Global control and elimination of tuberculosis are hindered by the high prevalence of drug-resistant strains, making the development of new drugs to fight tuberculosis a public health priority. In this study, we evaluated 118 extracts from 58 Venezuelan plant species for their ability to inhibit the growth of *Mycobacterium tuberculosis* mc26020, using the agar dilution method. Additionally, we determined the ability of these extracts to inhibit the activity of PknB protein, an essential *M. tuberculosis* serine/threonine kinase, using a high-throughput luminescent assay. Of the 118 extracts tested, 14 inhibited bacterial growth with a minimum inhibitory concentration $\leq 500 \mu g/ml$, and 36 inhibited the kinase activity with a half-maximal inhibitory concentration $< 200 \mu g/ml$. Five extracts inhibited *M. tuberculosis* growth and inhibited the activity of the kinase protein, suggesting that this could be the basis of their growth inhibition.

1. Introduction

According to the data from the World Health Organization (WHO), 10 million people developed tuberculosis (TB) in 2018, while 1.5 million died from this disease [1]. In 2014, the WHO launched the “END TB,” strategy, which seeks to end the global tuberculosis epidemic. One of the pillars of this strategy is the search for new treatment alternatives for both drug-sensitive and multidrug-resistant tuberculosis strains.

Just three new compounds, bedaquiline, delamanid, and pretomanid, have received approval for use against TB [2, 3]. Although they appear to have good anti-TB activity and could be useful for treating strains resistant to other agents, their potential for side effects and the possible emergence of resistant strains [4, 5] have led to caution and reservations about their appropriate role in treatment regimens. Therefore, the search for new drugs that are safe and effective in the control of TB continues to be a priority.

Recent studies have shown the potential of natural extracts as the basis for new drugs [6, 7]. Microorganisms and plants have exceptional chemical and structural diversity and represent a valuable source of biologically active molecules with potential as new antimicrobials [8]. For example, ursolic acid and hydroquinone, isolated from methanolic extracts of *Artemisia capillaris*, inhibit the growth of susceptible and resistant strains of *M. tuberculosis* and have promise as potential chemotherapeutic agents [9]. Ethnopharmacological research helps to focus screening efforts by identifying groups of plants that are used in traditional medicine to treat infectious diseases. Screening performed with extracts of medicinal plants used in India, Mexico, and South Africa [10–12] demonstrated that some of these extracts have high activity for inhibiting the growth of *M. tuberculosis* and other mycobacteria.

In Venezuela, many indigenous and local communities continue to use plants for medicinal purposes, but few of
these plants have been evaluated for their antituberculosis activity. We were particularly interested in extracts that inhibited the activity of PknB, a serine/threonine kinase that appears to be essential in Mycobacteria. However, compounds found to inhibit enzyme activity with in vitro screens can, for a variety of reasons, fail to inhibit the growth of the whole bacteria. Therefore, in this study, we selected 118 extracts from 58 plant species used in traditional Venezuelan medicine and tested their ability to inhibit the in vitro activity of the M. tuberculosis serine/threonine-protein kinase PknB and also their ability to inhibit the growth of M. tuberculosis mc²6020.

2. Materials and Methods

2.1. Plant Material. The extracts tested were obtained from plants in the botanical species collection (MedPlant) [13] of the Gastrointestinal Physiology Laboratory of Instituto Venezolano de Investigaciones Científicas (IVIC), which is covered by an "Access Contract to Genetic Resources" signed between IVIC and the Ministry of Environment and Natural Resources.

A total of 118 ethanolic extracts were obtained from 58 plant species, belonging to 45 genera and 33 families (see Table S1 in the Supplementary Material). The plants were selected according to their ethnopharmacological activity for the treatment of symptoms associated with lung diseases (cough, fever, nasal congestion, and asthma) from the PlantMed database, which contains data on Venezuelan and neotropical plants reported as having medicinal use.

The plant materials were dried at room temperature. After grinding in a blender, plant material was macerated in three volumes of 95% ethanol for at least 3 days. The material was filtered, and the alcoholic extract was concentrated and dried by rotary evaporator and lyophilization. Stock extract solutions (100 mg/ml) were prepared in 100% dimethyl sulfoxide (DMSO) immediately before use.

2.2. Strain and Growth Conditions. M. tuberculosis mc²6020 was grown in 7H9 and 7H11 Middlebrook media to which was added 10% ADC (0.5% bovine serum albumin, 0.2% glucose, and 0.85% NaCl), L-lysine (40 μg/ml), and pantetheine (20 μg/ml). The 7H9 medium additionally contained Tween-80 (0.5% v/v) and glycerol (0.2% v/v) [14]. The strain was incubated at 37°C in an incubator-shaker until reaching an optical density at 600 nm (OD₆₀₀nm) of 0.6 (approximately 3 × 10⁸ CFU/ml) and then diluted in a 1:2,000 ratio for studies of growth inhibition. Cultures of Escherichia coli BL21 (DE3 pLys) were cultured at 37°C in LB broth in an incubator-shaker until reaching an OD₆₀₀nm of 0.6.

