

Review Article

Phytochemical Composition and Its Role in Antimicrobial Efficacy of Plant Extracts

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A B S T R A C T

Phytochemicals, the bioactive compounds found in plants, have gained significant attention for their antimicrobial potential. This paper focuses on the phytochemical composition and its role in the antimicrobial efficacy of plant extracts. The paper found that the related major phytochemicals are classified as alkaloids, flavonoids, and terpenoids. These compounds exhibit diverse mechanisms of action, including disruption of microbial cell membranes, inhibition of DNA replication and protein synthesis, and impairment of enzymatic activity. The synergistic effects of combined phytochemicals further enhance their antimicrobial efficacy, offering a promising alternative to conventional antibiotics, especially in addressing the rising issue of antibiotic resistance. Concentration-dependent susceptibility patterns influence these plant-based compounds' effectiveness, highlighting the importance of understanding dose-response relationships and microbial strain variability. Despite the promising potential of phytochemicals, challenges such as standardization, bioavailability, and regulatory approval remain significant barriers to their widespread clinical use. As research progresses, optimizing extraction methods and enhancing delivery systems are crucial to realizing their therapeutic potential. Integrating phytochemicals into pharmaceutical and clinical applications could provide innovative solutions for combating microbial infections, making continued exploration of this field essential for future antimicrobial therapies.

Keywords: Phytochemicals, Antimicrobial Efficacy, Antibiotic Resistance, Synergistic Effects, Dose-Response, Bioavailability

Introduction

The increasing prevalence of antibiotic resistance poses significant challenges to conventional antibiotic therapies, necessitating the exploration of alternative antimicrobial agents (Enaregha et al., 2021; Kigigha et al., 2018a,b, 2016, 2015). Conventional antibiotics, while effective in treating bacterial infections, are often limited by their inability

to combat resistant strains of bacteria. This resistance arises from various factors, including the overuse and misuse of antibiotics, which lead to selective pressure on bacterial populations, allowing resistant strains to thrive and proliferate (Li & Li, 2013). The World Health Organization has highlighted this issue, indicating that antibiotic resistance is one of the most pressing global health challenges (Cao et al., 2018). Consequently, there is a critical need for

novel antimicrobial strategies that can circumvent these limitations.

Phytochemicals, the bioactive compounds found in plants, have emerged as promising candidates in the search for alternative antimicrobial agents (Izah et al., 2018a,b,c,d,e). These compounds, which include flavonoids, tannins, alkaloids, and phenolic acids, exhibit a range of biological activities, including antimicrobial properties (Shittu & Ephraim, 2014; Izah and Odubo, 2023). Research has demonstrated that phytochemicals can disrupt bacterial cell membranes, inhibit enzyme activity, and interfere with bacterial DNA synthesis, thereby exerting their antimicrobial effects (Yirdaw & Getahun, 2023). For instance, studies have shown that extracts from plants such as *Moringa oleifera* possess significant antimicrobial activities, attributed to their rich phytochemical composition (Moyo et al., 2012). This highlights the potential of phytochemicals as effective alternatives to conventional antibiotics.

The relationship between phytochemical composition and antimicrobial efficacy is complex and multifaceted. Different classes of phytochemicals exhibit varying degrees of antimicrobial activity, and their effectiveness can be influenced by factors such as concentration, extraction method, and the specific microbial strains being targeted (Izah, 2018; