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Multidimensional Mapping to Assess Phytochemical Diversity, Strength of Bioactivity Evidence, and Determinants of Variation in Mangrove Plants through a Mini Review

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ABSTRACT

This study aims to map phytochemical diversity, biological activity, strength of evidence, and factors that affect the variation in metabolite profiles in mangrove plants. The study used a *mini literature review design* with a multidimensional mapping approach to publications that discuss mangrove species, plant parts, extraction methods, compound identification techniques, and bioactivity testing. Data were collected through literature search, selection based on inclusion and exclusion criteria, structured data extraction, article quality assessment, and descriptive and narrative synthesis. The results showed that mangrove plants contain a diverse range of compounds, especially phenolics, flavonoids, tannins, alkaloids, saponins, steroids, glycosides, terpenoids, triterpenoids, limonoids, quinones, and fatty acids. The most commonly reported biological activities were antioxidants and antimicrobials, followed by anti-inflammatory, antidiabetic, anticancer, cytotoxic, hepatoprotective, analgesic, and neuroprotective activities. The phytochemical and bioactivity profiles are influenced by species, plant parts, tissue age, location, environmental conditions, solvent type, extraction techniques, purification, and analysis methods. Most of the evidence still comes from crude extracts and in vitro testing, while toxicity, pharmacokinetics, bioavailability, and clinical validation is still limited. This study concludes that mangroves have great potential as a source of bioactive compounds, but their utilization requires standardization of methods, tiered validation, and sustainable resource management.

Keywords: phytochemicals, mangrove plants, biological activity, multidimensional mapping, literature review

I. INTRODUCTION

Mangroves are coastal plants that are able to survive saline conditions, are flooded, and change with the tides, thus forming secondary metabolites as part of their adaptation and defense mechanisms. These peculiarities make mangroves a source of phenolics, flavonoids, tannins, alkaloids, saponins, steroids, glycosides, terpenoids, triterpenoids, limonoids, quinones, fatty acids, and aromatic compounds that have the potential to be used in the fields of pharmaceuticals and biotechnology. These various metabolites have been linked to antioxidant, antimicrobial, anti-inflammatory, antidiabetic, anticancer, cytotoxic, hepatoprotective, analgesic, and neuroprotective activity. Ethnopharmacological and global distribution studies show that the traditional use of mangroves has become the gateway for

pharmacological exploration, but only a fraction of species have obtained adequate chemical and biological validation (Bibi et al., 2019; Christopher, 2024). Research on Indian mangroves and the Rhizophoraceae family has collected hundreds of metabolites, but exploration is still concentrated on a number of species so they do not yet represent the full taxonomic diversity (Nebula et al., 2013; Parthiban et al., 2022). Previous reviews have also confirmed the prospects of mangroves as a source of therapeutic substances and multi-target specific metabolites, although their application is still dominated by the early discovery stage (Kiran Kumar & Pola, 2022; Mitra et al., 2021; Murthy et al., 2025, 2026). Genus and species-based studies, such as *Avicennia marina* and *Sonneratia caseolaris*, enrich knowledge of their composition and activity, but at the same time reveal the inequalities of the organs studied and the weak translation towards standardized products (Beniwal et al., 2024; Cerri & Galli, 2025; ElDohaji et al., 2020). Therefore, a mini review is needed that does not stop at the inventory of compounds, but assesses the linkages between phytochemical profiles, biological activity, research methods, and the strength of the available evidence (Chavan et al., 2026).

The fundamental problem in the mangrove phytochemical literature is the high heterogeneity of results due to differences in species, organs, tissue age, location, solvents, extraction techniques, purification, and analytical instruments. Basyuni et al. (2019b) show that true mangrove leaf simplicia can contain saponins and triterpenoids or phytosterols, while n-hexane extracts mainly feature lipophilic components; findings on association plants need to be separated so as not to be equated with true mangroves (Basyuni et al., 2019a). Solvent comparisons prove that methanol, ethyl acetate, and n-hexane can produce different renditions, metabolite groups, and activities even though the species or organs used are the same (Ernawati et al., 2019; Mitra et al., 2023). Conventional and modern techniques also have different selectivity, energy requirements, compound stability, and efficiency, so there is no one method that is always the most appropriate for all materials (Chuo et al., 2020). Gradual extraction and green solvents can expand the range of compounds obtained, but they do not guarantee the highest bioactivity and still require equivalent comparators (Djamaludin et al., 2025; Nastić et al., published online 2025, 2026 edition). The purification stage can even remove certain tannin oligomers, so the instrument profile may not fully describe the initial ingredients (Lang et al., 2022). Variation between organs, between species, and between locations is also seen through metabolomics, chemometrics, phenolic measurements, and HPLC profiles, which means that species names alone are inadequate as units of comparison (Rozirwan et al., 2023; Saputri et al., 2026; Wu et al., 2023). Chemotaxonomy and chemical fingerprint data must therefore be read together with age, location, and tissue so that metabolite markers are not considered an absolute feature (Andianto et al., 2024; Basyuni et al., 2025).

The next inequality appears between the number of biological activities reported and the quality of the evidence supporting them. Antioxidant and antimicrobial activity is most often tested through DPPH, total phenolic content, inhibition zones, and pathogen testing, while the results are strongly influenced by the concentration, solvent, and test organism (Dahibhate et al., 2020; Eswaraiah et al., 2020). More recent studies have assessed biofilm inhibition and extracellular matrix degradation, while a review of antimicrobial metabolites suggests possible work through membrane disruption as well as inhibition of biosynthesis pathways (Rajivgandhi et al., 2024; Valleti et al., 2025, 2026). However, the pentacyclic triterpenoid mechanism against *Staphylococcus aureus* cannot be directly attached to the coarse extract without isolation, structural confirmation, and dose testing of the compound (Chung, 2019). More specific evidence is obtained from the saponin *Aegiceras corniculatum* that inhibits pro-inflammatory cytokines and exhibits cytotoxicity to melanoma cells, but the mangrove anticancer literature in general is still dominated by in vitro or preclinical testing (Hridya et al.,

2023; Sarkar et al., 2024; Vinh et al., 2020). The safety evaluation is also not balanced with the claim of benefits, even though toxicity screening shows that active extracts are not always identical to safe ingredients (Fadilah et al., 2023). In addition to methodological factors, salinity, inundation, environmental stress, genotype variation, and ecological interactions can affect metabolism, but evidence from protists or nonmangrove plants is only feasible to use as supporting context (Akter et al., 2025; Braby, 2012; Martins et al., 2024; Talebi, 2023; Zhao et al., 2025). Fungi from mangrove ecosystems and nanoparticles synthesized using extracts also produce interesting biological activity, but both must be separated from plant phytochemicals because the producing organisms and the active ingredients end up being different (Bakshi et al., 2015; Gnanadesigan et al., 2012; Job et al., 2023; Rathod & Pathak, 2020; Saha et al., 2021; Wang et al., 2022; Zhou et al., 2025).

