

Cite this: *RSC Med. Chem.*, 2023, 14, 644

## Recent developments of imidazo[1,2-a]pyridine analogues as antituberculosis agents

Sauvik Samanta, <sup>a</sup> Sumit Kumar,<sup>a</sup> Eswar K. Aratikatla,<sup>a</sup> Sandeep R. Ghorpade <sup>a</sup> and Vinayak Singh \*<sup>ab</sup>

Over the past 2000 years, tuberculosis (TB) has killed more people than any other infectious disease. In 2021, TB claimed 1.6 million lives worldwide, making it the second leading cause of death from an infectious disease after COVID-19. Unfortunately, TB drug discovery research was neglected in the last few decades of the twentieth century. Recently, the World Health Organization has taken the initiative to develop new TB drugs. Imidazopyridine, an important fused bicyclic 5,6 heterocycle has been recognized as a “drug prejudice” scaffold for its wide range of applications in medicinal chemistry. A few examples of imidazo[1,2-a]pyridine exhibit significant activity against multidrug-resistant TB (MDR-TB) and extensively drug-resistant TB (XDR-TB). Here, we critically review anti-TB compounds of the imidazo[1,2-a]pyridine class by discussing their development based on the structure–activity relationship, mode-of-action, and various scaffold hopping strategies over the last decade, which is identified as a renaissance era of TB drug discovery research.

Received 14th January 2023,  
Accepted 27th February 2023

DOI: 10.1039/d3md00019b

rsc.li/medchem

### Introduction

Tuberculosis (TB) is an ancient airborne infectious disease caused by the acid-fast bacterium *Mycobacterium tuberculosis*

(*Mtb*) that primarily affects the lungs and eventually can spread to other parts of the body. It is estimated that nearly 10.6 million people were affected by TB with 1.6 million deaths worldwide, in 2021.<sup>1</sup> After the invention of the current 1st line drug regimen for the treatment of drug-sensitive TB in the 1960s, the TB drug discovery research was neglected for almost half a century, unfortunately. Recently, the World Health Organization (WHO) has taken several initiatives to reduce TB-related deaths by 95% and TB infection incidents by 90% by the

<sup>a</sup> Holistic Drug Discovery and Development (H3D) Centre, University of Cape Town, Rondebosch 7701, South Africa. E-mail: vinayak.singh@uct.ac.za

<sup>b</sup> South African Medical Research Council Drug Discovery and Development Research Unit, Institute of Infectious Disease and Molecular Medicine, University of Cape Town, Rondebosch 7701, South Africa



Sauvik Samanta

Dr. Sauvik Samanta obtained his Ph.D. in Synthetic Organic Chemistry from the Indian Institute of Technology Kanpur, India in 2015. He worked as an Erasmus Mundus postdoctoral fellow at the University of Warsaw, Poland from November 2014 for a year and thereafter joined as a Claude Leon Foundation postdoctoral fellow at the University of Cape Town in May 2016. Dr. Samanta joined H3D in July 2018 as a Medicinal Chemistry postdoctoral researcher

and in February 2022 he was appointed as a Medicinal Chemistry Investigator at H3D. His research areas include medicinal chemistry and drug discovery research for infectious diseases.



Sumit Kumar

Sumit Kumar obtained his Ph.D. in 2019 in the field of Medicinal Chemistry from Guru Nanak Dev University, Amritsar in the research group of Prof. Vipran Kumar. He worked for one year at Sphaera Pharmaceutical Pvt. Ltd. in India as Research Associate and thereafter, moved to Seoul National University, South Korea for his first post-doctorate and gained experience in the field of nanomedicine. Sumit joined Dr. Sandeep at

H3D Drug Discovery and Development as a Post-Doc in the year 2021 and is currently exploring the area of tuberculosis drug discovery.



end of 2035 to terminate the TB epidemic.<sup>1</sup> WHO has set up a target of \$2 billion annually<sup>1</sup> for TB drug discovery research to develop new TB drugs.

Drug resistance (DR) is one of the main challenges in TB treatment. Resistant *Mtb* strains of newly developed anti-TB drugs are generally found within 10 years of their first use.<sup>2,3</sup> Almost 2 in 3 individuals who develop multi-drug resistant TB (MDR-TB) each year are not receiving appropriate treatment.<sup>2</sup> Encouragingly, recent clinical uses of new and repurposed drugs have simplified and shortened the treatment regimens of MDR-TB.<sup>2–5</sup> After almost 50 years of a drought of novel TB drugs, recently,



**Eswar K. Aratikatla**

*Dr. Eswar K. Aratikatla was born in Vizianagaram, Andhra Pradesh, India. He received his M.Sc. in Organic Chemistry (2010) from Andhra University, India, and subsequently worked as a Research Chemist (2010–2012) in the pharmaceutical industry. He received his Ph.D. in Organic and Natural Product Chemistry (2019) from CSIR-National Chemical Laboratory, Pune, India. He joined the Drug Discovery and Development Centre (H3D) at the University of Cape Town in 2022 as a postdoctoral research fellow. His current research at H3D aims at developing novel antituberculosis agents. His research interests include medicinal chemistry, natural product chemistry, and the synthesis of biologically active molecules.*

*Dr. Eswar K. Aratikatla was born in Vizianagaram, Andhra Pradesh, India. He received his M.Sc. in Organic Chemistry (2010) from Andhra University, India, and subsequently worked as a Research Chemist (2010–2012) in the pharmaceutical industry. He received his Ph.D. in Organic and Natural Product Chemistry (2019) from CSIR-National Chemical Laboratory, Pune, India. He joined the Drug Discovery and Development*

new drugs bedaquiline (BDQ; Janssen Therapeutics, 2012)<sup>6</sup> and pretomanid (TB Alliance, 2019)<sup>7</sup> have been approved by the U.S. Food and Drug Administration (FDA), whereas delamanid (Otsuka Pharmaceutical Co., 2014)<sup>8</sup> was approved by European Medicines Agency (EMA) for the treatment of DR-TB. There are a few new drug candidates in the clinical development pipeline.<sup>3,9</sup> However, considering the reports of the emergence of DR against newly approved drugs and the high attrition rate of drugs in the pipeline, continuous discovery and development of new TB drugs are needed. At present, 17 drug candidates from 14 different chemical classes are being listed at various stages of clinical development (Table 1).<sup>3,9–11</sup> With few exceptions, fused bicyclic rings are a commonly observed structural feature of the TB drugs in the clinical pipeline, which often leads to issues with physicochemical properties such as high lipophilicity and low aqueous solubility, *etc.* This review focuses on one such fused bicyclic ring system, imidazo[1,2-*a*]pyridine (IP), represented by telacebec (Q203) in this list, highlighting the efforts to overcome these challenges in identifying a compound with drug-like properties.

IP, a 5,6-fused ring systems, is an important class of compounds having a range of medicinal chemistry applications. For example, zolimidine (**1**, gastroprotective drug),<sup>12,13</sup> alpidem (**2**, anxiolytic drug),<sup>14,15</sup> and zolpidem (**3**, insomnia drug)<sup>16</sup> are in clinical use (Fig. 1). Along with anticancer, antileishmanial, anticonvulsant, antimicrobial, antiviral, antidiabetic, proton pump inhibition, and insecticidal activities, this class has also shown significant potency against *Mtb*.<sup>17</sup> In this review, we discuss the recent developments of IP analogues as anti-TB agents.



**Sandeep Ghorpade**

*Dr. Sandeep R. Ghorpade heads the medicinal chemistry section of the Holistic Drug Discovery and Development Centre (H3D) of the University of Cape Town and leads H3D's TB and AMR portfolios. Before joining H3D in 2014, he worked as a team leader and senior scientist at AstraZeneca India Pvt Ltd. Bangalore, India, for ten years. Dr. Ghorpade did a Master of Pharmaceutical Sciences from the University of Mumbai and completed a Ph.D. in organic chemistry at National Chemical Laboratory, India, followed by two years of post-doctoral studies in asymmetric catalysis at the University of North Dakota, USA.*

*Dr. Sandeep R. Ghorpade heads the medicinal chemistry section of the Holistic Drug Discovery and Development Centre (H3D) of the University of Cape Town and leads H3D's TB and AMR portfolios. Before joining H3D in 2014, he worked as a team leader and senior scientist at AstraZeneca India Pvt Ltd. Bangalore, India, for ten years. Dr. Ghorpade did a Master of Pharmaceutical Sciences from the University of Mumbai and*



**Vinayak Singh**

*Vinayak Singh obtained his Ph.D. in Biochemistry from the University of Lucknow (India) in 2010, where he carried out his research at CSIR-Central Drug Research Institute, Lucknow. He then moved to the University of Cape Town (UCT) for his postdoctoral studies (2011–2016). Vinayak joined the Drug Discovery & Development Centre (H3D) at UCT in 2017; currently, he is leading tuberculosis and antimicrobial resistance biology research. Being an artist of molecular networks, genomics, and metabolomics, his main interest is to deconvolute the mechanism of action of potential compounds – to fulfil a broad and acute interest in the discovery of new innovative drugs.*

*Vinayak Singh obtained his Ph.D. in Biochemistry from the University of Lucknow (India) in 2010, where he carried out his research at CSIR-Central Drug Research Institute, Lucknow. He then moved to the University of Cape Town (UCT) for his postdoctoral studies (2011–2016). Vinayak joined the Drug Discovery & Development Centre (H3D) at UCT in 2017; currently, he is leading tuberculosis and antimicrobial resistance biology*



**Table 1** Global pipeline of new tuberculosis drugs in clinical development

Name	Chemical class	Structure	Phase
SQ109	Ethylenediamine		IIb/III
Delpazolid	Oxazolidinone		IIb
Sutezolid	Oxazolidinone		IIb
Sudapyridine (WX-081)	Triarylpyridine		IIa/IIIb
Telacebec (Q203)	Imidazo[1,2- <i>a</i> ]pyridine		IIa
Macozinone (PBTZ169)	Benzothiazinone		IIa
GSK3036656	Benzoxaborole		IIa
TBA-7371	1,4-Azaindole		IIa
Pyrifazimine	Riminophenazine		IIa



Table 1 (continued)

Name	Chemical class	Structure	Phase
OPC-167832	3,4-Dihydrocarbostyrl		(I/IIa) IIb/IIc
BTZ043	Benzothiazinone		I/IIa
TBI-223	Oxazolidinone		I
SPR720	Benzimidazole urea		I
TBAJ-876	Diarylquinoline		I
TBAJ-587	Diarylquinoline		I
GSK2556286	Pyrimidine-2,4-dione		I
BVL-GSK098	Amido-piperidine		I



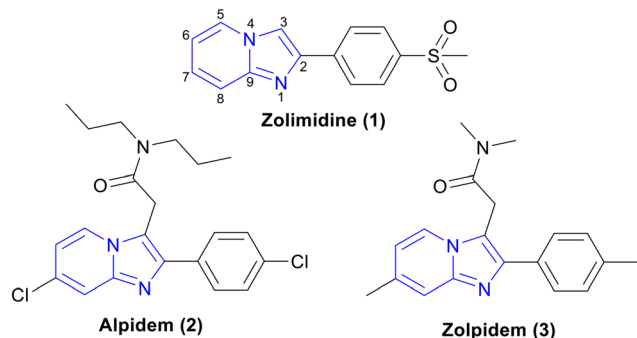


Fig. 1 Imidazo[1,2-*a*]pyridine-based drugs available in the market.

## Imidazo[1,2-*a*]pyridine amides as QcrB inhibitors

Since the approval of BDQ in 2012, anti-TB drug discovery targeting energy generation and adenosine triphosphate (ATP) synthesis became an attractive approach.<sup>18–21</sup> Oxidative phosphorylation (OxPhos) is the key factor for *Mtb* survival and growth.<sup>22</sup> In this pathway, electrons are transferred from the oxidation of organic substrates to oxygen *via* a series of protein complexes. Simultaneously, proton transportation across the inner membrane creates a proton motive force that helps ATP synthase to produce ATP from ADP. Targeting the OxPhos pathway by interacting with a protein or by blocking any step in the pathway of OxPhos, the anti-TB agents can combat mycobacterial infections and may lead to the treatment-shortening.<sup>23,24</sup> Complex III containing cytochrome *bcc* oxidase is one of the important protein complexes of *Mtb*, responsible for OxPhos pathway.<sup>25,26</sup> The QcrB, a subunit of cytochrome *bcc* is a popular target for small molecule drug discovery, including telacebec (Q203) which is an imidazo[1,2-*a*]pyridine amide (IPA) class of anti-TB drug and currently in phase II clinical trials.<sup>25,26</sup> Here we provide a brief overview of various reports on IPAs.

Vast exploration of anti-TB activity of IP analogues was started at the beginning of the last decade. Abrahams *et al.*

identified four hit compounds of the imidazo[1,2-*a*]pyridine class as potent inhibitors of *Mtb* and *M. bovis* BCG by performing a high throughput screening (HTS) approach.<sup>27</sup> The minimum inhibitory concentration (MIC), resulting in an 80% reduction in bacterial growth (MIC<sub>80</sub>), was quite promising (0.03 to 5.0 μM) against the *Mtb* H37Rv strain.

Moraski and co-workers reported a set of nine 2,7-dimethylimidazo[1,2-*a*]pyridine-3-carboxamides showing *in vitro* anti-TB activity against replicating and non-replicating (MIC<sub>90</sub>, MIC resulting in a 90% reduction in bacterial growth, range: 0.4–1.9 μM), MDR (MIC<sub>90</sub> range: 0.07–2.2 μM), and extensively drug-resistant (XDR, activity range: 0.07–0.14 μM) *Mtb*.<sup>28</sup> These compounds were non-cytotoxic against the *verda reno* (VERO) cell line (IC<sub>50</sub> >128 μM). They further explored the structure–activity relationship (SAR) of imidazo[1,2-*a*]pyridine-3-carboxamides and developed several compounds with improved activity against *Mtb*.<sup>29</sup> Five compounds showed an impressive MIC<sub>90</sub> of ≤0.006 μM against the *Mtb*. SAR investigation revealed that the bulky and more lipophilic biaryl ethers had a nanomolar range of potency. One of the front-runners 4 (Fig. 2) showed excellent activity against MDR and XDR *Mtb* strains (MIC<sub>90</sub> range: ≤0.03–0.8 μM), which is better than one of the recently approved anti-TB drugs, pretomanid. Further, a promising *in vivo* mouse pharmacokinetic (PK) profile (AUC 3850 ng h mL<sup>-1</sup> at 3 mg kg<sup>-1</sup> PO, *t*<sub>1/2</sub> 13.2 h and bioavailability 31.1%) supported the series as an exciting class of anti-TB agents.

Zolpidem (3), an FDA-approved drug for the treatment of insomnia contains imidazo[1,2-*a*]pyridine core, which inspired the same investigators to re-purpose it for TB.<sup>30</sup> Subsequently, 3 was modified to 3-carboxylates, 3-oxoacetamides, and 3-acetamides analogues, and the modified analogues were evaluated against replicating *Mtb* in various growth media. SAR studies revealed that 3-carboxylates series was more potent (MIC<sub>90</sub> range: 0.003 to 0.05 μM) than 3-oxoacetamides and 3-acetamides. However, among all the synthesized series of compounds, benzyl amides containing analogues were the most active. Most

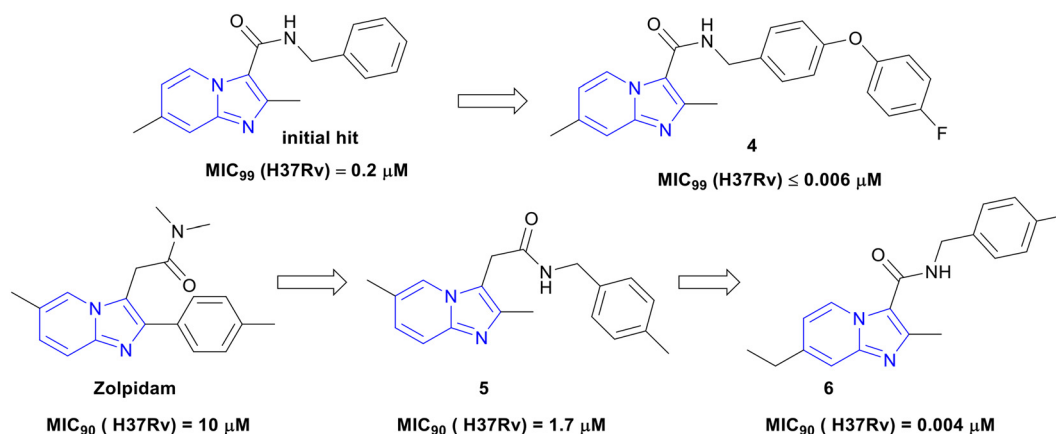


Fig. 2 First-generation highly potent IPAs.



potent compounds were profiled for the cytotoxicity against VERO, Hela (Henrietta Lacks' cells), PC-3 (prostate cancer), and MCF-7 (Michigan Cancer Foundation-7) cell lines. With a few exceptions, most of the compounds showed non-toxicity against the tested cell lines. These IPAs were also tested against non-tubercular *Mycobacteria* and were found active. These compounds were also identified as QcrB inhibitors, and the most potent compound **6** showed an MIC<sub>90</sub> of 0.004 μM against replicating *Mtb* and was nontoxic (Fig. 2). Compounds **4** and **6** in Fig. 2, which were synthetically accessible IPAs showing excellent potency against *Mtb*, can be considered as the 1st generation IPAs for the treatment of TB.

Japanese Global Health Innovative Technology (GHIT) Fund and Bill & Melinda Gates Foundation came together with the experts from the Medicines for Malaria Venture (MMV), the Drugs for Neglected Diseases initiative (DNDi), and the TB Alliance, to set disease-specific criteria for hits and leads for different infectious diseases including TB to achieve good quality starting point of the projects that can improve the likelihood of clinical success.<sup>31</sup> The hit and lead

compounds are shown in Fig. 2, which followed a set criteria (for detailed criteria of anti-TB hits and leads, please refer to the original report)<sup>31</sup> in terms of activity, cytotoxicity, tractable SAR, *etc.* Compounds **4** and **6** were the ideal starting points to develop the IPA series for anti-TB drug discovery research.