2.3. Antituberculosis Screening. The antituberculosis activity of the extracts was determined using the agar dilution method. For this, 35 × 10 mm Petri dishes were prepared with medium supplemented with a plant extract at a final concentration of 500 μg/ml. Petri dishes with 0.5% DMSO but without extracts were prepared as growth controls, while as a positive control, plates supplemented with Kanamycin (25 mg/ml) were used. M. tuberculosis mc²6020 cultures (10 μl) were spread onto the medium, and then, the Petri dishes were incubated at 37°C for 25 to 30 days, or until growth was observed in the control without extract. The extract containing plates on which no growth was seen was taken to indicate growth inhibition, and the minimum inhibitory concentration (MIC) was established by repeating the above procedure with medium containing 100, 200, 300, 400, and 500 μg/ml.

2.4. Recombinant Protein Expression and Purification. The 279-residue kinase domain of PknB (DQPknB) [15] and full-length GarA [16], natural substrates for the PknB protein, were expressed in Escherichia coli BL21 (DE3 pLys). Cultures were grown until an OD₆₀₀nm of 0.6 and induced by the addition of IPTG (final conc. 1 mM), incubated at 37°C for an additional eight hours and then centrifuged at 1,503 g. The pellet was resuspended in lysis buffer (50 mM of Tris-HCl, 500 mM of NaCl, and 20 mM of imidazole, at a pH of 7.5) in the presence of lysozyme and DNase I from bovine pancreas (Sigma, St Louis, MO, USA). The bacteria were sonicated, and the resulting lysate was centrifuged at 18,407 g for 15 min. The supernatant was passed through a 0.45 μm syringe filter and then loaded onto a Ni Sepharose™ high-performance column (Amersham) using a fast protein liquid chromatography (FPLC) system. The elution was performed with an imidazole gradient (0.0–0.5 M), and the fractions containing the protein of interest were visualized by sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE).

2.5. Phosphorylation Test.Phosphorylation assays were carried out using the commercial Kinase Glo kit (Promega) in a final volume of 100 μl in 96-well solid white polystyrene microplates. The concentrations of ATP (10 μM), DQPknB (0.056 μM), and GarA (0.48 μM) were standardized using the manufacturer’s recommendations. All reactions were carried out at room temperature and were started with reaction buffer mixture (200 mM of Tris, 8 mM of MnCl₂, 10 mM of KF, and 1 mM of DTT), GarA, DQPknB, and the extract (10, 30, 65, 125, 250, and 500 μg/ml). A negative control was elaborated by replacing the volume of the extract with DMSO. After 10 min, ATP was added, and the reaction was incubated for an additional 10 min. At the end of this period, the reaction was stopped by the addition of 50 μl of the Kinase Glo reagent, and after another 10 min, the luminescent signal was measured on a SpectraMax Gemini XS microplate spectrofluorometer (Molecular Devices). Half-maximal inhibitory concentration (IC₅₀) values were calculated using the GraphPad Prism 5 software.

3. Results

We evaluated the inhibitory activity of 118 extracts of Venezuelan medicinal plants on the in vitro activity of the PknB protein and on the growth of the M. tuberculosis
The results obtained show that 14 extracts (11.76%) inhibited the growth of the bacteria at a concentration \( \leq 500 \mu g/ml \) (Table 1).

The leaf extract of the species *Piper sanvicentense* exhibited the best activity against the growth of *M. tuberculosis* mc²6020 with an MIC of 100 \( \mu g/ml \), followed by the inner bark of *Eschweilera parvifolia* with an MIC of 300 \( \mu g/ml \) and extracts of inner bark and branch of *Protium heptaphyllum* with an MIC of 400 \( \mu g/ml \). All other growth inhibiting extracts (*Piper marginatum* (stem), *Macoubea guianensis* (leaf), *Senna silvestris* (flower), *Bromelia goeldiana* (fruit), *Polypodium aureum* (stem), *Byrsonima crassifolia* (flower and root), *Xylopia aromatica* (leaf), and *Curatella americana* (leaf)) showed MICs of 500 \( \mu g/ml \).

Of the 36 extracts capable of inhibiting the *in vitro* activity of DQPknB, four had an IC₅₀ lower than 50 \( \mu g/ml \), while 19 had an IC₅₀ between 50 and 100 \( \mu g/ml \) and the remaining 13 exhibited an IC₅₀ between 100 and 200 \( \mu g/ml \) (Table 2).

