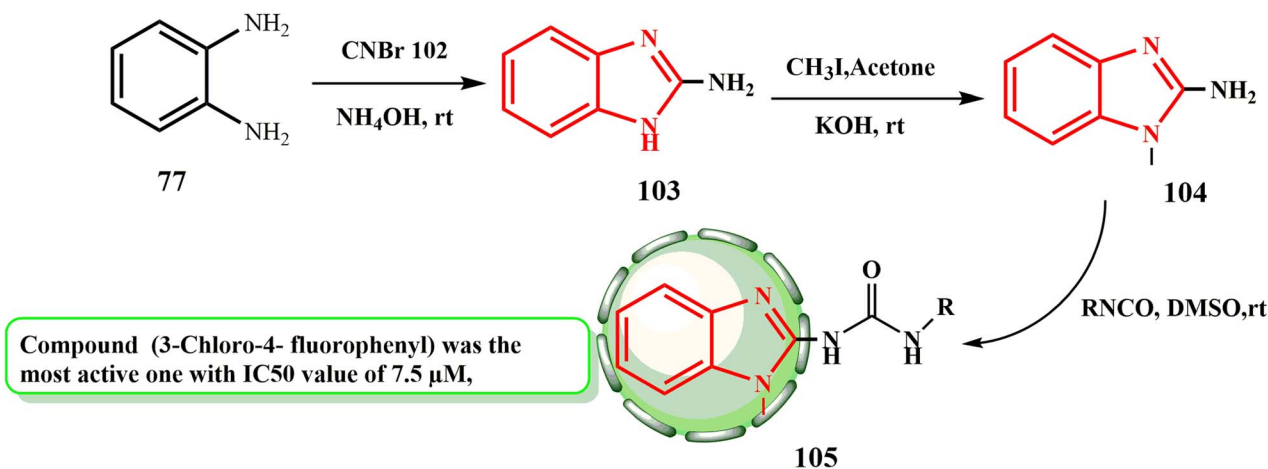
Scheme 23 Synthesis route to target compounds **101**.



on the benzimidazole scaffold were shown to be associated with variations in the  $IC_{50}$  values. We established additional benzimidazole derivatives with various substituents on the 2-phenyl ring system, such as  $-OH$ ,  $-NO_2$ ,  $-CF_3$ ,  $-I$ ,  $-OMe$ ,  $-NMe_2$ , and  $-OCH_2-C_6H_5$ , in parallel to provide more information about the impact of the electron-donating and withdrawing groups on the phenyl ring at the 2-position as well as on the benzimidazole frame. Remarkably, the bioactivities of compounds **86** on the A549 and PC-3 cell lines showed that the methyl group at position 5 is crucial in enhancing their bioactivities (**86a** > **86b** > **86c** > **86e** > **86f** > **86g** > **86h** > **86i**).

Scheme 20 illustrates the three-step synthesis of target compounds **92** used in this investigation. Following the procedure outlined in the literature, the substrates, 1-(4-(5-substituted-1*H*-benzo[*d*]imidazol-2-yl)phenyl)ethan-1-ones (**89**) and 4-(5-substituted-1*H*-benzo[*d*]imidazol-2-yl)benzohydrazides (**90**), were created.<sup>52</sup> Condensation of the hydrazide with diverse

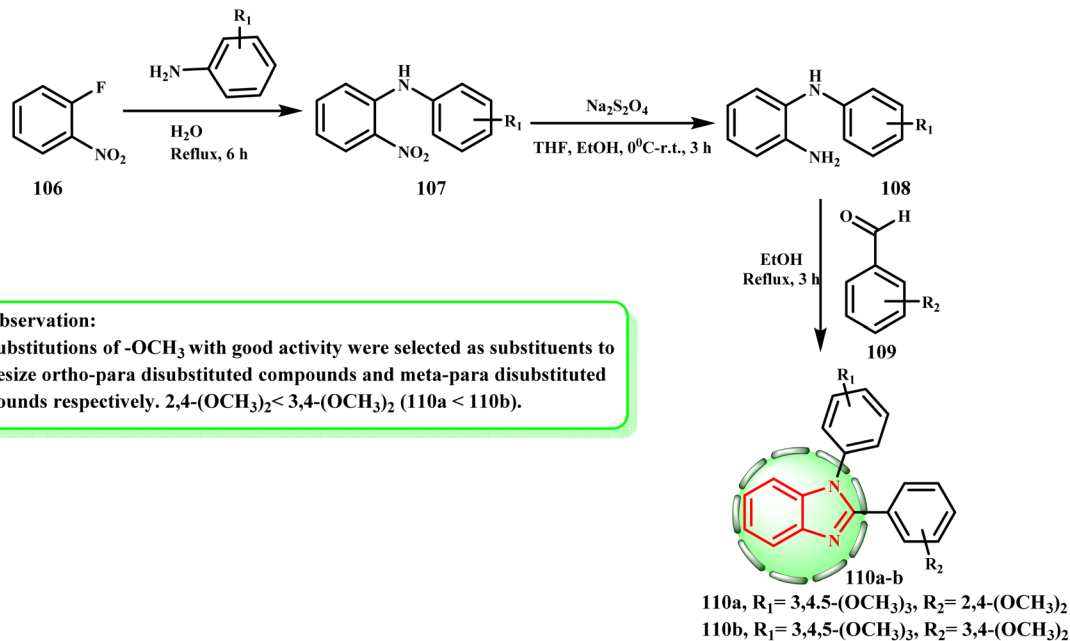
substituted benzaldehydes **91** (ref. 53) led to the related arylidene hydrazides **92**. Çevik *et al.*<sup>54</sup> produced a variety of 4-(5-substituted-1*H*-benzimidazol-2-yl)-*N*-((5-substitutedthiophen/furan-2-yl)methylene)benzohydrazides (**92**) and used the MTT assay to evaluate them for their ability to kill A549 and MCF-7 (breast) cancer cell lines, using cisplatin as a (+ve) control. The normal NIH/3T3 cell line was also employed to check the synthesized synthetic substances. Compound **92g** exhibited no effect on the normal cell line, while it had the maximum cytotoxic potential in the A549 cell line ( $IC_{50}$  against A549 = 0.316  $\mu$ M). Compared to cisplatin, compound **92j** ( $IC_{50}$  = 0.0316  $\mu$ M) exhibited the most potent selective cytotoxicity against the MCF-7 cell line. In comparison to 5-fluoro substitution, SAR investigations demonstrated that 5-chloro substitution at the 1*H*-benzimidazole ring improved the cytotoxicity against MCF-7 cells.



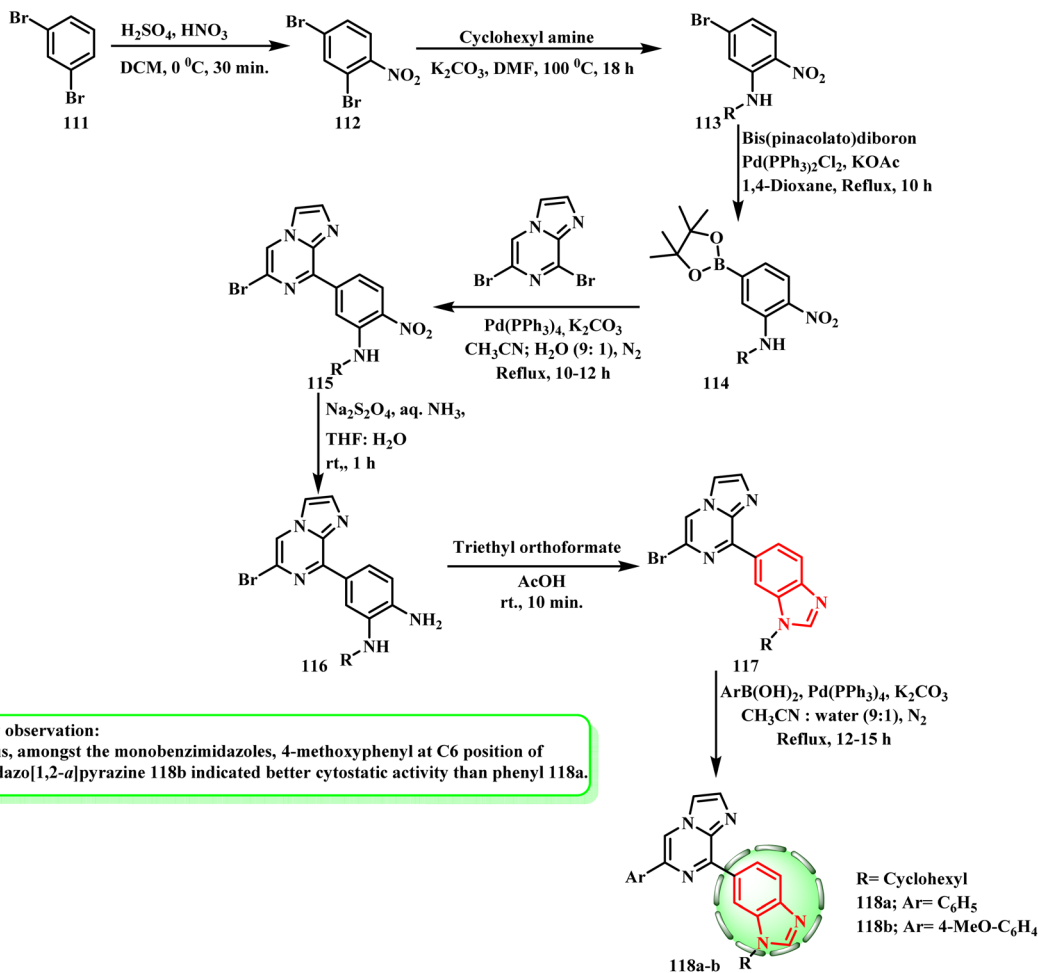
Compound	R	Compound	R
<b>105a</b>		<b>105f</b>	
<b>105b</b>		<b>105g</b>	
<b>105c</b>		<b>105h</b>	
<b>105d</b>		<b>105i</b>	
<b>105e</b>		<b>105j</b>	

Scheme 24 Synthesis of benzimidazole-urea derivatives **105**.





Scheme 25 General synthesis of compounds 110a and b.



Scheme 26 Synthesis of mono benzimidazole derivatives 117 and 118a and b.



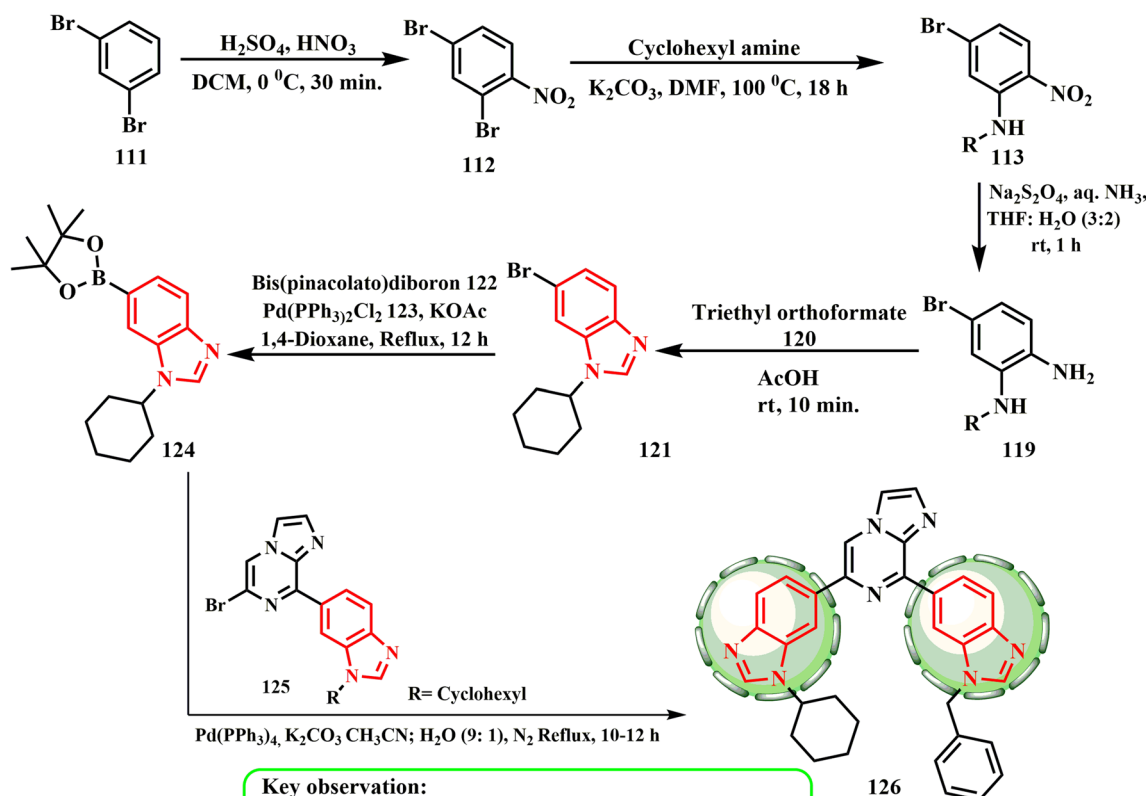
The appropriate benzyloxybenzaldehyde **94** was produced by reacting 4-hydroxybenzaldehyde (**93**) with benzyl chloride to synthesize target compounds **95** (Scheme 21). Abdel-Mohsen *et al.*<sup>55</sup> investigated the effects of a novel class of 1,2-disubstituted 1*H*-benzimidazoles as VEGFR-2 inhibitors on the HepG-2 hepatocellular carcinoma cell line. According to the results, sorafenib ( $IC_{50} = 10.99 \mu\text{M}$ ) had lower cytotoxic activity than one of the created hybrids, **95** ( $IC_{50} = 1.98 \mu\text{M}$ ). According to the SAR evaluations, the elongated side chains of 1*H*-benzimidazole at the one position resulted in activity as a VEGFR-2 inhibitor. It was discovered that the presence of a linker and substituents at positions N-1, C-2, C-5, and C-6 is promising in the anticancer action.

**1.1.2. Acidic compounds.** As shown in Scheme 22, the appropriate 2-acetylbenzofurans (**97**) were produced by cyclizing salicylaldehyde (**96**) with chloroacetone in the presence of potassium hydroxide.<sup>56</sup> 2-Substituted thiobenzimidazole sulfate salts (**98**) were produced when compounds (**97**) and 2-mercaptobenzothiazole reacted in acidic medium of two equivalents of conc. sulfuric acid using the modified procedure described by Abdel-Aziz *et al.*<sup>57</sup> At room temperature and to provide the appropriate free bases **99**, the free molecules were liberated from the sulfate salts by neutralizing through stirring with an  $\text{NaHCO}_3$  solution. With sunitinib serving as the reference medication ( $IC_{50} = 0.18 \mu\text{M}$ ), compound **99**

demonstrated excellent inhibitory efficacy against the A498 human kidney cancer cell line ( $IC_{50} = 6.97 \mu\text{M}$ ).<sup>58</sup> Mixing 2-thiobenzimidazole with 2-acetylbenzofuran and 4-aminoacetophenone had the most cytotoxic effect, according to the SAR investigations. Benzo-fused heterocyclic acetyl derivatives were shown to have the strongest anticancer activity, but the addition of a 5-bromo substituent reduced this activity.

Niementowski heated free base **84** with appropriate amides **100** to produce methyl benzimidazole (**101**,  $R_1 = 5$  (6)1-methyl,  $R = \text{H}$ ,  $\text{CH}_3$ , or  $\text{Ph}$ ) (Scheme 23).

Here, we describe how we produced benzimidazole-urea derivatives **105**. The reaction of *O*-phenylene diamine (**77**) and cyanogen bromide (**102**) in methanol at room temperature produced 2-aminobenzimidazole (**103**) in 88% yield by ammonium hydroxide workup (Scheme 24). Compound **105j** (3-chloro-4-fluorophenyl) was the most active compound against a liver cancer cell lines (HepG-2), with an  $IC_{50}$  value of  $7.5 \mu\text{M}$ . The anticancer activity of the other compounds followed the order of **105d** > **105a** > **105b** > **105e** > **105c** > **105g** > **105f**. The anticancer activity of the other compounds followed the sequence of **105a** > **105b** > **105d** > **105i** > **105f** > **105h** > **105g** with  $IC_{50}$  values in the range of 2.4–38.5  $\mu\text{M}$ , among which compound **105j** was the most effective ( $IC_{50} = 1.9 \mu\text{M}$ ) against non-small lung cancer (A549).<sup>59</sup>



Scheme 27 Schematic of the route for the synthesis of bisbenzimidazole **126**.

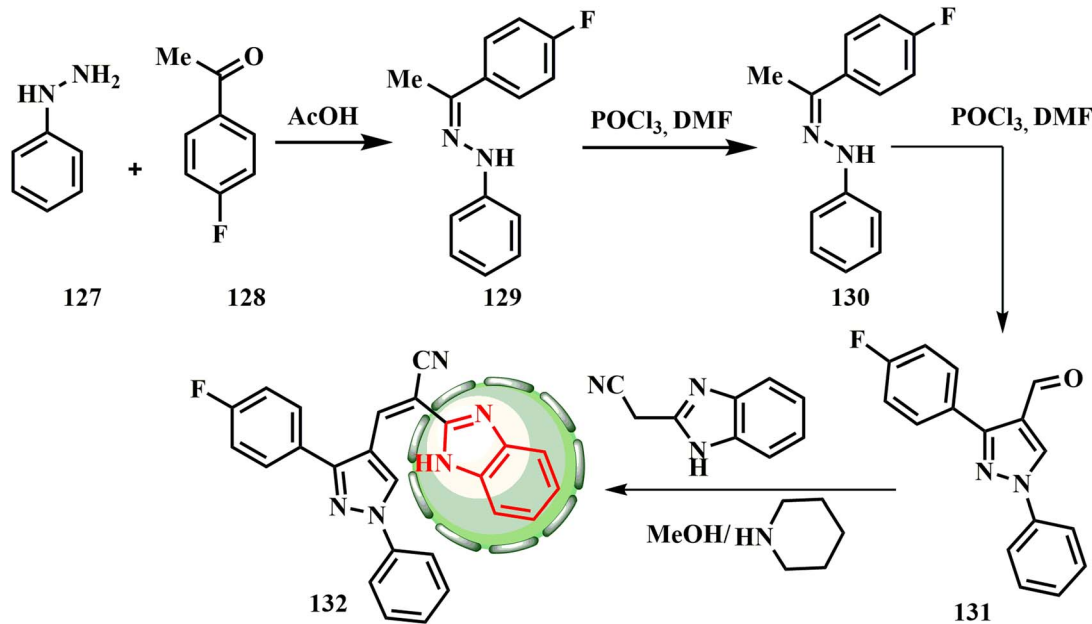


**1.1.3. *o*-(*N*-Arylamino)arylamines.** The production and cytotoxic potential of novel 1,2-diarylbenzimidazole analogues were examined by Zhang *et al.* Following the general procedure indicated in Scheme 25, compounds **110a** and **b** were synthesized by refluxing *o*-fluoronitrobenzene (**106**), neutralizing it with NaHCO<sub>3</sub>, and then obtaining analogue **107**. After dissolving compound **107** in a mixed solution of ethanol and tetrahydrofuran, the reduction process was initiated by the addition of Na<sub>2</sub>S<sub>2</sub>O<sub>4</sub> solution. Following NaHCO<sub>3</sub> alkalization, compounds **108** were produced. Imidazole rings **110a** and **b** were finally formed by refluxing compounds **108** with substituted benzaldehyde **109** after they had been dissolved in anhydrous ethanol. Compound **110b** demonstrated minimal toxicity to normal cells and maximum anticancer activity against HeLa, HepG-2, A549, and MCF-7 cells, with IC<sub>50</sub> values of 1.71 ± 0.14, 0.71 ± 0.07, 2.41 ± 0.31, and 1.94 ± 0.08 μM, respectively.<sup>60</sup> The impact of double substitution on activity was also considered. To develop *ortho-para* disubstituted compounds and *meta-para* disubstituted compounds, respectively, -OCH<sub>3</sub> with excellent activity was chosen as the substituent, where **110a** < **110b** = 2,4-(OCH<sub>3</sub>)<sub>2</sub> < 3,4-(OCH<sub>3</sub>)<sub>2</sub>. As a result, 3,4-(OCH<sub>3</sub>)<sub>2</sub> had the best activity in *meta-para* disubstitution, which had higher activity than *ortho-para* disubstitution.

After being nitrated with sulfuric and nitric acids, the commercially available 1,3-dibromobenzene (**111**) was converted to **112**, which was then selectively replaced with

cyclohexylamine in DMF to produce **113**. Bis(pinacolato) diboron was used to boronate **113** in the presence of Pd(PPh<sub>3</sub>)<sub>2</sub>Cl<sub>2</sub> and KOAc, producing **114**. Suzuki–Miyaura cross-coupling of **114** with dibromo-imidazo[1,2-*a*]pyrazine<sup>61,62</sup> and Pd(PPh<sub>3</sub>)<sub>4</sub> afforded compound **115** together with traces of disubstituted products. Amines **116** were obtained by reducing the derivatives with Na<sub>2</sub>S<sub>2</sub>O<sub>4</sub> in ammonia. Then, triethyl orthoformate was cyclized in acetic acid to produce intermediate **117**. Using Pd(PPh<sub>3</sub>)<sub>4</sub> and K<sub>2</sub>CO<sub>3</sub>, Suzuki reactions of the intermediates with unsubstituted and substituted phenylboronated were performed in CH<sub>3</sub>CN:H<sub>2</sub>O, yielding **118a** and **b** (ref. 63) (Scheme 26). Mono benzimidazole derivatives **118a** and **b** showed specific effectiveness against subpanels of melanoma, colon, leukemia, and central nervous system (GI<sub>50</sub> = 0.31–0.39 μM). Therefore, 4-methoxyphenyl at the C6 position of imidazo[1,2-*a*]pyrazine **118b** showed superior cytostatic activity compared to phenyl **118a** among the mono benzimidazoles.

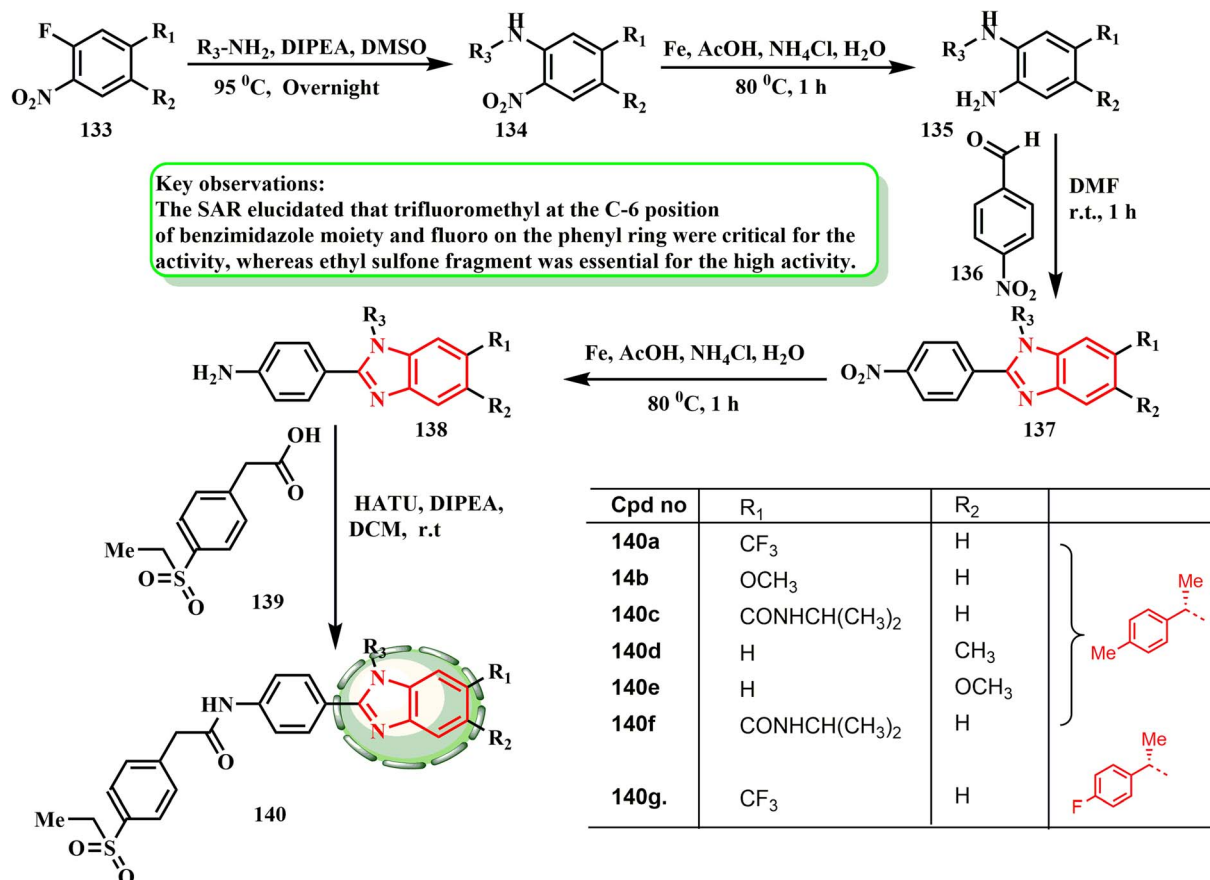
The commercially available 1,3-dibromobenzene (**111**) was nitrated to produce **112**, which was then replaced with cyclohexylamine in DMF to produce **113**. After reducing **113** with Na<sub>2</sub>S<sub>2</sub>O<sub>4</sub> in ammonia to yield **119**, the corresponding benzimidazole **121** was obtained by cyclization with triethyl orthoformate (**120**) in acetic acid. Bis(pinacolato)diboron (**122**) was used to boronate the derivative in the presence of Pd(PPh<sub>3</sub>)<sub>2</sub>Cl<sub>2</sub> (**123**) and KOAc, yielding **124**. Using Pd(PPh<sub>3</sub>)<sub>4</sub> and K<sub>2</sub>CO<sub>3</sub>, Suzuki–Miyaura cross-coupling of benzimidazole boronated



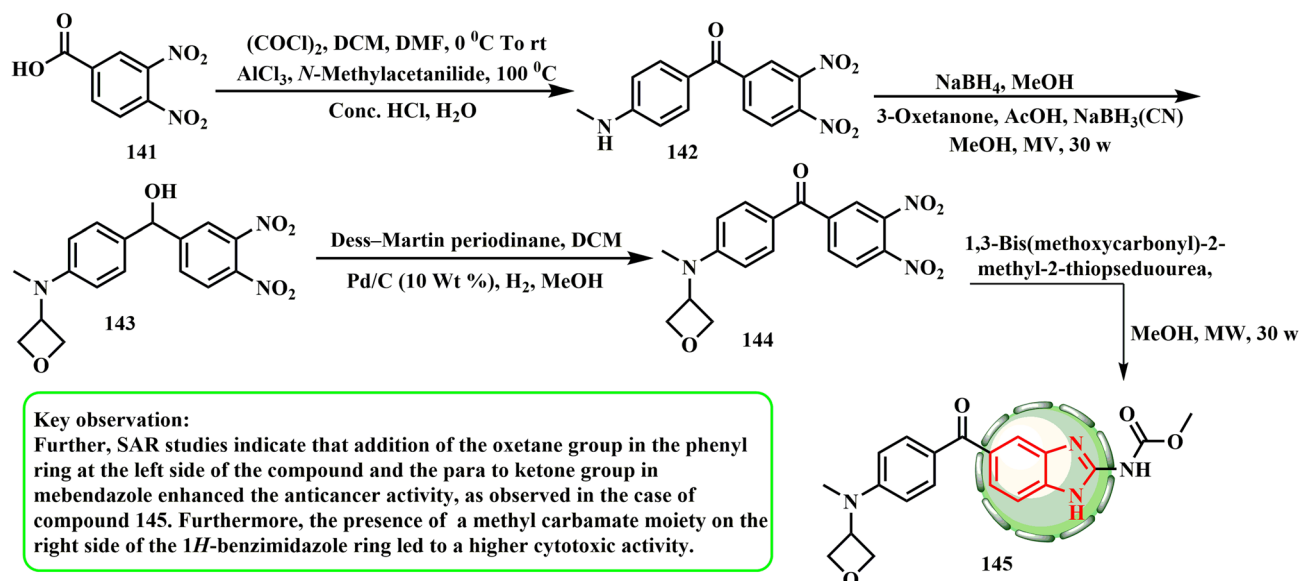
**Key observation:**  
Among the benzimidazole–pyrazole hybrids one possessing the para-fluoro moiety connected to a pyrazole ring **132** offered the highest anticancer activity when evaluated.

Scheme 28 Synthesis of benzimidazole-tethered pyrazole **132**.





Scheme 29 Synthesis of benzimidazole derivatives 140a–g.



Scheme 30 Synthesis of (1H-benzo[d]imidazol-2-yl)carbamate analogue 145.

125 with intermediate 124 was carried out to yield 126 (Scheme 27). All the screened cell lines showed the cytotoxicity of compounds 118b and 126, which also displayed significant growth inhibitory concentrations of 2.10 and 2.23  $\mu\text{M}$ ,

respectively.<sup>63</sup> The colon cancer cell line HCC-2998 was discovered to be extremely sensitive to derivative 126 among these tumor-sensitive cell lines, exhibiting a negative growth percentage value (lethal impact). The cancer cell line from the



central nervous system (SF-539) was found to be highly susceptible to derivative **118b**. Ct-DNA intercalates with imidazo [1,2-*a*]pyrazine-benzimidazoles **118a** and bisbenzimidazole **126**,<sup>64</sup> exhibiting superior activity than bisbenzimidazole, as a key interaction for basic physiologically noteworthy effects. With cytostatic effects on the cell line, mono benzimidazole derivative **118a** was superior to bisbenzimidazole **126**; nevertheless, compound **126** subsequently revealed a cytotoxic influence on various cancer cell lines.

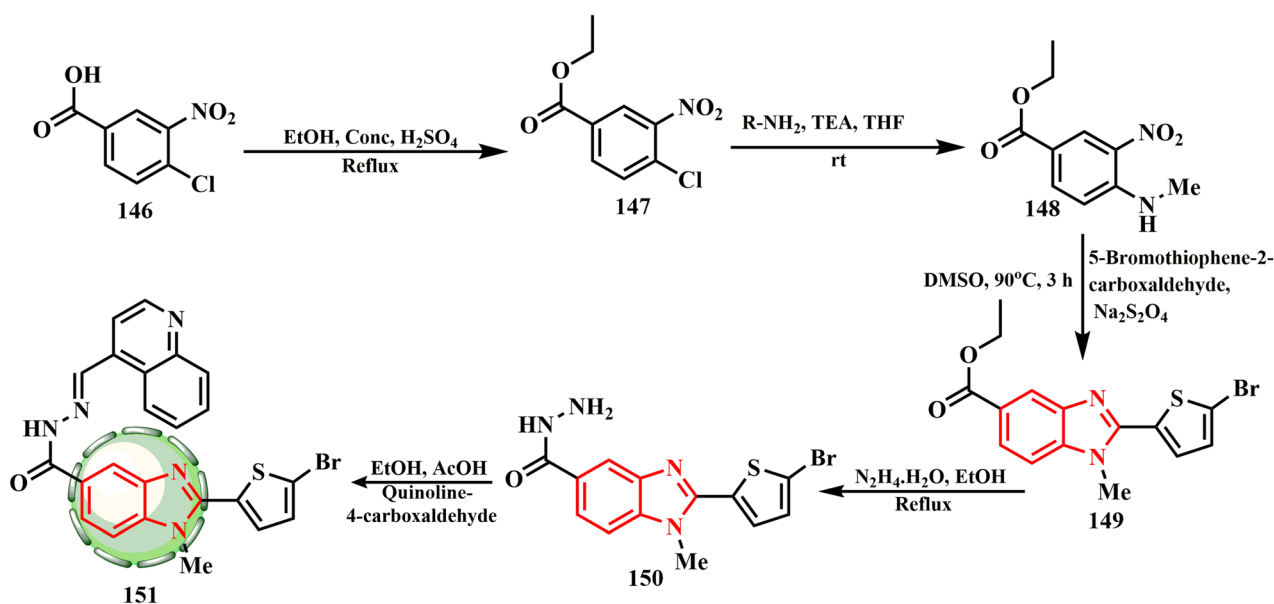
Scheme 28 shows the synthesis of benzimidazole-tethered pyrazole **132**. Arylhydrazine and suitable aralkyl ketone **128** are first condensed in glacial acetic acid to produce pyrazole-based carbaldehyde **131**. Hydrazone intermediate **129** is then cyclized utilizing Vilsmeier–Haack reaction. Compound **132** had the least toxicity and most promising effects, with IC<sub>50</sub> values of 30.9, 32.8, and 80 μM against MRC5 cells, AsPC1, and SW1990.<sup>65</sup> Additionally, SAR investigations showed that a 4-fluorophenyl moiety increased its efficacy against all the evaluated cell lines.

**1.1.4. *o*-Nitro arylamines or *o*-dinitro arenes.** In their study aimed at selectively targeting cancer cells, Wu *et al.*<sup>66</sup> established a novel category of chemicals called benzimidazoles. Scheme 29 shows how various amines reacted with commercial substance **133** to produce amine-substituted nitrobenzene intermediates **134**. The corresponding anilines **135** and **138** were obtained by reducing the nitro groups in **134**. Subsequently, the final products **140a–g** were obtained by coupling with 2-(4-(ethylsulfonyl)phenyl)acetic acid (Scheme 29). The SAR revealed that the ethyl sulfone fragment was necessary for the high activity, while trifluoromethyl at the C-6 position of the benzimidazole moiety and fluoro on the phenyl ring were crucial for the activity. Moreover, hybrids **140a** and **b** showed encouraging efficacy against the AR-positive LNCaP, 22Rv1, and C4–2B prostate cancer cell lines (IC<sub>50</sub>: 6.3–8.3 μM and 4.6–8.1

μM, respectively). When the size was increased to isopropyl formamide (**140c**), the activity was reduced by almost nine-fold. These findings showed that the best methyl group substituent for RORγ transcriptional activity was located at the R<sub>1</sub> position. Potency losses of 73 and 3.7 times were seen in comparable compounds **140d** and **140e** when the methyl or methoxy group at the R<sub>1</sub> position was fused to the R<sub>2</sub> position, respectively. However, the resultant compound **140f** had somewhat increased efficacy when the isopropyl formamide moiety at the R<sub>1</sub> position was fused to the R<sub>2</sub> location.

Methyl(5-(4-(methyl(oxetan-3-yl)amino)benzoyl)-1*H*-benzo[*d*]imidazol-2-yl)carbamate (**145**) was obtained *via* the microwave<sup>67</sup> condensation cyclization of 1,3-bis(methoxycarbonyl)-2-methyl-2-thiopseudourea and intermediate **143** (Scheme 30). Compound **145** with oxetanyl substitution demonstrated significant cytotoxic activity against prostate (PC-3 and PC3MLN4 cell lines), lung (A549 cell lines), and ovarian cancers with considerable activity toward profoundly aggressive carcinogenic cell lines (IC<sub>50</sub> = 0.9–3.8 μM).<sup>68</sup> The growth of existing tumors was greatly suppressed by compound **145** (30 mg kg<sup>-1</sup>) without causing any detectable toxicity (T/C: 0.36). Additionally, as seen in compound **145**, SAR studies showed that the addition of the *para* to ketone group in mebendazole and the oxetane group in the phenyl ring on the left side of the compound increased the anticancer activity. A methyl carbamate moiety on the right side of the 1*H*-benzimidazole ring also increased the cytotoxic activity of the compound.

The synthetic route for benzimidazole–quinoline<sup>69</sup> hybrid **151** is presented in Scheme 31. Firstly, key intermediate **150**,<sup>70</sup> obtained initially from core nucleus benzimidazole-5-carboxylate **149**, was effectively produced by a ‘one pot’ nitro reductive cyclization process between ethyl 3-nitro-4-(substituted amino)benzoate **148** and 5-bromothiophene-2-carbaldehyde using Na<sub>2</sub>S<sub>2</sub>O<sub>4</sub> in DMSO.<sup>71</sup> When tested against



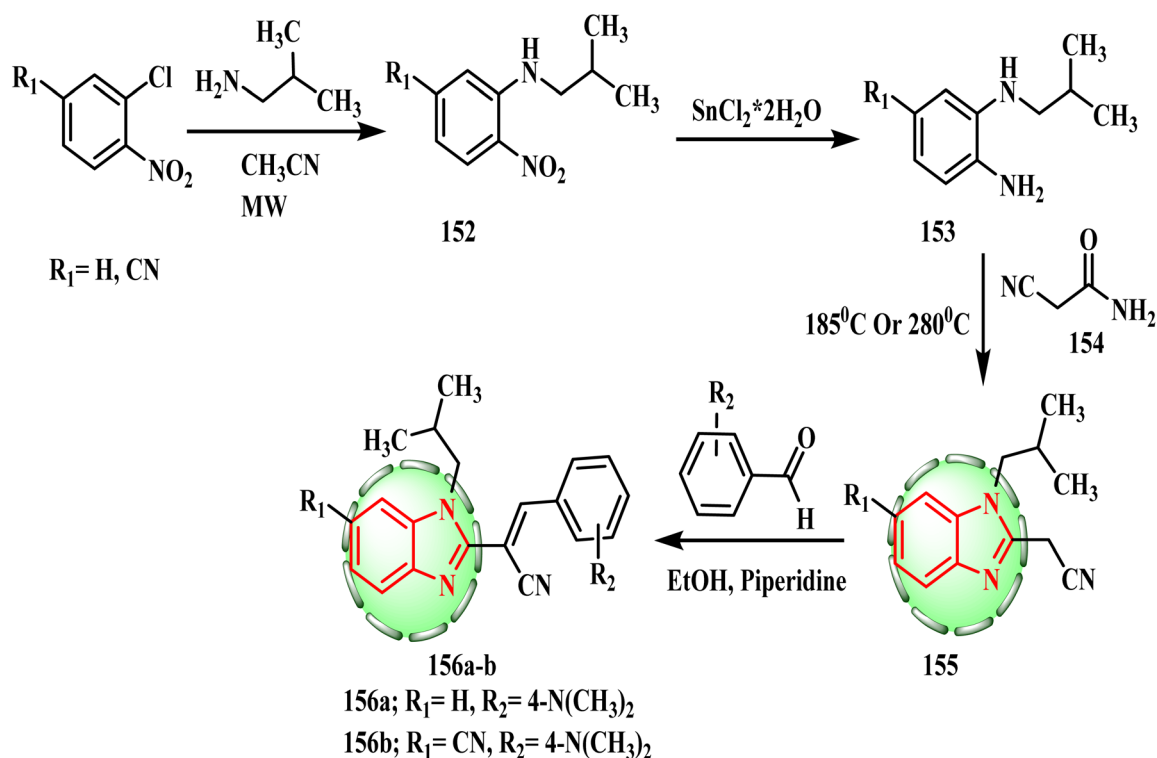
Scheme 31 Synthetic route for benzimidazole–quinoline hydride **151**.



two distinct cell lines, all other drugs showed moderate to good anticancer efficacy. Using cisplatin as a reference medication, compound **151** demonstrated activity against the A37 ( $IC_{50} = 34.7 \pm 0.9 \mu\text{g mL}^{-1}$ ) and MDA-MB-231 ( $IC_{50} = 20.4 \pm 1.1 \mu\text{g mL}^{-1}$ ) cell lines using the MTT test. However, the other substances did not show preference for these specific cell lines. Chemical substance **151** also showed cytotoxic properties. The  $IC_{50}$  value of compound **151** (A375) was  $34.7 \pm 0.9 \mu\text{g mL}^{-1}$ .<sup>42</sup> Compound **151** presented the highest % inhibition and lowest  $IC_{50}$  value of  $604.8 \mu\text{g mL}^{-1}$ .

**1.1.5. *o*-Substituted-*N*-substituted.** The production and cytotoxic potential of *N*-substituted benzimidazole acrylonitrile hybrids were examined by Perin *et al.* Unsubstituted or cyano substituted *N*-isobutyl **152** was produced by uncatalyzed microwave-assisted amination beginning with the corresponding *o*-chloronitrobenzenes. Then, compounds **152** were reduced with  $\text{SnCl}_2 \times 2\text{H}_2\text{O}$  in MeOH, which served as the primary precursor for the production of target molecules **156a** and **b**. The cyclocondensation reaction of amino derivative **153** with 2-

cynoacetamide (**154**) at elevated temperatures produced *N*-substituted-2-cyanomethylbenzimidazoles **155**. The condensation reaction of systems **155** with a chosen aromatic aldehyde in pure ethanol, followed by the addition of a few drops of piperidine as a weak base yielded the equivalent *N*-substituted-2-benzimidazolyl acrylonitrile **156a** and **b**, as demonstrated in Scheme 32. As lead compounds, *N*-substituted benzimidazole acrylonitrile, which has *N*-isobutyl and cyano substituents on the benzimidazole nuclei (**156a** and **b**), demonstrated potent antiproliferative action, while being noticeably less hazardous than the reference systems staurosporine and docetaxel.<sup>72</sup> According to SAR investigations, the affinity of the phenyl moiety significantly increased when an electron-donating *para*-substituted  $\text{NMe}_2$  group was added. This tendency for access to optimum binding with Cys241 was reduced by substituting the electron-withdrawing cyano group (**156b**). The chance of favorable positioning was increased by the inclusion of the significant *N*-isobutyl group.

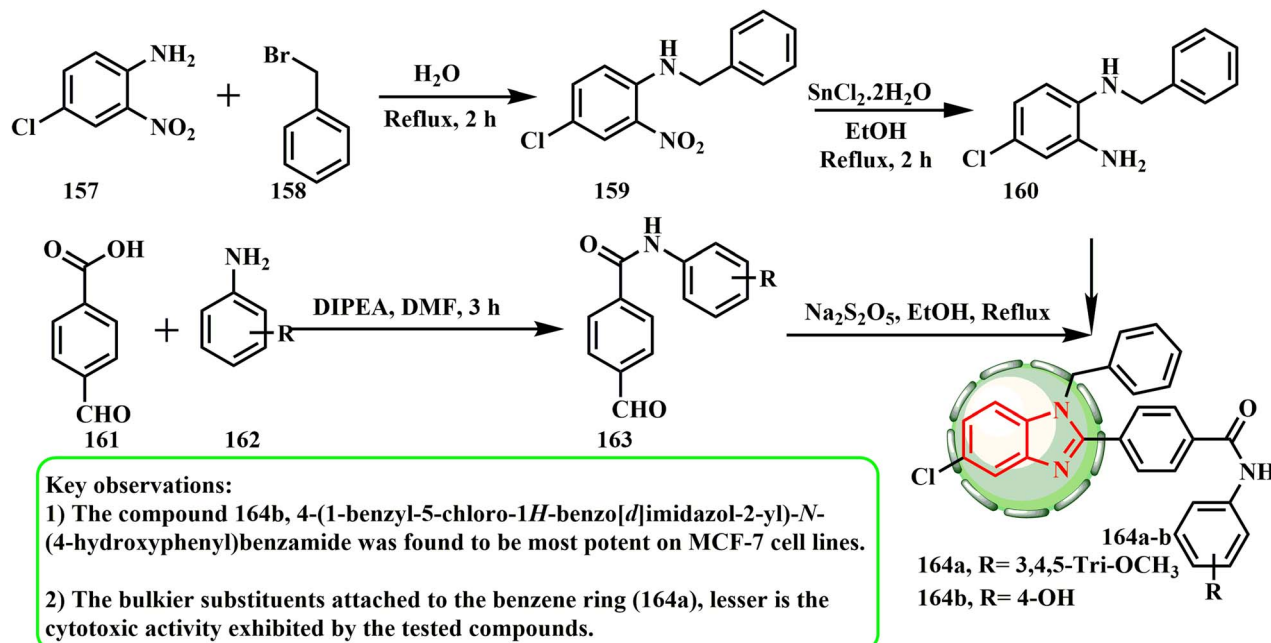


#### Key observations:

- 1) Both cyano as well as isobutyl substituents attached to the benzimidazole nuclei electron-donating *para*-substituted  $\text{NMe}_2$  group on the phenyl moiety showed most promising anticancer activity.
- 2) Substitution of electron-withdrawing {cyano} group (**156b**) decreased the potential to take part in optimal binding with Cys241.

Scheme 32 Synthesis of *N*-substituted-2-benzimidazolyl acrylonitrile derivatives **156a** and **b**.



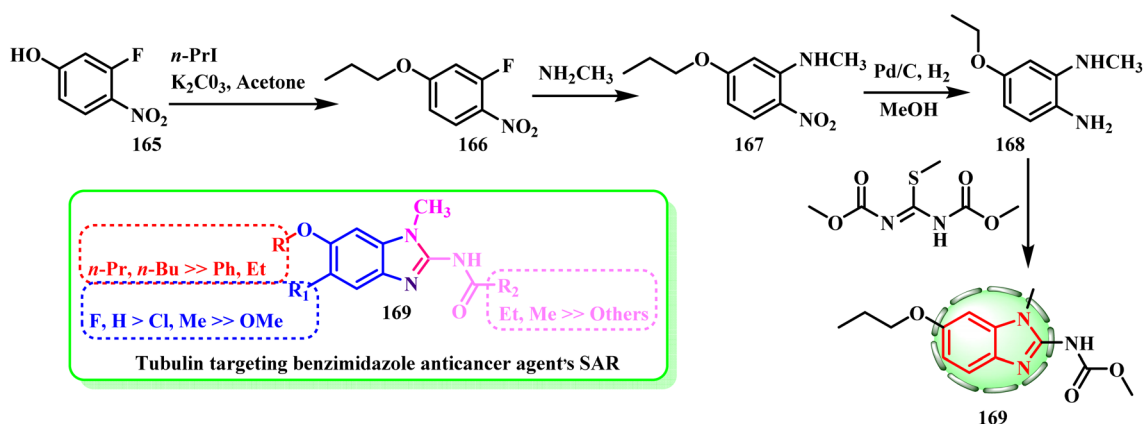
Scheme 33 Synthesis of various 1-benzyl-1*H*-benzimidazole analogues **164a** and **b**.

Kommi *et al.* investigated the production and cytotoxic potential of benzimidazole derivatives. Scheme 33 depicts the synthetic method utilized to prepare 1-benzyl-1*H*-benzimidazole analogues **164a** and **b**. 4-Formyl-*N*-phenylbenzamide **163** was utilized to condense *N*<sup>1</sup>-benzyl-4-chlorobenzene-1,2-diamine (**160**). Using benzyl bromide (**158**) and the nitro group of compound **159**, the commercially available 4-chloro-2-nitroaniline (**157**) was first converted to *N*-benzyl-4-chloro-2-nitroaniline (**159**). Then, it was further reduced to an amino functional group using stannous chloride dihydrate, which produced *N*<sup>1</sup>-benzyl-4-chlorobenzene-1,2-diamine (**160**).<sup>73</sup> Alternatively, the commercially existing 4-formyl benzoic acid (**161**) and aniline derivative (**162**) were used to create 4-formyl-*N*-phenylbenzamide (**163**).<sup>74</sup> Lastly, 4-formyl-*N*-phenylbenzamide (**163**) and *N*<sup>1</sup>-benzyl-4-chloro orthophenylene diamine (**160**) were refluxed in ethanol in the presence of Na<sub>2</sub>S<sub>2</sub>O<sub>5</sub>, yielding

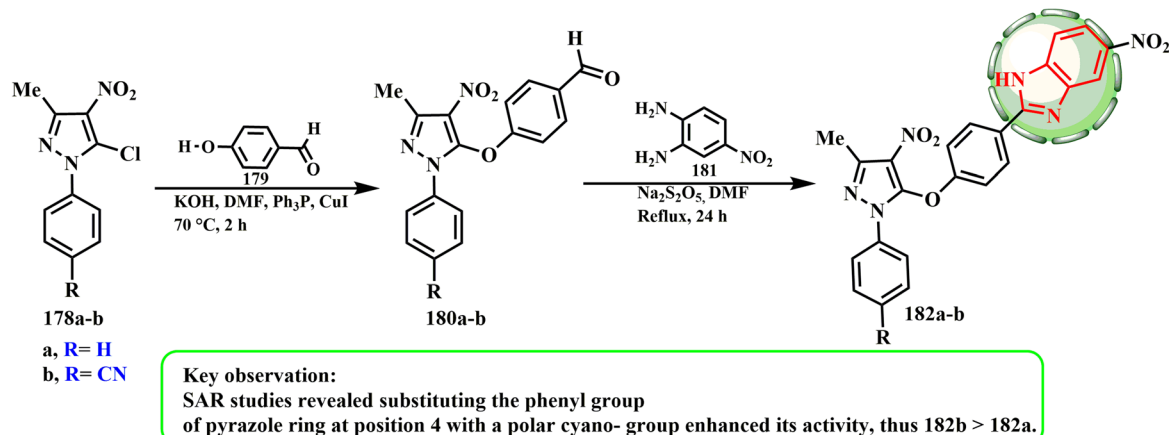
target compounds **164a** and **b**.<sup>75</sup> Among the compounds, with an IC<sub>50</sub> value of 7.01 ± 0.20 μM, **164b** (4-(1-benzyl-5-chloro-1*H*-benzo[*d*]imidazol-2-yl)-*N*-(4-hydroxyphenyl)benzamide) demonstrated the highest efficacy and stopped the MCF-7 cell cycle in the G2/M phase and S-phase.<sup>76</sup> The SAR investigations revealed that larger substituents linked to the benzene ring (**164a**) reduced the cytotoxic activity of the examined compounds.

**1.1.6. Imines.** Oxibendazole with *O*-*n*-propyl was chosen for further investigation. In this phenotypic screening assay, *O*-*n*-propyl was determined to be the ideal size for hydrophobic interaction with tubulin binding, while *O*-ethyl and *O*-*n*-butyl derivatives were less active than oxibendazole. Thus, as a default benzimidazole C6 tail, oxibendazole with *O*-*n*-propyl was used (Scheme 34).<sup>77</sup>

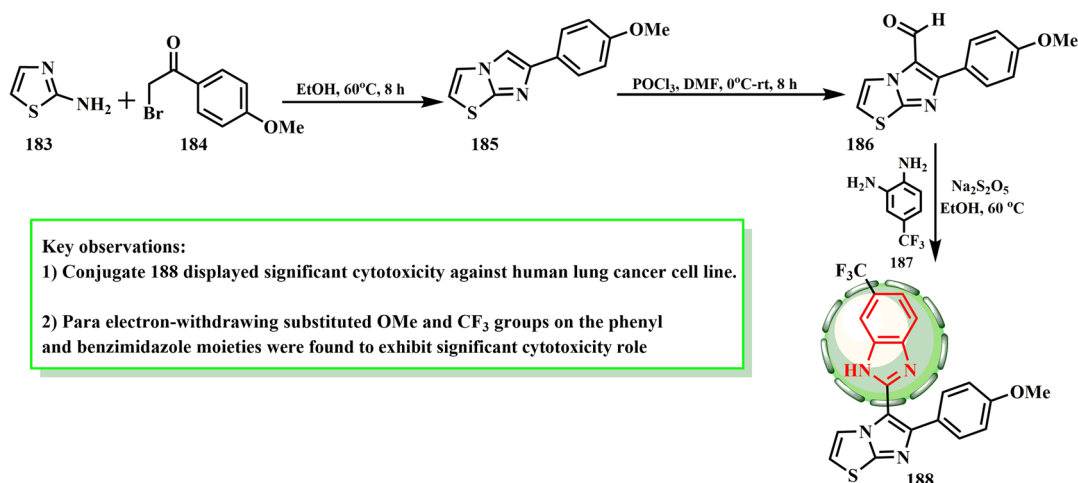
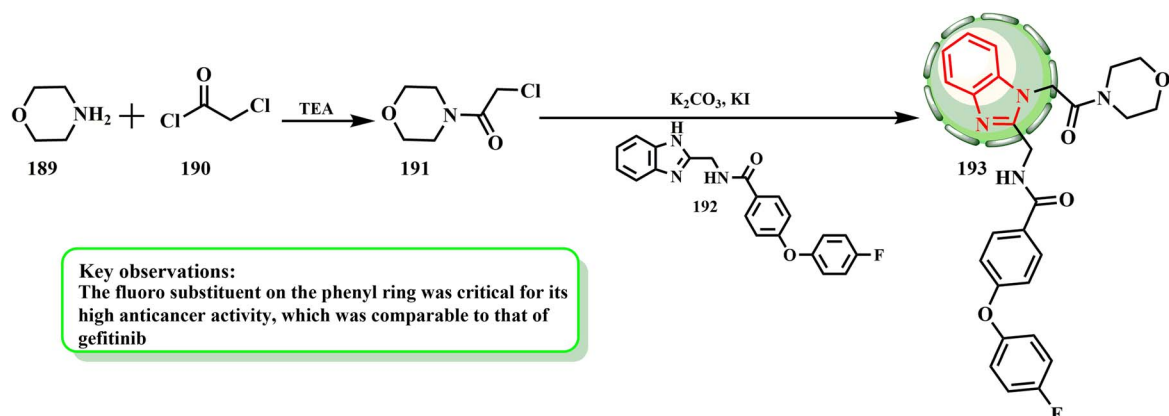
**1.1.7. Amidines.** Target compound 2-(2-pyrimidinylamino) benzimidazole **172** (ref. 78) was produced, as indicated in

Scheme 34 General synthesis of compound **169**.





Scheme 37 Synthetic route from pyrazoles 178a and b to pyrazole–benzimidazole conjugates 182a and b, respectively.

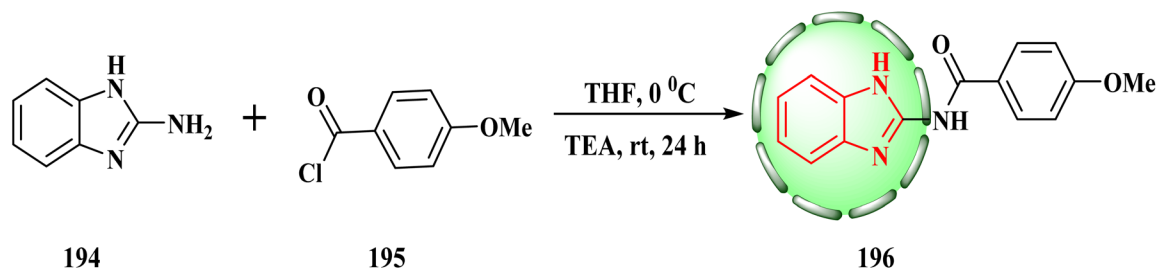
Scheme 38 Synthesis of imidazo[2,1-*b*]thiazole–benzimidazole conjugate 188.

Scheme 39 Synthesis of designed compound 193.

various amines **176** using the TBTU coupling reagent at ambient temperature in DMF solvent. Rasal *et al.*<sup>83</sup> produced a unique array of 2,4-dimethyl-1*H*-pyrrole-3-carboxamide hybrids with a 1*H*-benzimidazole moiety using the molecular hybridization

approach. At a dose of 10 μM, they were tested for their anti-cancer activity against a variety of human cancer cell lines. Even at low concentrations, some of them demonstrated strong antiproliferative effects by functioning as VEGF inhibitors,





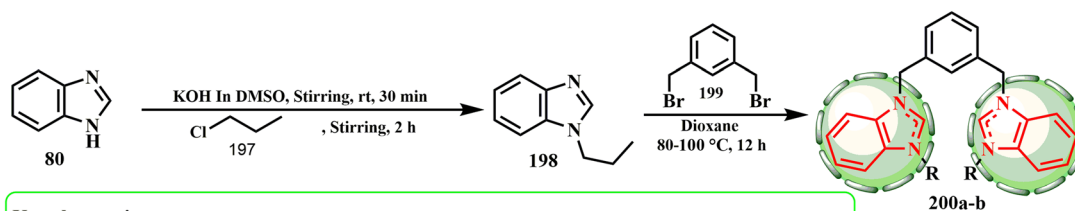
Scheme 40 Reaction of substituted benzoyl chloride with 2-aminobenzimidazole.

whereas compound **177**, or 5-(1*H*-benzo[*d*]imidazol-2-yl)-*N*-(1-cyclohexylethyl)-2,4-dimethyl-1*H*pyrrole-3-carboxamide, showed notable anticancer activity. According to SAR evaluations, the amide linkage had an impact on the anticancer efficacy of the compounds.

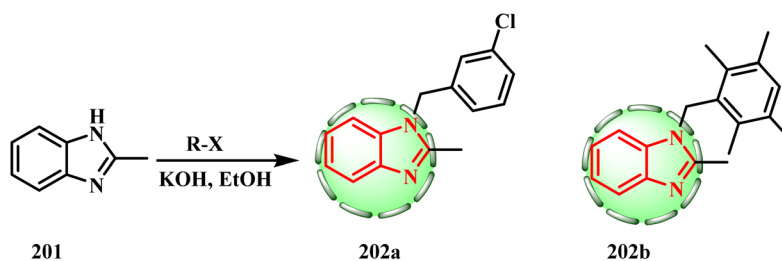
4-(5-(4-Formylphenoxy)-3-methyl-4-nitro-1*H*-pyrazol-1-yl)benzotrile (**180b**) was obtained by reacting 4-(5-chloro-3-methyl-4-nitro-1*H*-pyrazol-1-yl)benzotrile (**178b**) with 4-hydroxybenzaldehyde (**179**) in the presence of potassium hydroxide, DMF, and a catalytic amount of copper(i)iodide and triphenylphosphine, respectively. 4-(3-Methyl-4-nitro-5-(4-(5-nitro-1*H*-benzo[*d*]imidazol-2-yl)phenoxy)-1*H*-pyrazol-1-yl)benzotrile (**182b**) was produced by the cyclocondensation

reaction of compound **180a** and **b** with 4-nitro-1,2-phenylenediamine (**181**) in the presence of sodium thio-sulphate and DMF (Scheme 37). Combining compound (**182b**) with doxorubicin was shown to greatly boost the anticancer effect of the drug and limit MCF-7 cell cycle growth.<sup>84</sup> According to SAR investigations, the anticancer activity of the 1*H*-benzimidazole moiety decreased when carboxylic or nitro groups were present at position 5, but it increased when a polar cyano-group was substituted for the phenyl group in the pyrazole ring at position 4.

The synthesis and cytotoxic potential of imidazo[2,1-*b*]thiazole-benzimidazole conjugate **188** were examined by Baig *et al.* As illustrated in Scheme 38, imidazothiazole-

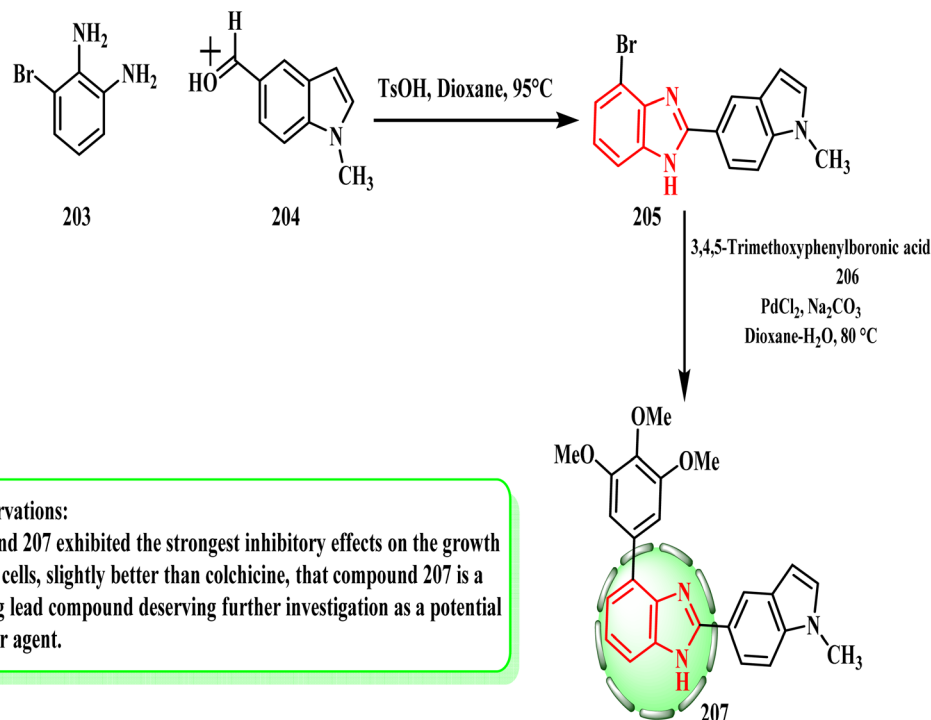
**Key observation:**

- 1) SAR studies suggest that the presence of a long *N*-substituted alkyl chain was responsible for the remarkable pharmacological action of compound **200a-b** as it made it highly lipophilic.
- 2) *N*-methylene phenyl substitutions revealed more potent cytotoxic activity than the compounds with smaller chain lengths and nonaromatic substitutions.

Scheme 41 Reaction representation of 1*H*-benzimidazole with propyl chloride.**Key observation:**

Compound **202a** showed better, albeit low, activity against the cell lines studied than compound **202b**. The different substituents on the benzyl ring (electron donating or withdrawing) may be responsible for these differences

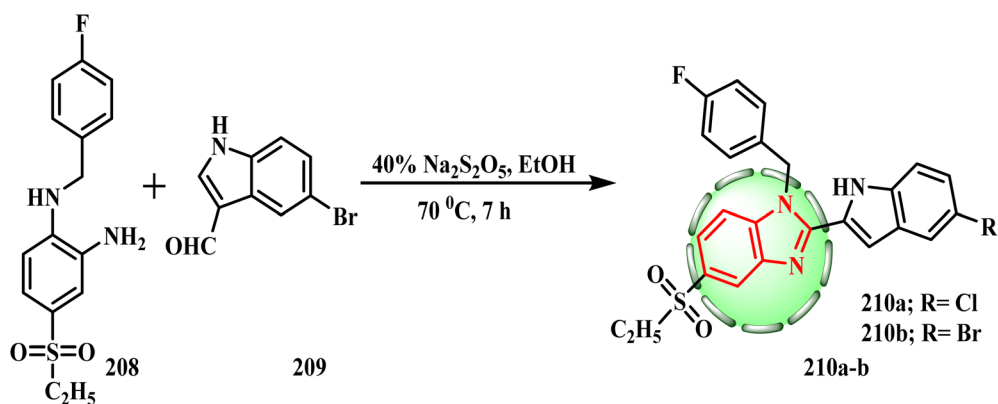
Scheme 42 Reaction of 2-methyl-1*H*-benzo[*d*]imidazole with alkyl halide.



Scheme 43 Synthesis of benzimidazole derivatives 205 and 207.

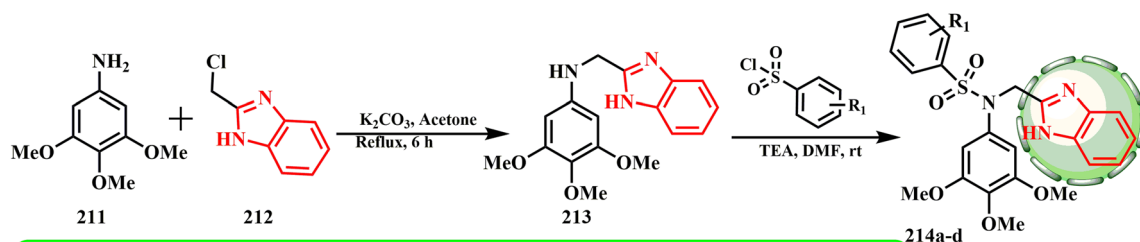
benzimidazole conjugate **188** was produced by oxidatively cyclizing imidazo[2,1-*b*]thiazole-5-carbaldehyde (**186**) and substituting *o*-phenylenediamine (**187**) with sodium metabisulphite in ethanol. By using the Vilsmeier-Haack reaction with the equivalent imidazo[2,1-*b*]thiazole (**185**), which was derived from suitable 2-bromo-1-arylethanone **184** and 2-

aminothiazole (**183**), imidazo[2,1-*b*]thiazole-5-carbaldehyde (**186**) was produced. Compound **188** ( $IC_{50} = 1.08 \mu M$ ) showed significant cytotoxicity against the A549 cell line.<sup>85</sup> The cytotoxicity of conjugates containing electron-withdrawing groups as substituents, such as *p*-trifluoromethyl and *p*-methoxy



Scheme 44 Synthetic route for the preparation of benzimidazoles 210a and b.



**Key observations:**

- 1) The potency of the compounds varies with respect to substitutions.
- 2) Compound 214d with 1H-benzimidazole moiety and methyl group displayed utmost activity against human gastric cancer cell lines.
- 3) All these modifications and the inhibitory results revealed that the sulfonyl groups were important for their inhibitory activity which can maintain or enhance the antiproliferative activity against three tested human cancer cells.
- 4) The correlation between halogen substitution and anticancer activity was found to be 4-Br (214b) > 4-F (214a) > 2-Cl (214c).

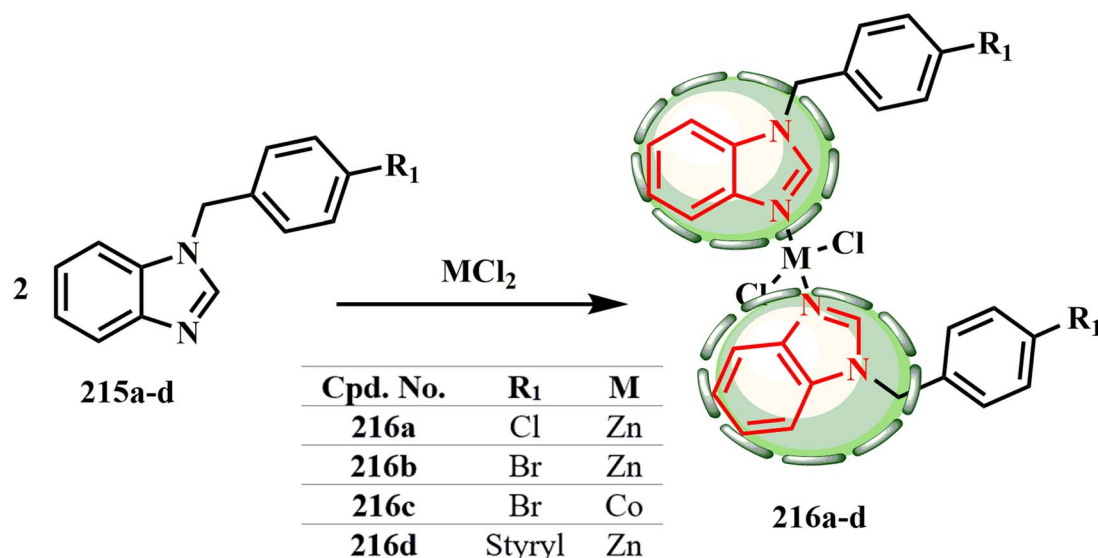
214a, R<sub>1</sub> = 4-F  
 214b, R<sub>1</sub> = 4-Br  
 214c, R<sub>1</sub> = 2-Cl  
 214d, R<sub>1</sub> = 4-C(CH<sub>3</sub>)<sub>3</sub>

Scheme 45 Synthesis of tertiary sulfonamide derivatives containing a benzimidazole moiety 214a–d.

substituents, against A549 cells was demonstrated by SAR evaluations.

The synthesis and cytotoxic potential of 2-(aminomethyl) benzimidazole derivatives were examined by Al-Sultan *et al.* Scheme 39 states that all synthesized compounds began with amine derivative 189 and an equivalent quantity of TEA

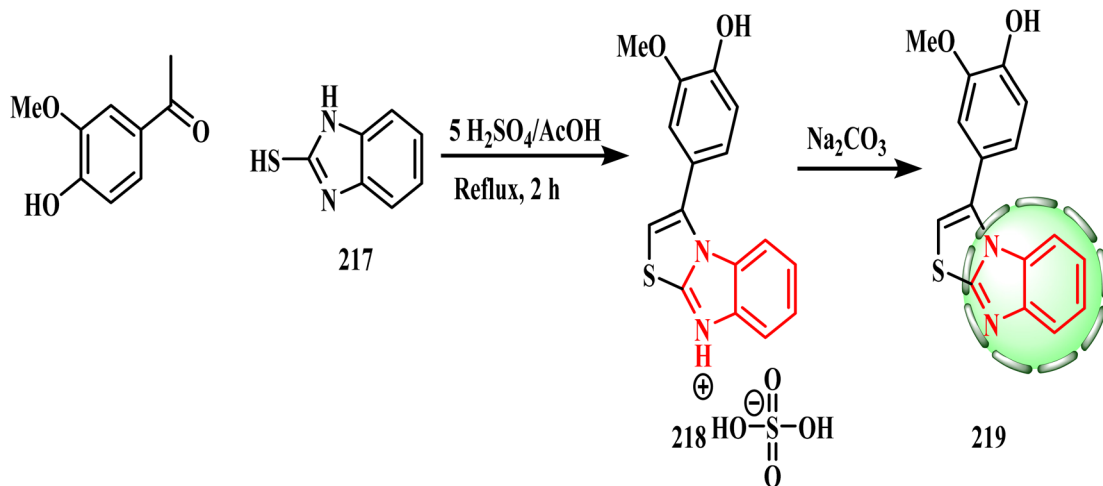
(primary amines did not use TEA). After being dissolved in 25 mL of diethyl ether and allowed to cool to 5 °C, chloroacetyl chloride (190) was gradually added to the mixture until the fumes stopped.<sup>86</sup> The antiproliferative features of the developed compounds on human breast cancer (T47D) and human alveolar cell carcinoma (A549) cells were evaluated *in vitro* using

**Key observations:**

- 1) Complex 216(a-b) showed better anticancer activity than the standard drug docetaxel at a concentration of 0.1 μM against the A-2780 cell line.
- 2) The well-known zinc metal structural were found to be favorable than cobalt metal ligand with the benzimidazole skeleton for the activity against A-2780 cell line.

Scheme 46 Synthesis of benzimidazole metal complexes 216a–d.



**Key observation:**

compound **219** bearing a terminal phenyl ring substituted with two electron-donating groups proved to be the most potent against both cell lines; HT-29 and MDA-MB-468.

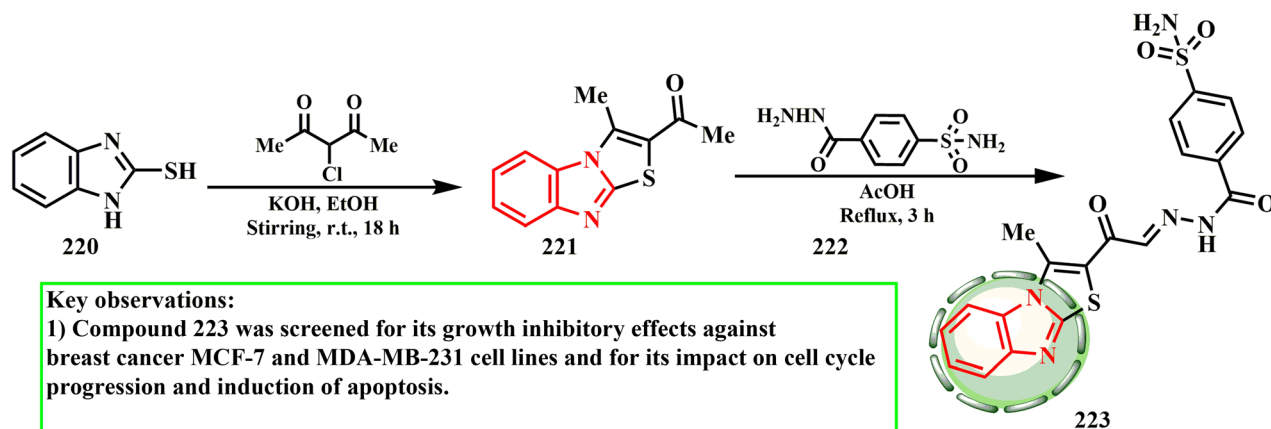
Scheme 47 Synthesis of compound phenylthiazolo[3,2-a]benzimidazole **219**.

Vero cells (from the kidney of an African green monkey) as a standard control. The morphology of T47D with an inhibitory concentration of the cytotoxic chemicals, gefitinib, and the control was explained by additional research to confirm the antiproliferative effects of the extremely toxic substances (**193**) on T47D. Lastly, compounds **193** displayed  $IC_{50}$  values that were nearly identical to that of the positive control.

In THF and TEA, we used a normal reaction between substituted benzoyl chloride **195** (1.1 mmol) and 2-amino-benzimidazole (**194**) (1 mmol) (Scheme 40). *N*-(Benzimidazol-2-

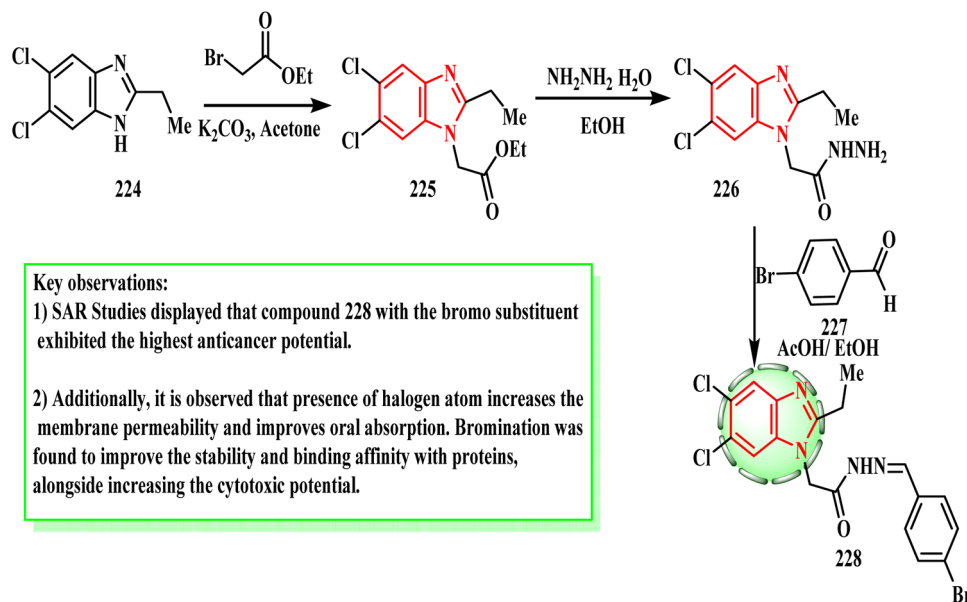
yl)-2-substituted benzamide structures **196** were synthesized efficiently in a single step. Interestingly, compound **196** showed the strongest anti-proliferative action against MCF-7 cancer cells ( $IC_{50} = 3.84 \pm 0.62 \mu\text{M}$ ).<sup>87</sup>

A series of 3,3'-(1,3-phenylene(methylene))(1-alkyl-benzimidazolium)salts (**200**) was produced and characterized using the stated approach (Scheme 41).<sup>88</sup> We previously employed propyl chloride (**197**) as the electrophile for 1,2-(bromomethylene)benzene.<sup>89</sup> The method adopted for the synthesis of the title compounds was selective for the 1-position

**Key observations:**

- 1) Compound **223** was screened for its growth inhibitory effects against breast cancer MCF-7 and MDA-MB-231 cell lines and for its impact on cell cycle progression and induction of apoptosis.
- 2) SAR studies revealed that shifting of sulfamoyl group to para-position enhanced the hCA I and II inhibition activities.
- 3) Enaminone spacer in compound **223**, incorporating hydrazide linker displayed the best hCA IX inhibitory action.

Scheme 48 Synthesis of 3-methylthiazolo[3,2-a]benzimidazole-benzene sulfonamide conjugate **223**.



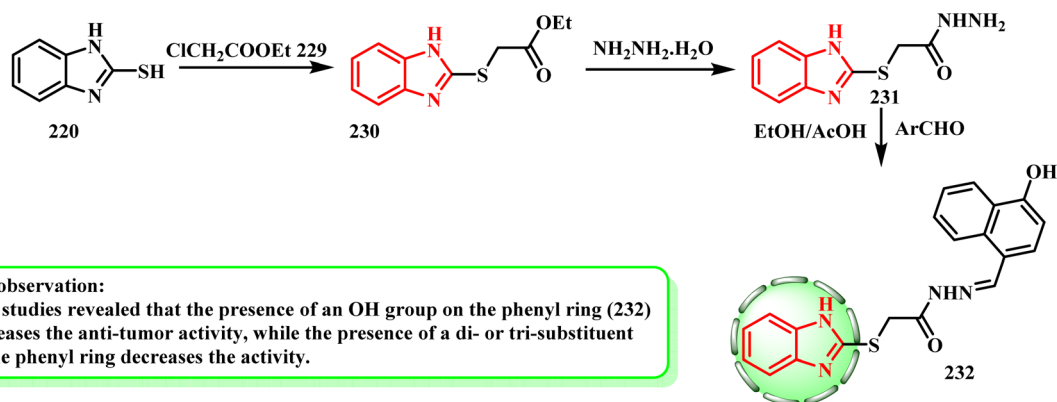
Scheme 49 Synthesis of benzimidazole derivative 228.

heterocycle. Indeed, upon treating alkyl benzimidazole **198** with *m*-xylyl dibromide (1,3-(bromomethylene)benzene) (**199**), the respective bisbenzimidazolium salt was observed to give **200**. ul Huda *et al.*<sup>90</sup> developed and produced unique 1,10-(1,3-phenylenebis(methylene))bis(3-alkyl/aryl-1*H*-benzimidazol-3-ium) salt hybrids, and using the SRB assay, evaluated their anticancer potential against the MCF-7 and HCT-116 (CRC) human breast cancer cell lines. Compound **200b** was shown to be the most effective anticancer drug overall, inhibiting the growth of HCT-116 cells with an  $IC_{50}$  of  $0.1 \mu\text{g mL}^{-1}$ . According to the SAR evaluations, the notable pharmacological effect of compound **200** was caused by its lengthy *N*-substituted alkyl chain, which presented it as extremely lipophilic. Compounds with shorter chain lengths, such as isopropyl chain (**200a**) and nonaromatic replacements, exhibited less cytotoxic action than *N*-methylene phenyl (**200b**) substitutions.

The compounds were prepared in accordance with the literature<sup>91,92</sup> (Scheme 42). Because of its efficiency in supplying

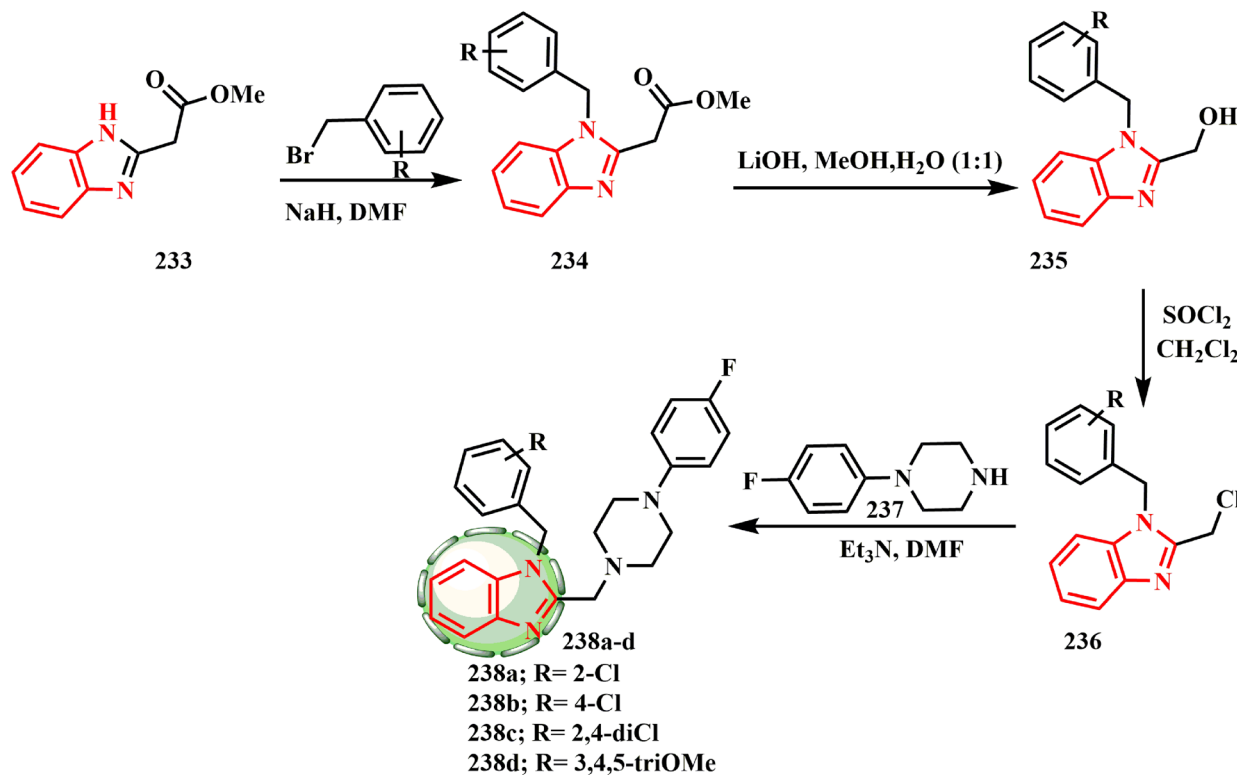
high quantities of hydroxide ions, KOH is a characteristically strong base utilized in a range of laboratory and chemical synthesis applications. For 12 h, the reaction was carried out at  $80^\circ\text{C}$ . According to the results, **202a** had relatively anti-proliferative efficacy against the A549, DLD-1, and L929 cell lines compared to cisplatin; however, **202b** was essentially effective against the A549 cell line. Compound **202b** has substituents with the methyl group at the 2-, 3-, 5-, and 6-positions, whereas compound **202a** has a chloro group on the benzyl ring at the 3-position. Compared to compound **202b**, compound **202a** had more advanced, albeit weaker, activity against the cell lines under investigation. The various substituents on the benzyl ring, which may either donate or withdraw electrons, could be the cause of these variations.<sup>93</sup>

Ren *et al.* researched the production of benzimidazole derivatives and their potential for cytotoxicity. Scheme 43 shows the preparation of compound **207**. Benzimidazole intermediates **205** were produced by cyclizing 3-bromo-1,2-



Scheme 50 Synthesis of benzimidazole derivative 232.



**Key observations:**

- 1) Among the synthesized molecules, compound 238b showed the most balanced cytotoxic effect against lung (A-549) and breast (MCF-7) cancer cells with  $IC_{50}$  values of 4.6 and 11.0  $\mu$ M, respectively.
- 2) A chlorine is preferred either at para position of the *N*-benzyl ring along with para fluoro in the piperazine-phenyl part (i.e. 238b), affording potent antiproliferative activity in tested tumor cells in the low micromolar range.
- 3) Additionally, the presence of bulky groups like 2,4-dichloro (238c) and 3,4,5-trimethoxy on the *N*-benzyl ring (238d) decreased the activity.

Scheme 51 Synthesis of benzimidazole derivatives 238a–d.

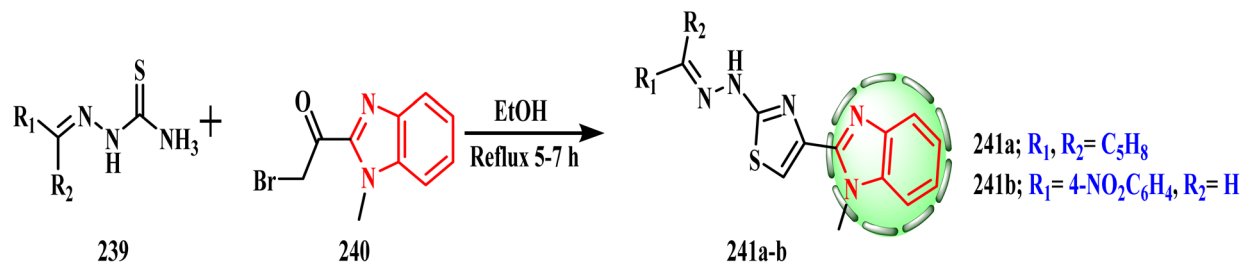
benzenediamine (203) with various aldehydes 204. Subsequently, compound 207 was produced by the Suzuki reaction between compound 205 and 3,4,5-trimethoxyphenylboronic acid (206). Compound 207, which is slightly more potent than colchicine, showed the strongest inhibitory effects on the growth of cancer cells ( $IC_{50} = 50$  nM).<sup>94</sup> In melanoma tumors, compound 207 showed a 78.70% inhibition rate. Stronger hydrogen bonds and hydrophobic interactions may be the cause of the significant activity of 207, according to the SAR evaluations.

Until the starting materials were exhausted (as determined by TLC), a combination of the proper *o*-phenylenediamine (1 mmol) (208), related indole derivative (1 mmol) (209), and  $Na_2S_2O_5$  (40%) (2 mL) in EtOH (4 mL) was refluxed<sup>95,96</sup> (Scheme 44). Especially compound 210a and b could alter the ER target gene expression, and an integrated stress response

was induced in a dose-related manner.<sup>97</sup> The MCF-7 transcriptome was shown to be significantly influenced by compounds 210a and b, which resulted in the upregulation and downregulation of an appropriate number of genes. According to the SAR investigations, the presence of an electron-withdrawing group at the indole ring and 4-fluorobenzyl at the 1*H*-benzimidazole ring demonstrated comparatively stronger anticancer effects. Furthermore, the lipophilic characteristic of the indole moiety was improved by the presence of –Br, which facilitated effective binding.

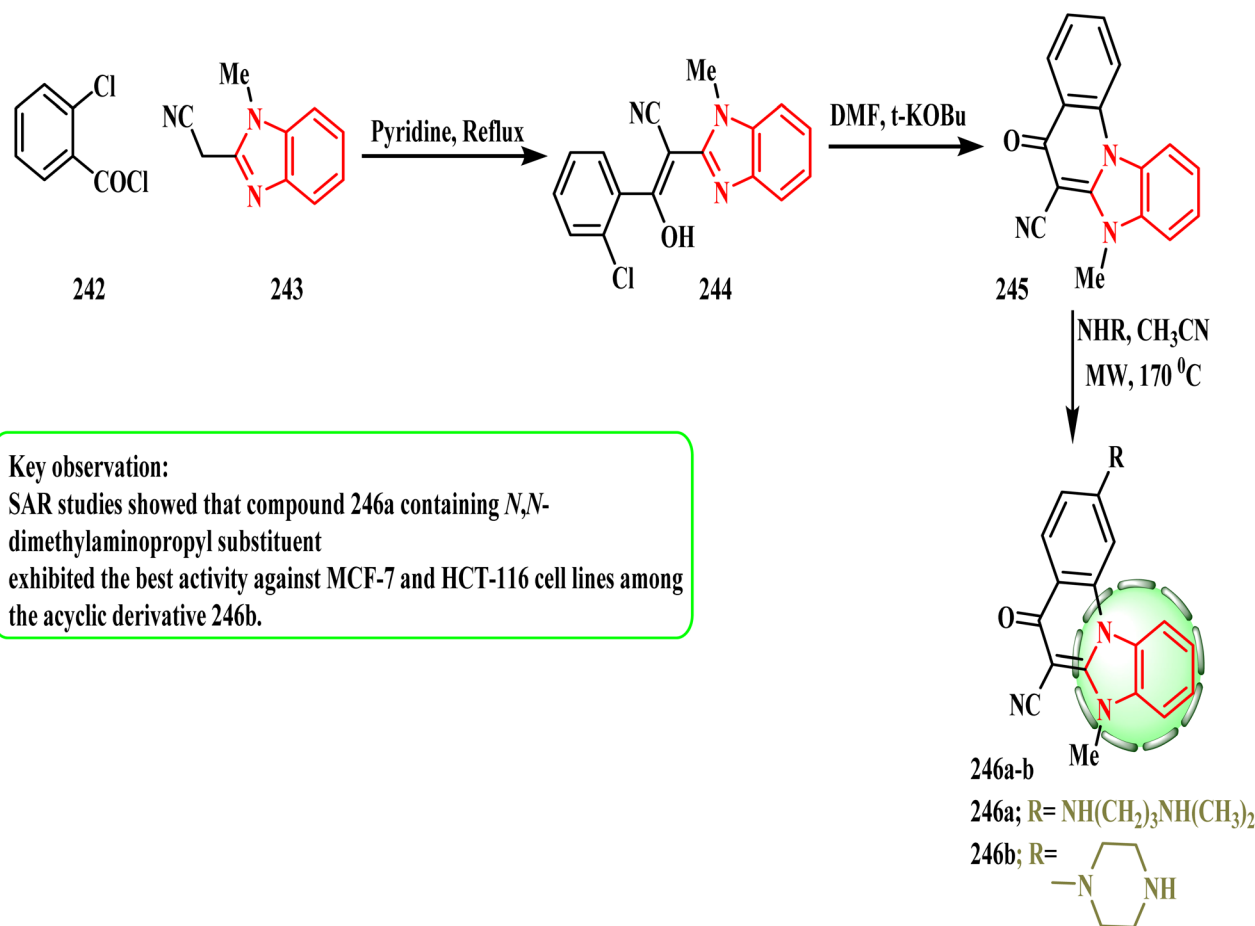
The synthesis and cytotoxic potential of tertiary sulfonamide derivatives with a benzimidazole moiety were examined by Gao *et al.* Benzyl chloride 212 and 3,4,5-trimethoxyaniline (211) interacted in the presence of  $K_2CO_3$  in acetone to give secondary amine 213, which reacted with different benzene sulfonyl chloride derivatives 37 to obtain tertiary sulfonamide



**Key observations:**

- 1) Furthermore, the cyclopentyl 241a derivative was less likely to inhibit the viability of the cancer cells than erlotinib.
- 2) SAR studies suggested that when 4-nitrophenyl 241b was replaced with cyclopentyl (as in compound 241a) there was a significant reduction in the potency. It was also observed that reduction in the polarity of molecules and increase in the bulkiness of the substituent decreased the effectiveness of the tested compound i.e. 241a > 241b.

Scheme 52 Route for constructing the target thiazolo-benzimidazole hybrids 241a and b.

**Key observation:**

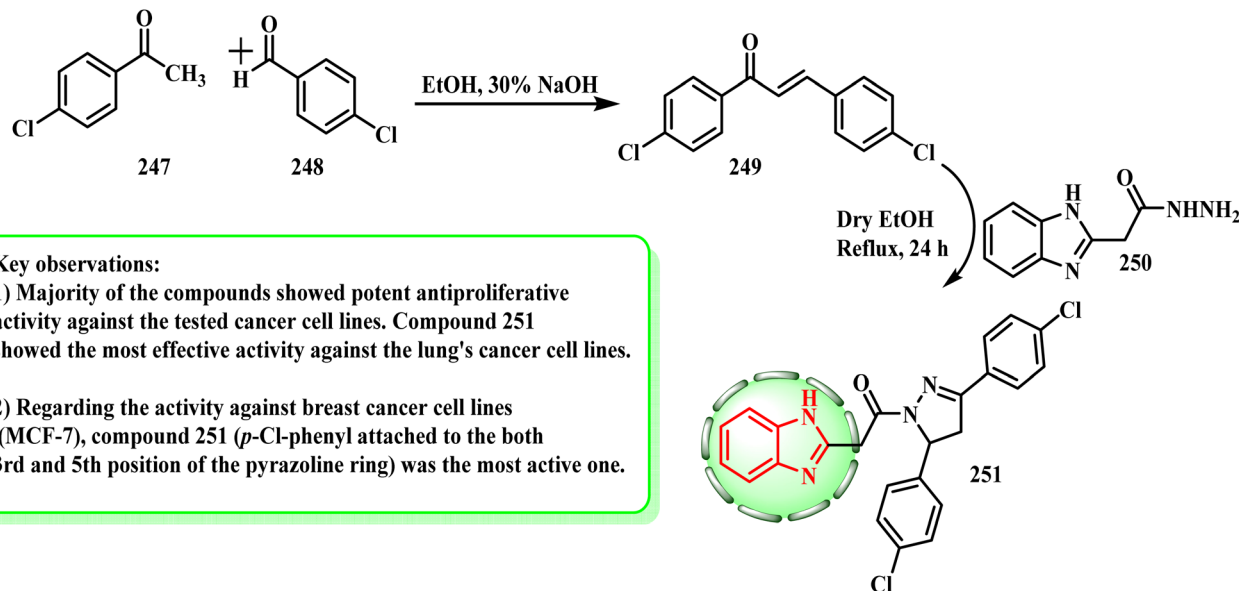
SAR studies showed that compound 246a containing *N,N*-dimethylaminopropyl substituent exhibited the best activity against MCF-7 and HCT-116 cell lines among the acyclic derivative 246b.

Scheme 53 Synthesis of new fused benzimidazole analogues 246a and b.

derivatives **214a–d** (Scheme 45). MGC-803 cells were more sensitive to compounds **214a–d** than PC-3 and MCF-7 cells. Among the compounds that had notable antiproliferative activity, compound **214b** demonstrated the strongest anticancer

activity against MGC-803 cells ( $IC_{50} = 2.19 \mu M$ ).<sup>98</sup> The presence of a 3,4,5-trimethoxy group at the phenyl ring was crucial for the anticancer actions according to the SAR evaluations. The most effective compound against human stomach cancer cell lines

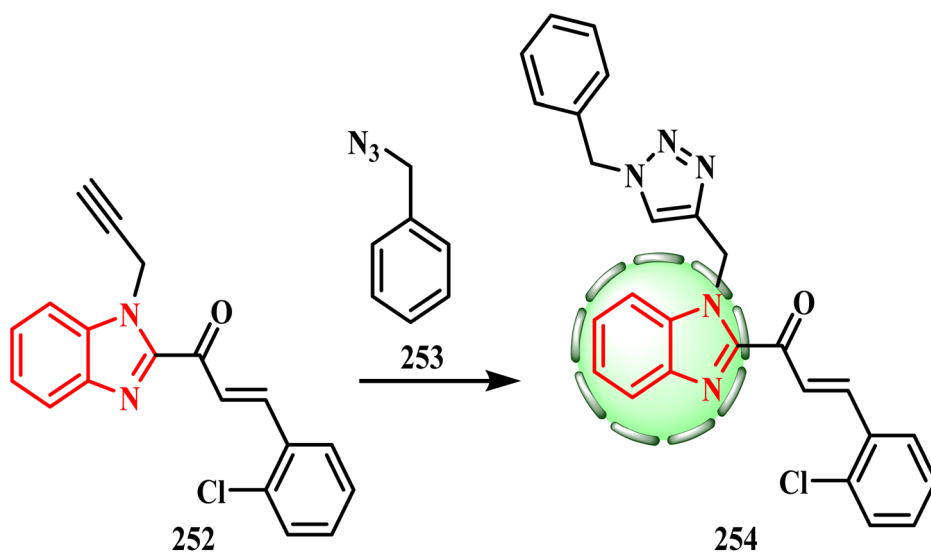




Scheme 54 Synthesis of benzimidazole-bearing pyrazole derivative 251.

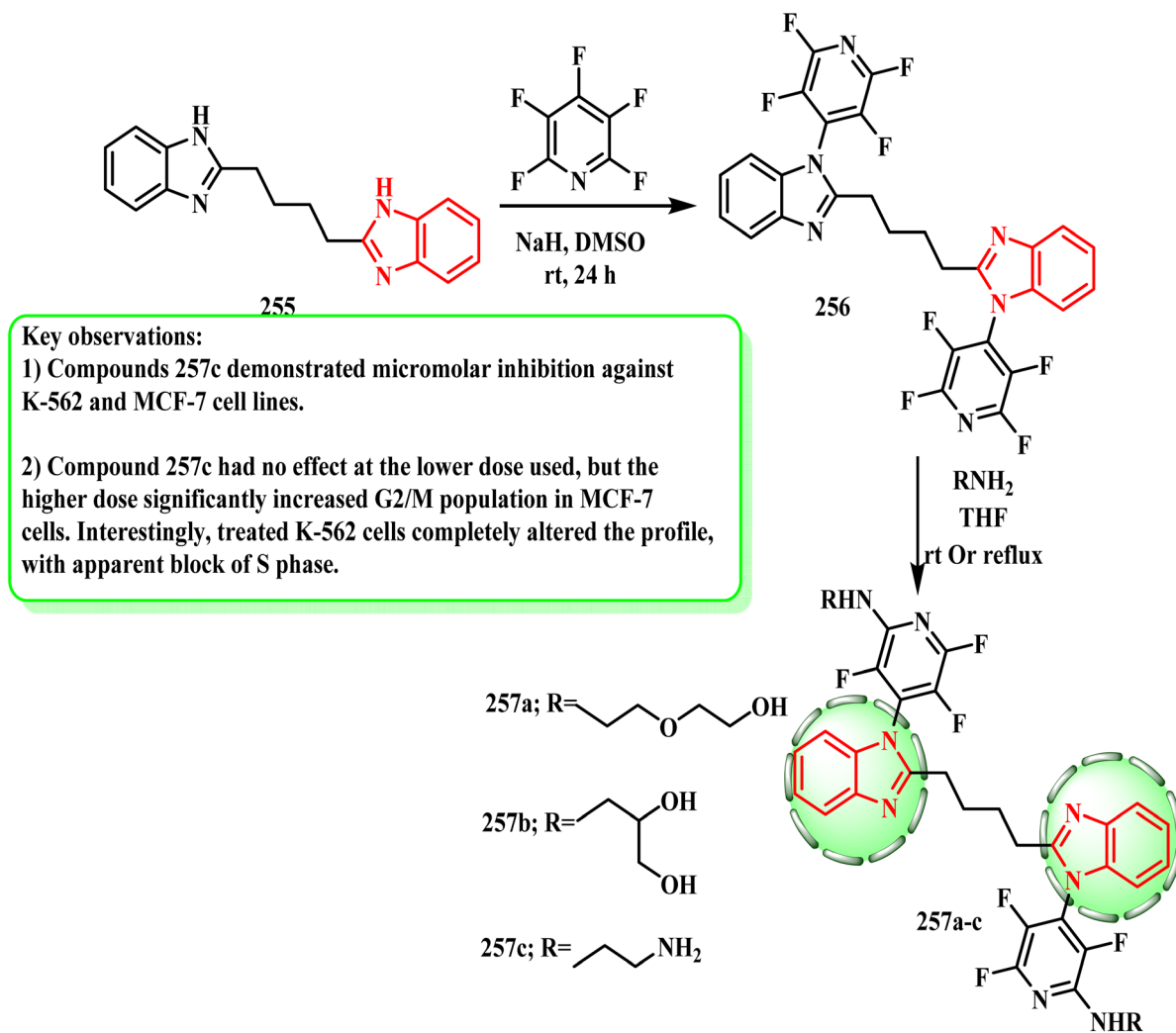
was compound **214d**, which had a methyl group and a *1H*-benzimidazole moiety. 4-Br (**214b**) > 4-F (**214a**) > 2-Cl (**214c**) was the association between halogen substitution and anticancer efficacy. The sulfonyl groups were crucial for their inhibitory

effect, which can maintain or improve the antiproliferative activity against the three tested human cancer cells, according to all the reported changes and inhibitory findings.



Scheme 55 Reaction between the azide derivative 253 and propargyl molecule 252.





Scheme 56 Synthesis of different fluoroaryl benzimidazole derivatives 257a–c.

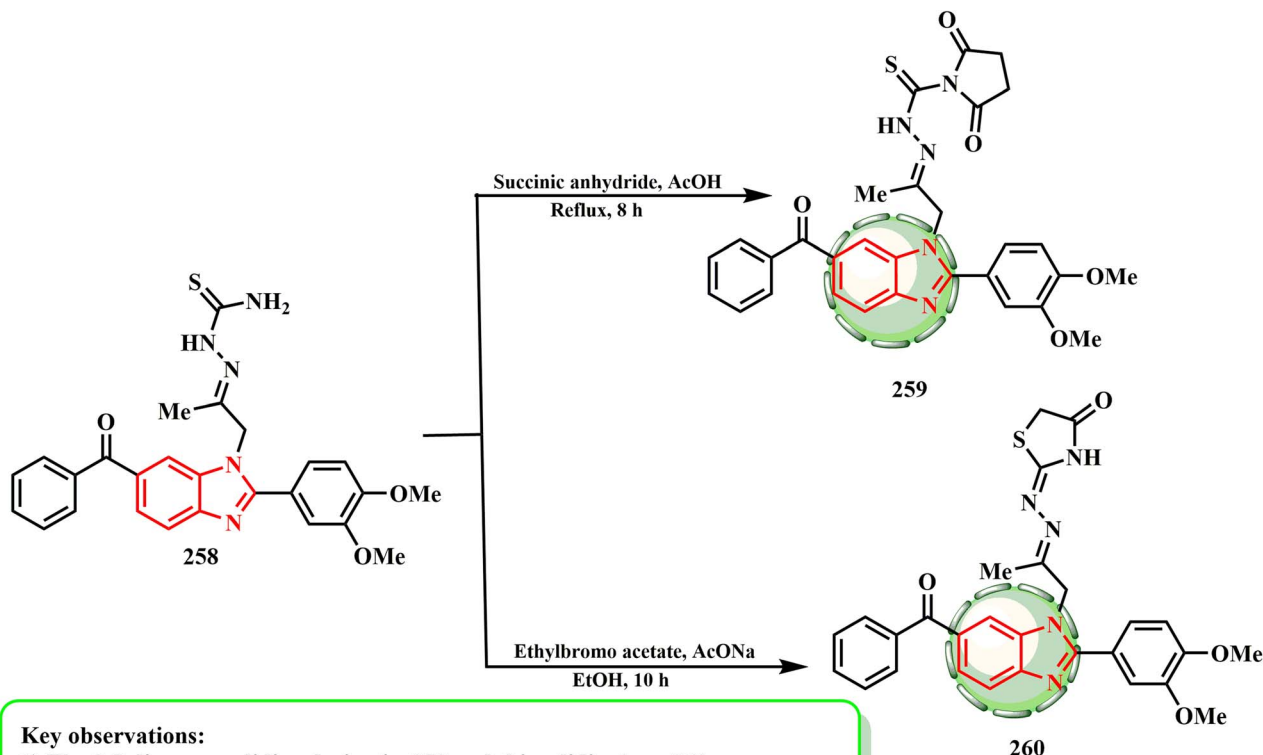
The production and cytotoxic potential of new benzimidazole ligands and their cobalt(II) and zinc(II) complexes were examined by Yılmaz *et al.* ZnCl<sub>2</sub>·6H<sub>2</sub>O or CoCl<sub>2</sub> in EtOH was used to produce benzimidazole complexes **216a–d** from benzimidazole ligands (**215a**, **215b**, and **215c**). Ligands of benzimidazoles **215a** (ref. 99) and **215b** (ref. 100) were produced using the methods outlined in the literature. In this work, the Mizoroki–Heck reaction was used to synthesize benzimidazole ligand **215d** for the first time, similar to the literature technique<sup>101,102</sup> (Scheme 46). Compounds **216a–d** (log IC<sub>50</sub> = −0.97, −1.30, 1.13, and −0.73 μM, respectively) were identified to have higher anticancer potency than the standard docetaxel medication (log IC<sub>50</sub> = −0.81 μM) against the A-2780 cell line at 0.1 μM concentration.<sup>99</sup>

Scheme 47 shows the route for the preparation of target compound **219** in this work. Acetophenone and 2-mercapto-benzimidazole **217** reacted in refluxing acetic acid with five equivalents of sulphuric acid to produce sulphate salt **218** in a one-pot, two-component heterocyclization process. Phenylthiazolo[3,2-*a*]benzimidazole **219** was obtained by neutralizing sulphate salt **218** by stirring with an aqueous solution of sodium

bicarbonate. HT-29 (colon) and MDA-MB-468 (breast) cancer cell lines were used to investigate the cytotoxic potential of synthetic compound **219**. CD133 inhibition in cancer stem cells and the cytotoxicity of specific 3-phenylthiazolo[3,2-*a*]benzimidazoles including their design, direct synthesis, and *in vitro* biology were investigated.<sup>103</sup> Compound **219** decreased the surface expression of CD133 on cells by 50% and showed strong anticancer activity against both cancer cell lines with IC<sub>50</sub> values of 9 and 12 μM, respectively. According to the SAR investigation, the electron-donating group in the phenyl ring of **219** enhanced the suppression of tumor cells.

However, employing 3-chloro-2,4-pentanedione, the acetyl thiazolo[3,2-*a*]benzimidazole derivative (**221**) was constructed as previously described for the mercaptan alternative **220**. The target **223** was obtained, as shown in Scheme 48, by condensing the acetylthiazolo[3,2-*a*]benzimidazole derivative (**221**) with 4-(hydrazinocarbonyl)benzene sulfonamide (**222**) in acetic acid. Compound **223** was found to induce cell cycle arrest and death and exhibit prospective proliferation inhibition against the MCF-7 and MDA-MB231 breast cancer cell lines.<sup>104</sup> According to the SAR investigations, the hCA I and II inhibitory activities



**Key observations:**

1) The 2,5-dioxypyrrolidine derivative 259 and thiazolidin-4-one 260 exhibited the most potent cytotoxic activity that was higher than that exhibited by the reference drug.

2) SAR studies revealed that an increment in the nitrogen atoms and addition of the thiazole ring or pyrrolidine increased the cytotoxic potential.

Scheme 57 Reaction representative of benzimidazole with different reagents.

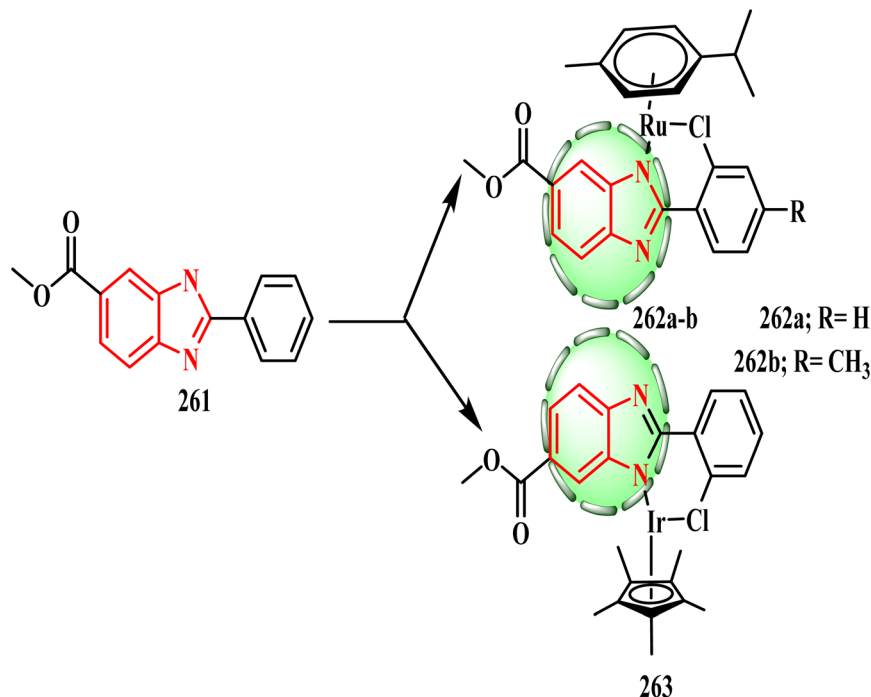
were improved by moving the sulfamoyl group to the *para*-position. Compound 223, which has a hydrazide linker and an enaminone spacer, exhibited the highest hCA IX inhibitory activity.

The synthesis and cytotoxic potential of benzimidazole derivatives were examined by Atmaca *et al.* By first reacting the amino group of 224 with ethylbromo acetate to produce ethyl [5,6-dichloro-2-ethyl-1*H*-benzimidazol-1-yl]acetate (225), the intended powerful derivative 228 was synthesized. Subsequently, compound 226 was produced by reacting acetate derivative 225 with hydrazine hydrate in ethanol. Finally, the desired hybrid molecule 228 was produced by the successful condensation of the nucleophilic nitrogen with the substituted aromatic aldehyde 227 (Scheme 49). Compound 228 was found to exhibit a potential cytotoxic effect against the MCF-7 ( $IC_{50} = 17.8 \pm 0.24 \mu\text{g mL}^{-1}$ ), DU-145 ( $IC_{50} = 10.2 \pm 1.4 \mu\text{g mL}^{-1}$ ), and H69AR ( $IC_{50} = 49.9 \pm 0.22 \mu\text{g mL}^{-1}$ ) cancer cell lines.<sup>105</sup> Compound 228 with a bromo substituent showed the strongest anticancer potential and may be a promising anticancer treatment drug according to the SAR investigations. Furthermore, it was noted that the presence of halogen atoms enhanced its oral absorption and increased its membrane permeability. It was discovered that bromination increased the cytotoxic potential, while also improving the stability and protein binding affinity.

The synthesis of benzimidazole derivatives was reported by Yadav *et al.*<sup>106</sup> By first esterifying mercaptan derivative 220 with ethyl chloroacetate (229) to produce acetate 230, the desired derivative 232 was synthesized. After that, 230 was subjected to hydrazinolysis reaction with hydrazine hydrate to yield 231. Lastly, the Schiff base reaction of acetohydrazide 231 with aromatic aldehyde gave 232 (Scheme 50). Yadav *et al.*<sup>106</sup> established a novel series of 1*H*-benzimidazole compounds and tested their anti-proliferative properties *in vitro*. When tested against the MCF-7 cell line, compound 232 ( $IC_{50} = 0.0013 \mu\text{M}$ ) was found to be a more effective anti-cancer therapeutic candidate than 5-fluorouracil. According to the SAR investigations, the anti-tumor activity increased when an OH group was present on the phenyl ring and decreased when a di- or tri-substituent was present.

Using the well-known general techniques, compounds 238a-d were produced in accordance with the reaction sequence shown in Scheme 51. Thus, using established techniques, 2-acetyloxymethylbenzimidazole (233), which was produced by acetylating 2-hydroxymethylbenzimidazole,<sup>107</sup> was converted into *N*-benzylated derivatives 234 by treating it with substituted benzyl halides in the presence of a base. *N*-Benzyl-2-hydroxymethylbenzimidazoles 235 were produced by hydrolyzing intermediates 234 in aqueous alkali, and they then



**Key observations:**

1) SAR studies revealed that a phenyl substitution on the 1*H*-benzimidazole increased the potency in both the ligand complexes and that ruthenium complexes 262 were more effective than their iridium counterparts that is, compound 263.

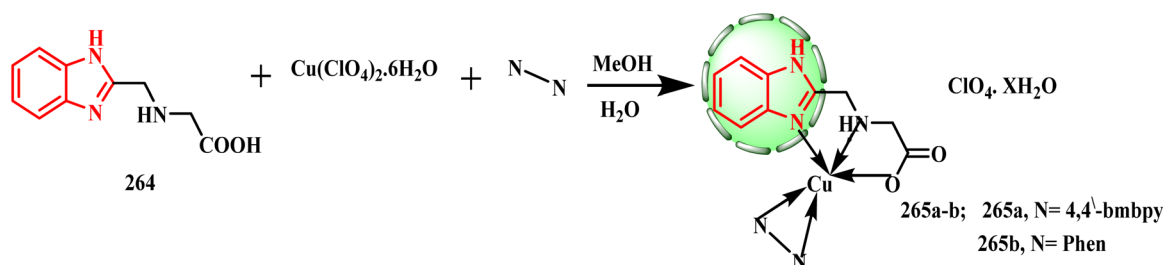
2) Methyl substitution 262b produces no effect on potency compared to the unsubstituted compound 262a in ruthenium series but it loses some potency in iridium complexes 263 for most of cell lines.

Scheme 58 Generalized process to synthesize benzimidazole complex 262a and b and 263.

reacted with thionyl chloride to form alkyl chlorides 236. To obtain the target compounds 238a–d, intermediate alkyl chlorides 236 were finally treated with the relevant phenylpiperazine derivatives 237. Özdemir *et al.*<sup>108</sup> developed and produced a unique range of 1*H*-benzimidazole-piperazine hybrids, and then tested them against two human cancer cell lines (MCF-7 and A549) to determine whether they have antiproliferative properties. Compound 238b demonstrated the most potent cytotoxicity ( $IC_{50} = 11.0 \mu\text{M}$  against MCF-7 cells and  $4.6 \mu\text{M}$  against A549 cells). A mono-chloro substituent on the *N*-benzyl ring at the *ortho*- (238a) or *para*-positions (238b) increased the potency against the A549 cell line, according to the SAR evaluations. Furthermore, the activity was reduced when large groups

such as 3,4,5-trimethoxy and 2,4-dichloro (238c) were present on the *N*-benzyl ring (238d).

Scheme 52 showed the synthesis methods used for constructing the target thiazol–benzimidazole hybrids 241a and b. Thiosemicarbazone 239 (ref. 109–113) with 2-bromo-1-(1-methyl-1*H*-benzo[*d*]imidazo-2-yl)ethan-1-one (240) in refluxing ethanol<sup>114,115</sup> afforded the corresponding targeted 2-(2-(substituted)hydrazinyl)-4-(1-methyl-1*H*-benzo[*d*]imidazol-2-yl)thiazole derivative<sup>116</sup> 241a and b. Compound 241a revealed strong cytotoxic activity by EGFR TK inhibition<sup>117</sup> ( $IC_{50} = 109.71 \text{ nM}$ )<sup>109</sup> as well as an anti-breast cancer agent.<sup>118,119</sup> SAR evaluations of this study revealed a notable decrease in potency when 4-nitrophenyl 241b was substituted with cyclopentyl (as in

**Key observations:**

1) Complexes 265a-b showed good anticancer activity.

2) SAR studies revealed that the electron-donating ability of the methyl group in 265a enhances the stacking of the substituted compound and that the higher binding affinity of complex 265b was due to the hydrophobic nature of methyl-substituted bipyridyl which increased intercalating of the complex.

Scheme 59 Reaction representative of benzimidazole with BIGH ligand.



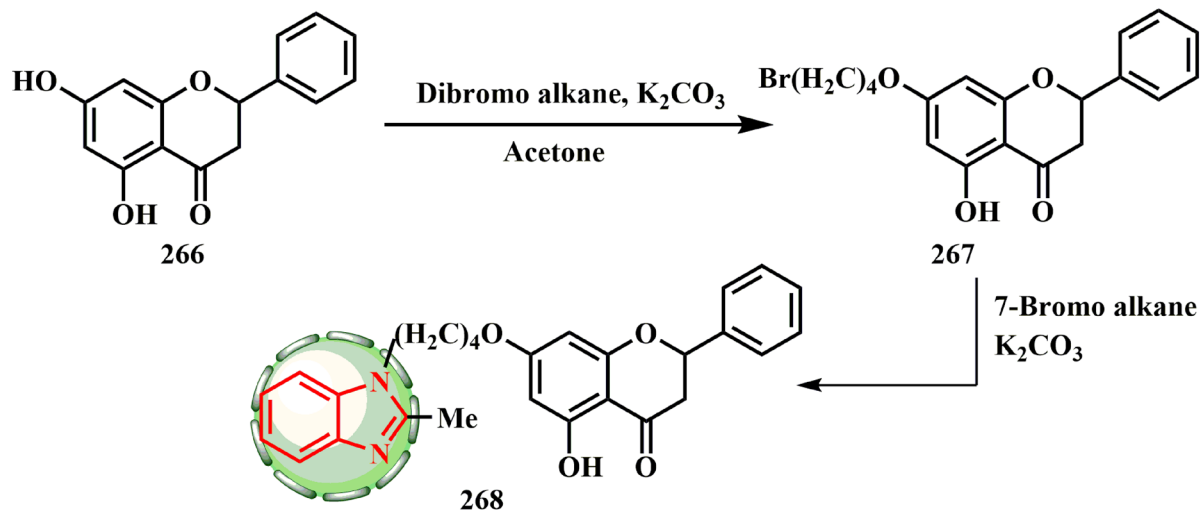
compound **241a**). Additionally, it was found that the efficacy of the tested drug was reduced when the polarity of the molecules decreased and the bulkiness of the substituent increased.

Subsequently, compound **245** was converted into the intended 2-amino-substituted analogues **246a** and **b** in the reaction with an excess of the appropriate amine microwave irradiation utilizing the previously disclosed optimized reaction conditions<sup>120,121</sup> (Scheme 53). Perin *et al.*<sup>122</sup> produced amino-substituted *N*-methylated-benzimidazo[1,2-*a*]quinolines and tested them against human cancer cell lines *in vitro* to determine if they had any anti-proliferative properties. Two of the strongest substances, **246a** and **246b**, were specifically active against the HCT-116 cancer cell line, causing cell death and a reduction in the proportion of cells in the S phase ( $IC_{50}$  values of 0.2 and 0.4  $\mu\text{M}$ , respectively). Between the acyclic derivatives, compound **246a** with the *N,N*-dimethylaminopropyl substituent demonstrated stronger efficacy against the MCF-7 and HCT-116 cell lines, according to the SAR evaluations.

Scheme 54 lists the synthetic pathways for the synthesis of **251**. Substituted benzaldehyde **248** and acetophenone **247** were chosen and stirred in a pure form in 30% NaOH to produce chalcone **249**. Intermediate compound **250** with compound **249** under reflux in absolute ethanol could be readily converted into the final compound **251**.<sup>123</sup> By causing cell cycle arrest in the G2/M phase and apoptosis by binding to active pockets of EGFR ( $IC_{50} = 0.97 \mu\text{M}$ ), compound **251** demonstrated encouraging

growth inhibition on the A549 cell line ( $IC_{50} = 2.2 \mu\text{M}$ ).<sup>124</sup> Additional research revealed that the effectiveness of compound **251** is attributed to its chloro atom at the 4-position of the phenyl substituent connected to C3 and C5 of the pyrazoline ring.

Therefore, the reaction between the pre-synthesized azide derivative **253** and propargyl molecule **252** (ref. 125 and 126) produced a structural alternative of 1,2,3-triazole-benzimidazole-chalcone hybrid **254** (Scheme 55) by using dichloromethane/water (1 : 1) as the solvent solution, catalyzed by  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$  and sodium ascorbate at room temperature. On all the chosen cancer cell lines, hybrid **254** with the chloro-substituent (2-Cl) demonstrated the strongest cytotoxic effect.<sup>127</sup> Compared to doxorubicin, the most active compound, **254**, was almost fourfold less active in MDA-MB-231 cells, forty-eight times less active in T47-D cells, and fifteen-fold less active in PC-3 cells. The documented chloro-substituted benzimidazole-triazole hybrids were already demonstrated to have good cytotoxic effects against mouse embryonic fibroblast cell lines NIH/3T3 ( $IC_{50} 1.63 \mu\text{M}$ ) according to their structure-activity-relationship (SAR).<sup>128</sup> Additionally, the SAR showed that the inclusion of chloro-substituents in the chalcone ring increased the cytotoxic effect of the hybrid 1*H*-benzimidazole derivative against the PC-3, MDA-MB-231, and T47-D cell lines. Furthermore, the antiproliferative properties of the compound were

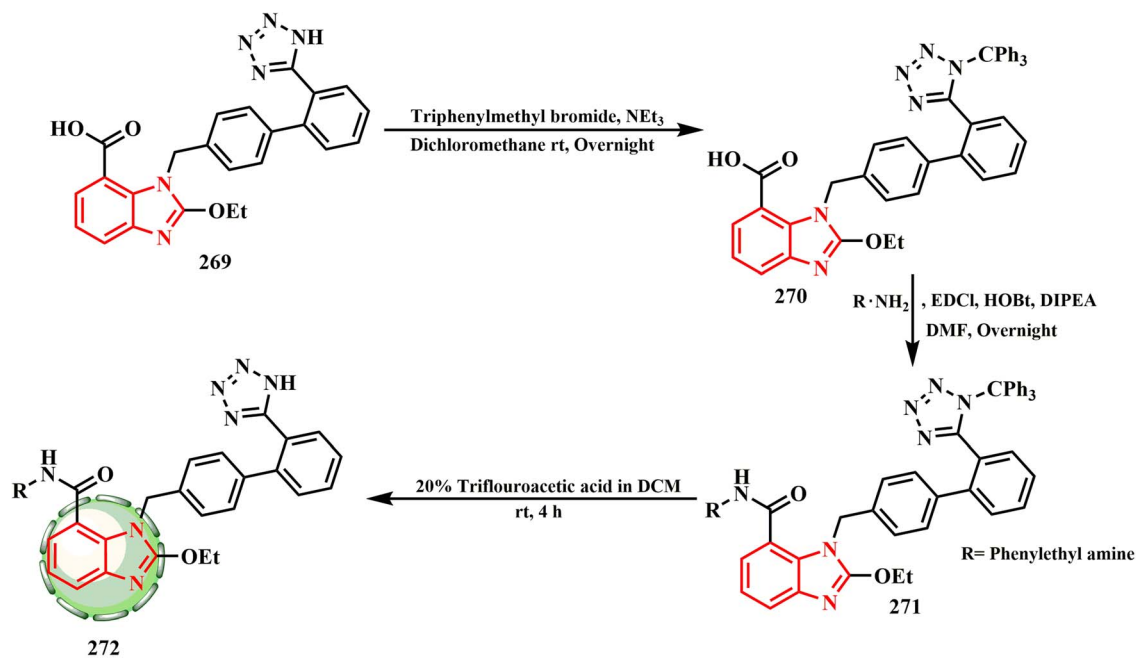


#### Key observations:

- 1) SAR studies revealed that compound **268** which had methyl substituent at 2-position of 1*H*-benzimidazole ring exhibited better inhibitory activity than those which had it at 5- or 6-position of the ring.
- 2) It was also reported in previous year studies that chrysin derivatives with higher polarity exhibited more potent anticancer activities and that the OH group at position 5 was important.

Scheme 60 General synthesis of compound **268**.

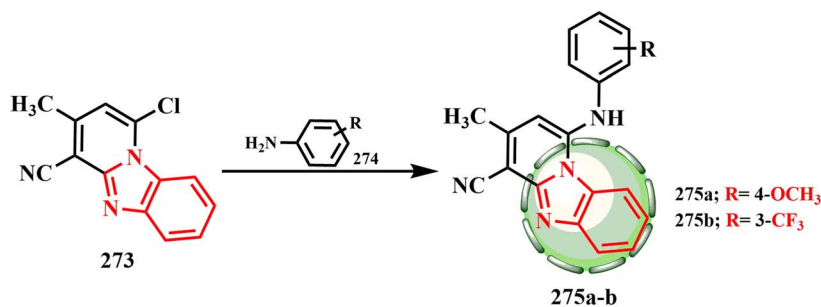


**Key observations:**

1) SAR studies revealed that the core structures of the 1*H*-benzimidazole and tetrazole are significant for increasing the neddylation inhibition activities of the derivatives, and changing the substitutions of heterocyclic cycloallylic and benzoallylic groups decreases the aforementioned activity of the compounds.

2) The phenylethylamine led to the superior inhibition of derivatives, such as 272.

Scheme 61 Preparation of derivative 272.

**Key observations:**

1) Compound 275b exhibits potent cytotoxic activity against the UACC-62 and breast cancer BT-549 cancer cells lines due to the impact of the lipophilic trifluoromethyl substitution on the biological activity profile. .

2) The well-known 4-methoxy structural setting on the pyrido[1,2-*a*]benzimidazole skeleton 275a was found to be showed different cytotoxic profiles.

Scheme 62 Synthesis of pyrido benzimidazole derivatives 275a and b.

further strengthened by the attachment of a benzyl moiety to the triazole ring.

In the tetrafluoropyridine rings (256), the amines all reacted at the next most electrophilic site, adding to C-2 to create aminopyridine derivatives 257a-c (ref. 129) (Scheme 56), adding to C-2, forming aminopyridine derivatives 257a-c (Scheme 56).

Bhambra *et al.*<sup>45</sup> established a library of fluoroaryl benzimidazole derivatives 257a-c, which showed micromolar inhibition against the K-562 and MCF-7 cell lines. The product obtained by adding ethylenediamine 257c was considerably less active against G361 and HOS, but exhibited good activity against two other cell lines. According to reports, compounds 257a and 257c



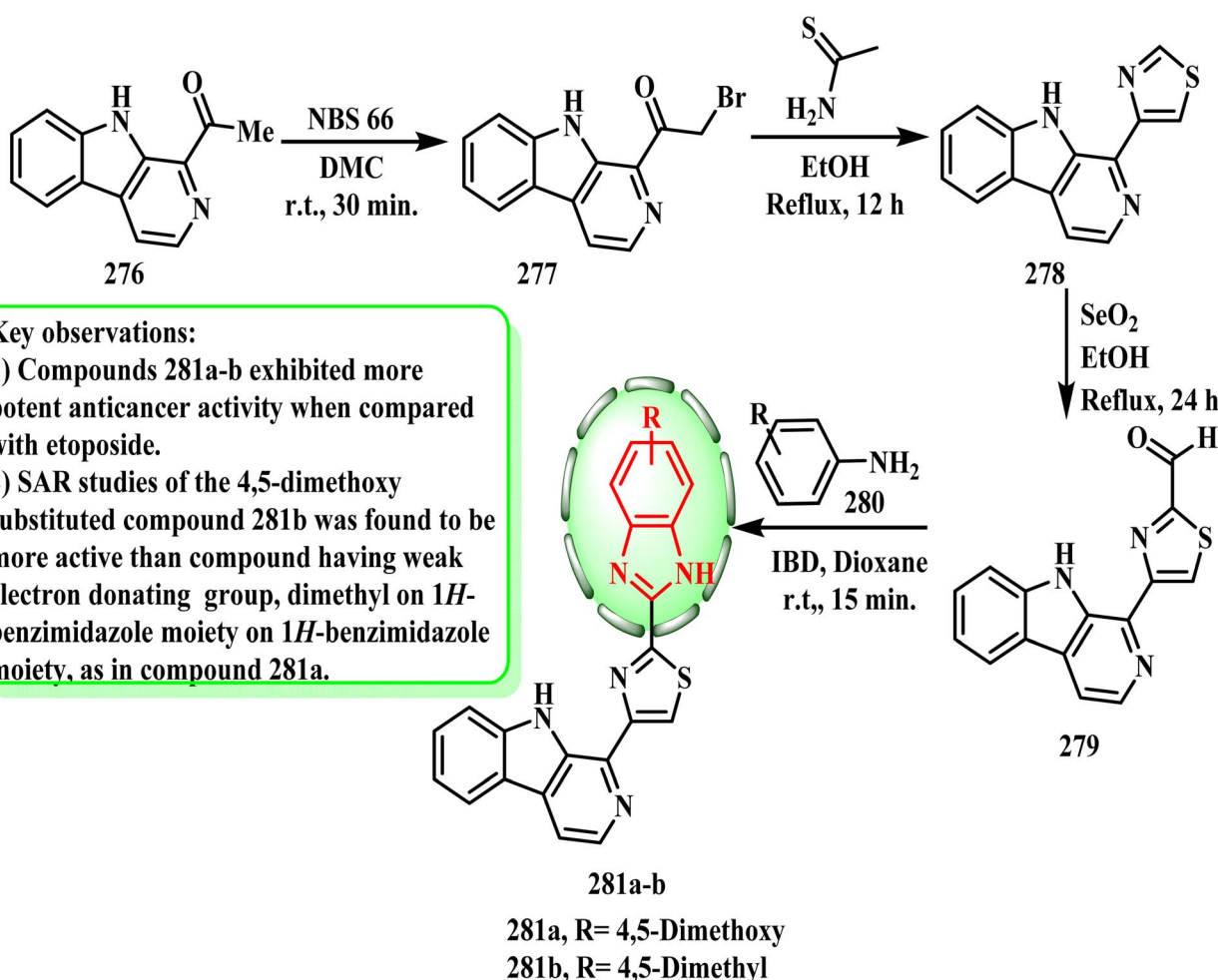
activate caspases, which are crucial for the death of cancer-causing cells.

An effective intermediary for the subsequent synthesis of various benzimidazole-heterocyclic compounds was thiosemicarbazone analogue **258**. Thus, 2,5-dioxopyrrolidine derivative **259** was formed by the condensation of **258** with various acid anhydrides, such as succinic anhydride in acetic acid. Additionally, thiazolidinone derivative **260** was produced by cyclizing **258** with a halo ketone, such as ethyl bromoacetate (Scheme 57). Abd El-Meguid *et al.*<sup>130</sup> established a novel series of 1*H*-benzimidazole compounds, which were evaluated against the HeLa cell line using doxorubicin as the standard medication. The compounds with the strongest anti-cancer activity against the HeLa cell line were **259** ( $1.62 \pm 0.16 \mu\text{M}$ ) and **260** ( $1.44 \pm 0.06 \mu\text{M}$ ). According to the SAR evaluations, the cytotoxic potential was enhanced by an increase in nitrogen atoms and presence of pyrrolidine or thiazole rings.

The generalized process illustrated in Scheme 58 was used to synthesize each of the ruthenium compounds. The analogue of ruthenium metal complex **262a** was obtained by treating benzimidazole ligand **261** with *para*-cymene ruthenium(II) [ $(p\text{-cymene})\text{RuCl}_2$ ]<sub>2</sub> and sodium acetate in dichloromethane for 24 h at room temperature. Pentamethylcyclopentadienyl chlorido

iridium(III) was the starting point for the preparation of half-sandwich iridium(III) complexes **263**. Yellol *et al.*<sup>131</sup> established a variety of novel iridium(III) **263** and ruthenium(II) **262a** and **b** *C,N*-cyclometalated benzimidazole complexes. The A2780 (ovary), 5637 (bladder), SISO (uterine cervical), and HT29 (rectal) human cancer cell lines were used to investigate their cytotoxicity. In the active hy926 (umbilical vein endothelial) human cell line, certain complexes were anti-angiogenic and triggered apoptosis by enhancing caspase-3 at a concentration of  $0.5 \mu\text{M}$ . In contrast to their respective ligands, the metal complexes exhibited noticeably higher cell growth inhibitory rates. According to the SAR evaluations, ruthenium complex **262a** was more potent than its iridium counterpart, compound **263**, where a phenyl substitution on the 1*H*-benzimidazole enhanced the potency in both ligand complexes.

The ligand BIGH was produced using a well-known process<sup>132</sup> (Scheme 59). By using DOX according to the MTT assay, the produced complexes were tested for their pro-apoptotic and anticancer effectiveness against the normal HEK293 (embryonic kidney), HeLa (cervical), MCF-7 (breast), and A549 human cancer cell lines.<sup>133</sup> The produced complexes exhibited a moderate level of activity against the A549, HeLa and MCF-7 cancer cell lines. All the evaluated cancer cell lines were successfully inhibited by



Scheme 63 Synthesis of benzimidazole analogous **281a** and **b**.

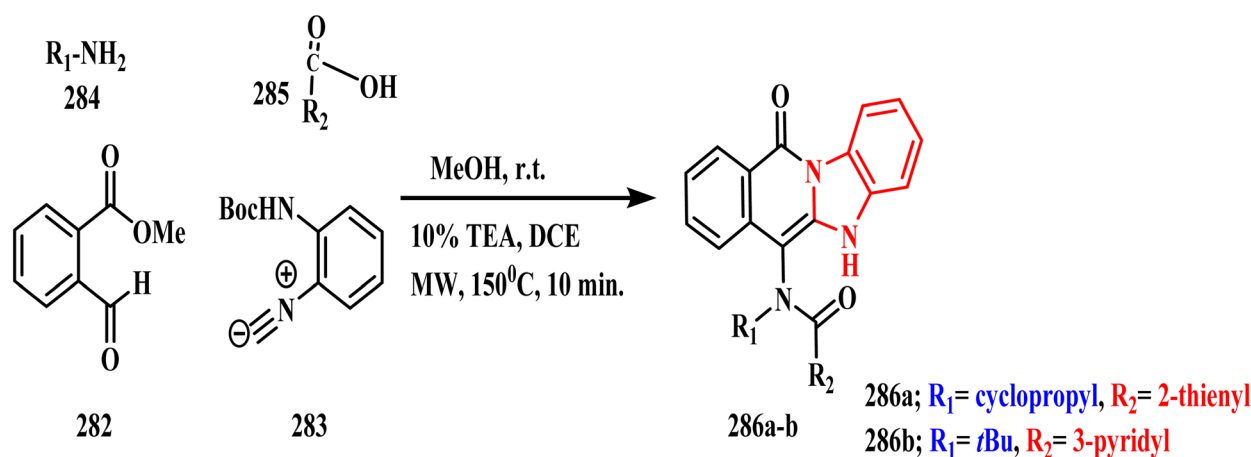


complexes **265a** ( $IC_{50}$  HeLa =  $36.70 \pm 0.073 \mu\text{M}$ ;  $IC_{50}$  MCF-7 =  $43.20 \pm 0.048 \mu\text{M}$ ; and  $IC_{50}$  A-549 =  $51.30 \pm 0.018 \mu\text{M}$ ) and **265b** ( $IC_{50}$  HeLa =  $45.85 \pm 0.031 \mu\text{M}$ ;  $IC_{50}$  MCF-7 =  $51.30 \pm 0.083 \mu\text{M}$ ; and  $IC_{50}$  A549 =  $32.30 \pm 0.052 \mu\text{M}$ ), respectively. The SAR studies indicate that the hydrophobic nature of the methyl-substituted bipyridyl contributed to the higher binding affinity of complex **265b** by increasing its intercalation, whereas the electron-donating capacity of the methyl group in complex **265a** enhanced the stacking of the substituted molecule.

The synthesis and cytotoxic potential of chrysin-benzimidazole derivatives were examined by Wang *et al.*<sup>134</sup> By first reacting the hydroxy group of **266** with dibromo alkane to yield **267**, the most powerful derivatives were synthesized. The essential hybrid molecule **268** was later produced by reacting bromide derivative **267** with benzimidazole in acetone (Scheme 60). Wang *et al.*<sup>134</sup> established a novel variety of chrysin-1*H*-benzimidazole compounds and tested them against the MFC cell line to see if they may be used as anti-carcinogenic agents. Compound **268** was determined to be the most promising antiproliferative drug among the derivatives ( $IC_{50} = 25.72 \pm 3.95 \mu\text{M}$ ), causing MFC cells to undergo apoptosis and inhibiting the progression of the cell cycle in the G0/G1 phase in a dose-dependent manner. According to the SAR evaluations, the compounds with a methyl substituent at the 1*H*-benzimidazole ring 2-position had enhanced inhibitory efficacy compared to those with that at the 5- or 6-position of the ring. Additionally, investigations from the previous year revealed that when the OH group was at position 5 and the chrysin derivatives had higher polarity, they showed stronger anti-cancer effects.

Derivative **272** was prepared according to the route shown in Scheme 61. Trifluoroacetic acid was hydrolyzed to get derivatives **272**, and after candesartan and triphenylmethyl bromide reacted to form intermediate **270**, which was subsequently condensed with different substituted amines. Compared to candesartan cilexetic, the optimal benzimidazole-derived **272** demonstrated enhanced NAE inhibition, namely CDC ( $IC_{50} = 5.51 \mu\text{M}$  vs.  $16.43 \mu\text{M}$ ), together with effective target inhibitory action and selective death of cancerous cells according to research.<sup>135</sup> In an enzyme assay, the optimal benzimidazole-derived **272** showed better neddylation inhibition than CDC. It also showed promising target inhibitory action and cancer cell killing selectivity. The results of cellular mechanism investigations and tumor growth suppression in A549 human lung cancer cells *in vivo* suggest that **272** may be developed as a promising neddylation inhibitor for anticancer treatment. According to SAR investigations, the core structures of tetrazole and 1*H*-benzimidazole are significant for increasing the neddylation inhibitory activities of the derivatives, whereas changing the substitutions of the heterocyclic cycloallylic and benzoallylic groups diminished the activity of the compounds.

The production and cytotoxic potential of pyrido[1,2-*a*]benzimidazole hybrids were examined by Samia *et al.*<sup>136</sup> The initial reaction of chloro derivative **273** resulted in the development of the most effective derivative that was investigated,<sup>136</sup> and dioxane with appropriate arylamines **274** produced the intended hybrid molecules **275a** and **b** (Scheme 62). The anti-cancer activity results showed that compound **275b** had the most significant inhibition, as indicated by the growth percentage (*G*%), against the breast cancer BT-549 (19.39%) and

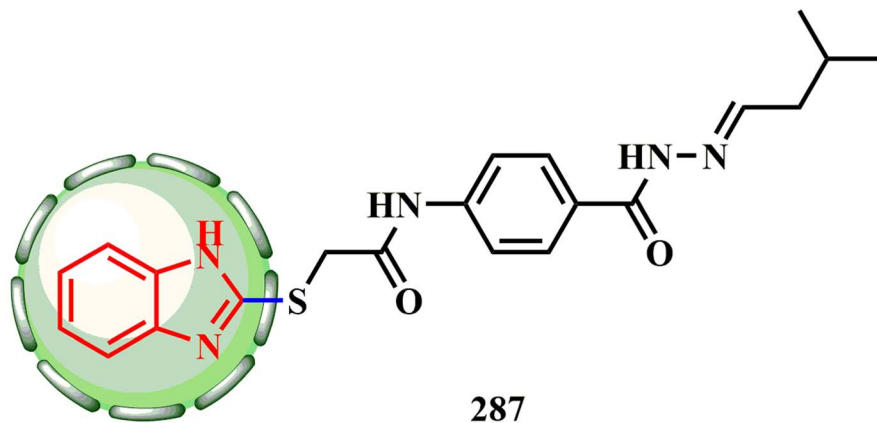


#### Key observations:

- 1) Of the compounds evaluated, **286b** exhibited the most promising anticancer properties.
- 2) Presence of a *N*-substituted bulky group and a 5-membered ring at carbonyl group of amide side linkage (**286a**) suppressed the activity of the compound.

Scheme 64 Synthesis of fused benzimidazole-isoquinolinone scaffolds **286a** and **b**.



**Key observation:**

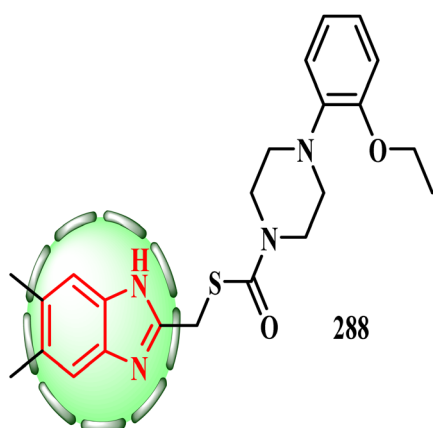
SAR studies revealed that substitution of a branched aliphatic aldehyde moiety increased the anticancer potential (compound **287**).

Fig. 1 2-Mercapto-1H-benzimidazole nucleus with anticancer activity.

melanoma UACC-62 (11.90%) cell lines. Among the compounds tested, compound **275b** was found to have promising anticancer activity. This might be because of how the biological activity profile is affected by the lipophilic trifluoromethyl substitution. Compound **275a** exhibits weak activity against the breast cancer BT-549 (87.45%) and melanoma UACC-62 (86.58%) cell lines.

Scheme 63 describes the synthetic procedures used to establish logically constructed 1-(9H-pyrido[3,4-*b*]indol-1-yl) (**281a** and **b**) derivatives that are connected to benzimidazole and benzoxazole. Pure 2-bromo-1-(9H-pyrido[3,4-*b*]indol-1-yl) ethanone (**277**) was obtained by reacting the starting compound 1-(9H-pyrido[3,4-*b*]indol-1-yl)ethanone (**276**) with *N*-bromo succinimide (NBS) in dry dichloromethane (DCM) solvent and stirring the reaction mixture for approximately 30 min at room temperature. 1-(2-Methylthiazol-4-yl)-9H-pyrido

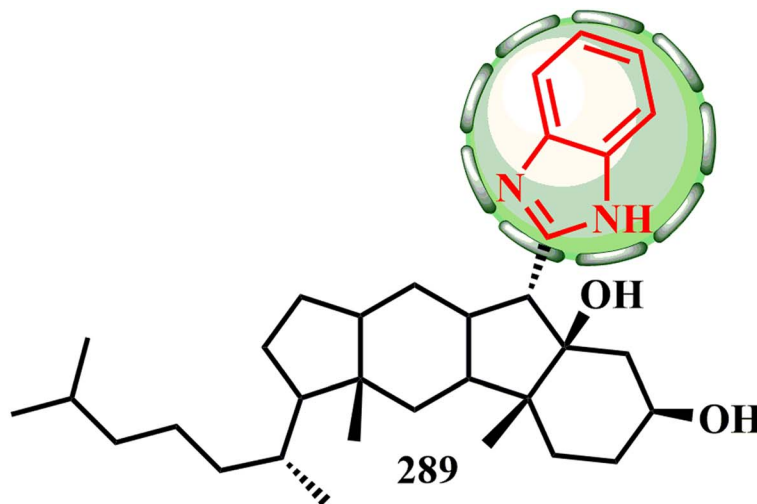
[3,4-*b*]indole (**278**) was obtained by refluxing the resultant ethanone intermediate **277** with ethanethioamide in pure EtOH for approximately 12 h. The obtained thiazole **278** (ref. 137) was converted to pure 4-(9H-pyrido[3,4-*b*]indol-1-yl)thiazole-2-carbaldehyde (**279**) by oxidizing it with selenium dioxide in ethanol for 24 h at 100 °C. To produce their respective benzimidazoles/benzoxazoles as pure final compounds **281a** and **b**, aldehyde **279** was finally allowed to react with different substituted 1,2-diamine **280** in the presence of diacetox-yiodobenzene (IBD) in dry 1,4-dioxane by stirring at room temperature for around 15 min. In the study conducted by Siresha *et al.*,<sup>138</sup> a novel type of 1H-benzimidazole-linked  $\beta$ -carboline was produced, and its anticancer activity against a range of human cancer cell lines was evaluated. Compounds **281a** ( $IC_{50} = 0.092 \pm 0.001 \mu M$ ) and **281b** ( $IC_{50} = 0.81 \pm 0.062$

**Key observation:**

The SAR study showed that a thiocarbamate linker was essential for activity.

Fig. 2 Benzimidazole moiety with its antiproliferative activity.





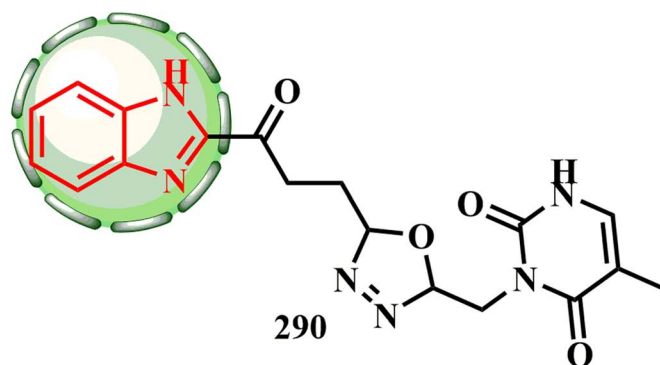
### Key observation:

The SAR study proved that the electron-donating group smoothed the insertion of the molecule **289** into DNA.

Fig. 3 *1H*-Benzimidazole scaffold with its *in vitro* studies.

$\mu\text{M}$ ) had the greatest anticarcinogenic properties against the MCF-7 cell line, according to the findings. According to the SAR evaluations, compound **281a** was more active than the reference standard due to the presence of 4,5-dimethoxy substitutions (MCF-7 =  $0.092 \pm 0.001 \mu\text{M}$ , A549 =  $0.72 \pm 0.042 \mu\text{M}$ , Colo-205 =  $0.34 \pm 0.071 \mu\text{M}$ , and A-2780 =  $1.23 \pm 0.55 \mu\text{M}$ ). Alternatively,

compound **281b** showed good action on four cancer cell lines despite having weak electron-donating 4,5-dimethyl substitutions on the benzimidazole moiety (A-2780 =  $1.80 \pm 0.59 \mu\text{M}$ , MCF-7 =  $0.81 \pm 0.062 \mu\text{M}$ , A549 =  $1.90 \pm 0.88 \mu\text{M}$ , and Colo-205 =  $0.41 \pm 0.12 \mu\text{M}$ ).

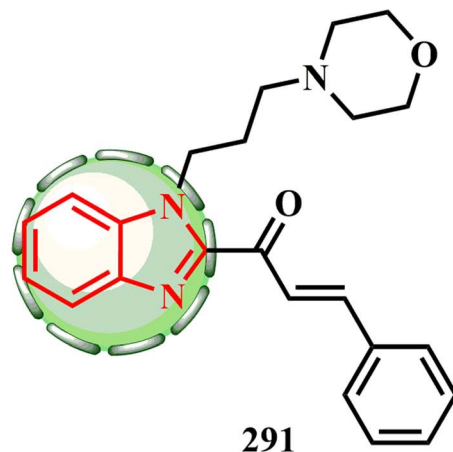


### Key observation:

SAR studies showed that benzimidazole derivatives containing a 1,3,4-oxadiazole ring (**290**) had greater anticancer activity than benzimidazoles with other heterocyclic rings.

Fig. 4 Hybrid **290** with its antiproliferative properties.



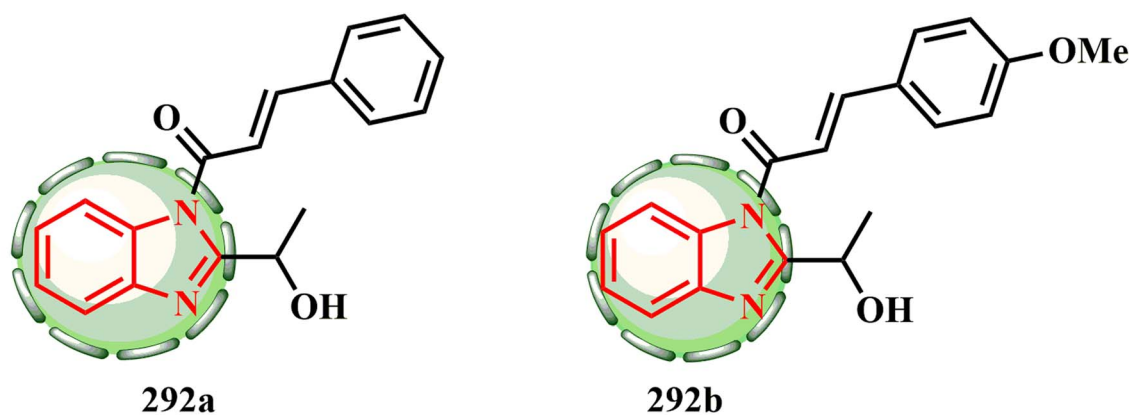
**Key observation:**

SAR studies showed that the *N*-substitution of benzimidazole with a hydrocarbon spacer linked to nitrogen (**291**) was essential for activities.

Fig. 5 Benzimidazole–chalcone hybrid **291** with its promising antiproliferative character.

**1.1.9. Four components.** Both the production and cytotoxic potential of fused benzimidazole–isoquinoline scaffolds were examined by He *et al.*<sup>139</sup> They used amine **284**, carboxylic acid **285**, methyl 2-formylbenzoate (**282**), and isonitrile **283** in methanol to perform a Ugi four-component reaction (U-4CR). This was followed by overnight stirring at normal room temperature and 15 min of microwave irradiation with 10% TFA/DCE at 150 °C (Scheme 64).<sup>139</sup> The findings indicated that

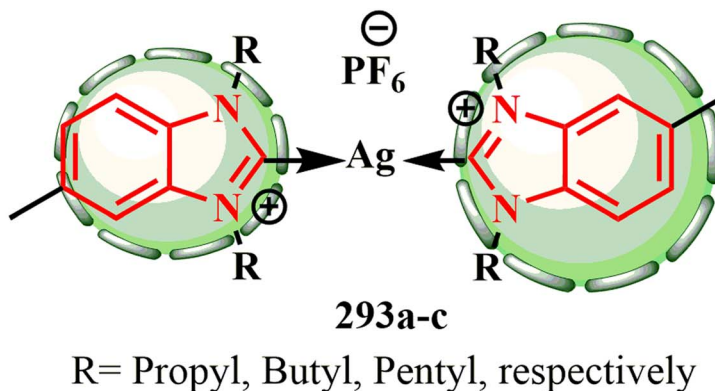
**286b** exhibited the most promising cytotoxic activity among the compounds ( $GI_{50} = 23.78 \mu\text{M}$  [SW620] and  $GI_{50} = 24.13 \mu\text{M}$  [HT29]), suppressing growth and causing cell cycle arrest at the G2/M checkpoint because of the weakened signaling *via* CDK1 and cyclin B1 protein and increased p21 and p53 action.<sup>139</sup> SAR evaluations revealed that the activity of this compound was inhibited by the presence of a 5-membered ring and an *N*-

**Key observation:**

SAR studies have shown the importance of *p*-methoxy phenyl substituents and unsubstituted phenyl rings in chalcones for anticancer activity.

Fig. 6 Benzimidazole–chalcone hybrids **292a** and **b** with their SAR.



**Key observation:**

An SAR study showed that the activity of these complexes was enhanced by increasing the length of the side chain, which in turn increased the lipophilicity of the benzimidazole ring.

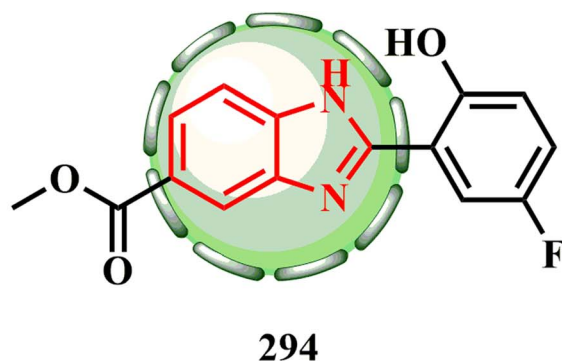
Fig. 7 Benzimidazole complexes 293a–c with their SAR.

substituted bulky group at the carbonyl group of the amide side linkage (**286a**).

Tahlan *et al.*<sup>140</sup> employed ((1*H*-benzo[*d*]imidazol-2-ylthio)acetamido)benzo hydrazide to establish a novel azomethine of 2-mercapto-1*H*-benzimidazole. Using 5-fluorouracil as the standard medication, they were screened *in vitro* using the SRB assay against the HCT-116 (colorectal) human cancer cell line. Compound **287** was found to be the most potent of all the

synthesized derivatives and have strong anticancer activity ( $IC_{50} = 30 \mu\text{g mL}^{-1}$ ). According to the SAR study findings, the anti-cancer potential was enhanced by substituting a branched aliphatic aldehyde moiety (compound **287**) (Fig. 1).

However, compound **288** had strong antiproliferative activity against MCF-7 cells, with an  $IC_{50}$  of  $5.58 \mu\text{g mL}^{-1}$ , which was similar to the  $IC_{50}$  of the common therapeutic doxorubicin, which has an  $IC_{50}$  of  $4.1 \mu\text{g mL}^{-1}$ . The fundamental manner of

**Key observation:**

Methyl ester is substituted with a hydroxyl group at C-2, whereas a fluoro group at the C5 position in the aryl ring (**294**) inhibits microtubule and is very active against breast cancer cells

Fig. 8 1*H*-Benzimidazole-5-carboxylate **294** with its activity on MCF-7 cell line.



action of compound **288** was to induce cell cycle arrest and apoptosis at the G2/M phase. A thiocarbamate linker was necessary for action, according to the SAR investigation, as shown in Fig. 2.<sup>141</sup>

Compound **289** (ref. 142) B-norcholesteryl benzimidazole demonstrated activity when tested against the HeLa, MCF-7, T-47D, and SKOV3 cell lines, with an IC<sub>50</sub> in the range of 7.90 μM to 20.10 μM.<sup>143,144</sup> The SAR<sup>145</sup> study demonstrated that the electron-donating group enhanced the insertion of this molecule into DNA<sup>142</sup> (Fig. 3).

Hybrid **290** (ref. 146) exhibited strong antiproliferative properties; its GI<sub>50</sub> values against the SNB-75 and COLO 205 cell lines were 0.09 μM and 0.35 μM, respectively. Additionally, with a selectivity index of 3.66, it demonstrated moderate selectivity towards prostate cancer cell lines. According to SAR research, the benzimidazole derivatives with a 1,3,4-oxadiazole ring exhibited stronger anticancer properties than those with other heterocyclic rings<sup>147,148</sup> (Fig. 4).

Moreover, compound **291** (ref. 149 and 150) had IC<sub>50</sub> values of 8.91 μM, 10.93 μM, and 10.67 μM against the MCF-7, HepG-2, and OVCAR-3 cell lines, respectively, indicating its promising antiproliferative action. Alternatively, cisplatin had IC<sub>50</sub> values of 11.70 μM, 3.97 μM, and 16.04 μM, respectively.<sup>151</sup> According

to the SAR investigations, the activities were attributed to the *N*-substitution of benzimidazole with a nitrogen-linked hydrocarbon spacer<sup>149,152</sup> (Fig. 5).

Compounds **292a** and **b** had IC<sub>50</sub> values in the range of 6.83 μM to 18.16 μM. Both substances exhibited strong affinity for the tyrosine kinase receptor. *P*-Methoxy phenyl substituents and unsubstituted phenyl rings are crucial for the anticancer action of the chalcones, according to the SAR studies<sup>153</sup> (Fig. 6).

When tested against the MDA-MB-231 and HCT-116 cell lines, complexes **293a–c** demonstrated greater anticancer activity than their respective benzimidazole ligands, with IC<sub>50</sub> values ranging from 4.22 μM to 10.3 μM. Additionally, their ligands showed reduced activity, with IC<sub>50</sub> values between 25.51 μM and 34.21 μM, which were similar to that of the reference pharmaceuticals 5-FU (IC<sub>50</sub> = 5.5 μM against HCT-116 cells) and tamoxifen (IC<sub>50</sub> = 8.20 μM against MDA-MB-231 cells). Increasing the side chain length improved the activity of the complexes, according to a SAR investigation, in which it additionally contributed to making the benzimidazole ring more lipophilic<sup>154</sup> (Fig. 7).

Methyl 2-(5-fluoro-2-hydroxyphenyl)-1*H*-benzimidazole-5-carboxylate (MBIC)<sup>155</sup> (**294**) with a methyl ester is substituted with a hydroxyl group at C-2, whereas a fluoro group at the C5

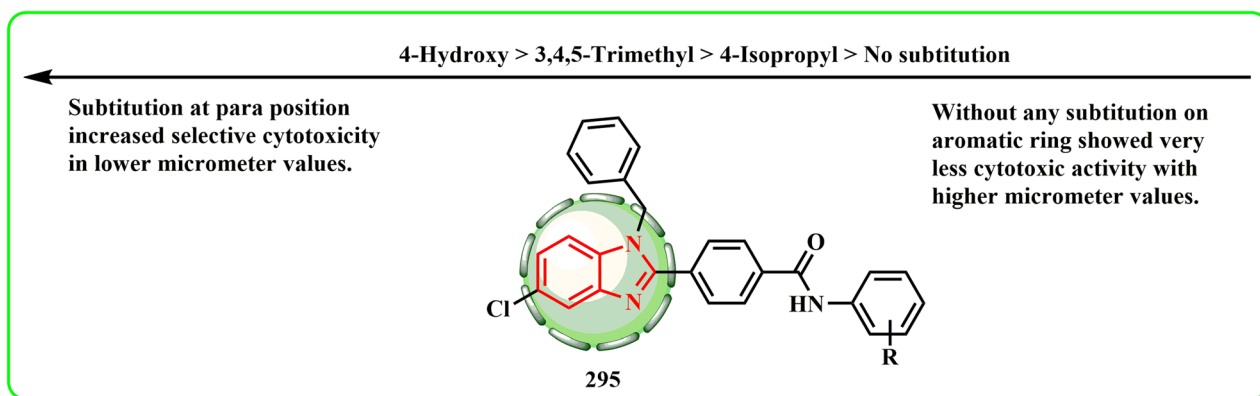


Fig. 9 Representative SAR studies of 1-benzyl-1*H*-benzimidazole analogues as anticancer agents.

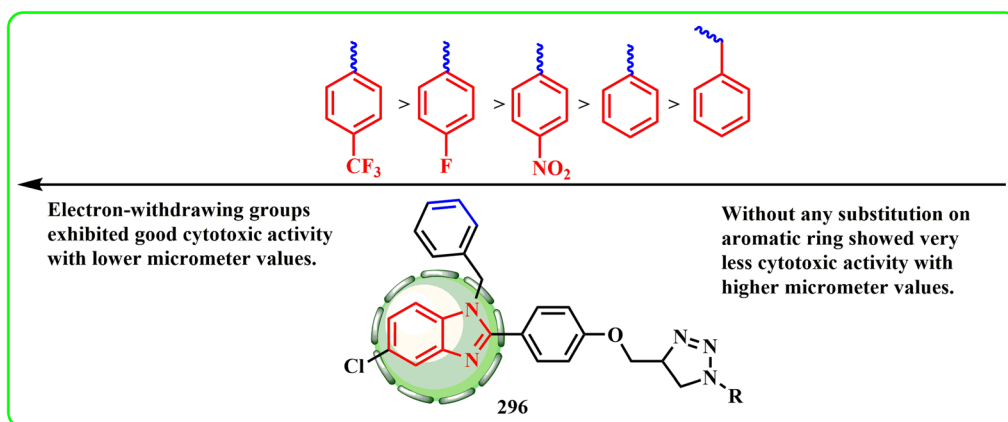


Fig. 10 Representative SAR studies of 1-benzyl-1*H*-benzimidazole-triazole analogues as anticancer agents.



position in the aryl ring inhibits microtubule<sup>156</sup> and is very active against breast cancer cells<sup>157,158</sup> (Fig. 8).

With an  $IC_{50}$  of  $10.69 \pm 0.14 \mu\text{M}$ ,  $13.89 \pm 0.74 \mu\text{M}$ ,  $7.01 \pm 0.20 \mu\text{M}$ ,  $14.04 \pm 0.62 \mu\text{M}$ , and  $12.91 \pm 0.52 \mu\text{M}$  against the A-549, DU-145, MCF-7, MDA-MB-231, and HCT-116 cancer cell lines, the 4-hydroxy compound **295** showed a noticeable decrease in tumor cell proliferation (Fig. 9). The 4-hydroxy arylamide moiety **295** of the 1*H*-benzyl benzimidazole derivative had strong anticancer activity, according to the SAR analysis. MCF-7 development was significantly inhibited when aromatic or heterocyclic rings, such as pyrrole, 3-ethoxy-4-hydroxyphen, and 3,5-dimethoxy-4-hydroxyphen, were connected to benzyl benzimidazole scaffolds.<sup>159</sup>

Further investigation of the distinct 1-benzyl-1*H*-benzimidazole hybrids for selective gal-1 inhibition resulted in the development of a variety of novel 1-benzyl-1*H*-benzimidazole-triazole analogues due to the promoting results of 1-benzyl-1*H*-benzimidazole analogues as possible anticancer agents mediated by gal-1. The 1,3-dipolar cycloaddition of the benzimidazole

intermediate with a terminal alkyne group to various benzyl and phenyl azides in the presence of a copper(i) catalyst produced 1-benzyl-1*H*-benzimidazole-triazole hybrids. 4-Trifluorophenyl compound **296** showed no cytotoxicity against normal embryonic kidney cells, but it displayed cytotoxic function against MCF-7, NCI-H460, MDA-MB-231, A-549, and HaCaT cells with  $IC_{50}$  values of  $1.3 \pm 0.18 \mu\text{M}$ ,  $0.99 \pm 0.01 \mu\text{M}$ ,  $0.94 \pm 0.02 \mu\text{M}$ ,  $0.63 \pm 0.21 \mu\text{M}$ , and  $2.99 \pm 0.09 \mu\text{M}$ , respectively. The SAR investigations demonstrated that in comparison to electron-donating groups and in the absence of any substitution on the aromatic ring, electron-withdrawing groups on the aromatic ring have remarkably greater cytotoxicity (Fig. 10).<sup>160</sup>

Hagar *et al.*<sup>161</sup> benzimidazole-1,3,4-oxadiazole-chalcone hybrids were established and synthesized (Fig. 11), and their ability to inhibit EGFR for cell destruction was studied. According to cell line tests, compound **297**, which has a paramethoxyphenyl group at the second position of the benzimidazole ring, demonstrated potential potency in inhibiting apoptosis and EGFR inhibition.

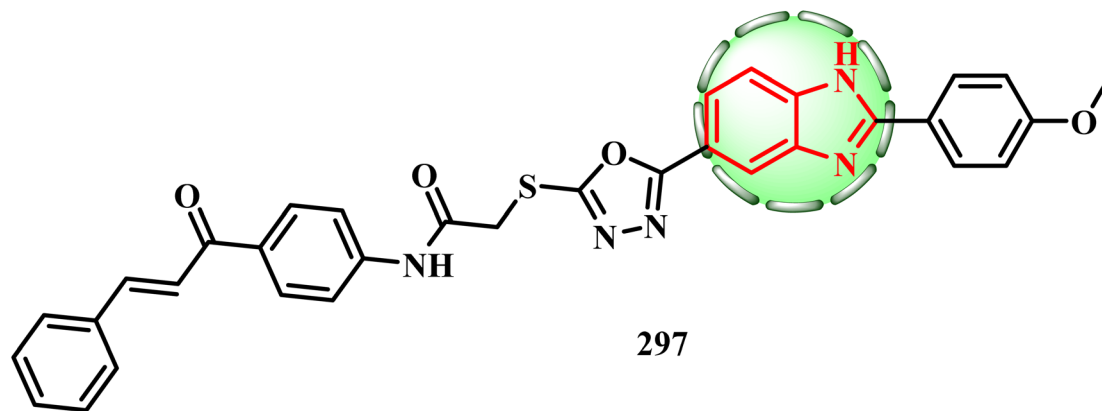
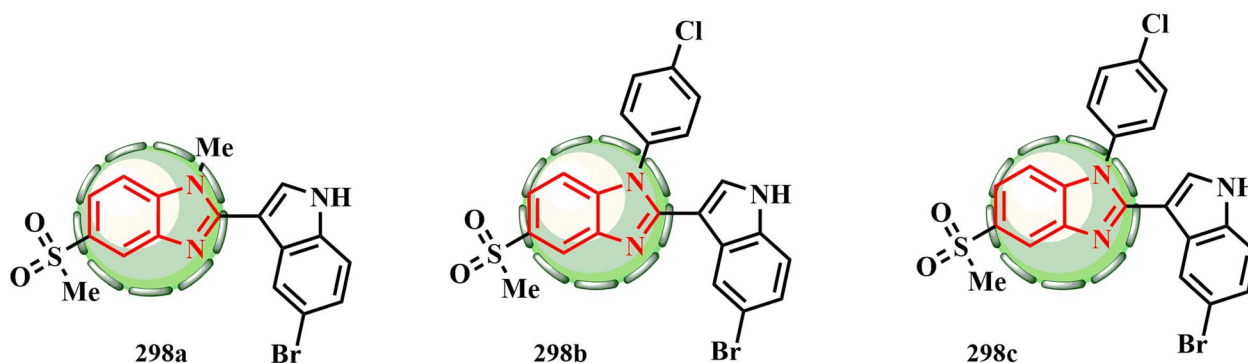


Fig. 11 Benzimidazole-containing moiety exhibiting anticancer activity.

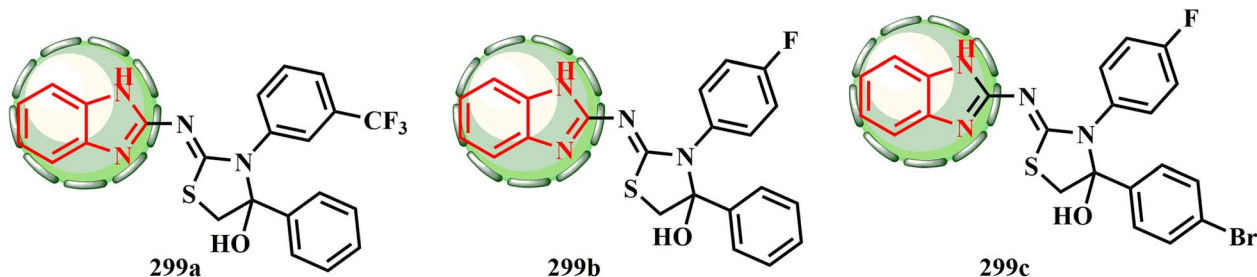


**Key observation;**

SAR showed that the replacement of *p*-fluorophenyl **298b** with *p*-chlorophenyl **298c** decreased anticancer activity.

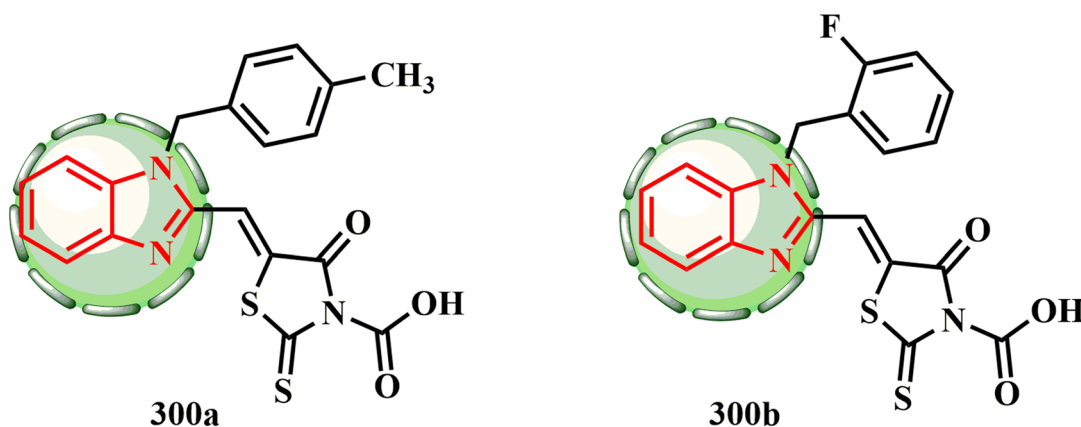
Fig. 12 Indole-benzimidazole derivatives with anticancer properties.



**Key observation;**

SAR, the fluorophenyl derivatives **299b-c** increased the inhibitory activity in comparison to trifluoromethylphenyl derivative **299a**

Fig. 13 Benzimidazoldiphenyl-2-imino-thiazolidine-4-ol **299a-c** derivatives with anticancer properties.

**Key observation:**

SAR studies have shown the presence of the benzyl and electron donor groups on the compounds **300a-b** revealed a significant impact on Topo II inhibitory activity

Fig. 14 Benzimidazole–rhodanine conjugates **300a** and **b** with anticancer properties.

The anticancer activities of indole–benzimidazole derivatives were reported.<sup>162</sup> Among the evaluated compounds, **298a** (ref. 163) ( $R_1 = \text{methyl}$  and  $R_2 = \text{Br}$ ) had the highest activity, with an  $\text{IC}_{50}$  value of  $28.73 \mu\text{M}$ . As a result, compound **298a** may have anticancer properties together with potential modulatory effects on estrogen and the corresponding receptors. The *p*-fluorophenyl scaffold molecule **298b** exhibited less productive anticancer properties, according to the structural activity relationship (SAR). At this point, the anticancer activity was reduced when *p*-chlorophenyl **298c** was substituted for *p*-fluorophenyl (Fig. 12).

Under efficient metal-free conditions, benzimidazoldiphenyl-2-imino-thiazolidine-4-ol derivatives **299a-c** were synthesized.<sup>164-166</sup> Doxorubicin was administered as a control for evaluating the targeted compounds against four distinct human

cancer cell lines, including breast, colon, prostate, and lung panels. In comparison to doxorubicin ( $\text{IC}_{50} = 1.75 \mu\text{M}$ ), compounds **299a** ( $\text{IC}_{50} = 3.89 \mu\text{M}$ ), **299b** ( $\text{IC}_{50} = 2.80 \mu\text{M}$ ), and **299c** ( $\text{IC}_{50} = 3.14 \mu\text{M}$ ) had the strongest inhibitory activity against the lung cancer cell line among the published compounds characterized for anticancer activity. Additionally, compared to trifluoromethylphenyl functionalities **299a**, the inhibitory effect was enhanced by the fluorophenyl functions **299b-c** (Fig. 13).

In another study, Li *et al.*<sup>167</sup> showed that a panel of benzimidazole–rhodamine conjugates have potent antiproliferative properties against human cervical, breast, lung, and prostate cancer cells, as well as human lymphoma and acute leukemia. As non-intercalative Topo II inhibitors, compounds **300a** and **b** bind to the Topo II enzyme ATP-binding site to inhibit enzymatic activity. The Topo II inhibitory action was significantly



influenced by the benzyl and electron donor groups in the compounds (Fig. 14).

## 2 Conclusion

The structural analogy of benzimidazole to nucleosides presents it as a potentially effective anticancer agent. The metal complexes or benzimidazole hybrids with antiproliferative properties were presented in this review. The examples included in this overview demonstrated the variety of synthetic preparation techniques used to achieve benzimidazoles and their antiproliferative properties. Additionally, we focused our attention to the SAR of the various molecular templates based on BZ that have been established by researchers globally. To accomplish our objectives, we collected information from an extensive range of publications to provide researchers, medicinal chemists, and drug designers with an excellent foundation for the development of the next generation of safe and effective BZ-based therapy. This review may shed light on the wide range of cancers that benzimidazoles can target, such as MCF-7, HepG2, MGC-803, HeLa, HCT-116, A-549, PC-3, MDA-MB-231, HUVEC, NIH/3T3, RMS, C-26, HT1080, LNCaP, 22Rv1, C4-2B prostate, DU-145, HEK293, MCF12A, H69AR, A2780, SISO, HT29, HCC2998, SF-539, UACC-62, and breast cancers BT-549, SW620, K-562, A37, SNB-75, COLO 205, and OVCAR-3. Their ability to disrupt important cellular processes such as Topo II-mediated DNA, VEGF, hCA IX, cell cycle progression, and mitosis has been demonstrated by investigations. This can lead to novel possibilities for the development of precision medicine-based benzimidazole anticancer drugs. Furthermore, this is the route forward to develop new medicinal compounds and benzimidazole anticancer drugs.

## Data availability

The article describes a study that did not utilize any data.

## Author contributions

Basant Farag, Sobhi M. Gomha, and Doaa A. Elsayed contributed to the conceptualization, supervision, and writing – review and editing. Basant Farag and Doaa A. Elsayed performed formal analysis and data curation. Magdi Zaki and Doaa A. Elsayed were responsible for investigation, methodology, and validation. Basant Farag and Doaa A. Elsayed led the writing – original draft preparation. All authors read and approved the final version of the manuscript.

## Conflicts of interest

The authors declare that they have no known financial conflicts of interest or personal relationships that could have influenced the work presented in this study.

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## References

- 1 A. Jemal, F. Bray, M. M. Center, J. Ferlay, E. Ward and D. Forman, Global cancer statistics, *Ca-Cancer J. Clin.*, 2011, **61**(2), 69–90.
- 2 V. Careaga and M. Maier, *Handbook of Anticancer Drugs from Marine Origin*, 2015.
- 3 J. Ferlay, H. Shin, F. Bray, D. Forman, C. Mathers and D. Parkin, *GLOBOCAN V1. 2, Cancer Incidence and Mortality Worldwide: IARC Cancer Base No. 10*, International Agency for Research on Cancer, Lyon, France, 2010, vol. 2008.
- 4 M. Mareel and A. Leroy, Clinical, cellular, and molecular aspects of cancer invasion, *Physiol. Rev.*, 2003, **83**(2), 337–376.
- 5 J. Wesche, K. Haglund and E. M. Haugsten, Fibroblast growth factors and their receptors in cancer, *Biochem. J.*, 2011, **437**(2), 199–213.
- 6 G. Vardatsikos, A. Sahu and A. K. Srivastava, The insulin-like growth factor family: molecular mechanisms, redox regulation, and clinical implications, *Antioxid. Redox Signaling*, 2009, **11**(5), 1165–1190.
- 7 A. A. Bhat, N. Tandon and R. Tandon, Pyrrolidine Derivatives as Anti-diabetic Agents: Current Status and Future Prospects, *ChemistrySelect*, 2022, **7**(6), e202103757.
- 8 S. Vijayaraghavalu, C. Peetla, S. Lu and V. Labhassetwar, Epigenetic modulation of the biophysical properties of drug-resistant cell lipids to restore drug transport and endocytic functions, *Mol. Pharm.*, 2012, **9**(9), 2730–2742.
- 9 A. A. Bhat, I. Singh, N. Tandon and R. Tandon, Structure activity relationship (SAR) and anticancer activity of pyrrolidine derivatives: Recent developments and future prospects (A review), *Eur. J. Med. Chem.*, 2023, **246**, 114954.
- 10 H. Sachdeva, S. Khaturia, M. Saquib, N. Khatik, A. R. Khandelwal, R. Meena and K. Sharma, Oxygen- and sulphur-containing heterocyclic compounds as potential anticancer agents, *Appl. Biochem. Biotechnol.*, 2022, **194**(12), 6438–6467.
- 11 A. Amin, T. Qadir, P. K. Sharma, I. Jeelani and H. Abe, A review on the medicinal and industrial applications of N-containing heterocycles, *Open Med. Chem. J.*, 2022, **16**(1), e187410452209010.
- 12 B. Negi and A. Kwatra, A Review of Recent Progress on the Anticancer Activity of Heterocyclic Compounds, *SynOpen*, 2024, **8**(03), 185–210.
- 13 J. Valdez, R. Cedillo, A. Hernandez-Campos, L. Yopez, F. Hernandez-Luis, G. Navarrete-Vazquez, A. Tapia, R. Cortes, M. Hernández and R. Castillo, Synthesis and antiparasitic activity of 1H-benzimidazole derivatives, *Bioorg. Med. Chem. Lett.*, 2002, **12**(16), 2221–2224.



- 14 F. M. Abdelrazek, M. E. Zaki, S. A. Al-Hussain, B. Farag, A. M. Hebishy, M. S. Abdelfattah, S. M. Hassan, A. F. El-Faragy, L. Iovkova and D. Mross, Facile one-pot synthesis and in silico study of new heterocyclic scaffolds with 4-pyridyl moiety: Mechanistic insights and X-ray crystallographic elucidation, *Heliyon*, 2024, **10**(7), e29221.
- 15 H. Debus, Ueber die einwirkung des ammoniaks auf glyoxal, *Justus Liebigs Ann. Chem.*, 1858, **107**(2), 199–208.
- 16 G. Satija, B. Sharma, A. Madan, A. Iqbal, M. Shaquiquzzaman, M. Akhter, S. Parvez, M. A. Khan and M. M. Alam, Benzimidazole based derivatives as anticancer agents: Structure activity relationship analysis for various targets, *J. Heterocycl. Chem.*, 2022, **59**(1), 22–66.
- 17 R. Ranjith, The chemistry and biological significance of imidazole, benzimidazole, benzoxazole, tetrazole and quinazolinone nucleus, *J. Chem. Pharm. Res.*, 2016, **8**(5), 505–526.
- 18 D. I. Othman, A. Hamdi, S. S. Tawfik, A. A. Elgazar and A. S. Mostafa, Identification of new benzimidazole-triazole hybrids as anticancer agents: multi-target recognition, in vitro and in silico studies, *J. Enzyme Inhib. Med. Chem.*, 2023, **38**(1), 2166037.
- 19 N. A. Nawareg, A. S. Mostafa, S. M. El-Messery and M. N. Nasr, New benzimidazole based hybrids: Synthesis, molecular modeling study and anticancer evaluation as TopoII inhibitors, *Bioorg. Chem.*, 2022, **127**, 106038.
- 20 I. Sović, S. Jambon, S. K. Pavelić, E. Markova-Car, N. Ilić, S. Depauw, M.-H. David-Cordonnier and G. Karminski-Zamola, Synthesis, antitumor activity and DNA binding features of benzothiazolyl and benzimidazolyl substituted isoindolines, *Bioorg. Med. Chem.*, 2018, **26**(8), 1950–1960.
- 21 C. Sheng, Z. Miao and W. Zhang, New strategies in the discovery of novel non-camptothecin topoisomerase I inhibitors, *Curr. Med. Chem.*, 2011, **18**(28), 4389–4409.
- 22 S. A. Galal, K. H. Hegab, A. M. Hashem and N. S. Youssef, Synthesis and antitumor activity of novel benzimidazole-5-carboxylic acid derivatives and their transition metal complexes as topoisomerase II inhibitors, *Eur. J. Med. Chem.*, 2010, **45**(12), 5685–5691.
- 23 R. M. Noha, M. K. Abdelhameid, M. M. Ismail, M. R. Mohammed and E. Salwa, Design, synthesis and screening of benzimidazole containing compounds with methoxylated aryl radicals as cytotoxic molecules on (HCT-116) colon cancer cells, *Eur. J. Med. Chem.*, 2021, **209**, 112870.
- 24 A. Saini, G. P. Kumar and G. Singh, A review of Benzimidazole derivatives potential activities, *Int. J. Pharm. Clin. Res.*, 2023, **5**, 35–40.
- 25 W. Zhou, W. Zhang, Y. Peng, Z.-H. Jiang, L. Zhang and Z. Du, Design, synthesis and anti-tumor activity of novel benzimidazole-chalcone hybrids as non-intercalative topoisomerase II catalytic inhibitors, *Molecules*, 2020, **25**(14), 3180.
- 26 J. L. Delgado, C.-M. Hsieh, N.-L. Chan and H. Hiasa, Topoisomerases as anticancer targets, *Biochem. J.*, 2018, **475**(2), 373–398.
- 27 W. Hu, X.-S. Huang, J.-F. Wu, L. Yang, Y.-T. Zheng, Y.-M. Shen, Z.-Y. Li and X. Li, Discovery of novel topoisomerase II inhibitors by medicinal chemistry approaches, *J. Med. Chem.*, 2018, **61**(20), 8947–8980.
- 28 S. Wang, L. Guan, J. Zang, K. Xing, J. Zhang, D. Liu and L. Zhao, Structure-based design of novel benzimidazole derivatives as Pin1 inhibitors, *Molecules*, 2019, **24**(7), 1198.
- 29 J. Gowda, A. Khader, B. Kalluraya and S. Hidayathulla, Synthesis, characterization and antibacterial activity of benzimidazole derivatives carrying quinoline moiety, *Indian J. Chem.*, 2011, **50B**, 1491–1495.
- 30 N. El-Gohary and M. Shaaban, Synthesis, antimicrobial, anti-quorum-sensing and antitumor activities of new benzimidazole analogs, *Eur. J. Med. Chem.*, 2017, **137**, 439–449.
- 31 K. Petkar, P. Parekh, P. Mehta, A. Kumari and A. Baro, Synthesis & evaluation of 2-chloromethyl-1H-benzimidazole derivatives as antifungal agents, *Int. J. Pharm. Pharm. Sci.*, 2013, **5**(2), 115–119.
- 32 N. El-Gohary and M. Shaaban, Synthesis and biological evaluation of a new series of benzimidazole derivatives as antimicrobial, anti-quorum-sensing and antitumor agents, *Eur. J. Med. Chem.*, 2017, **131**, 255–262.
- 33 G. Sindhu, R. Kholiya, S. Kidwai, P. Singh, R. Singh and D. S. Rawat, Design and synthesis of benzimidazole derivatives as antimycobacterial agents, *J. Biochem. Mol. Toxicol.*, 2022, **36**(9), e23123.
- 34 B. Soni, A short review on potential activities of benzimidazole derivatives, *PharmaTutor*, 2014, **2**(8), 110–118.
- 35 M. M. Morcos, E. S. Abdelhafez, H. M. Abdel-Rahman, M. Abdel-Aziz, A. El-Ella and A. Dalal, Novel Benzimidazole/Hydrazone Derivatives as Promising Anticancer Lead Compounds: Design, Synthesis, and Molecular Docking Study, *J. Adv. Biomedical Pharm. Sci.*, 2020, **3**(2), 45–52.
- 36 J. Zhang, D. Yao, Y. Jiang, J. Huang, S. Yang and J. Wang, Synthesis and biological evaluation of benzimidazole derivatives as the G9a Histone Methyltransferase inhibitors that induce autophagy and apoptosis of breast cancer cells, *Bioorg. Chem.*, 2017, **72**, 168–181.
- 37 P. Sharma, T. S. Reddy, N. P. Kumar, K. R. Senwar, S. K. Bhargava and N. Shankaraiah, Conventional and microwave-assisted synthesis of new 1H-benzimidazole-thiazolidinedione derivatives: A potential anticancer scaffold, *Eur. J. Med. Chem.*, 2017, **138**, 234–245.
- 38 U. Acar Çevik, B. N. Sağlık, D. Osmaniye, S. Levent, B. Kaya Çavuşoğlu, A. B. Karaduman, Ö. Atlı Eklioğlu, Y. Özkay and Z. A. Kaplançıklı, Synthesis, anticancer evaluation and molecular docking studies of new benzimidazole-1,3,4-oxadiazole derivatives as human topoisomerase types I poison, *J. Enzyme Inhib. Med. Chem.*, 2020, **35**(1), 1657–1673.
- 39 H. T. Abdel-Mohsen and A. M. Nageeb, Benzimidazole-dioxisoindoline conjugates as dual VEGFR-2 and FGFR-1 inhibitors: design, synthesis, biological investigation, molecular docking studies and ADME predictions, *RSC Adv.*, 2024, **14**(39), 28889–28903.



- 40 P. Astles, T. Brown, C. Handscombe, M. Harper, N. Harris, R. Lewis, P. Lockey, C. McCarthy, I. McLay and B. Porter, Selective endothelin A receptor ligands. 1. Discovery and structure-activity of 2,4-disubstituted benzoic acid derivatives, *Eur. J. Med. Chem.*, 1997, **32**(5), 409–423.
- 41 D. Kumar, M. R. Jacob, M. B. Reynolds and S. M. Kerwin, Synthesis and evaluation of anticancer benzoxazoles and benzimidazoles related to UK-1, *Bioorg. Med. Chem.*, 2002, **10**(12), 3997–4004.
- 42 S. B. Srinivasa, B. Poojary, B. S. Kalal, U. Brahmavara, D. Vaishali, A. J. Das, T. M. Kalenga, M. Paidikondala and M. K. Shankar, Design, synthesis and anticancer activity of Novel benzimidazole containing quinoline hybrids, *Results Chem.*, 2024, **9**, 101631.
- 43 S.-T. Huang, I.-J. Hsei and C. Chen, Synthesis and anticancer evaluation of bis (benzimidazoles), bis(benzoxazoles), and benzothiazoles, *Bioorg. Med. Chem.*, 2006, **14**(17), 6106–6119.
- 44 L. Xi, J.-Q. Zhang, Z.-C. Liu, J.-H. Zhang, J.-F. Yan, Y. Jin and J. Lin, Novel 5-anilinoquinazoline-8-nitro derivatives as inhibitors of VEGFR-2 tyrosine kinase: synthesis, biological evaluation and molecular docking, *Org. Biomol. Chem.*, 2013, **11**(26), 4367–4378.
- 45 A. S. Bhambra, M. Edgar, M. R. Elsegood, L. Horsburgh, V. Kryštof, P. D. Lucas, M. Mojally, S. J. Teat, T. G. Warwick and G. W. Weaver, Novel fluorinated benzimidazole-based scaffolds and their anticancer activity in vitro, *J. Fluorine Chem.*, 2016, **188**, 99–109.
- 46 X. Yuan, Q. Yang, T. Liu, K. Li, Y. Liu, C. Zhu, Z. Zhang, L. Li, C. Zhang and M. Xie, Design, synthesis and in vitro evaluation of 6-amide-2-aryl benzoxazole/benzimidazole derivatives against tumor cells by inhibiting VEGFR-2 kinase, *Eur. J. Med. Chem.*, 2019, **179**, 147–165.
- 47 M. Sugumaran and M. Y. Kumar, Synthesis and biological activity of novel 2,5-disubstituted benzimidazole derivatives, *Int. J. Pharm. Sci. Drug Res.*, 2012, **4**(1), 80–83.
- 48 F. Hoebrecker, Benzimidazole, *Ber.*, 1872, (5), 920–926.
- 49 S. Banerjee, S. Mukherjee, P. Nath, A. Mukherjee, S. Mukherjee, S. A. Kumar, S. De and S. Banerjee, A critical review of benzimidazole: Sky-high objectives towards the lead molecule to predict the future in medicinal chemistry, *Results Chem.*, 2023, **6**, 101013.
- 50 E. C. Pham, T. V. Le Thi, H. H. L. Hong, B. N. V. Thi, L. B. Vong, T. T. Vu, D. D. Vo, N. V. T. Nguyen, K. N. B. Le and T. N. Truong, N,2,6-Trisubstituted 1H-benzimidazole derivatives as a new scaffold of antimicrobial and anticancer agents: design, synthesis, in vitro evaluation, and in silico studies, *RSC Adv.*, 2023, **13**(1), 399–420.
- 51 T.-K.-C. Huynh, T.-H.-A. Nguyen, N.-H.-S. Tran, T.-D. Nguyen and T.-K.-D. Hoang, A facile and efficient synthesis of benzimidazole as potential anticancer agents, *J. Chem. Sci.*, 2020, **132**, 1–9.
- 52 U. Acar Cevik, B. Nurpelin Saglik, Y. Ozkay, Z. Canturk, J. Bueno, F. Demirci and A. Savas Koparal, Synthesis of new fluoro-benzimidazole derivatives as an approach towards the discovery of novel Intestinal antiseptic drug candidates, *Curr. Pharm. Des.*, 2017, **23**(15), 2276–2286.
- 53 E. O. Hamed, M. G. Assy, N. H. Ouf, D. A. Elsayed and M. H. Abdellatif, Cyclization of N-acetyl derivative: Novel synthesis–azoles and azines, antimicrobial activities, and computational studies, *Heterocycl. Commun.*, 2022, **28**(1), 35–43.
- 54 U. Acar Çevik, B. N. Sağlık, C. M. Ardiç, Y. Özkay and Ö. Atlı, Synthesis and evaluation of new benzimidazole derivatives with hydrazone moiety as anticancer agents, *Turk. J. Biochem.*, 2018, **43**(2), 151–158.
- 55 H. T. Abdel-Mohsen, M. A. Abdullaziz, A. M. El Kerdawy, F. A. Ragab, K. J. Flanagan, A. E. Mahmoud, M. M. Ali, H. I. El Diwani and M. O. Senge, Targeting receptor tyrosine kinase VEGFR-2 in hepatocellular cancer: rational design, synthesis and biological evaluation of 1,2-disubstituted benzimidazoles, *Molecules*, 2020, **25**(4), 770.
- 56 F. Sonmez, B. Zengin Kurt, I. Gazioglu, L. Basile, A. Dag, V. Cappello, T. Ginex, M. Kucukislamoglu and S. Guccione, Design, synthesis and docking study of novel coumarin ligands as potential selective acetylcholinesterase inhibitors, *J. Enzyme Inhib. Med. Chem.*, 2017, **32**(1), 285–297.
- 57 H. A. Abdel-Aziz, H. A. Ghabbour, W. M. Eldehna, S. T. Al-Rashood, K. A. Al-Rashood, H.-K. Fun, M. Al-Tahhan and A. Al-Dhfyhan, 2-((Benzimidazol-2-yl)thio)-1-arylethan-1-ones: Synthesis, crystal study and cancer stem cells CD133 targeting potential, *Eur. J. Med. Chem.*, 2015, **104**, 1–10.
- 58 H. S. Ibrahim, M. E. Albakri, W. R. Mahmoud, H. A. Allam, A. M. Reda and H. A. Abdel-Aziz, Synthesis and biological evaluation of some novel thiobenzimidazole derivatives as anti-renal cancer agents through inhibition of c-MET kinase, *Bioorg. Chem.*, 2019, **85**, 337–348.
- 59 S. Rawat and M. Ghate, Benzimidazole-Urea Derivatives as Anti-cancer Agents: In-silico Study, Synthesis and In-vitro Evaluation, *Int. J. Health Sci.*, 2022, **6**(S5), 5187–5217.
- 60 Y.-L. Zhang, R. Yang, L.-Y. Xia, R.-J. Man, Y.-C. Chu, A.-Q. Jiang, Z.-C. Wang and H.-L. Zhu, Synthesis, anticancer activity and molecular docking studies on 1,2-diarylbenzimidazole analogues as anti-tubulin agents, *Bioorg. Chem.*, 2019, **92**, 103219.
- 61 R. Goel, V. Luxami and K. Paul, Palladium catalyzed novel monoarylation and symmetrical/unsymmetrical diarylation of imidazo[1,2-a]pyrazines and their in vitro anticancer activities, *RSC Adv.*, 2014, **4**(19), 9885–9892.
- 62 H. Zeng, D. B. Belanger, P. J. Curran, G. W. Shipps Jr, H. Miao, J. B. Bracken, M. A. Siddiqui, M. Malkowski and Y. Wang, Discovery of novel imidazo[1,2-a]pyrazin-8-amines as Brk/PTK6 inhibitors, *Bioorg. Med. Chem. Lett.*, 2011, **21**(19), 5870–5875.
- 63 I. Singh, V. Luxami and K. Paul, Effective synthesis of benzimidazoles-imidazo[1,2-a]pyrazine conjugates: A comparative study of mono-and bis-benzimidazoles for antitumor activity, *Eur. J. Med. Chem.*, 2019, **180**, 546–561.
- 64 W. Shehta, F. Agili, B. Farag, S. A. Said, S. Youssif, M. E. Abdraboh and S. El-Kalyoubi, Design, synthesis and antitumor activity of novel pyran-functionalized uracil



- derivatives: docking studies, *Future Med. Chem.*, 2023, **15**(5), 421–436.
- 65 R. Sivaramakarthikeyan, S. Iniyaval, V. Saravanan, W.-M. Lim, C.-W. Mai and C. Ramalingan, Molecular hybrids integrated with benzimidazole and pyrazole structural motifs: Design, synthesis, biological evaluation, and molecular docking studies, *ACS Omega*, 2020, **5**(17), 10089–10098.
- 66 X. Wu, H. Shen, Y. Zhang, C. Wang, Q. Li, C. Zhang, X. Zhuang, C. Li, Y. Shi and Y. Xing, Discovery and characterization of benzimidazole derivative XY123 as a potent, selective, and orally available ROR $\gamma$  inverse agonist, *J. Med. Chem.*, 2021, **64**(12), 8775–8797.
- 67 S. M. Gomha, S. M. Riyadh, R. A. Alharbi, M. E. Zaki, T. Z. Abolibda and B. Farag, Green route synthesis and molecular docking of azines using cellulose sulfuric acid under microwave irradiation, *Crystals*, 2023, **13**(2), 260.
- 68 J. E. Cheong, M. Zaffagni, I. Chung, Y. Xu, Y. Wang, F. E. Jernigan, B. R. Zetter and L. Sun, Synthesis and anticancer activity of novel water soluble benzimidazole carbamates, *Eur. J. Med. Chem.*, 2018, **144**, 372–385.
- 69 W. S. Shehab, M. M. Amer, D. A. Elsayed, K. K. Yadav and M. H. Abdellatif, Current progress toward synthetic routes and medicinal significance of quinoline, *Med. Chem. Res.*, 2023, **32**(12), 2443–2457.
- 70 S. M. Gomha, S. M. Riyadh, B. Farag, S. A. Al-Hussain, M. E. Zaki and M. A. Mohamed, Green synthesis of hydrazono-thiazolones using vitamin B1 and their antibacterial implications, *Green Chem. Lett. Rev.*, 2024, **17**(1), 2380746.
- 71 A. Y. Alzahrani, S. M. Gomha, M. E. Zaki, B. Farag, F. E. Abdelgawad and M. A. Mohamed, Chitosan–sulfonic acid-catalyzed green synthesis of naphthalene-based azines as potential anticancer agents, *Future Med. Chem.*, 2024, **16**(7), 647–663.
- 72 N. Perin, L. Hok, A. Beč, L. Persoons, E. Vanstreels, D. Daelemans, R. Vianello and M. Hranjec, N-substituted benzimidazole acrylonitriles as in vitro tubulin polymerization inhibitors: Synthesis, biological activity and computational analysis, *Eur. J. Med. Chem.*, 2021, **211**, 113003.
- 73 D. N. Kommi, D. Kumar, R. Bansal, R. Chebolu and A. K. Chakraborti, “All-water” chemistry of tandem N-alkylation–reduction–condensation for synthesis of N-arylmethyl-2-substituted benzimidazoles, *Green Chem.*, 2012, **14**(12), 3329–3335.
- 74 J. M. Humphrey and A. R. Chamberlin, Chemical synthesis of natural product peptides: coupling methods for the incorporation of noncoded amino acids into peptides, *Chem. Rev.*, 1997, **97**(6), 2243–2266.
- 75 S. I. Alaqeel, Synthetic approaches to benzimidazoles from *o*-phenylenediamine: A literature review, *J. Saudi Chem. Soc.*, 2017, **21**(2), 229–237.
- 76 N. S. Goud, S. M. Ghouse, J. Vishnu, D. Komal, V. Talla, R. Alvala, J. Pranay, J. Kumar, I. A. Qureshi and M. Alvala, Synthesis of 1-benzyl-1*H*-benzimidazoles as galectin-1 mediated anticancer agents, *Bioorg. Chem.*, 2019, **89**, 103016.
- 77 J. Jang, B. Koh and K. Lee, Discovery of benzimidazole-2-amide BNZ-111 as new tubulin inhibitor, *Bioorg. Med. Chem. Lett.*, 2024, **113**, 129953.
- 78 W. S. Shehab, H. A. Haikal, D. A. Elsayed, A. F. El-Faragy, A.-R. B. El-Gazzar, G. T. El-Bassyouni and S. M. Mousa, Pharmacokinetic and molecular docking studies to pyrimidine drug using Mn<sub>3</sub>O<sub>4</sub> nanoparticles to explore potential anti-Alzheimer activity, *Sci. Rep.*, 2024, **14**(1), 15436.
- 79 F. King, R. Acheson and P. Spensley, 275. Benzimidazole analogues of paludrine, *J. Chem. Soc.*, 1948, 1366–1371.
- 80 S. A. El-Hawash, E.-S. A. Badawey and I. M. El-Ashmawey, Nonsteroidal antiinflammatory agents—part 2 antiinflammatory, analgesic and antipyretic activity of some substituted 3-pyrazolin-5-ones and 1,2,4,5,6,7-3*H*-hexahydroindazol-3-ones, *Eur. J. Med. Chem.*, 2006, **41**(2), 155–165.
- 81 M. M. Ismail, H. El-Sehrawi, H. S. Elzahabi, T. Shower and Y. A. Ammar, Synthesis and antitumor activity of novel hybrids of pyrimidine/benzimidazole scaffolds, *Polycyclic Aromat. Compd.*, 2022, **42**(5), 2363–2377.
- 82 L. Sun, C. Liang, S. Shirazian, Y. Zhou, T. Miller, J. Cui, J. Y. Fukuda, J.-Y. Chu, A. Nematalla and X. Wang, Discovery of 5-[5-fluoro-2-oxo-1,2-dihydroindol-(3*Z*)-ylidenemethyl]-2, 4-dimethyl-1*H*-pyrrole-3-carboxylic acid (2-diethylaminoethyl)amide, a novel tyrosine kinase inhibitor targeting vascular endothelial and platelet-derived growth factor receptor tyrosine kinase, *J. Med. Chem.*, 2003, **46**(7), 1116–1119.
- 83 N. K. Rasal, R. B. Sonawane and S. V. Jagtap, Potential 2,4-dimethyl-1*H*-pyrrole-3-carboxamide bearing benzimidazole template: Design, synthesis, in vitro anticancer and in silico ADME study, *Bioorg. Chem.*, 2020, **97**, 103660.
- 84 S. A. Galal, A. S. Abdelsamie, S. A. Shouman, Y. M. Attia, H. I. Ali, A. Tabll, R. El-Shenawy, Y. S. El Abd, M. M. Ali and A. E. Mahmoud, Part I: Design, synthesis and biological evaluation of novel pyrazole-benzimidazole conjugates as checkpoint kinase 2 (Chk2) inhibitors with studying their activities alone and in combination with genotoxic drugs, *Eur. J. Med. Chem.*, 2017, **134**, 392–405.
- 85 M. F. Baig, V. L. Nayak, P. Budaganaboyina, K. Mullagiri, S. Sunkari, J. Gour and A. Kamal, Synthesis and biological evaluation of imidazo[2,1-*b*]thiazole-benzimidazole conjugates as microtubule-targeting agents, *Bioorg. Chem.*, 2018, **77**, 515–526.
- 86 S. Q. Al-Sultan, M. H. Mohammed and W. H. Talib, Newly designed 2-(aminomethyl) benzimidazole derivatives as possible tyrosine kinase inhibitors: synthesis, characterization, preliminary cytotoxic evaluation and in Silico studies, *Chem. Rev. Lett.*, 2024, **7**(3), 545–559.
- 87 E. Akgöz and S. Colak, Synthesis and antiproliferative activities against breast cancer of *N*-(benzimidazol-2-yl)-substituted benzamide derivatives, *Bioorg. Med. Chem. Rep.*, 2024, **7**(1), 1–9.



- 88 R. A. Haque, M. A. Iqbal, M. B. Khadeer Ahamed, A. A. Majid and Z. A. Abdul Hameed, Design, synthesis and structural studies of meta-xylyl linked bis-benzimidazolium salts: potential anticancer agents against 'human colon cancer', *Chem. Cent. J.*, 2012, **6**, 1–14.
- 89 R. A. Haque and M. A. Iqbal, Synthesis and characterization of ortho-xylyl linked bis-benzimidazolium salts, *Asian J. Chem.*, 2012, **24**(6), 2625–2628.
- 90 N. ul Huda, S. Islam, M. Zia, K. William, F. i Abbas, M. I. Umar, M. A. Iqbal and A. Mannan, Anticancer, antimicrobial and antioxidant potential of sterically tuned bis-*N*-heterocyclic salts, *Z. Naturforsch., C: J. Biosci.*, 2019, **74**(1–2), 17–23.
- 91 S. Bouchekioua, S. Akkoc and R. Menacer, In Vitro and In Silico Studies on Benzimidazole-Based Compounds, *ChemistrySelect*, 2024, **9**(1), e202304347.
- 92 D. Başat Dereli, S. Akkoc and E. Çubuk Demiralay, Protonation Constant Determination of Some Benzimidazole-Based Drug Candidates by Reverse Phase Liquid Chromatography Method and Cytotoxic Activity Studies, *ChemistrySelect*, 2023, **8**(28), e202301192.
- 93 S. C. Yavuz, Synthesis of new two 1,2-disubstituted benzimidazole compounds: their in vitro anticancer and in silico molecular docking studies, *BMC Chem.*, 2024, **18**(1), 146.
- 94 Y. Ren, Y. Wang, G. Li, Z. Zhang, L. Ma, B. Cheng and J. Chen, Discovery of novel benzimidazole and indazole analogues as tubulin polymerization inhibitors with potent anticancer activities, *J. Med. Chem.*, 2021, **64**(8), 4498–4515.
- 95 M. S. Ibrahim, B. Farag, J. Y. Al-Humaidi, M. E. Zaki, M. Fathalla and S. M. Gomha, Mechanochemical Synthesis and Molecular Docking Studies of New Azines Bearing Indole as Anticancer Agents, *Molecules*, 2023, **28**(9), 3869.
- 96 Z. ALAGÖZ, C. Kus and T. Coban, Synthesis and antioxidant properties of novel benzimidazoles containing substituted indole or 1,1,4,4-tetramethyl-1,2,3,4-tetrahydro-naphthalene fragments, *J. Enzyme Inhib. Med. Chem.*, 2005, **20**(4), 325–331.
- 97 F. Z. Karadayi, M. Yaman, M. M. Kislá, A. G. Keskus, O. Konu and Z. Ates-Alagoz, Design, synthesis and anticancer/antiestrogenic activities of novel indole-benzimidazoles, *Bioorg. Chem.*, 2020, **100**, 103929.
- 98 Q.-L. Gao, B.-W. Wu, D. Li, L. Shi, T. Zhu, J.-F. Lou, C.-Y. Jin, Y.-B. Zhang, S.-Y. Zhang and H.-M. Liu, Novel tertiary sulfonamide derivatives containing benzimidazole moiety as potent anti-gastric cancer agents: Design, synthesis and SAR studies, *Eur. J. Med. Chem.*, 2019, **183**, 111731.
- 99 Ü. Yılmaz, S. Tekin, N. Buğday, K. Yavuz, H. Küçükbay and S. Sandal, Synthesis and evaluation of anticancer properties of novel benzimidazole ligand and their cobalt (II) and zinc (II) complexes against cancer cell lines A-2780 and DU-145, *Inorg. Chim. Acta*, 2019, **495**, 118977.
- 100 C. Xie, X. Han, J. Gong, D. Li and C. Ma, One-pot strategy of copper-catalyzed synthesis of 1,2-disubstituted benzimidazoles, *Org. Biomol. Chem.*, 2017, **15**(27), 5811–5819.
- 101 H. Küçükbay, N. Şireci, Ü. Yılmaz, M. Akkurt, Ş. P. Yalçın, M. Nawaz Tahir and H. Ott, Synthesis, characterization and microwave-assisted catalytic activity of novel benzimidazole salts bearing piperidine and morpholine moieties in Heck cross-coupling reactions, *Appl. Organomet. Chem.*, 2011, **25**(4), 255–261.
- 102 Ü. Yılmaz, H. Küçükbay, S. Deniz and N. Şireci, Synthesis, characterization and microwave-promoted catalytic activity of novel *N*-phenylbenzimidazolium salts in Heck-Mizoroki and Suzuki-Miyaura cross-coupling reactions under mild conditions, *Molecules*, 2013, **18**(3), 2501–2517.
- 103 G. H. Al-Ansary, W. M. Eldehna, H. A. Ghabbour, S. T. Al-Rashood, K. A. Al-Rashood, R. A. Eladwy, A. Al-Dhfyán, M. M. Kabil and H. A. Abdel-Aziz, Cancer stem cells CD133 inhibition and cytotoxicity of certain 3-phenylthiazolo[3,2-*a*]benzimidazoles: design, direct synthesis, crystal study and in vitro biological evaluation, *J. Enzyme Inhib. Med. Chem.*, 2017, **32**(1), 986–991.
- 104 A. A. Alkhaldi, M. M. Al-Sanea, A. Nocentini, W. M. Eldehna, Z. M. Elsayed, A. Bonardi, M. F. Abo-Ashour, A. K. El-Damasy, M. S. Abdel-Maksoud and T. Al-Warhi, 3-Methylthiazolo [3,2-*a*]benzimidazole-benzenesulfonamide conjugates as novel carbonic anhydrase inhibitors endowed with anticancer activity: Design, synthesis, biological and molecular modeling studies, *Eur. J. Med. Chem.*, 2020, **207**, 112745.
- 105 H. Atmaca, S. İlhan, M. B. Batır, Ç. Ç. Pulat, A. Güner and H. Bektaş, Novel benzimidazole derivatives: Synthesis, in vitro cytotoxicity, apoptosis and cell cycle studies, *Chem.-Biol. Interact.*, 2020, **327**, 109163.
- 106 S. Yadav, B. Narasimhan, S. M. Lim, K. Ramasamy, M. Vasudevan, S. A. A. Shah and A. Mathur, Synthesis and evaluation of antimicrobial, antitubercular and anticancer activities of benzimidazole derivatives, *Egypt. J. Basic Appl. Sci.*, 2018, **5**(1), 100–109.
- 107 P. Dubey, P. P. Reddy and K. Srinivas, Alternate Method for the Synthesis of *N*-Alkyl/aralkyl-2-( $\alpha$ -hydroxy Alkyl/aralkyl) benzimidazoles via Regiospecific Acetylation, *Synth. Commun.*, 2007, **37**(10), 1675–1681.
- 108 A. Özdemir, S. Turanlı, B. Çalışkan, M. Arka and E. Banoglu, Evaluation of cytotoxic activity of new benzimidazole-piperazine hybrids against human MCF-7 and A549 cancer cells, *Pharm. Chem. J.*, 2020, **53**, 1036–1046.
- 109 A. M. Srour, N. S. Ahmed, S. S. Abd El-Karim, M. M. Anwar and S. M. El-Hallouty, Design, synthesis, biological evaluation, QSAR analysis and molecular modelling of new thiazol-benzimidazoles as EGFR inhibitors, *Bioorg. Med. Chem.*, 2020, **28**(18), 115657.
- 110 W. Yi, C. Dubois, S. Yahiaoui, R. Haudecoeur, C. Belle, H. Song, R. Hardré, M. Réglie and A. Boumendjel, Refinement of arylthiosemicarbazone pharmacophore in inhibition of mushroom tyrosinase, *Eur. J. Med. Chem.*, 2011, **46**(9), 4330–4335.



- 111 G. D. Coxon, D. Craig, R. M. Corrales, E. Vialla, L. Gannoun-Zaki and L. Kremer, Synthesis, antitubercular activity and mechanism of resistance of highly effective thiacetazone analogues, *PLoS One*, 2013, **8**(1), e53162.
- 112 M.-H. Shih, Y.-S. Su and C.-L. Wu, Syntheses of aromatic substituted hydrazino-thiazole derivatives to clarify structural characterization and antioxidant activity between 3-arylsydnonyl and aryl substituted hydrazino-thiazoles, *Chem. Pharm. Bull.*, 2007, **55**(8), 1126–1135.
- 113 R. B. de Oliveira, E. M. de Souza-Fagundes, R. P. Soares, A. A. Andrade, A. U. Krettli and C. L. Zani, Synthesis and antimalarial activity of semicarbazone and thiosemicarbazone derivatives, *Eur. J. Med. Chem.*, 2008, **43**(9), 1983–1988.
- 114 V. M. Reddy and K. R. Reddy, Synthesis and antimicrobial activity of some novel 4-(1*H*-benz [*d*]imidazol-2-yl)-1,3-thiazol-2-amines, *Chem. Pharm. Bull.*, 2010, **58**(7), 953–956.
- 115 R. Polunin, A. Kozytshkiy and S. Kolotilov, Photovoltaic Characteristics of Bis(2-Benzimidazolyl)-Bisthiazole Deposited on TiO<sub>2</sub> in the Presence of Zn<sup>2+</sup> Ions, *Theor. Exp. Chem.*, 2015, **51**, 196–201.
- 116 S. M. Gomha, A.-A. A. El-Sayed, A. Alrehaily, H. M. Elbadawy, B. Farag, A. A. Al-Shahri, S. R. Alsenani, F. E. Abdelgawad and M. E. Zaki, Synthesis, molecular docking, in silico study, and evaluation of bis-thiazole-based curcumin derivatives as potential antimicrobial agents, *Results Chem.*, 2024, **7**, 101504.
- 117 J. Y. Al-Humaidi, S. M. Riyadh, B. Farag, M. E. Zaki, T. Z. Abolibda and S. M. Gomha, Synthesis of Bis-thiazoles Tethered 1,4-Dihydropyridine and Pyridine Linkers via Simple Oxidation and their Molecular Docking as VEGFR-TK Inhibitors, *Curr. Med. Chem.*, 2025, **32**(9), 1789–1802.
- 118 T. Z. Abolibda, M. Fathalla, B. Farag, M. E. Zaki and S. M. Gomha, Synthesis and molecular docking of some novel 3-thiazolyl-coumarins as inhibitors of VEGFR-2 kinase, *Molecules*, 2023, **28**(2), 689.
- 119 W. Shehta, F. Agili, B. Farag, S. Youssif, S. J. Almeahadi, S. M. Elfeky and S. El-Kalyoubi, Synthesis and in vitro study of pyrimidine-phthalimide hybrids as VEGFR2 inhibitors with antiproliferative activity, *Future Med. Chem.*, 2023, **15**(8), 661–677.
- 120 N. Perin, R. Nhili, M. Cindrić, B. Bertoša, D. Vušak, I. Martin-Kleiner, W. Laine, G. Karminski-Zamola, M. Kralj and M.-H. David-Cordonnier, Amino substituted benzimidazo [1, 2-*a*]quinolines: Antiproliferative potency, 3D QSAR study and DNA binding properties, *Eur. J. Med. Chem.*, 2016, **122**, 530–545.
- 121 N. Perin, K. Bobanović, I. Zlatar, D. Jelić, V. Kelava, S. Koštrun, V. G. Marković, K. Brajša and M. Hranjec, Antiproliferative activity of amino substituted benzo[*b*]thieno[2,3-*b*]pyrido[1,2-*a*]benzimidazoles explored by 2D and 3D cell culture system, *Eur. J. Med. Chem.*, 2017, **125**, 722–735.
- 122 N. Perin, S. Škulj, I. Martin-Kleiner, M. Kralj and M. Hranjec, Synthesis and antiproliferative activity of novel 2-substituted N-methylated benzimidazoles and tetracyclic benzimidazo[1,2-*a*] quinolines, *Polycyclic Aromat. Compd.*, 2018, **40**(2), 343–354.
- 123 M. J. Akhtar, A. A. Siddiqui, A. A. Khan, Z. Ali, R. P. Dewangan, S. Pasha and M. S. Yar, Design, synthesis, docking and QSAR study of substituted benzimidazole linked oxadiazole as cytotoxic agents, EGFR and erbB2 receptor inhibitors, *Eur. J. Med. Chem.*, 2017, **126**, 853–869.
- 124 M. J. Akhtar, A. A. Khan, Z. Ali, R. P. Dewangan, M. Rafi, M. Q. Hassan, M. S. Akhtar, A. A. Siddiqui, S. Partap and S. Pasha, Synthesis of stable benzimidazole derivatives bearing pyrazole as anticancer and EGFR receptor inhibitors, *Bioorg. Chem.*, 2018, **78**, 158–169.
- 125 E. O. Hamed, D. A. Elsayed, M. G. Assy and W. S. Shehab, Design, Synthesis, Docking, 2D-QSAR Modelling, Anticancer and Antioxidant Evaluation of Some New Azo-Compounds Derivatives and Investigation of Their Fluorescence Properties, *ChemistrySelect*, 2022, **7**(41), e202202534.
- 126 D. A. Elsayed, Design, Synthesis, Biological Evaluation, and Molecular Docking Studies of novel Azo-compounds derivatives as Significant Antioxidants, *Bull. Fac. Sci. Zagazig Univ.*, 2023, **2023**(1), 1–9.
- 127 A. Djemoui, A. Naouri, M. R. Ouahrani, D. Djemoui, S. Lahcene, M. B. Lahrech, L. Boukenna, H. M. Albuquerque, L. Saher and D. H. Rocha, A step-by-step synthesis of triazole-benzimidazole-chalcone hybrids: Anticancer activity in human cells+, *J. Mol. Struct.*, 2020, **1204**, 127487.
- 128 H. Karaca Gençer, U. Acar Çevik, S. Levent, B. N. Sağlık, B. Korkut, Y. Özkay, S. İlgin and Y. Öztürk, New benzimidazole-1,2,4-triazole hybrid compounds: Synthesis, anticandidal activity and cytotoxicity evaluation, *Molecules*, 2017, **22**(4), 507.
- 129 S. A. Ouf, S. M. Gomha, B. Farag, M. E. Zaki, M. M. Ewies, I. A. Sharawy, F. O. Khalil and H. K. Mahmoud, Synthesis of novel Bis-1,2,4-Triazolo[3,4-*b*][1,3,4]Thiadiazines from natural camphoric acid as potential anti-candidal agents, *Results Chem.*, 2024, **7**, 101406.
- 130 E. A. Abd El-Meguid, E. M. M. El-Deen, M. A. Nael and M. M. Anwar, Novel benzimidazole derivatives as anti-cervical cancer agents of potential multi-targeting kinase inhibitory activity, *Arabian J. Chem.*, 2020, **13**(12), 9179–9195.
- 131 J. Yellol, S. A. Perez, A. Buceta, G. Yellol, A. Donaire, P. Szumlas, P. J. Bednarski, G. Makhloufi, C. Janiak and A. Espinosa, Novel C, *N*-cyclometalated benzimidazole ruthenium (II) and iridium (III) complexes as antitumor and antiangiogenic agents: a structure–activity relationship study, *J. Med. Chem.*, 2015, **58**(18), 7310–7327.
- 132 P. Verweij, J. Van der Geest, W. Driessen, J. Reedijk and D. Sherrington, Metal uptake by a novel benzimidazole ligand immobilized onto poly (glycidyl methacrylate-co-ethylene glycol dimethacrylate), *React. Polym.*, 1992, **18**(3), 191–201.
- 133 T. Sabithakala and V. R. R. Chittireddy, DNA binding and in vitro anticancer activity of 2-((1*H*-benzimidazol-2-yl)



- methylamino)acetic acid and its copper (II) mixed-polypyridyl complexes: Synthesis and crystal structure, *Appl. Organomet. Chem.*, 2018, **32**(12), e4550.
- 134 Z. Wang, X. Deng, S. Xiong, R. Xiong, J. Liu, L. Zou, X. Lei, X. Cao, Z. Xie and Y. Chen, Design, synthesis and biological evaluation of chrysin benzimidazole derivatives as potential anticancer agents, *Nat. Prod. Res.*, 2018, **32**(24), 2900–2909.
- 135 X. Chen, X. Yang, F. Mao, J. Wei, Y. Xu, B. Li, J. Zhu, S. Ni, L. Jia and J. Li, Development of novel benzimidazole-derived neddylation inhibitors for suppressing tumor growth in vitro and in vivo, *Eur. J. Med. Chem.*, 2021, **210**, 112964.
- 136 S. M. Rida, F. S. Soliman, E. S. A. Badawey and T. Kappe, Benzimidazole condensed ring systems. 2. New synthesis of substituted 1-oxo-1*H*,5*H*-pyrido[1,2-*a*]benzimidazole-4-carbonitriles and related derivatives, *J. Heterocycl. Chem.*, 1988, **25**(6), 1725–1728.
- 137 J. Y. Al-Humaidi, S. M. Gomha, N. A. A. El-Ghany, B. Farag, M. E. Zaki, T. Z. Abolibda and N. A. Mohamed, Green synthesis and molecular docking study of some new thiazoles using terephthalohydrazide chitosan hydrogel as ecofriendly biopolymeric catalyst, *Catalysts*, 2023, **13**(9), 1311.
- 138 R. Sireesha, R. Sreenivasulu, C. Chandrasekhar, S. S. Jadav, Y. Pavani, M. V. B. Rao and M. Subbarao, Design, synthesis, anti-cancer evaluation and binding mode studies of benzimidazole/benzoxazole linked  $\beta$ -carboline derivatives, *J. Mol. Struct.*, 2021, **1226**, 129351.
- 139 L.-J. He, D.-L. Yang, S.-Q. Li, Y.-J. Zhang, Y. Tang, J. Lei, B. Frett, H.-k. Lin, H.-y. Li and Z.-Z. Chen, Facile construction of fused benzimidazole-isoquinolinones that induce cell-cycle arrest and apoptosis in colorectal cancer cells, *Bioorg. Med. Chem.*, 2018, **26**(14), 3899–3908.
- 140 S. Tahlan, B. Narasimhan, S. M. Lim, K. Ramasamy, V. Mani and S. A. Shah, Design, synthesis, SAR study, antimicrobial and anticancer evaluation of novel 2-mercaptobenzimidazole azomethine derivatives, *Mini-Rev. Med. Chem.*, 2020, **20**(15), 1559–1571.
- 141 S. Nashaat, M. A. Henen, S. M. El-Messery and H. Eisa, Synthesis, state-of-the-art NMR-binding and molecular modeling study of new benzimidazole core derivatives as Pin1 inhibitors: Targeting breast cancer, *Bioorg. Med. Chem.*, 2020, **28**(11), 115495.
- 142 C. Gan, X. Huang, J. Zhan, X. Liu, Y. Huang and J. Cui, Study on the interactions between B-norcholesteryl benzimidazole compounds with ct-DNA, *Spectrochim. Acta, Part A*, 2020, **227**, 117525.
- 143 C. Gan, X. Huang, Y. Wu, J. Zhan, X. Zhang, Q. Liu and Y. Huang, Untargeted metabolomics study and proapoptotic properties of B-norcholesteryl benzimidazole compounds in ovarian cancer SKOV3 cells, *J. Steroid Biochem. Mol. Biol.*, 2020, **202**, 105709.
- 144 J. Cui, B. Qi, C. Gan, Z. Liu, H. Huang, Q. Lin, D. Zhao and Y. Huang, Synthesis and in vitro antiproliferative evaluation of some B-norcholesteryl benzimidazole and benzothiazole derivatives, *Mar. Drugs*, 2015, **13**(4), 2488–2504.
- 145 M. G. Badrey, S. M. Gomha, M. E. Zaki, B. Farag and A. A. El-Reedy, Cyanauric Chloride as a key precursor and a core component for Three-Armed Triazolopyrimidines: Recent finding about SARs and docking analyses, *Results Chem.*, 2024, **7**, 101337.
- 146 W. Shehta, N. A. Alsaiari, B. Farag, M. M. Abdel-Aziz, S. Youssif, S. M. Elfeky, S. El-Kalyoubi and N. Awni, *Novel phthalimide-pyrimidine hybrids as potent anti-tubercular agents*, 2024.
- 147 M. Rashid, A. Husain, R. Mishra, S. Karim, S. Khan, M. Ahmad, N. Al-Wabel, A. Husain, A. Ahmad and S. A. Khan, Design and synthesis of benzimidazoles containing substituted oxadiazole, thiadiazole and triazolo-thiadiazines as a source of new anticancer agents, *Arabian J. Chem.*, 2019, **12**(8), 3202–3224.
- 148 B. Farag, F. Agili, S. El-Kalyoubi, S. A. Said, S. Youssif and W. Shehta, Synthesis, molecular docking and anticancer activity of some 5-aryl-5,10-dihydropyrido[2, 3-*d*:6,5-*d'*]dipyrimidine-2, 4,6,8-tetraone derivatives and pyrido [2,3-*d*]pyrimidines, *ChemistrySelect*, 2022, **7**(7), e202103834.
- 149 C.-Y. Hsieh, P.-W. Ko, Y.-J. Chang, M. Kapoor, Y.-C. Liang, H.-L. Chu, H.-H. Lin, J.-C. Horng and M.-H. Hsu, Design and synthesis of benzimidazole-chalcone derivatives as potential anticancer agents, *Molecules*, 2019, **24**(18), 3259.
- 150 D. A. Elsayed, M. E. Abdu, M. A. Marzouk, E. M. Mahmoud, W. H. El-Shwiniy, A. M. Spring and W. S. Shehab, Bio-computational modeling, POM analysis and molecular dynamic simulation for novel synthetic quinolone and benzo[*d*][1,3]oxazine candidates as antimicrobial inhibitors, *Sci. Rep.*, 2024, **14**(1), 28709.
- 151 S. Kaur, J. Kaur, A. Anand, K. Kaur and V. Choudhary, Chalcones: Effective Agents for Fighting Cancer Across Multiple Cell Lines, *ChemistrySelect*, 2024, **9**(9), e202304546.
- 152 K. A. Sheikh, A. Gupta, M. Umar, R. Ali, M. Shaquiquzzaman, M. Akhter, M. A. Khan, M. Kaleem, P. K. Ambast and S. Charan, Advances in chalcone derivatives: Unravelling their anticancer potential through structure-activity studies, *J. Mol. Struct.*, 2024, **1299**, 137154.
- 153 S. S. Chhajer, S. S. Sonawane, C. D. Upasani, S. J. Kshirsagar and P. P. Gupta, Design, synthesis and molecular modeling studies of few chalcone analogues of benzimidazole for epidermal growth factor receptor inhibitor in search of useful anticancer agent, *Comput. Biol. Chem.*, 2016, **61**, 138–144.
- 154 A. Habib, M. Nazari, M. A. Iqbal, H. N. Bhatti, M. K. Ahmed and A. A. Majid, Unsymmetrically substituted benzimidazolium based Silver (I)-*N*-heterocyclic carbene complexes: Synthesis, characterization and in vitro anticancer study against human breast cancer and colon cancer, *J. Saudi Chem. Soc.*, 2019, **23**(7), 795–808.
- 155 M. Hasanpourghadi, N. A. Majid and M. R. Mustafa, The role of miRNAs 34a, 146a, 320a and 542 in the synergistic anticancer effects of methyl 2-(5-fluoro-2-hydroxyphenyl)-



- 1*H*-benzo[*d*] imidazole-5-carboxylate (MBIC) with doxorubicin in breast cancer cells, *PeerJ*, 2018, **6**, e5577.
- 156 Y. T. Lee, Y. J. Tan and C. E. Oon, Benzimidazole and its derivatives as cancer therapeutics: The potential role from traditional to precision medicine, *Acta Pharm. Sin. B*, 2023, **13**(2), 478–497.
- 157 C. Karthikeyan, V. R. Solomon, H. Lee and P. Trivedi, Synthesis and biological evaluation of 2-(phenyl)-3*H*-benzo[*d*]imidazole-5-carboxylic acids and its methyl esters as potent anti-breast cancer agents, *Arabian J. Chem.*, 2017, **10**, S1788–S1794.
- 158 M. Hasanpourghadi, A. K. Pandurangan, C. Karthikeyan, P. Trivedi and M. R. Mustafa, Mechanisms of the anti-tumor activity of Methyl 2-(-5-fluoro-2-hydroxyphenyl)-1*H*-benzo[*d*] imidazole-5-carboxylate against breast cancer in vitro and in vivo, *Oncotarget*, 2017, **8**(17), 28840.
- 159 S. G. Nerella, Non-Carbohydrate Galectin-1 Inhibitors as Promising Anticancer Agents: Design Strategies, Structure Activity Relationship and Mechanistic Insights, *Eur. J. Med. Chem. Rep.*, 2024, 100170.
- 160 N. S. Goud, V. Pooladanda, K. M. Chandra, P. L. Soukya, R. Alvala, P. Kumar, C. Nagaraj, R. D. Bharath, I. A. Qureshi and C. Godugu, Novel benzimidazole-triazole hybrids as apoptosis inducing agents in lung cancer: Design, synthesis, 18F-radiolabeling & galectin-1 inhibition studies, *Bioorg. Chem.*, 2020, **102**, 104125.
- 161 F. F. Hagar, S. H. Abbas, H. A. Goma, B. G. Youssif, A. M. Sayed, D. Abdelhamid and M. Abdel-Aziz, Chalcone/1,3,4-Oxadiazole/Benzimidazole hybrids as novel anti-proliferative agents inducing apoptosis and inhibiting EGFR & BRAFV600E, *BMC Chem.*, 2023, **17**(1), 116.
- 162 F. Z. Karadayi, M. Yaman, M. M. Kisla, O. Konu and Z. Ates-Alagoz, Design, synthesis, anticancer activity, molecular docking and ADME studies of novel methylsulfonyl indole-benzimidazoles in comparison with ethylsulfonyl counterparts, *New J. Chem.*, 2021, **45**(20), 9010–9019.
- 163 O. Ebenezer, F. Oyetunde-Joshua, O. D. Omotoso and M. Shapi, Benzimidazole and its derivatives: Recent Advances (2020–2022), *Results Chem.*, 2023, **5**, 100925.
- 164 V. Bangade, P. Mali and H. Meshram, Solid-phase reactive chromatography (SPRC): a sustainable method for the synthesis of benzimidazol-diphenyl-2-imino-thiazolidine-4-ols (hemiaminals) which are active against lung cancer, *RSC Adv.*, 2021, **11**(4), 2320–2324.
- 165 J. Y. Al-Humaidi, L. A. Albedair, B. Farag, M. E. Zaki, Y. E. Mukhrish and S. M. Gomha, Design and synthesis of novel hybrids incorporating thiadiazole or thiazole-naphthalene: Anticancer assessment and molecular docking study, *Results Chem.*, 2024, **7**, 101475.
- 166 W. A. Mokbel, M. A. Hosny, S. M. Gomha, M. E. Zaki, B. Farag, A. F. El Faragy, A. Al Bahir and Y. H. Zaki, Synthesis, molecular docking study, and biological evaluation and of new thiadiazole and thiazole derivatives incorporating isoindoline-1,3-dione moiety as anticancer and antimicrobial agents, *Results Chem.*, 2024, **7**, 101375.
- 167 P. Li, W. Zhang, H. Jiang, Y. Li, C. Dong, H. Chen, K. Zhang and Z. Du, Design, synthesis and biological evaluation of benzimidazole-rhodanine conjugates as potent topoisomerase II inhibitors, *MedChemComm*, 2018, **9**(7), 1194–1205.