### Discovery of telacebec (Q203)

Kang and co-workers explored a novel series of imidazo[1,2-*a*]pyridine amides leading to a clinical candidate **Q203** which was active against MDR- and XDR-TB.<sup>32</sup> A library of novel IPAs was synthesized to obtain lead compounds with good drug-like properties against *Mtb*. IPA series was evaluated against both extracellular and intracellular *Mtb*. To prioritize the compounds for *in vivo* efficacy, metabolic studies were performed both in mouse and human liver microsomes and based on the data a good structure–property relationship (SPR) was established. Initial SAR studies were explored across 3-carboxamide. *N*-Benzylcarboxamide *e.g.*, compound **7** showed potent activity (MIC<sub>80</sub>, 0.045 μM) while all other

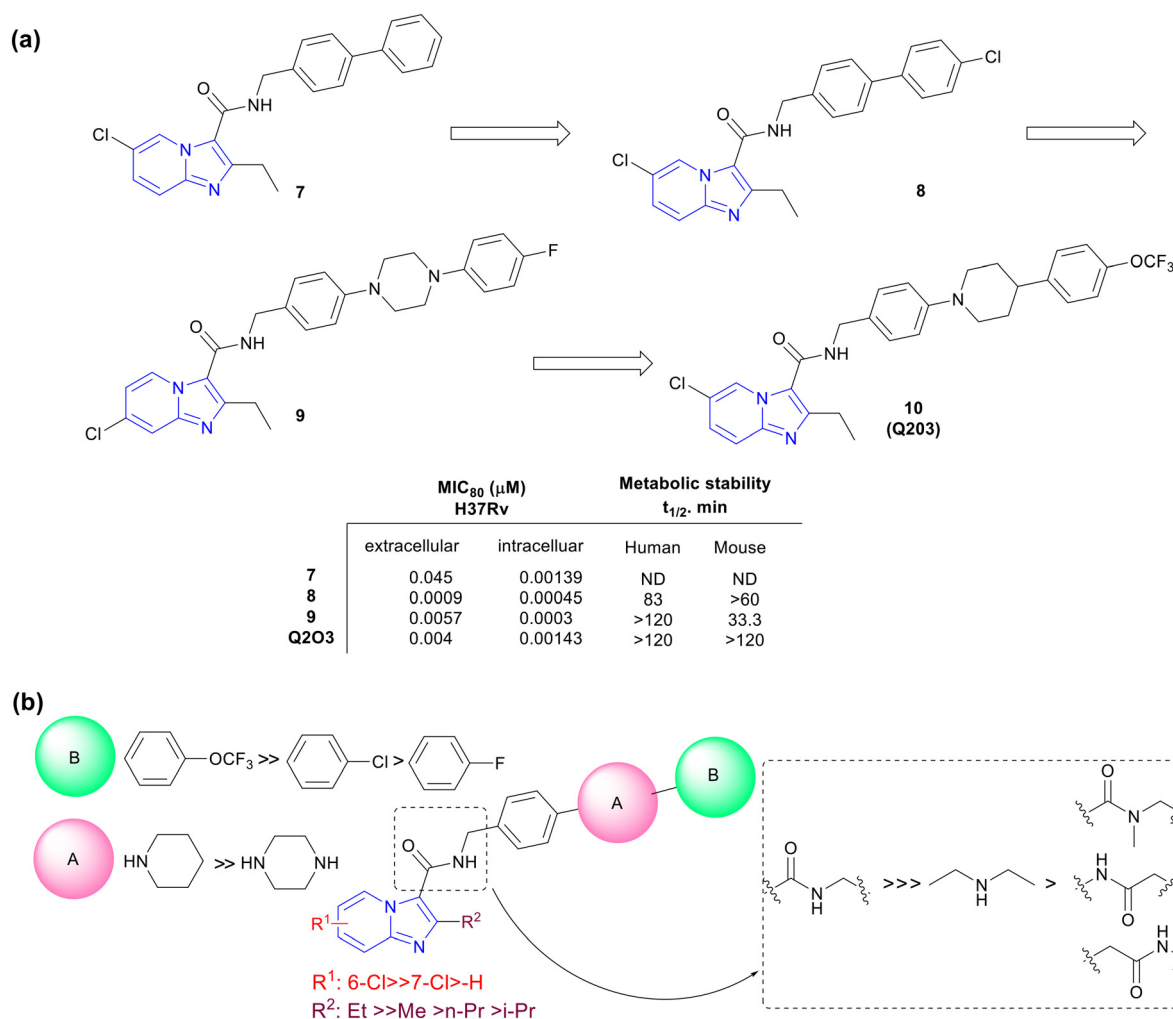


Fig. 3 (a) Schematic representation of lead optimization towards the discovery of **Q203**. (b) Generic SAR for anti-*Mtb* potency of IPA series.



modifications like tertiary carboxamide, reversed amide, insertion of methylene between the IP ring, and amide functionality abolished the activity (Fig. 3a). Further exploration of substituents at C2 and C6 positions identified compound **8**, having 2-ethyl-6-chloro imidazo[1,2-*a*]pyridine ring, with significantly improved potency against extracellular ( $MIC_{80}$ , 0.0009  $\mu\text{M}$ ) as well as intracellular ( $MIC_{80}$ , 0.00045  $\mu\text{M}$ ) *Mtb* with good microsomal stability ( $t_{1/2}$  – human 83 min and mouse 63 min). Unfortunately, the high lipophilic nature of this compound resulted in the precipitation and extended absorption in the gut resulting in suboptimal plasma exposure, hence requiring further lead optimization. Insertion of piperidine and piperazine (ring A) between two phenyl rings helped to improve microsomal stability (Fig. 3b). The second phenyl ring with C-4 substitution (ring B) was essential to maintain the potency. *e.g.*, compound **9**

with *N*-4-phenylpiperazine showed enhanced stability in both human and mouse liver microsomes with potent intracellular activity ( $MIC_{80}$ , 0.0003  $\mu\text{M}$ ) (Fig. 3a). Additionally, the ionizable nature of the basic saturated ring *viz.* piperazine and piperidine increased the solubility under acidic conditions without losing overall activity. The metabolic stability was influenced by C4-substituent on ring B following an order of substituents *viz.* trifluoromethoxy > chlorine > fluorine, respectively. Further lead optimization afforded **Q2O3** (**10**) showing  $MIC_{80}$  0.004  $\mu\text{M}$  against extracellular and 0.0014  $\mu\text{M}$  against intracellular *Mtb* with high microsomal stability and minimal cytochrome P450 inhibition (CYP450,  $IC_{50}$  >100  $\mu\text{M}$ ; Fig. 3a).

**Q2O3** showed a good PK profile ( $t_{1/2}$ , 23.4 h; oral bioavailability, 90.7%; and IV-Cl, 4.0  $\text{mL min}^{-1} \text{kg}^{-1}$ ) in mice and no cytotoxicity ( $IC_{50}$ , >10  $\mu\text{M}$ ) against three human cell

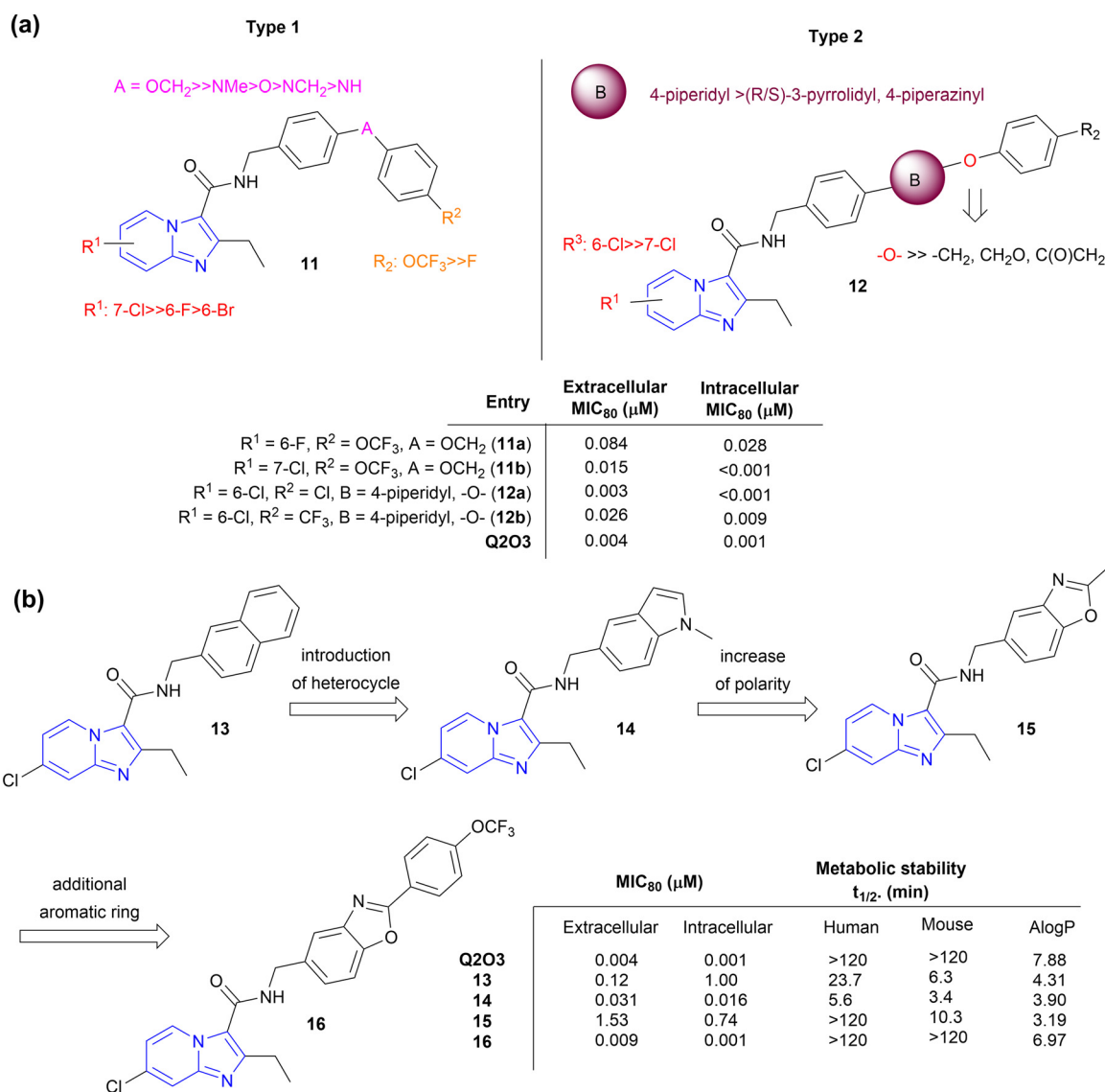


Fig. 4 Side-chain modification of **Q2O3**. (a) Generic SAR of side-chain modification with linkers, (b) Lead optimization of side-chain modification with a fused ring system.



lines *e.g.*, neuroblastoma cell line (SH-SY5Y), human embryonic kidney 293 (HEK293), and human liver cancer cell line (HepG2). The compound did not inhibit the human *ether-à-go-go*-related gene (hERG), suggesting a low risk of cardiotoxicity. The acute TB mouse model (BALB/c mice infected with *Mtb* H37Rv)<sup>33</sup> indicated 90%, 99%, and 99.9% reduction of bacterial load when treated with 0.4, 2.0, and 10.0 mg kg<sup>-1</sup> doses of **Q203**, respectively, after 4 weeks of treatment. Importantly, **Q203** displayed pharmacokinetic and safety profiles compatible with once-daily dosing. Hence it was selected as a clinical candidate for further development.<sup>34</sup>

### Side chain modification of Q203

Kang *et al.* focused on side chain modification of **Q203** to understand the role of the right-hand side chain moiety on anti-tubercular activity.<sup>35</sup> Two types of compounds were synthesized *viz.* type 1 (compound **11**) and type 2 (compound **12**), respectively (Fig. 4a). Type 1 compounds contained linkers like ether, methyl ether, amine, and methyl amines between two aryl moieties which made them conformationally more flexible than **Q203**. The introduction of 6-Br on the IP ring resulted in a decrease in activity by 16-fold while the Cl atom enhanced the potency, indicating a crucial role of a steric factor over an electronic factor in determining extracellular MIC<sub>80</sub>. Type 1 compounds with -OCH<sub>2</sub>, -O, and -NMe linkers in combination with trifluoromethoxy substituents on the terminal phenyl ring showed potent MICs whereas those with -NCH<sub>2</sub>, and -NH linkers showed significantly weaker MICs. Type 2 analogues contained cyclic amines like piperidine, pyrrolidine, and piperazine along with the extended phenyl ring. Regardless of the R<sup>2</sup> substituent on the phenyl ring in type 2, analogues having ether linker next to the piperidine ring displayed excellent activity (MIC<sub>80</sub>, 0.003–0.026 μM). It was suggested that the lipophilicity is more important than the linearity of the side chain in retaining activity, and a flexible linker will help reorientation of the side chain for strong target binding. The *in vivo* pharmacokinetic properties study of the most potent analogues (**11a**, **11b**, **12a**, **12b**; Fig. 4) showed low systemic clearance (2.23–5.77 mL min<sup>-1</sup> kg<sup>-1</sup>) with good oral bioavailability (51.4–80.5%) indicating the potential to further evaluate these analogues for their *in vivo* efficacy.

Similarly, the introduction of fused bicyclic rings such as naphthyl, indole, and benzo[*d*]oxazole (compounds **12–15**, Fig. 4b) maintained anti-TB activity with a reduction of lipophilicity compared to **Q203** (AlogP, 4.3–3.2), but compounds were rapidly metabolized in human and mouse liver microsomes with exception of **15** that showed relatively better stability in human microsomes.<sup>36,37</sup> Compound **16** with 4-F-phenyl group added at C2-position of benzo[*d*]oxazole ring showed >100-fold better anti-TB activity and high metabolic stability in both human and mouse microsomes. On oral administration at a dose of 10 mg kg<sup>-1</sup>, **16** showed low systemic clearance and high drug exposure

levels (AUC<sub>0-inf</sub>, 116 400 h ng mL<sup>-1</sup>) with a long half-life of 36.3 h.

### Core modifications of Q203

The success of **Q203** kindled interest in exploring scaffold hopping,<sup>38–42</sup> *i.e.*, the replacement of the fused bicyclic imidazo[1,2-*a*]pyridine framework of IPAs with another fused bicyclic scaffolds, to identify molecules targeting the QcrB complex. In 2015, Tang and co-workers<sup>43</sup> reported a scaffold hopping study on Ambien “anagram” (**17**)<sup>30</sup> as an anti-TB agent, derived from the sleep aid, Ambien (zolimidine, **1**). The investigators designed and synthesized a library of pyrazolo[1,5-*a*]pyridines-3-carboxamides (PPAs). One of the lead compounds **18** was encouragingly active against *Mtb* (Fig. 5a). Further SAR studies on **18** led to a highly potent anti-TB compound **TB47** (**19**), a structurally matched pair of **Q203** with a PPA core. **TB47** was equipotent to **Q203** (Fig. 5a) and was confirmed to be a QcrB inhibitor.<sup>44</sup> The compound was not cytotoxic (CC<sub>50</sub>, >100 μM on Vero and HepG2 cells) or cardiotoxic (hERG IC<sub>50</sub>, >30 μM).<sup>43</sup> The compound showed high plasma protein binding and poor CaCo-2 permeability but demonstrated an excellent rat PK profile (*t*<sub>1/2</sub>, 19 h; oral bioavailability, 94%). Furthermore, **19** was efficacious in the acute mouse model and showed synergy when combined with rifampicin (10 mg kg<sup>-1</sup>) or pyrazinamide (150 mg kg<sup>-1</sup>), but was less active in the chronic mouse model compared to **Q203**,<sup>45</sup> but it demonstrated good *in vivo* synergy with other anti-TB agents such as clofazimine and linezolid in mouse relapse model of TB.<sup>46</sup> It also showed good *in vivo* efficacy against *M. ulcerans*.<sup>47</sup> The compound is undergoing preclinical safety studies.<sup>48</sup> The backup candidate, analogue **20** with heterobiaryl side chain, was 3-fold more active against *Mtb* than **19** and did not show cytotoxicity against VERO cells (CC<sub>50</sub>, >110 μM, Fig. 5a).<sup>49</sup> It displayed a moderate rat PK profile (*t*<sub>1/2</sub>, 5.1 h; oral bioavailability, 41%). Efficacy in an acute mouse model suggested that the compound has the potential to be a lead candidate for further anti-TB drug discovery.<sup>48,50</sup>

Moraski *et al.* performed scaffold hopping SAR study<sup>51</sup> and developed imidazo[2,1-*b*]thiazole derivative **ND-11543** (**21**) (Fig. 5b).<sup>52</sup> Compound **21** exhibited excellent activities against both replicating (MIC<sub>90</sub> 0.008 μM) and nonreplicating (LORA, MIC<sub>90</sub>, 1.1 μM) *Mtb* and was shown to target QcrB. It was noncytotoxic against VERO cells (CC<sub>50</sub>, >100 μM), had reasonable solubility (50 μM), showed moderate human liver microsomal stability (*t*<sub>1/2</sub>, 28 min), but showed 100% plasma protein binding with low CaCo-2 permeability. The compound had reasonable total drug exposure that remained above the MIC for 24 h at 200 mg kg<sup>-1</sup> oral dose in mice but showed only ~0.3 log CFU reduction in the chronic model most likely due to inadequate free drug exposure above MIC. Further optimization of the physicochemical and pharmacokinetic properties is warranted for progressing this class of compounds into preclinical studies.



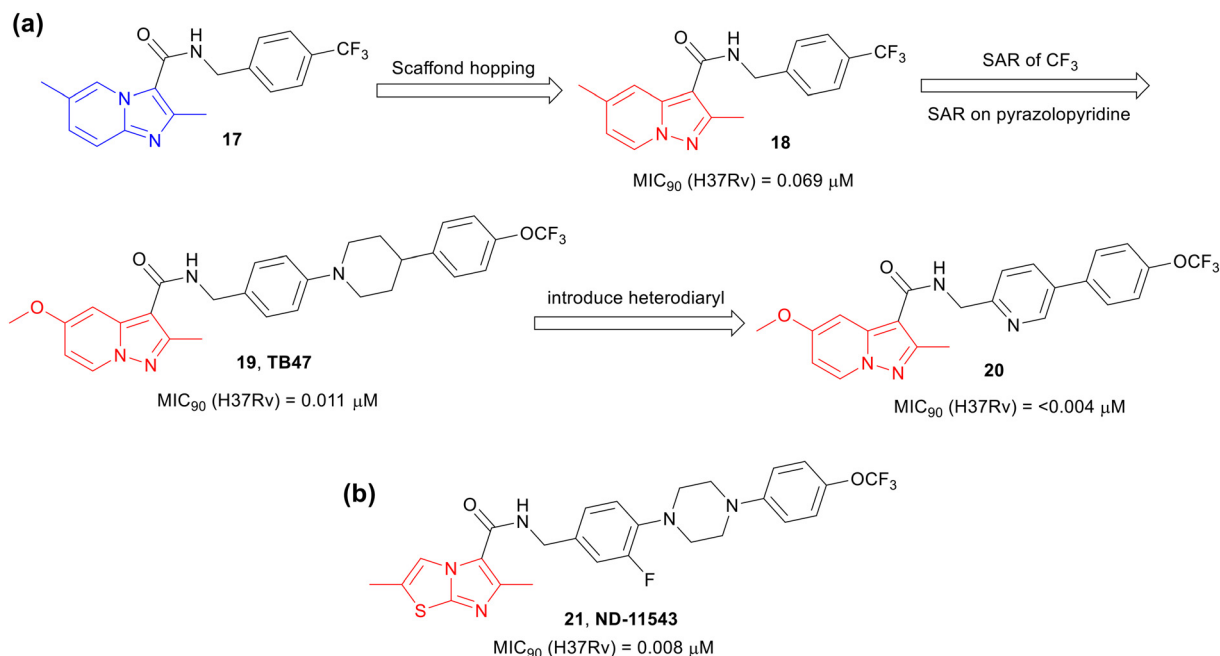


Fig. 5 Scaffold hopping of Q203. (a) Development of TB47 and further optimization, (b) ND-11543.

### Other IPs targeting QcrB

To reduce the lipophilicity of Q203, Wang and co-workers explored new series of IPA derivatives with basic heterocycles,

tetrahydroisoquinolines, obtained by the fusion of benzene with piperidine or pyrrolidine rings.<sup>53</sup> They optimized IPA 22 (Fig. 6) which was equipotent as Q203 with  $\text{MIC}_{90} < 0.035 \mu\text{M}$  against both drug-susceptible (DS) and DR *Mtb* strains. It was

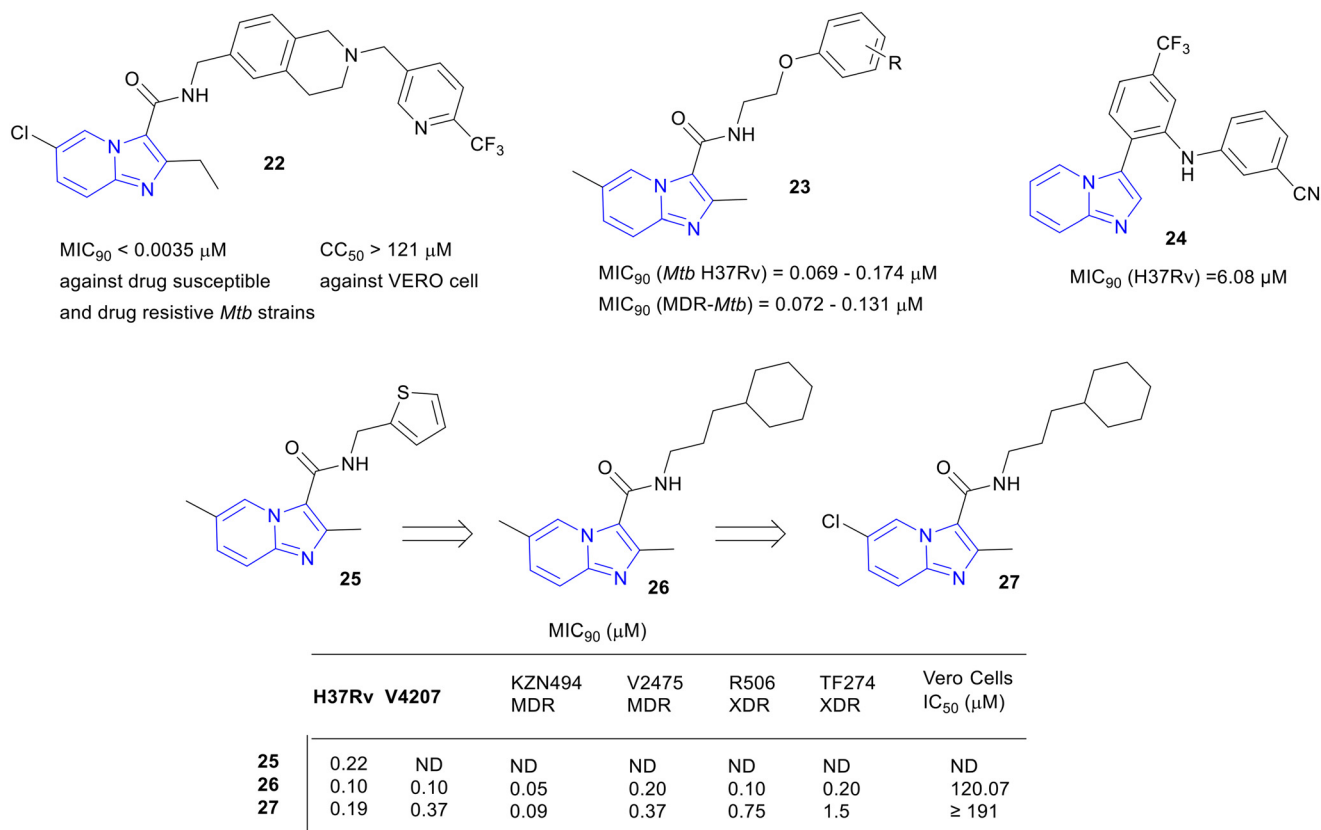


Fig. 6 IPs as potent *Mtb* inhibitors, targeting QcrB.



non-cytotoxic against the VERO cell line ( $CC_{50}$ ,  $>121 \mu\text{M}$ ) and showed better aqueous solubility compared to **Q203** ( $2.10 \text{ mg mL}^{-1}$  vs.  $0.079 \text{ mg mL}^{-1}$ ) resulting in better drug levels in plasma at an oral dose of  $25 \text{ mg kg}^{-1}$  in mice ( $AUC_{0-\infty}$   $54916 \text{ h ng mL}^{-1}$  vs.  $46637 \text{ h ng mL}^{-1}$ ).

A series of *N*-(2-phenoxyethyl)imidazo[1,2-*a*]pyridine-3-carboxamides **23** was designed and synthesized as a novel anti-TB agent (Fig. 6).<sup>54</sup> Seven most active compounds from the series showed excellent *in vitro* activity ( $MIC_{90}$ ,  $0.069$ – $0.174 \mu\text{M}$ ) against DS *Mtb*. The compounds were also active against MDR-*Mtb* strains. The lead compound, where  $R = 4\text{-Br}$ , demonstrated an acceptable safety profile in the acute toxicity study and a good PK profile ( $AUC_{0-\infty}$ ,  $288.22 \text{ h ng mL}^{-1}$ ;  $t_{1/2}$ ,  $1.5 \text{ h}$ ) in rats.

With an intent to explore other IPs, Karale *et al.* reported a new potent anti-TB agent, 3-arylsubstituted IP, by replacing the extended amide side chain of **Q203** with different substituted aryl or heteroaryl rings at the C-3 position.<sup>55,56</sup> Initially they found a hit compound with a trifluoromethylphenyl substitution at the C-3 position ( $MIC_{90}$ ,  $21.16 \mu\text{M}$ ). Further SAR exploration of the aromatic ring on C-3, led to amine-substituted 3-arylimidazo[1,2-*a*]pyridine analog with promising activity against *Mtb*. Despite good anti-*Mtb* activities, most of the compounds showed significant cytotoxicity against Chinese hamster ovary cells (CHO-K1). However, compound **24** ( $MIC_{90}$ ,  $6.08 \mu\text{M}$ ) indicated significant improvement in cytotoxicity (CHO-K1,  $IC_{50}$ ,  $216.72 \mu\text{M}$ ) (Fig. 6). The docking model of **24** in the active side of *Mtb* QcrB showed significant  $\pi$ - $\pi$  interactions with amino acid residues, confirming **24** as a promising lead compound to proceed further (refer to Fig. 3 in the original article).<sup>55</sup>

Onajole *et al.* reported IPA analogues containing cyclic aliphatic rings at the amide end and evaluated against DS H37Rv, V4207, MDR KZN494, MDR V2475, XDR R506, and TF274 strains of *Mtb*.<sup>57</sup> SAR studies revealed that the potency

of analogues is dependent on the carbon spacer between amide nitrogen and the cyclic aliphatic ring. In general, a three-carbon spacer enhanced the overall activity. Most active compounds **26** and **27** were 1.5–3-fold more potent than the reference drug isoniazid (Fig. 6). Most potent compounds were tested against MDR and XDR clinical isolates, and results demonstrated their high efficiency to treat DR TB. The toxicity of the active compounds was screened against VERO cells and the compounds were non-cytotoxic with a good selectivity index ( $IC_{50} \text{ VERO}/MIC_{90}$ ,  $\geq 1024$ ).

## IPs with other MOAs

### 2-*Trans*-enoyl-acyl carrier protein reductase (InhA) inhibitors

Synthesis of various imidazo[1,2-*a*]pyridine-2-carboxamide derivatives and their profiling against *Mtb* and human cell line were done by Jose and co-workers.<sup>58</sup> Synthesized series of IPAs (**28**) were screened against *Mtb* and the most potent derivatives of the series showed a  $MIC$  ranging from 17 to  $30 \mu\text{M}$  (Fig. 7) with no cytotoxicity. The molecular docking study of the InhA domain with a few synthesized compounds showed good inhibition against the enzyme. The SAR study indicated that 2-carboxamides IPAs showed much weaker  $MICs$  than the IPAs with 3-carboxamides and a switch in the mode of action (MoA) could be a possible reason.