Six extracts (5.04%) were found to inhibit both the *in vitro* activity of PknB and the growth of *M. tuberculosis* mc²6020 (3), the inner bark of *Eschweilera parvifolia* and *Protium heptaphyllum*, the branch of *Protium heptaphyllum*, the flower of *Byrsonima crassifolia*, and the young leaves of *Curatella americana* and *Xylopia aromatica*.

4. Discussion

In this study, we selected 58 species of Venezuelan medicinal plants used by indigenous communities for the treatment of respiratory symptoms and evaluated extracts of different plant parts in a screen for natural compounds that have potential as antituberculosis. We tested a total of 118 extracts of different plant parts and of the 14 that inhibited the growth of *M. tuberculosis* mc²6020 and 36 that inhibited the *in vitro* activity of PSTK PknB, and there were five that had both inhibitory activities.

The plants that showed activity against growth were *P. sanvicentense* (Piperaceae), *E. parvifolia* (Lecythidaceae), *Pro. heptaphyllum* (Burseraceae), *B. goeldiana* (Bromeliaceae), *B. crassifolia* (Malpighiaceae), *C. americana* (Dilleniaceae), *H. dilatata* (Lamiaceae), *M. guianensis* (Apocynaceae), *P. marginatum* (Piperaceae), *Pol. aureum* (Polypodiaceae), *S. silvestris* (Caesalpiniaceae), and *X. aromatica* (Annonaceae).

Our finding that an ethanolic extract bark of *C. americana* inhibited *M. tuberculosis* growth with an MIC of 500 \( \mu g/ml \) agreed with the results of Pavan et al. [17], who found that a methanolic extract of the bark inhibited the growth of *M. tuberculosis* H37Rv with the same MIC (Table 1), thus confirming the presence of compounds with antituberculosis activity in this species. We also tested extracts of young leaves, leaves, flowers, and branches of *C. americana*, but these had MICs that were higher than 500 \( \mu g/ml \) (data not shown), suggesting a differential distribution of the active metabolites throughout the plant. All *C. americana* extracts also showed activity against DQPknB, with an IC₅₀ lower than 200 \( \mu g/ml \). However, while the lowest MIC for growth inhibition was in the bark extract, the extract with the lowest IC₅₀ for inhibiting PknB activity was from young leaves, with an IC₅₀ of 39.5 \( \mu g/ml \), while that of the bark was 124.9 \( \mu g/ml \).

Similarly, the plant parts of *H. dilatata* and *E. parvifolia* whose extracts had the greatest capacity to inhibit kinase activity were not the parts of these plants that were best at inhibiting bacterial growth (Tables 1 and 2). This could suggest that the molecules that inhibit kinase activity are different from those that mediate growth inhibition.
Another possibility is that molecules that inhibit kinase activity in vitro have trouble penetrating the bacterial cell wall to inhibit the enzyme in live bacteria. Nevertheless, our study shows that C. americana, H. dilatata, and E. parvifolia are promising species for molecules with antituberculosis potential.
The stem extract from *P. marginatum* inhibited *M. tuberculosis* growth with an MIC of 500 μg/ml. Ethanolic extracts of *P. marginatum* have been previously shown to inhibit the growth of *Porphyromonas gingivalis* ATCC 33277, *Fusobacterium nucleatum* ATCC 25586, and *Prevotella intermedia* ATCC 25611 [18]. *P. marginatum* essential leaf oil showed a bactericidal effect against *Xanthomonas albinines* and *X. campestris* pv. *campestris* and a fungistatic effect against *Alternaria solani* [19]. Terpenoid compounds have shown to have moderate to high activity against *M. tuberculosis*, and the presence of these compounds in *P. marginatum* could explain their antituberculosis and antimicrobial activity [18].

Previous research established the potential of the ethanolic extract of *P. sanvicentense* against breast cancer MDA-MB-231, prostate cancer PC-3, and human colon cancer HT29 cell lines [13], but this is the first report of its antibacterial activity. Of the 118 extracts we tested, the *P. sanvicentense* extract had lowest MIC for inhibiting *M. tuberculosis* growth (100 μg/ml). Although it did not show any ability to inhibit kinase activity, *P. sanvicentense* could be a promising candidate for chemical analysis. This is also the first report of antibacterial activity in the species *Brom. goeldiana*, *M. guianensis*, and *Pol. aureum*, whose fruit, leaf, and stem extracts, respectively, showed activity only against bacterial growth at an MIC of 500 μg/ml.

Although antibacterial activity has previously been described in *B. crassifolia*, *Pro. heptaphyllum*, and *Xylopia aromatica* [20–24], we found that only some of the plant part extracts inhibited both *M. tuberculosis* growth and the kinase activity. The flower extract of *B. crassifolia* had an IC₅₀ of 30.4 μg/ml and an MIC of 500 μg/ml, while the inner bark extract showed an IC₅₀ of 144 μg/ml but an MIC higher than 500 μg/ml. Similarly, an extract of the inner bark of *Pro. heptaphyllum* had an IC₅₀ of 37.4 μg/ml and an MIC of 400 μg/ml, but the leaf extract had an IC₅₀ of 95.7 μg/ml and an MIC over 500 μg/ml. The young leaf extract of *Xylopia aromatica* inhibited both growth and kinase activity (MIC = 500 μg/ml and IC₅₀ = 93.6 μg/ml), while the other extracts of this plant showed neither activity. Terpenoid compounds have been shown to possess high antituberculosis activity [25]. Phytochemical studies of the essential oils of *X. aromatica* and *Prot. heptaphyllum* leaves demonstrated the presence of various terpenes, including spathulenol [20, 21]. This sesquiterpene has been shown to have antibacterial activity against *Cryptococcus neoformans*, *Enterococcus faecalis*, and *Staphylococcus aureus* [26].

The extracts of *Jacaranda copaia*, *Oenocarpus bataua*, *Parkia pendula*, *Protium crassipetalum*, *Tapirira guianensis*, *Uncaria guianensis*, *Vismia cayennensis*, *Vismia guianensis*, *Vochysia ferruginea*, *Waltheria indica*, and *Warscewiczia coccinea* inhibited the kinase, but not mycobacterial growth. Nevertheless, identification of the kinase inhibiting metabolites could provide new lead compounds for the design of new drugs.

The search for new antituberculosis drugs continues to be a challenge, but the high incidence of this disease makes it an important priority. In this study, we documented the antimycobacterial potential of some Venezuelan plants for which antibacterial activity has not been previously reported and demonstrated the importance of ethnopharmacological knowledge in the search for botanical sources with biological activity. To our knowledge, this is the first study demonstrating the *in vitro* activity of natural extracts on the activity of the catalytic domain of the *M. tuberculosis* protein PknB. Serine/threonine kinases are important targets for anticancer agents [27] and have been proposed as targets for antituberculosis drugs. PknB is essential for *M. tuberculosis* [28], but no drug targeting it has yet been identified. In the extracts, we identified that plant extracts inhibit both *M. tuberculosis* growth and the kinase, and it is tempting to believe the same molecules contain both inhibitory activities, but this must be proven when the active compounds are successfully isolated and identified.

### Table 3: Extracts that showed activity against DQPknB and *M. tuberculosis* mc²6020.

<table>
<thead>
<tr>
<th>Botanical species</th>
<th>Part</th>
<th>IC₅₀ (μg/ml)</th>
<th>CMI (μg/ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Eschweileria parvifolia</em></td>
<td>Internal bark (root)</td>
<td>76.53</td>
<td>300</td>
</tr>
<tr>
<td><em>Protium heptaphyllum</em></td>
<td>Internal bark (root)</td>
<td>37.40</td>
<td>400</td>
</tr>
<tr>
<td><em>Protium heptaphyllum</em></td>
<td>Branch</td>
<td>66.05</td>
<td>400</td>
</tr>
<tr>
<td><em>Byrsonima crassiofia</em></td>
<td>Flower</td>
<td>30.41</td>
<td>500</td>
</tr>
<tr>
<td><em>Caratella americana</em></td>
<td>Young leaf</td>
<td>146.04</td>
<td>500</td>
</tr>
<tr>
<td><em>Xylopia aromatica</em></td>
<td>Young leaf</td>
<td>93.63</td>
<td>500</td>
</tr>
</tbody>
</table>

5. Conclusions

*P. sanvicentense* (Piperaceae), *E. parvifolia* (Lecythidaceae), *Pro. heptaphyllum* (Burseraceae), *Brom. goeldiana* (Bromeliaceae), *B. crassifolia* (Malpighiaceae), *C. americana* (Dilleniaceae), *H. dilatata* (Lamiaceae), *M. guianensis* (Apocynaceae), *P. marginatum* (Piperaceae), *Pol. aureum* (Polypodiaceae), *S. silvestris* (Caesalpiniiaceae), and *X. aromatica* (Annonaceae) total ethanol extracts presented outstanding antimicrobial activity against *M. tuberculosis* mc²6020.

Of the 36 extracts that were shown to inhibit the activity of the PknB protein, only 5 were able to inhibit the growth of *M. tuberculosis*. Further studies should be performed to determine whether compounds that inhibit the activity of protein kinase also affect bacterial growth.

### Data Availability

The data used to support the findings of this study are included within the article and are available from the corresponding author upon request.

### Conflicts of Interest

The authors have declared that there are no conflicts of interest.

### Acknowledgments

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**Supplementary Materials**

Table S1: medicinal plant extracts evaluated in this study. (Supplementary Materials)

**References**