Based on these conditions, this study is important because the available literature is still fragmented by species, organs, location, type of compound, extraction method, bioactivity model, and validation level. Previous studies have provided a broad foundation, but have not yet fully compiled evidence within a single framework that distinguishes between cluster screening, tentative identification, isolation of compounds, extract assays, pure compound assays, and in silico, in vitro, in vivo, and clinical validation. The research titled "Multidimensional Mapping to Assess Phytochemical Diversity, Strength of Bioactivity Evidence, and Determinants of Variation in Mangrove Plants through a Mini Literature Review" aims to build a structured, critical, and comparable map of evidence. The first objective of the study is to identify and classify phytochemical groups and compounds based on species and parts of mangrove plants. The second goal is to map the biological activity of pure extracts, fractions, and compounds, then assess the strength of the evidence supporting each bioactivity claim. The third objective is to explain the influence of biological, ecological, and methodological factors on variations in phytochemical profiles and biological activities, as well as to identify research gaps. On the basis of these objectives, the formulation of the first problem is how the diversity of phytochemical groups and compounds that have been identified in various species and parts of mangrove plants based on published research, while the formulation of the second problem asks what biological activities are reported and what is the level of strength of the evidence. The formulation of the third problem is how biological, ecological, and methodological factors affect variations in the phytochemical profile and bioactivity of mangrove plants, as well as what gaps still need to be studied in order for their use to develop scientifically, safely, and sustainably.

II. METHODS

This study uses *a mini literature review design* with a multidimensional mapping approach to identify phytochemical diversity, evaluate the strength of evidence of biological activity, and explain the determinants of variation in mangrove plants. The unit of analysis of research is not human or experimental animals, but scientific articles that discuss phytochemical compounds, extracts, fractions, pure compounds, and biological activity of mangrove plants. Literature searches were conducted on Scopus, ScienceDirect, PubMed, and Google Scholar databases to obtain relevant publications until June 2026. The publication year range is set from 2012 to June 2026 so that the study covers developments from basic phytochemical screening to metabolomics, compound purification, chemometrics and mechanistic testing. Keywords are compiled using a combination of Boolean operators, namely ("mangrove" OR "mangrove plant") AND ("phytochemical" OR "secondary metabolite" OR "bioactive compound" OR "metabolomic") AND ("biological activity" OR "antioxidant" OR "antimicrobial" OR "antibiofilm" OR "anti-inflammatory" OR "anticancer" OR "antidiabetic"

OR "cytotoxic"). Additional search is done by checking the reference list of review articles that have been available to find primary research that may not have appeared in the initial search results. This strategy was chosen because previous research showed that the study of mangrove phytochemicals is spread in the fields of pharmacognomy, natural material chemistry, microbiology, pharmacology, biotechnology, and ecology (Bibi et al., 2019; Chavan et al., 2026; Mitra et al., 2021). All search results are then entered into an electronic worksheet and checked by title, abstract, keyword, DOI, author's name, and year of publication to remove duplicate articles.

The main sample includes primary research articles and review articles that meet the inclusion criteria, namely discussing true mangrove plants, mentioning the species or genus being studied, describing plant parts, reporting the group or identity of compounds, and presenting biological activities or factors that affect metabolite profiles. Indonesian and English articles are included as long as the full text is accessible and the methodological information is sufficient for extraction. Articles that only discuss the ecological function of mangroves without phytochemical or bioactivity data were excluded from the main sample. Research on mangrove association plants, endophytic fungi, sedimentary microorganisms, marine protists, and extract-based nanoparticles was not directly excluded, but was placed as a group of supporting evidence so as not to be confused with metabolites produced directly by plants. The separation is necessary because research on fungi from mangroves produces microbial metabolites, while the activity of nanoparticles is also influenced by the properties of metal materials, particle size, and stability (Bakshi et al., 2015; Gnanadesigan et al., 2012; Job et al., 2023; Wang et al., 2022; Zhou et al., 2025). The selection process is carried out through four stages, namely identification of search results, elimination of duplication, examination of titles and abstracts, and assessment of complete texts. Two reviewers independently screened using the same criteria, then discussed each decision difference until they reached agreement. The reasons for exclusion at the full text stage are noted, for example, the object is not a mangrove plant, there is no phytochemical data, there are no bioactivity results, or the method is not adequately explained.

The research instruments are in the form of data extraction forms and article quality assessment matrices arranged in structured worksheets. The form contains the author's name, year, country, sampling location, species, mangrove status, plant parts, tissue age, habitat conditions, drying methods, solvents, extraction techniques, purification methods, and compound identification instruments. Phytochemical data are recorded based on the group of compounds, the name of the compound, and the level of certainty of its identification, i.e. qualitative screening, quantification of compound groups, tentative identification through spectrum libraries, or confirmation of the structure of pure compounds. Bioactivity data includes the type of test material, concentration, organism or test model, controls, outcome indicators, reported mechanisms, and the level of proof in silico, in vitro, in vivo, preclinical, or clinical. The quality matrix uses eight indicators, namely clarity of species identification, reporting of organs and locations, completeness of extraction procedures, accuracy of analytical methods, use of controls, presence of replication, clarity of concentration, and adequacy of reporting results. Each indicator is given a score of 0 if not reported, 1 if reported partially, and 2 if reported complete, so that the maximum score for each article is 16. Articles with a score of 13–16 are categorized as high-quality, score 8–12 of medium quality, and score 0–7 of low quality. This assessment is based on the problem of method comparability that has been repeatedly found in studies on the extraction, purification, and analysis of mangrove metabolites (Chuo et al., 2020; Lang et al., 2022; Nastić et al., 2026).

Data analysis was carried out through descriptive analysis, thematic coding, and multidimensional narrative synthesis. The frequency of publication is calculated based on species, family, plant organs, metabolite groups, extraction methods, identification techniques, and categories of biological activity. The relationship between solvents and compounds is analyzed by grouping solvents into polar, semipolar, and nonpolar, then comparing the groups of metabolites and the activities that occur most frequently in each group. The strength of the evidence for bioactivity was determined based on a combination of methodological quality, the shape of the test material, the certainty of the identity of the compound, the use of controls, the dose-response relationship, and the level of the test model. Evidence of in vitro crude extracts is placed at a lower level than evidence of pure compounds with confirmed structures and clear biological mechanisms. Biological, ecological, and methodological factors were analyzed as determinants of variation by comparing results based on species, organs, tissue age, location, salinity, extraction methods, purification, and analysis techniques. Findings derived from associate plants, fungi, marine organisms, or nanoparticles were analyzed separately as supporting context and were not counted as primary evidence of mangrove plant phytochemistry. The final results are presented in the form of species–organs–compounds–bioactivity matrices, a table of evidence strength levels, and research gap maps to show species, plant parts, activities, and methods that are still understudied. This approach allows research to be replicated through the use of the same keywords, selection criteria, extraction forms, scoring systems, and analysis procedures.

Research Question

RQ1: How is the diversity of phytochemical groups and compounds that have been identified in different species and parts of mangrove plants based on published research?

RQ2: What are the reported biological activities of mangrove plant extracts, fractions, and phytochemical compounds, and what is the level of strength of evidence supporting such activity?

RQ3: How do biological, ecological, and methodological factors affect variations in the phytochemical profile and biological activity of mangrove plants, as well as what research gaps still need to be studied?

III. RESULTS AND DISCUSSION

3.1 Result

The results of the synthesis show that the literature reviewed includes phytochemical screening research, pharmacognostic characterization, isolation of compounds, metabolomics, chemotaxonomy, bioactivity testing, molecular modeling, and pharmacological review. The reported groups of compounds include phenolics, flavonoids, tannins, alkaloids, saponins, steroids, sterols, glycosides, diterpenoids, triterpenoids, limoids, quinones, naphthokuinones, organic acids, fatty acids, alcohols, aldehydes, amides, lactons, polysaccharides, stilbens, and aromatic derivatives. Bibi et al. (2019) discussed 84 species of mangroves and noted 27 species used in traditional medicine, with terpenoids, tannins, steroids, alkaloids, flavonoids, and saponins as the main groups. Parthiban et al. (2022) collected about 249 bioactive compounds isolated from 18 Indian mangrove species. Nebula et al. (2013) noted 268 metabolites from 16 species of Rhizophoraceae, while 12 of the 24 species reviewed had not been adequately examined for phytochemical content. The dominant groups in Rhizophoraceae are diterpenoids and triterpenoids with the skeletons of pimarana, beyerana, kaurana, dolabrana, labdana, lupana, dammarana, and oleanana. Cerri and Galli (2025) collected 141 compounds from the leaves, fruits, bark, stems, and twigs *of Sonneratia caseolaris*, while phytochemical data on the roots are still very limited. Wu et al. (2023) detected 532 compounds from 18 chemical

classes in the roots, stems, and leaves of five mangrove species and obtained 18 interspecies differentiating compounds and nine inter-organ differentiating compounds. In *Avicennia marina*, Mitra et al. (2023) reported fatty acids, flavonoids, phenols, terpenoids, steroids, aldehydes, alkaloids, plant hormones, and alcohol through LC-MS analysis. Data on these groups of compounds and species were also recorded in the studies of Beniwal et al. (2024), Christopher (2024), ElDohaji et al. (2020), Kiran Kumar and Pola (2022), Mitra et al. (2021), and Murthy et al. (2025, 2026).

The plant parts used in the study included leaves, roots, stems, bark, twigs, fruits, hypocotyls, wood, and reproductive tissues, with leaves being the most frequently reported parts. Basyuni et al. (2019b) found saponins as well as triterpenoids or phytosterols in the simplicia of the leaves of five true mangroves, while their n-hexane extract mainly contains triterpenoids or phytosterols. In five mangrove association plants, Basyuni et al. (2019a) also noted saponins and triterpenoids or phytosterols in simplicia, as well as triterpenoids or steroids in n-hexane extracts. Andianto et al. (2024) reported triterpenoids, flavonoids, and fat outcomes in *Rhizophora apiculata* wood, steroids and naphthalene in *Bruguiera gymnorhiza*, and alkaloids and fatty amides in *Bruguiera cylindrica*. Basyuni et al. (2025) recorded dolicol and polyprenols in reproductive tissues as components in chemotaxonomic grouping. Ernawati et al. (2019) obtained *a yield of Rhizophora mucronata* fruit extract of 5.38% with methanol, 3.34% with ethyl acetate, and 1.26% with n-hexane. Such methanol extracts contain alkaloids, flavonoids, saponins, triterpenoids, and tannins, while n-hexane extracts mainly contain triterpenoids. Djamaludin et al. (2025) recorded the moisture content of old leaves *of A. marina* of 8.4% and young leaves of 15.19%, with the highest yield of citric acid–glucose NADES of 4:1. Lang et al. (2022) reported differences in the distribution of oligomers and tannin polymers after purification using ethyl acetate, pure ethanol, and 50% methanol. Extraction methods used in the literature include maceration, Soxhlet, sonication, *ultrasound-assisted extraction*, supercritical carbon dioxide, sequential extraction, as well as NADES (Chuo et al., 2020; Nastić et al., 2025).

Table 1. Summary of key phytochemicals and bioactivity of mangrove plants

Species or groups	Parts or material s	Compounds/main groups	Key activity data
Avicennia marina	Leaves, stems, bark of the stem	Phenolics, flavonoids, terpenoids, steroids, alkaloids, fatty acids	Antioxidant, antibacterial, antibiofilm
Rhizophora mucronata	Leaves, fruits	Alkaloids, flavonoids, saponins, tannins, triterpenoids	Antioxidant, antimicrobial
Bruguiera gymnorhiza	Leaves, wood, bark	Steroids, naphthalene, tannins, triterpenoids	Antioxidant, antimicrobial
Sonneratia caseolaris	Leaves, fruits, stems, twigs	Phenolic acids, flavonoids, tannins, steroids, polysaccharides	Antioxidant, antimicrobial, antidiabetic
Aegiceras corniculatum	Leaves, bark, roots, fruits	Saponins, triterpenoids, flavonoids, stilbens	Anti-inflammatory, cytotoxic, neuropharmacological
Rhizophoraceae	Various organs	Diterpenoids and triterpenoids	Antimicrobial, antioxidant, antiviral, cytotoxic
Mangrove-associated fungi	Fungi culture	Azaphilone, alkaloid, polyketida, terpenoid	Phytotoxic, antibacterial, antifungal, cytotoxic

Biological activities recorded in the literature include antioxidants, antibacterial, antifungal, antibiofilm, anti-inflammatory, antidiabetic, anticancer, cytotoxic, antiviral,

antiulcer, hepatoprotective, analgesic, antipyretic, antidiarrheal, neuroprotective, insecticide, antifeedant, and phytotoxic. Mitra et al. (2023) obtained a total phenolic content of 148.0 mg

GAE/g and a total flavonoid of 251.9 mg CE/g in methanol extract *of A. marina*. At a concentration of 250 µg/mL, the methanol extract produced 96.0% DPPH radical capture, while the ethyl acetate extract produced 73.7%. Eswaraiah et al. (2020) recorded the highest antioxidant activity in *Lumnitzera racemosa* and the lowest activity in *Suaeda nudiflora*. Rajivgandhi et al. (2024) reported DPPH activity of approximately 79–88%, inhibition zone of 18–26 mm, biofilm inhibition 84–92%, and EPS matrix degradation of 86–94% in *A. marina extract*. Djamaludin et al. (2025) recorded the inhibition zone against *Propionibacterium acnes* as 37.38 ± 4.34 mm in old leaf extracts and 24.51 ± 0.75 mm in young leaves. Vinh et al. (2020) reported that the saponins *of Aegiceras corniculatum* inhibit TNF-α, IL-6, and IL-12 p40, with one of the compounds producing IC50 values of 0.40 µM, 0.79 µM, and 1.58 µM, respectively. Chung (2019) noted pentacyclic triterpenoid targets on cell division, ABC transporters, fatty acid biosynthesis, peptidoglycans, ribosomes, and membrane permeability of *Staphylococcus aureus*. Anticancer, antidiabetic, anti-inflammatory, and neuroprotective activity was also reported by Chavan et al. (2026), Hridya et al. (2023), Sarkar et al. (2024), and Valleti et al. (2025, 2026).



Figure 1. Literature Synthesis Map of Mangrove Phytochemistry and Biological Activities

Variation factor data include species, families, organs, tissue age, geographic location, salinity, inundation, solvents, extraction methods, purification, identification instruments, concentrations, and test models. Saputri et al. (2026) recorded 618 compounds in *A. marina* samples from several locations in Indonesia and obtained a grouping of metabolites based on location and extraction method. Rozirwan et al. (2023) reported an IC50 DPPH value of 28.064

μg/mL in *Sonneratia alba*, 105.09 μg/mL in *Bruguiera gymnorrhiza*, and 171.16 μg/mL in *A. marina*. Zhao et al. (2025) recorded a squalene production of 17.27 mg/g under the NaCl condition of 45 g/L in marine protists, or 3.26 times higher than the condition without the addition of NaCl. Martins et al. (2024), Talebi (2023), and Akter et al. (2025) reported data on metabolic responses to salinity, stagnation, ionic stress, and oxidative stress in the organisms and plants studied. Wang et al. (2022) isolated seven pairs of azaphilone isomers from fungi of mangrove origin with an EC50 value of about 234.87–320.84 μM against the growth *of Amaranthus retroflexus*. Zhou et al. (2025) collected 417 natural products of *the Penicillium* fungi, including 170 new compounds, 11 new structural skeletons, 26 halogenated compounds, and 126 compounds with biological activity. Gnanadesigan et al. (2012) and Bakshi et al. (2015) reported silver nanoparticles measuring about 71–110 nm and D90 18.3 nm synthesized using mangrove extract. The literature reviewed noted data limitations on understudied species and organs, toxicity, pharmacokinetics, bioavailability, formulation, in vivo testing, and clinical trials (Fadilah et al., 2023; Job et al., 2023; Rathod & Pathak, 2020; Saha et al., 2021).

3.2 Discussion

3.2.1 Discussion of RQ1: Diversity of Phytochemical Groups and Compounds in Mangrove Plants

The findings of this study show that the phytochemical diversity of mangrove plants is not only indicated by the number of groups of compounds found, but also by differences in distribution according to family, genus, species, organs, tissue age, and growing location. The most consistent groups reported include phenolics, flavonoids, tannins, alkaloids, saponins, steroids, glycosides, diterpenoids, triterpenoids, limonoids, quinones, naphthokuinones, organic acids, fatty acids, alcohols, aldehydes, amides, lactones, polysaccharides, and aromatic derivatives. These results are in line with Bibi et al. (2019), who identified terpenoids, tannins, steroids, alkaloids, flavonoids, and saponins as the main metabolite groups in mangrove plants that are used ethnopharmacologically. Parthiban et al. (2022) strengthened this extent through the collection of about 249 compounds from 18 Indian mangrove species, while Nebula et al. (2013) recorded 268 metabolites from 16 species of the Rhizophoraceae family. The study of Mitra et al. (2021), Christopher (2024), and Chavan et al. (2026) also shows that the chemical diversity of mangroves is related to a broad spectrum of traditional uses and pharmacological activities. However, large amounts of compounds do not mean that the entire mangrove has been studied in a balanced manner as most of the information is still concentrated on popular species. Bibi et al. (2019) showed that only a fraction of the species discussed have been used and validated pharmacologically, while Parthiban et al. (2022) found that deep isolation of compounds has only been performed on a small portion of India's mangrove diversity. Thus, the diversity that has been identified illustrates great chemical potential, but at the same time shows a taxonomic gap in mangrove phytochemical research.

The distribution patterns of compounds in the Rhizophoraceae family show that phytochemical variations are not random, but can follow specific taxonomic lines and biosynthesis pathways. Nebula et al. (2013) show that diterpenoids and triterpenoids dominate this family, including the skeletons of pimarana, beyerana, kaurana, dolabrana, labdana, lupana, dammarana, and oleanana. Disulfide, dolabrana, and labdana are also said to have potential as chemical markers for the genus *Bruguiera*, *Ceriops*, and *Rhizophora*. The findings are supported by Andianto et al. (2024), who show differences in the wood profiles *of Rhizophora apiculata*, *Bruguiera gymnorhiza*, and *Bruguiera cylindrica*. *Rhizophora apiculata* is more characterized by triterpenoids, flavonoids, and fat derivatives, while *B. gymnorhiza* exhibits steroids and naphthalene, and *B. cylindrica* exhibits alkaloids and fatty amides. Basyuni et al. (2025) added that dolicol and polyprenols in reproductive tissues can be used in

cluster analysis and chemotaxonomy of mangroves. The set of results shows that phytochemistry has a broader function than just demonstrating drug potential because compound profiles can also help identify, classify, and understand biological relationships between taxons. The significance of these findings lies in the opening of opportunities to combine chemical data with morphology, anatomy, and ecology in the determination of the identity of plant materials. However, phytochemical markers still need to be tested on different populations and environmental conditions before they are declared stable as characteristic of a species.

Variation between organs is an important finding because previous research has shown that one species does not have a uniform chemical composition in all parts of the plant. Wu et al. (2023) detected 532 compounds from 18 classes in the roots, stems, and leaves of five species, and found 18 interspecies differentiating compounds and nine inter-organ differentiating compounds. Species factors are reported to have a greater influence than organs, but leaves still have a different profile than roots and stems. Basyuni et al. (2019b) found saponins and triterpenoids or phytosterols in true mangrove five-leaf simplicia powder, while n-hexane extracts mainly showed triterpenoid or phytosterol components. In association plants, Basyuni et al. (2019a) obtained a pattern that resembled such results, but the status of associate plants must be distinguished from true mangroves. Cerri and Galli (2025) noted 141 compounds from different parts of *Sonneratia caseolaris*, while the root part is still largely unexplored. Vinh et al. (2020) used the leaves of *Aegiceras corniculatum* and succeeded in isolating saponins with specific anti-inflammatory and cytotoxic activities. Gnanadesigan et al. (2012) also showed differences in the ability of leaf, bark, and root extracts of *Avicennia marina* in the formation of silver nanoparticles. These findings confirm that the mention of species names without plant part information is not sufficient to compare their phytochemical content and biological activity.

The results of this study also show that tissue age is an often overlooked biological variable, although it can result in noticeable differences in compound and activity profiles. Djamaludin et al. (2025) compared young leaves and old *leaves of A. marina* extracted using *natural deep eutectic solvent*. Old leaves and young leaves have different moisture content, yield, metabolite composition, and activity against *Propionibacterium acnes* . In the 4:1 NADES formulation of citric acid and glucose, old leaf extract yields an inhibition zone of 37.38 ± 4.34 mm, while young leaf extract yields 24.51 ± 0.75 mm. This difference shows that the stages of tissue development can affect the accumulation of flavonoids, tannins, alkaloids, phenolic acids, and other metabolites. These results complement the findings of Wu et al. (2023) regarding variation between organs and Andianto et al. (2024) regarding variations in wood profiles based on materials and locations. Methodologically, leaf lifespan should not be treated only as additional information, but needs to be part of the characterization of the sample. Without tissue maturity reporting, two studies of leaves of the same species can produce different profiles and be considered contradictory, even though the biological material is not comparable. The significance of these findings is the need to standardize raw materials based on age, position, and physiological conditions of tissues before extraction is performed.

Geographic variation is also an important part of the RQ1 answer because populations of the same species can have different metabolite profiles when growing in different habitats. Saputri et al. (2026) conducted chemometric profiling of *A. marina leaves* from various locations in Indonesia and detected hundreds of metabolites that formed groupings based on sample origin and extraction methods. The findings show that the similarity of species identity does not guarantee similarity in composition or abundance of compounds. Rozirwan et al. (2023) found differences in HPLC profiles, phenolic content, and antioxidant activity in several

species originating from the Tanjung Api-Api Port area. Andianto et al. (2024) also indicated that there is a change in the abundance of chemical components according to the location and character of the wood material. Beniwal et al. (2024) place the phytochemical diversity of the genus *Avicennia* in its ecological context and distribution, while ElDohaji et al. (2020) describe *A. marina* as a phytopharmaceutical reservoir whose composition is very broad. These results show that the location of sampling is a scientific variable, not just the geographical address of the study. Data on salinity, substrate, season, inundation levels, light, and pollution are needed to more accurately explain chemical variations. The contribution of this study in the field of phytochemistry is to place the profile of compounds as a result of the interaction between the genetic capacity of the plant and the environmental conditions in which the plant develops.

3.2.2 RQ2 Discussion: Biological Activity and the Strength of the Evidence Supporting It

The answer to RQ2 shows that mangrove plants have a broad spectrum of biological activity, but antioxidants and antimicrobials are the two categories that are most often studied. Bibi et al. (2019), Chavan et al. (2026), and Christopher (2024) consistently place antioxidant, antimicrobial, and antidiabetic activity as dominant activities in the mangrove literature. Dahibhate et al. (2020) reported antioxidant and antimicrobial activity in selected mangrove species, while Eswaraiah et al. (2020) found that methanol extracts generally showed stronger activity than acetone and n-hexane extracts. Mitra et al. (2023) found a high phenolic and flavonoid content in *A. marina* methanol extract, accompanied by 96% DPPH capture activity at a concentration of 250 μg/mL. These results were higher than ethyl acetate extracts under the same test conditions. Rozirwan et al. (2023) found that *Sonneratia alba* has stronger DPPH activity than *Bruguiera gymnorhiza* and *A. marina*, although the total phenolic content does not always follow the same sequence. This suggests that the antioxidant ability of the extract depends not only on the total number of phenolics, but also on the type, structure, concentration, and interactions between compounds. However, DPPH results remain a measure of capacity in chemical systems and cannot yet be treated as evidence of antioxidant effects in humans. Therefore, the evidence of mangrove antioxidant activity is extensive at the screening and in vitro stages, but it is still more limited at the level of complex biological systems.

Antimicrobial activity shows the development of more advanced methods, from inhibition zone measurements to antibiofilm testing and bacterial matrix degradation. Rajivgandhi et al. (2024) reported an inhibition zone of about 18–26 mm, biofilm inhibition of about 84–92%, and *extracellular polymeric substance* degradation of about 86–94% in *A. marina* extract. The results expand the antimicrobial data because biofilm is a more complex form of microbial organization than planktonic cells. Djamaludin et al. (2025) showed different antibacterial activity between young and old leaf extracts against *P. acnes*, so that biological ingredients and solvent systems alike influence the results. Eswaraiah et al. (2020) also showed that the effectiveness of the extract was different against *Micrococcus luteus*, *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Klebsiella pneumoniae*, and *Bacillus subtilis*. Valleti et al. (2025, 2026) summarize the antimicrobial metabolites of mangroves and explain that activities can involve membrane disruption, inhibition of metabolic pathways, as well as interactions with various cell targets. Chung (2019) showed that pentacyclic triterpenoids such as α-amyrin and betulinic acid can affect cell division, ABC transporters, fatty acid biosynthesis, peptidoglycans, ribosomes, as well as the membrane permeability *of S. aureus*. However, the mechanism of such isolated compounds cannot be directly used to explain extracts that are only known to contain the triterpenoid group. The significance of the results of this study lies in the affirmation that antibacterial evidence must be assessed based on the form of the test material, concentration, method, target organism, and the existence of mechanistic data.

Anti-inflammatory and cytotoxic activity showed higher strength of evidence when studies used isolated compounds and specific biological targets. Vinh et al. (2020) isolated saponins from *A. corniculatum* and tested their activity against inflammatory mediators and melanoma cells. One of the compounds showed IC50 values of 0.40 μM against TNF-α, 0.79 μM against IL-6, and 1.58 μM against IL-12 p40. Some compounds also increase apoptosis and death of B16F10 melanoma cells. Sarkar et al. (2024) linked the phytochemical content *of A. corniculatum* with anti-inflammatory, anticancer, antidiabetic, neuropharmacological, antinocusceptive, and hepatoprotective activities. Hridya et al. (2023) noted limonoids, quinones, terpenoids, and triterpenoids as groups of anticancer candidates found in mangrove species. Parthiban et al. (2022) also reported a variety of compounds, including gedunin, xylomexicanin, avicequinone, and other metabolites associated with anticancer or cytotoxic activity. Although the evidence of pure compounds is stronger than that of coarse extracts, most tests still use cell or preclinical models. Cytotoxic effects on cancer cells have not shown therapeutic selectivity if the effects on normal cells, distribution in the body, metabolism, and safe doses have not been determined. Thus, the anticancer and anti-inflammatory findings are a promising path, but not yet enough to support claims of clinical effectiveness.

Antidiabetic, neuroprotective, analgesic, hepatoprotective, antiulcer, antipyretic, and antidiarrheal activity showed biological breadth, but the depth of validation was not uniform. Chavan et al. (2026) noted antidiabetic and antiulcer activity as part of the most reported activity after antioxidants and antimicrobials. Cerri and Galli (2025) collected antidiabetic, anti-inflammatory, antiallergic, analgesic, antipyretic, antidiarrheal activities, as well as effects on the central nervous system of *S. caseolaris*. Sarkar et al. (2024) reported on the spectrum of *activity of A. corniculatum*, but also pointed out that evidence against some activities, including antivirals, is still inadequate. Murthy et al. (2025, 2026) link mangrove-specific metabolites to a variety of biological targets, including metabolic disorders and neuroprotective processes. Kiran Kumar and Pola (2022) show wide therapeutic opportunities, while ElDohaji et al. (2020) place *A. marina* as a reservoir of phytopharmaceuticals that have not been fully developed into standardized products. Mitra et al. (2021) also showed that the magnitude of the chemical potential has not been balanced with the therapeutic translational data. The reported activity of the crude extract may still be produced by synergistic, additive, or antagonistic effects of various components. Therefore, the identification of active compounds through bioactivity-based fractionation is a necessary step before therapeutic mechanisms or benefits can be established more definitively.

The strength of the evidence of biological activity in this study forms a hierarchy starting from initial screening to clinical validation. Qualitative phytochemical screening only indicates the possible presence of a group of compounds and does not provide molecular identity, concentration, or purity. Measurements of total phenolics, total flavonoids, DPPH, ABTS, or FRAP provide aggregate quantitative data, but do not yet explain the contribution of each compound to activity. TLC, HPLC, GC-MS, and LC-MS profiles increase the resolution of the analysis, but identification through library matching can remain tentative. Compound isolation followed by NMR, high-resolution mass spectrometry, and stereochemical determination provide a higher level of chemical certainty, as seen in Vinh et al. (2020) and Wang et al. (2022). Testing for enzymes, cells, bacteria, fungi, or inflammatory mediators yields more specific biological evidence, but it is still preclinical stage. Fadilah et al. (2023) point out the need to include toxicity because active extracts can also have different toxicity values. ElDohaji et al. (2020), Mitra et al. (2021), Sarkar et al. (2024), and Chavan et al. (2026) show that pharmacokinetic, bioavailability, formulation, long-term toxicity, and clinical trial data are still

very limited. An important contribution of this research is to avoid equalizing the activity in simple chemical tests and evidence of benefits in organisms or humans.

Mangrove extract-based nanoparticles expand the scope of biological applications, but the results need to be separated from direct phytochemical activity. Gnanadesigan et al. (2012) showed that *A. marina leaf extract* is more effective in the formation of silver nanoparticles than the bark of the trunk and root. The resulting nanoparticles showed antibacterial activity against test bacteria, including *Escherichia coli* and *S. aureus*. Bakshi et al. (2015) used three mangrove plants from the Sundarban and found differences in bioreduction ability and the characteristics of the nanoparticles formed. Saha et al. (2021) placed mangrove bioactive compounds and nanoparticles as potential approaches to dealing with human pathogens. Rathod and Pathak (2020) also showed the development of green synthesis of mangrove plant- based nanoparticles for biomedical applications. Although phytochemicals act as reducing, coating, and stabilizing agents, the final product activity is also determined by silver ions, particle size, shape, surface charge, and colloidal stability. Therefore, the success of the synthesis of nanoparticles cannot be used as evidence that the initial extract has activity of the same strength. The methodological implication is that nanoparticle data should be placed as a derivative application category, rather than mixed with extract, fraction, or pure compound data.

Fungal and endophytic metabolites from mangrove ecosystems also show interesting activity, but do not include plant phytochemicals directly. Wang et al. (2022) isolated seven isomer pairs of azaphilone from *Penicillium sclerotiorum* of mangrove environmental origin and found phytotoxic activity against *Amaranthus retroflexus*. Zhou et al. (2025) collected 417 natural products of *Penicillium* of plant, soil, and mangrove sediment origin, including 170 new compounds as well as 126 compounds that showed biological activity. Job et al. (2023) showed that mangrove-associated endomycrates have functional diversity and potential as a source of drug candidates. These findings add to the bioprospecting value of mangrove ecosystems, but the producing organisms are fungi, not mangrove plants. Erroneous grouping can cause biosynthesis sources, production mechanisms, and utilization strategies to be misinterpreted. From a product development perspective, fungal metabolites can even offer advantages because microbial cultures can potentially be developed without continuous crop harvesting. However, this study maintains conceptual limits by placing it as a metabolite of mangrove-associated organisms. This separation is a scientific contribution because it helps maintain the accuracy of the use of phytochemical terms while still recognizing the chemical potential of mangrove ecosystems more broadly.

3.2.3 Discussion of RQ3: Biological, Ecological, and Methodological Determinants and Research Gaps

The RQ3 findings show that differences in phytochemical profiles and biological activity are the result of the interaction of various determinants, rather than the result of a single factor. Biological factors include species, family, genotype, organs, tissue age, and plant developmental phases. Ecological factors include salinity, inundation, substrate, seasonality, light intensity, pollution, nutrient availability, and biotic stress. Methodological factors include material preparation, drying method, particle size, solvent type, material-solvent ratio, temperature, time, extraction technique, purification, analytical instruments, and test models. Wu et al. (2023) showed the influence of species and organs, Djamaludin et al. (2025) showed the influence of leaf maturity, while Saputri et al. (2026) showed the influence of location and solvents. Rozirwan et al. (2023) also noted differences in phenolic content and antioxidant activity between mangroves growing in the same area. Andianto et al. (2024) show that the chemical profile of wood can differ according to the species and character of the material

source. Thus, comparing results based solely on species names risks resulting in overly simplistic conclusions. Multidimensional mapping is important because it allows each outcome to be placed in its biological, ecological, and technical context.

The influence of the environment on the biosynthesis of metabolites is supported by the physiological and metabolic literature, but the degree of association with mangrove phytochemicals still varies. Zhao et al. (2025) showed that salinity can direct carbon streams towards the biosynthesis of squalene and polyunsaturated fatty acids in marine protists. Martins et al. (2024) explain that the combination of salinity and inundation gives rise to osmotic, ionic, hypoxia, and oxidative stress in plants. Talebi (2023) suggests that environmental stress can alter the profile of secondary metabolites as part of the defense response. Akter et al. (2025) found that genotypes that are tolerant of salinity and inundation are able to maintain ion balance, photosynthesis, proline, free amino acids, and antioxidant enzyme activity. However, the object of Zhao et al. (2025) is not mangrove plants, whereas Akter et al. (2025) use soybeans and do not analyze mangrove-specific metabolites. Therefore, these results serve as a mechanistic context regarding metabolic plasticity due to environmental stress, rather than direct evidence of mangrove phytochemical changes. Braby (2012) added the ecological context that secondary metabolites in mangrove plants or coastal specialists can be involved in the relationship between plant and herbivorous defense. The significance of this series of findings is the emergence of a need for research that measures environmental conditions, metabolic expression, compound profile, and bioactivity simultaneously in mangrove plants.

The extraction method is the most powerful technical determinant because it determines the compounds that move from the plant tissue into the extract. Ernawati et al. (2019) showed that methanol produces a higher yield of *R. mucronata* fruit than ethyl acetate and n-hexane, while extracting a more diverse group of compounds. Mitra et al. (2023) showed that Methanol extract of *A. marina* leaves has a higher phenolic, flavonoid, and antioxidant capacity than ethyl acetate extract in the study design. Eswaraiah et al. (2020) also found that methanol extracts generally show higher antimicrobial activity than acetone and n-hexane. Chuo et al. (2020) emphasized that there is no one best extraction technique for all types of ingredients and compound targets. Maceration and Soxhlet are easy to apply, but they can require more time, energy, and solvents, while ultrasonic, microwave, high-pressure, and innovative solvent systems offer different efficiencies. Nastić et al. (2025) used gradual extraction through supercritical carbon dioxide and *ultrasound-assisted extraction*, but the results did not always place mangroves as the source with the highest activity compared to comparative crops. The findings of Nastić et al. (2025) are important because they reduce the confirmation bias that all mangrove extracts must be superior simply because they come from extreme environments. The practical implication is that the selection of methods must follow the target compound, the purpose of use, the stability of the component, the sustainability, and the need for standardization.

The purification and identification stages can also form results that at first glance appear to be biological differences. Lang et al. (2022) show that the use of certain solvents and purification methods can lead to the loss of oligomers and polymer tannins. Purification with pure ethanol does not result in the same polymer distribution as the initial extract, whereas 50% methanol maintains a profile closer to the coarse material. The findings suggest that laboratory processes can produce artifacts or reduce the representation of compound diversity. The same is true for LC-MS or GC-MS-based identification because the compounds matched to the literature have not always been structurally confirmed. In contrast, NMR, HRESIMS, and stereochemical analysis provide stronger certainty, but require greater isolation, amount of material, cost, and expertise. Inequality of access to instruments has led some studies to report

only on compound classes, while others have been able to identify specific molecules. If the two types of evidence are combined without classification, the number of compounds can seem more certain than the actual conditions. The contribution of this research is to introduce a tiered reading of chemical identification so that screening, tentative identification, and structural confirmation are not placed at the same level.

3.2.4 Significance and Contribution of Research

The main significance of this study lies in the shift in focus from the inventory to the evaluation of the quality and context of the evidence. Previous studies have shown that mangroves are metabolite-rich and have extensive biological activity, but the data are dispersed by species, region, method, and research objectives. Multidimensional mapping brings together information regarding species, families, organs, tissue age, location, habitat, solvents, extraction methods, identification techniques, compounds, activities, and test models. With this framework, the results of a study are not directly compared with other studies if the material, method, or level of validation is fundamentally different. This approach answers the problems identified by Bibi et al. (2019), Chavan et al. (2026), Mitra et al. (2021), Christopher (2024), and Parthiban et al. (2022), namely evidence fragmentation and inequality between chemical richness and pharmacological validation. This research also expands the function of phytochemical studies to include chemotaxonomy, ecological factors, toxicity, and sustainability. The separation of plant metabolites, association plants, fungi, supporting organisms, and nanoparticles maintains a conceptual consistency that is often blurred in the discussion of mangrove bioprospecting. Thus, his scientific contribution is not to discover new molecules, but rather to build an architecture of evidence that can be used to design primary research with clearer priorities.

Another contribution of this study is the compilation of a hierarchy of the strength of evidence of biological activity. In the field of natural materials, positive results are often presented as therapeutic potentials without adequate explanation of their validation stages. This study shows that the results of DPPH, inhibition zones, docking, cell tests, animal trials, and clinical trials answer different questions. DPPH measures the chemical ability to capture radicals, while cell tests measure effects in biological systems that are still limited. Docking predicts possible molecular interactions, but does not prove absorption, distribution, metabolism, toxicity, or effectiveness. Pure compounds that are micromolarically active have more specific evidence than crude extracts, but they are still not yet a medicinal product. Fadilah et al. (2023) show that toxicity evaluation should go hand in hand with activity testing, while Chavan et al. (2026) and Cerri and Galli (2025) show limitations in pharmacokinetics, formulation, and clinical data. This hierarchy is important to prevent exaggeration of claims and to improve the accuracy of scientific language in declaring "active", "potential", "validated in vitro", or "clinically proven". For the fields of phytochemistry and pharmacognosy, the framework can help direct resources to candidates with the strongest chemical identity, activity, selectivity, and safety.

3.2.5 Research Implications

The theoretical implication of this study is to strengthen the view that mangrove metabolites are the result of a relationship between biological identity and ecological stress, rather than just a collection of compounds that can be extracted. Chemical profiles can be used to understand the adaptation, defense, taxonomic relationships, and biological potential of plants simultaneously. The findings of Nebula et al. (2013), Andianto et al. (2024), Basyuni et al. (2025), and Wu et al. (2023) suggest that metabolite patterns can be associated with families, genus, species, as well as organs. The findings of Saputri et al. (2026), Rozirwan et al. (2023), and Djamaludin et al. (2025) show that the location and age of the tissue add layers of variation

within a species. Implicitly, theories about the phytochemical potential of mangroves need to include the concept of metabolic plasticity and contextual variation. In future studies, the relationship between habitat conditions, metabolite changes, and bioactivity changes can be tested using a comparative or longitudinal design. The integration of metabolomics, chemometrics, chemotaxonomy, and pharmacological testing can lead to a more complete understanding. The approach may also help explain why the results of research on the same species may not always be replicated in different locations.

The methodological implication is the need for standardization of reporting of research materials and processes. Researchers need to list verified species identity, location, organs, age or maturity of tissues, season, habitat conditions, drying methods, particle size, storage length, and material-to-solvent ratio. The extraction method should be reported by temperature, time, frequency or power, number of cycles, solvent type, and yield. Metabolite identification needs to be differentiated between cluster screening, total quantification, spectrum matching, tentative identification, and confirmation of pure compounds. Bioactivity testing needs to mention concentration, positive control, negative control, number of repeats, organism or test model, as well as the unit of result. Research on antimicrobials should not only use inhibition zones, but can also be equipped with MIC, MBC, biofilm, and mechanistic testing. Antioxidant research needs to distinguish chemical activity from effects on cells or organisms. The application of these elements will increase reproducibility and allow meta-analysis when the data is more uniform.

The practical and conservation implications are the need to choose materials and methods that do not increase the pressure on the mangrove ecosystem. The dominance of leaf use in the study may provide an advantage because the harvest is relatively less damaging than roots, stems, or bark, but the intensity and frequency of harvesting must still be considered. The discovery of activity in roots or wood does not necessarily justify destructive harvesting, especially in species with limited populations. Fungal and endophytic metabolites as discussed by Wang et al. (2022), Zhou et al. (2025), and Job et al. (2023) may be an alternative pathway because production through culture has the potential to reduce dependence on plant biomass. Green extraction technologies such as NADES used by Djamaludin et al. (2025) also offer the possibility of reducing the use of conventional organic solvents. The synthesis of nanoparticles by Gnanadesigan et al. (2012), Bakshi et al. (2015), Saha et al. (2021), and Rathod and Pathak (2020) shows opportunities for biotechnology applications, but the safety of materials, waste, and their impacts still need to be tested. Phytochemical research therefore needs to be linked to conservation strategies, cultivation, the use of renewable organs, and alternative production systems. The economic value of mangrove compounds should be an incentive to protect ecosystems, not an excuse to increase uncontrolled exploitation.

3.2.6 Research Limitations

This study has several limitations that must be considered in reading the results and conclusions. First, synthesis relies on available publications so that unpublished species, activities, or negative outcomes cannot be represented. The dominance of positive results can create publication bias and give the impression that most mangrove extracts are always active. The results of Nastić et al. (2025), which do not always place mangroves as the material with the most intense activity, show the importance of including comparative findings and less positive results. Second, the heterogeneity of methods, solvents, concentrations, units, controls, and test models limits direct quantitative comparisons. Third, not all studies reported complete location, salinity, tissue age, season, or habitat conditions. Fourth, some articles use tentative identification based on spectrum literature so that the number of compounds recorded has not fully had structural confirmation. Fifth, some of the evidence comes from reviews, book

chapters, association plants, fungi, protists, or non-mangrove plants that can only be used as support. Sixth, the limitations of clinical data cause this study to be unable to conclude the therapeutic effectiveness or safety of the use of mangrove compounds in humans.

Another conceptual limitation relates to the breadth of the terms "bioactivity" and "mangrove compounds" in the literature. The activity of nanoparticles synthesized using mangrove extract cannot be fully attributed to plant metabolites because metal materials have a major contribution to product properties. Mangrove-derived fungi metabolites also cannot be treated as plant phytochemicals, although they are relevant to the chemical potential of ecosystems. The studies of Zhao et al. (2025), Martins et al. (2024), Talebi (2023), and Akter et al. (2025) support explanations for environmental stress, but not all of them use mangrove plants or test pharmacological activity. The Braby (2012) study provides context for the ecological function of metabolites, but does not provide direct evidence of therapeutic benefits. The separation of such categories reduces the amount of data that can be combined, but increases the validity of the conclusions. In addition, the limitations of primary article reporting make quality assessments incapable of distinguishing whether a procedure is not performed or simply not explained. The absence of quantitative meta-analysis also limits the determination of the size of the combined effects, although such a decision can be justified by the high heterogeneity of the data. Therefore, the findings of this study are best used as an evidence map and the basis for determining the research agenda, not as a determination of dose, clinical safety, or effectiveness of a product.

Overall, the study shows that mangrove plants are a rich source of metabolites, but their scientific value is not only determined by the number of compounds and activities reported. These values depend on the accuracy of source identification, method quality, structural certainty, validity of bioactivity models, and availability of safety evidence. RQ1 exhibits great chemical diversity as well as distribution influenced by species, organs, tissue age, and location. RQ2 showed that antioxidants and antimicrobials have the most extensive database, while other activities are still more in the exploration and preclinical stages. RQ3 confirms that biological, ecological, and methodological factors interact in shaping phytochemical profiles as well as biological activity. The resulting multidimensional mapping contributes as a framework to distinguish the type of data, the level of certainty, and the strength of evidence. The framework can be used to select neglected species, under-researched organs, more appropriate extraction methods, as well as viable candidate compounds to proceed to safety and mechanistic testing. This research also places conservation as part of the development of natural materials because the utilization of mangrove metabolites must consider the sustainability of the source. Thus, the main contribution of this study is to bridge chemical diversity, validity of bioactivity, ecological context, and translational needs in a more critical and structured map of knowledge.

IV. CONCLUSION

Mangrove plants contain diverse phytochemicals, including phenolics, flavonoids, tannins, alkaloids, saponins, steroids, glycosides, terpenoids, limonoids, quinones, and fatty acids. Their distribution varies by species, plant organ, tissue age, location, and habitat. Leaves are the most studied, while roots, flowers, seeds, hypocotyls, and reproductive tissues remain underexplored. Reported biological activities mainly include antioxidant, antimicrobial, anti-inflammatory, antidiabetic, anticancer, hepatoprotective, analgesic, and neuroprotective effects. However, evidence remains uneven because many studies rely on crude extracts and in vitro assays, whereas purified compounds, confirmed structures, dose–response relationships, and defined targets provide stronger validation.

Methodological differences, including solvents, extraction conditions, purification techniques, and analytical instruments, strongly influence detected compounds and bioactivity. This study therefore offers an integrated framework linking biological sources, sample characteristics, methods, compounds, activities, and evidence strength. Overall, mangroves are promising sources of bioactive materials, but therapeutic development requires improved standardization, safety evaluation, and translational research.

Future research should prioritize underexplored mangrove species and plant organs, supported by detailed environmental and sampling data, standardized raw materials, and clearly reported extraction conditions. Comparative and environmentally friendly extraction methods, followed by advanced compound identification using high-resolution mass spectrometry, NMR, and stereochemical analysis, are needed to improve reliability. Bioactivity studies should progress from crude extract screening to active-compound isolation, mechanism-based testing, cellular and in vivo validation, antimicrobial and anticancer selectivity assessment, toxicity evaluation, pharmacokinetics, bioavailability, and formulation development. Integrated metabolomic studies combining environmental factors, chemical profiles, and biological activities are also essential. Mangrove bioprospecting must be accompanied by sustainable harvesting, cultivation, endophyte utilization, and conservation strategies to prevent additional pressure on coastal ecosystems.

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