### *Mtb* pantothenate synthetase (PS) inhibitors

2-Methylimidazo[1,2-*a*]pyridine-3-carbohydrazides were identified as *Mtb* pantothenate synthetase (PS) inhibitors.<sup>59</sup> Derivative **29** (Fig. 7) was the most active compound against *Mtb* ( $MIC_{90}$ ,  $4.53 \mu\text{M}$ ) from the library of synthesized hydrazides and it displayed no cytotoxicity against mouse macrophage cell line (RAW 264.7). The PS inhibition was confirmed by testing the compounds in a PS assay where adenosine monophosphate (AMP) was produced by the

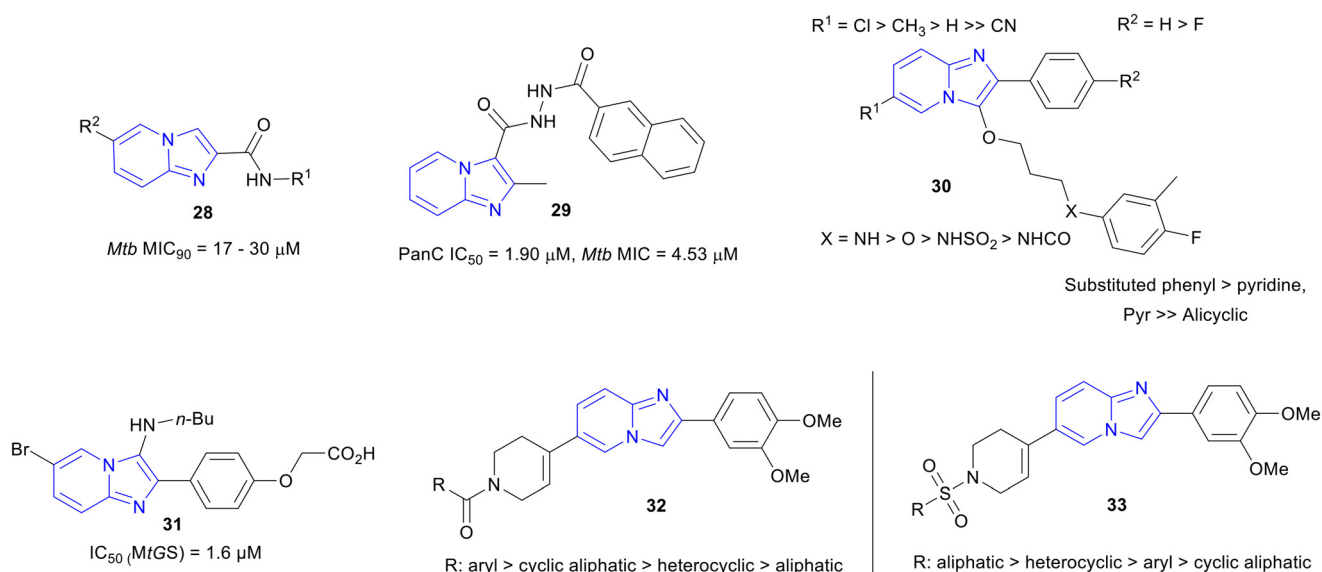


Fig. 7 IPs as potent *Mtb* inhibitors with various MoAs. The “>” sign indicates better target and whole cell activity.



oxidation of NADH to NAD<sup>+</sup>, because of the condensation of  $\beta$ -alanine and pantoate through different kinases. Most of the compounds showed more than 50% inhibition against *Mtb* PS.

### ATP synthase inhibitors

Imidazo[1,2-*a*]pyridine ethers (IPE, **30**) were discovered as selective and potent inhibitors of mycobacterial ATP synthesis (ATPS) and anti-*Mtb* activity (Fig. 7).<sup>60</sup> The IPE hit was identified from the AstraZeneca library using HTS. During the hit to lead, a library of IPEs was developed based on both ATP synthesis inhibition<sup>61–64</sup> and *Mtb* MIC. The most active compounds showed a potency of MIC<sub>80</sub> < 0.5  $\mu$ M with ATPS IC<sub>50</sub> < 0.02  $\mu$ M. The general SAR informed that the bridgehead nitrogen of IP and directly attached phenyl ring were essential for maintaining the biological activity (Fig. 7). Chloro/methyl substitutions at the R<sup>1</sup> position were responsible for the best potency, and H got preference over F at the R<sup>2</sup> position for improving potency. Interestingly, –NH– or –O– at the terminal aryl linkage yielded the best potency against both the target and the *Mtb*, among all the other linker functionalities. The detailed SAR trend showed that –NH– linkage acted slightly better than the –O– linker in terms of potency. The substituted phenyl was preferred over hetero aromatic rings at the terminal ring of the side chain for maintaining activity. However, the minimum bactericidal concentration (MBC) of many IPEs was >100  $\mu$ M against *Mtb*. In addition, the compounds from this series faced the barrier of poor solubility and PK profile that decided to deprioritize the series for further development.

### *Mtb* glutamine synthetase (MtGS) inhibitors

3-Amino-imidazo[1,2-*a*]pyridines as glutamine synthetase (MtGS) inhibitor, a potential target for the *Mtb* drug development, were developed.<sup>65,66</sup> A library of 3-amino-imidazo[1,2-*a*]pyridines was synthesized employing microwave-assisted one-pot Ugi-type multi-component reaction. The molecular docking model of one of the most active compounds **31** (MtGS IC<sub>50</sub>, 1.6  $\mu$ M) on the MtGS complex was found to be a very good fit in the ATP-binding site and confirmed the target (Fig. 7).<sup>65</sup>

### IPs with unknown MOAs

Recently, two novel imidazopyridine series were reported: *N*-carbonyl substituted IP (C-IP) and *N*-sulphonyl substituted IP (S-IP).<sup>67</sup> Libraries of C-IP (**32**) and S-IP (**33**) were synthesized and evaluated for *in vitro* anti-*Mtb* activity. A few compounds exhibited excellent activities (IPA MIC<sub>90</sub>, 0.11  $\mu$ M; IPS MIC<sub>90</sub>, 0.98  $\mu$ M). The SAR trends for both series were reported (Fig. 7). Aromatic and cyclic aliphatic amide groups were responsible for the improved potency of C-IP whereas, aliphatic and heterocyclic sulphonamides of S-IP were more active against *Mtb*. Active compounds from both series were found to be nontoxic against HEK cells (SI  $\geq$  66). Furthermore, predicted ADME (absorption–distribution–metabolism–excretion) values for the lead compounds were obtained within the range of the marketed drugs.

### Hybrid molecules

To expand SAR studies of potential anti-TB agents, a hybrid scaffold approach of combining two classes of known anti-TB

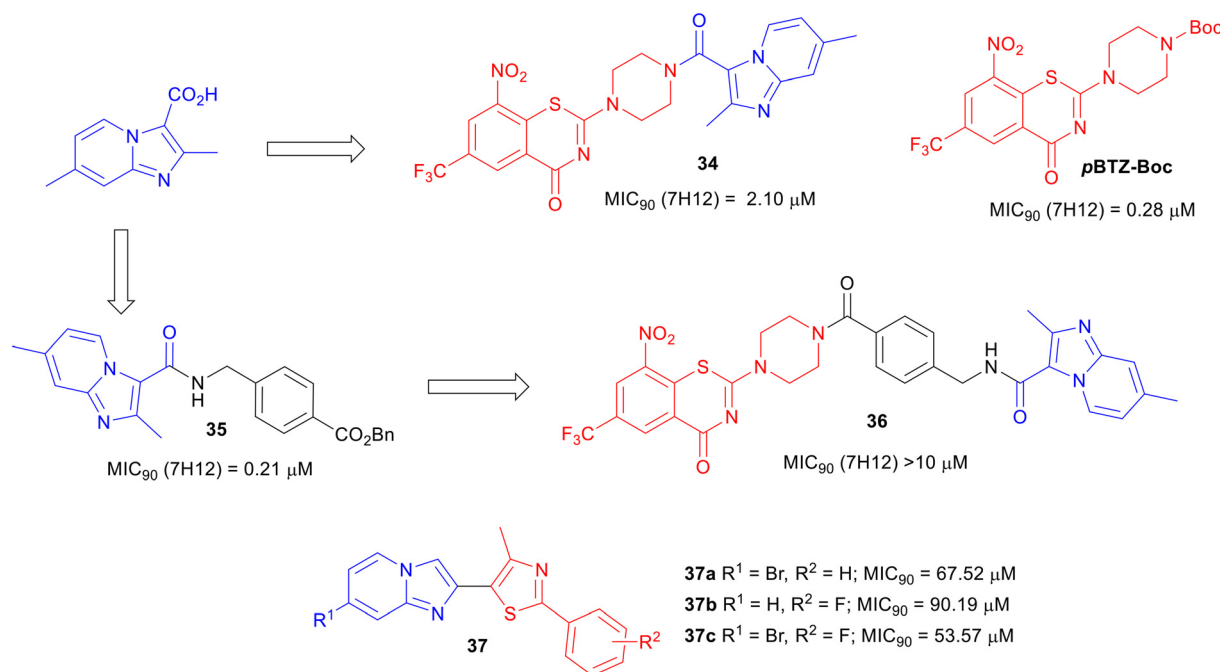


Fig. 8 Hybrid molecules having IP scaffold showing activities against *Mtb*.



compounds has been used. Majewski *et al.* reported the coupling of piperazino-1,3-benzothiazin-4-ones (PBTZs) with IP to explore the anti-TB potency of the synthesized conjugates.<sup>68</sup> Benzothiazinones are anti-TB drug candidates that target arabinan synthesis.<sup>69–71</sup> The conjugated compound **34** was synthesized by the coupling reaction between imidazopyridine carboxylic acid and TFA salt of PBTZ, obtained after Boc deprotection of PBTZ-Boc (Fig. 8). PBTZ-Boc showed an MIC<sub>90</sub> of 0.28 μM against *Mtb*, whereas the conjugate **34** lost about 7.5-fold potency. They introduced a 4-aminomethylphenylcarboxyl spacer in between IP and PBTZ but the strategy (compound **36**) was further detrimental to the activity. In summary, the conjugation of two potent anti-TB agents PBTZ and IPA did not yield improved potency.

Thiazoles are another important pharmacophore known for anti-TB activity.<sup>72–74</sup>

Abhale *et al.* synthesized a set of thiazole and IP conjugates **37**.<sup>75</sup> Only a few compounds (**37a**, **37b**, and **37c**) from their synthesized library showed a low potency against *M. smegmatis* (Fig. 8). Although a few conjugation strategies between two or more classes of pharmacophores have been able to yield anti-*Mtb* agents with good potency, the hybridization of IP with another class of compounds did not yield promising results in terms of TB drug discovery research.

## Conclusions

Despite significant challenges, the recent advancements in TB drug discovery and development provide a positive outlook for the future. In this respect, the imidazopyridine class of compounds, recognized as the ‘drug prejudice’,<sup>76</sup> have gained significant consideration in the recent past. **Q203**, the most advanced anti-TB drug candidate from this class, is in phase II clinical trial.<sup>77,78</sup> The development of **Q203** offered a new horizon to anti-TB drug discovery research targeting QcrB. Several synthetic modification strategies of imidazopyridine amides have been acquired around **Q203**, particularly the long-side chain modification to reduce lipophilicity and induce polarity. *In vivo* studies have been initiated with a few modified compounds. The case study of IPAs leading to the discovery of **Q203** demonstrates that the introduction of polar functionalities, such as amides and higher sp<sup>3</sup> character is essential to overcome issues of high lipophilicity and poor aqueous solubility of fused bicyclic systems, such as IPs, to deliver drug-like molecules. Further exploration in this area needs to incorporate these learnings. Scaffold hopping of **Q203** contributed significant advancement to the anti-TB drug discovery research. **TB47** is one of the promising scaffold-hopped candidates completing safety profiling at pre-clinical development. Other IP designs also showed promising initial results to take a few of them for further development. In summary, although TB drug discovery research of IP class looks promising, continuous discovery and development of anti-TB compounds are essential to fight against DR *Mtb*.

## Author contributions

S. S., S. K., E. K. A., S. R. G., and V. S. designed the content and flow of the paper. S. S., S. K., and E. K. A. collected the necessary information/data and prepared the first draft. S. S., S. K., E. K. A., S. R. G., and V. S. wrote the paper.

## Conflicts of interest

There are no conflicts to declare.

## Acknowledgements

The Bill and Melinda Gates Foundation (Global Health Grant Number OPP1066878), South African Medical Research Council (SAMRC), Strategic Health Innovation Partnerships (SHIP) unit of the SAMRC, Technology Innovation Agency (TIA), South African Department of Science and Innovation, and South African National Research Foundation are gratefully acknowledged for support.

## References

- 1 W. H. Organization, *Global tuberculosis report 2022*, 2022.
- 2 W. H. Organization, *WHO operational handbook on tuberculosis: module 4: treatment: drug-susceptible tuberculosis treatment*, Report 9240050760, 2022.
- 3 V. Singh and K. Chibale, *Acc. Chem. Res.*, 2021, **54**, 2361–2376.
- 4 B. B. Aldridge, D. Barros-Aguirre, C. E. Barry, R. H. Bates, S. J. Berthel, H. I. Boshoff, K. Chibale, X.-J. Chu, C. B. Cooper and V. Dartois, *Nat. Med.*, 2021, **27**, 1333–1337.
- 5 F. Conradie, A. H. Diacon, N. Ngubane, P. Howell, D. Everitt, A. M. Crook, C. M. Mendel, E. Egizi, J. Moreira and J. Timm, *N. Engl. J. Med.*, 2020, **382**, 893–902.
- 6 A. K. Kakkar and N. Dahiya, *Tuberculosis*, 2014, **94**, 357–362.
- 7 S. J. Keam, *Drugs*, 2019, **79**, 1797–1803.
- 8 N. J. Ryan and J. H. Lo, *Drugs*, 2014, **74**, 1041–1045.
- 9 G. F. Fernandes, A. M. Thompson, D. Castagnolo, W. A. Denny and J. L. Dos Santos, *J. Med. Chem.*, 2022, **65**, 7489–7531.
- 10 S. Huszár, K. Chibale and V. Singh, *Drug Discovery Today*, 2020, **25**, 772–780.
- 11 *New TB Drugs Clinical Pipeline*, <https://www.newtbdrugs.org/pipeline/clinical>.
- 12 C. Parisio and F. Clementi, *Lab. Invest.*, 1976, **35**, 484–495.
- 13 D. Belohlavek and P. Malfertheiner, *Scand. J. Gastroenterol., Suppl.*, 1979, **54**, 44–44.
- 14 B. Zivkovic, E. Morel, D. Joly, G. Perrault, D. Sanger and K. Lloyd, *Pharmacopsychiatry*, 1990, **23**, 108–113.
- 15 D. Sanger and B. Zivkovic, *Psychopharmacology*, 1994, **113**, 395–403.
- 16 J. Hoehns and P. Perry, *Clin. Pharm.*, 1993, **12**, 814–828.
- 17 A. Deep, R. Kaur Bhatia, R. Kaur, S. Kumar, U. Kumar Jain, H. Singh, S. Batra, D. Kaushik and P. Kishore Deb, *Curr. Top. Med. Chem.*, 2017, **17**, 238–250.
- 18 A. M. Thompson and W. A. Denny, in *Annual reports in medicinal chemistry*, Elsevier, 2019, vol. 52, pp. 97–130.



- 19 C. S.-Y. Foo, K. Pethe and A. Lupien, *Appl. Sci.*, 2020, **10**, 2339.
- 20 I. K. Iqbal, S. Bajeli, A. K. Akela and A. Kumar, *Pathogens*, 2018, **7**, 24.
- 21 Q. Li and X. Lu, *Chin. Chem. Lett.*, 2020, **31**, 1357–1365.
- 22 D. Bald, C. Villellas, P. Lu and A. Koul, *MBio*, 2017, **8**, e00272-17.
- 23 G. M. Cook, K. Hards, C. Vilchèze, T. Hartman and M. Berney, *Microbiol. Spectrum*, 2014, **2**, 2.3. 06.
- 24 T. O'malley, T. Alling, J. V. Early, H. A. Wescott, A. Kumar, G. C. Moraski, M. J. Miller, T. Masquelin, P. A. Hipskind and T. Parish, *Antimicrob. Agents Chemother.*, 2018, **62**, e02439-17.
- 25 H. Gong, J. Li, A. Xu, Y. Tang, W. Ji, R. Gao, S. Wang, L. Yu, C. Tian and J. Li, *Science*, 2018, **362**, eaat8923.
- 26 S. Safarian, H. K. Opel-Reading, D. Wu, A. R. Mehdipour, K. Hards, L. K. Harold, M. Radloff, I. Stewart, S. Welsch and G. Hummer, *Nat. Commun.*, 2021, **12**, 1–10.
- 27 K. A. Abrahams, J. A. Cox, V. L. Spivey, N. J. Loman, M. J. Pallen, C. Constantinidou, R. Fernandez, C. Alemparte, M. J. Remuinan and D. Barros, *PLoS One*, 2012, **7**, e52951.
- 28 G. C. Moraski, L. D. Markley, P. A. Hipskind, H. Boshoff, S. Cho, S. G. Franzblau and M. J. Miller, *ACS Med. Chem. Lett.*, 2011, **2**, 466–470.
- 29 G. C. Moraski, L. D. Markley, J. Cramer, P. A. Hipskind, H. Boshoff, M. A. Bailey, T. Alling, J. Ollinger, T. Parish and M. J. Miller, *ACS Med. Chem. Lett.*, 2013, **4**, 675–679.
- 30 G. C. Moraski, P. A. Miller, M. A. Bailey, J. Ollinger, T. Parish, H. I. Boshoff, S. Cho, J. R. Anderson, S. Mulugeta and S. G. Franzblau, *ACS Infect. Dis.*, 2015, **1**, 85–90.
- 31 K. Katsuno, J. N. Burrows, K. Duncan, R. H. Van Huijsduijnen, T. Kaneko, K. Kita, C. E. Mowbray, D. Schmatz, P. Warner and B. Slingsby, *Nat. Rev. Drug Discovery*, 2015, **14**, 751–758.
- 32 S. Kang, R. Y. Kim, M. J. Seo, S. Lee, Y. M. Kim, M. Seo, J. J. Seo, Y. Ko, I. Choi and J. Jang, *J. Med. Chem.*, 2014, **57**, 5293–5305.
- 33 J. Rullas, J. I. García, M. Beltrán, P.-J. Cardona, N. Cáceres, J. F. García-Bustos and I. Angulo-Barturen, *Antimicrob. Agents Chemother.*, 2010, **54**, 2262–2264.
- 34 K. Pethe, P. Bifani, J. Jang, S. Kang, S. Park, S. Ahn, J. Jiricek, J. Jung, H. K. Jeon and J. Cechetto, *Nat. Med.*, 2013, **19**, 1157–1160.
- 35 S. Kang, Y. M. Kim, R. Y. Kim, M. J. Seo, Z. No, K. Nam, S. Kim and J. Kim, *Eur. J. Med. Chem.*, 2017, **125**, 807–815.
- 36 S. Kang, Y. M. Kim, H. Jeon, S. Park, M. J. Seo, S. Lee, D. Park, J. Nam, S. Lee and K. Nam, *Eur. J. Med. Chem.*, 2017, **136**, 420–427.
- 37 *AlogP prediction was derived from Discovery Studio*, BIOVIA, San Diego, CA, 2016.
- 38 H.-J. Böhm, A. Flohr and M. Stahl, *Drug Discovery Today: Technol.*, 2004, **1**, 217–224.
- 39 H. Sun, G. Tawa and A. Wallqvist, *Drug Discovery Today*, 2012, **17**, 310–324.
- 40 S. R. Langdon, P. Ertl and N. Brown, *Mol. Inf.*, 2010, **29**, 366–385.
- 41 Y. Hu, D. Stumpfe and J. R. Bajorath, *J. Med. Chem.*, 2017, **60**, 1238–1246.
- 42 P. Ertl, Identification of Bioisosteric Scaffolds using Scaffold Keys, *ChemRxiv*, 2021, preprint, DOI: [10.26434/chemrxiv.13525457](https://doi.org/10.26434/chemrxiv.13525457).
- 43 J. Tang, B. Wang, T. Wu, J. Wan, Z. Tu, M. Njire, B. Wan, S. G. Franzblau, T. Zhang and X. Lu, *ACS Med. Chem. Lett.*, 2015, **6**, 814–818.
- 44 S. Zhou, W. Wang, X. Zhou, Y. Zhang, Y. Lai, Y. Tang, J. Xu, D. Li, J. Lin and X. Yang, *eLife*, 2021, **10**, e69418.
- 45 X. Lu, Z. Williams, K. Hards, J. Tang, C.-Y. Cheung, H. L. Aung, B. Wang, Z. Liu, X. Hu and A. Lenaerts, *ACS Infect. Dis.*, 2018, **5**, 239–249.
- 46 W. Yu, B. Yusuf, S. Wang, X. Tian, H. A. Hameed, Z. Lu, G. Chiwala, M. S. Alam, G. M. Cook and D. A. Maslov, *Antimicrob. Agents Chemother.*, 2021, **65**, e00706–e00721.
- 47 Y. Liu, Y. Gao, J. Liu, Y. Tan, Z. Liu, C. Chhotaray, H. Jiang, Z. Lu, G. Chiwala and S. Wang, *Nat. Commun.*, 2019, **10**, 1–9.
- 48 W. Yu, G. Chiwala, Y. Gao, Z. Liu, S. Sapkota, Z. Lu, L. Guo, S. A. Khan, N. Zhong and T. Zhang, *Biomed. Pharmacother.*, 2020, **131**, 110782.
- 49 X. Hu, B. Wan, Y. Liu, J. Shen, S. G. Franzblau, T. Zhang, K. Ding and X. Lu, *ACS Med. Chem. Lett.*, 2019, **10**, 295–299.
- 50 X. Lu, J. Tang, Z. Liu, M. Li, T. Zhang, X. Zhang and K. Ding, *Bioorg. Med. Chem. Lett.*, 2016, **26**, 5916–5919.
- 51 G. C. Moraski, N. Seeger, P. A. Miller, A. G. Oliver, H. I. Boshoff, S. Cho, S. Mulugeta, J. R. Anderson, S. G. Franzblau and M. J. Miller, *ACS Infect. Dis.*, 2016, **2**, 393–398.
- 52 G. C. Moraski, N. Deboosère, K. L. Marshall, H. A. Weaver, A. Vandeputte, C. Hastings, L. Woolhiser, A. J. Lenaerts, P. Brodin and M. J. Miller, *PLoS One*, 2020, **15**, e0227224.
- 53 A. Wang, H. Wang, Y. Geng, L. Fu, J. Gu, B. Wang, K. Lv, M. Liu, Z. Tao and C. Ma, *Bioorg. Med. Chem.*, 2019, **27**, 813–821.
- 54 Z. Wu, Y. Lu, L. Li, R. Zhao, B. Wang, K. Lv, M. Liu and X. You, *ACS Med. Chem. Lett.*, 2016, **7**, 1130–1133.
- 55 U. B. Karale, A. U. Shinde, D. A. Babar, K. G. Sangu, S. K. Vagolu, V. K. Eruva, S. S. Jadav, S. Misra, S. Dharmarajan and H. B. Rode, *Arch. Pharm.*, 2021, **354**, 2000419.
- 56 S. Kalari, D. A. Babar, U. B. Karale, V. B. Makane and H. B. Rode, *Tetrahedron Lett.*, 2017, **58**, 2818–2821.
- 57 O. K. Onajole, S. Lun, Y. J. Yun, D. Y. Langue, M. Jaskula-Dybka, A. Flores, E. Frazier, A. C. Scurry, A. Zavala and K. R. Arreola, *Chem. Biol. Drug Des.*, 2020, **96**, 1362–1371.
- 58 G. Jose, T. S. Kumara, G. Nagendrappa, H. Sowmya, D. Sriram, P. Yogeewari, J. P. Sridevi, T. N. G. Row, A. A. Hosamani and P. S. Ganapathy, *Eur. J. Med. Chem.*, 2015, **89**, 616–627.
- 59 G. Samala, R. Nallangi, P. B. Devi, S. Saxena, R. Yadav, J. P. Sridevi, P. Yogeewari and D. Sriram, *Bioorg. Med. Chem.*, 2014, **22**, 4223–4232.
- 60 S. J. Tantry, S. D. Markad, V. Shinde, J. Bhat, G. Balakrishnan, A. K. Gupta, A. Ambady, A. Raichurkar, C. Kedari and S. Sharma, *J. Med. Chem.*, 2017, **60**, 1379–1399.



- 61 A. Matsuno-Yagi and Y. Hatefi, *J. Biol. Chem.*, 1993, **268**, 1539–1545.
- 62 J. Zheng and V. D. Ramirez, *Br. J. Pharmacol.*, 2000, **130**, 1115–1123.
- 63 A. Koul, N. Dendouga, K. Vergauwen, B. Molenberghs, L. Vranckx, R. Willebrords, Z. Ristic, H. Lill, I. Dorange and J. Guillemont, *Nat. Chem. Biol.*, 2007, **3**, 323–324.
- 64 T. Yano, S. Kassovska-Bratinova, J. S. Teh, J. Winkler, K. Sullivan, A. Isaacs, N. M. Schechter and H. Rubin, *J. Biol. Chem.*, 2011, **286**, 10276–10287.
- 65 A. Nordqvist, M. T. Nilsson, O. Lagerlund, D. Muthas, J. Gising, S. Yahiaoui, L. R. Odell, B. R. Srinivasa, M. Larhed and S. L. Mowbray, *MedChemComm*, 2012, **3**, 620–626.
- 66 L. R. Odell, M. T. Nilsson, J. Gising, O. Lagerlund, D. Muthas, A. Nordqvist, A. Karlén and M. Larhed, *Bioorg. Med. Chem. Lett.*, 2009, **19**, 4790–4793.
- 67 Y. M. Khetmalis, S. Chitti, A. U. Wunnava, B. K. Kumar, M. M. K. Kumar, S. Murugesan and K. V. G. C. Sekhar, *RSC Med. Chem.*, 2022, **13**, 327–342.
- 68 M. W. Majewski, R. Tiwari, P. A. Miller, S. Cho, S. G. Franzblau and M. J. Miller, *Bioorg. Med. Chem. Lett.*, 2016, **26**, 2068–2071.
- 69 V. Makarov, G. Manina, K. Mikusova, U. Möllmann, O. Ryabova, B. Saint-Joanis, N. Dhar, M. R. Pasca, S. Buroni and A. P. Lucarelli, *Science*, 2009, **324**, 801–804.
- 70 C. Trefzer, H. Škovierová, S. Buroni, A. Bobovská, S. Nenci, E. Molteni, F. Pojer, M. R. Pasca, V. Makarov and S. T. Cole, *J. Am. Chem. Soc.*, 2012, **134**, 912–915.
- 71 V. Makarov, B. Lechartier, M. Zhang, J. Neres, A. M. van der Sar, S. A. Raadsen, R. C. Hartkoorn, O. B. Ryabova, A. Vocat and L. A. Decosterd, *EMBO Mol. Med.*, 2014, **6**, 372–383.
- 72 M. R. Shiradkar, K. K. Murahari, H. R. Gangadasu, T. Suresh, C. A. Kalyan, D. Panchal, R. Kaur, P. Burange, J. Ghogare and V. Mokale, *Bioorg. Med. Chem.*, 2007, **15**, 3997–4008.
- 73 G. Turan-Zitouni, A. Özdemir, Z. A. Kaplancikli, K. Benkli, P. Chevallet and G. Akalin, *Eur. J. Med. Chem.*, 2008, **43**, 981–985.
- 74 G. S. Kumar, Y. Rajendraprasad, B. Mallikarjuna, S. Chandrashekar and C. Kistayya, *Eur. J. Med. Chem.*, 2010, **45**, 2063–2074.
- 75 Y. K. Abhale, K. K. Deshmukh, A. V. Sasane, A. P. Chavan and P. C. Mhaske, *J. Heterocyclic Chem.*, 2016, **53**, 229–233.
- 76 A. K. Bagdi, S. Santra, K. Monir and A. Hajra, *Chem. Commun.*, 2015, **51**, 1555–1575.
- 77 V. R. de Jager, R. Dawson, C. van Niekerk, J. Hutchings, J. Kim, N. Vanker, L. van der Merwe, J. Choi, K. Nam and A. H. Diacon, *N. Engl. J. Med.*, 2020, **382**, 1280–1281.
- 78 I. Malík, J. Čižmárik, G. Kováč, M. Pecháčová and L. Hudecova, *Ceska Slov. Farm.*, 2021, **70**, 164–171.

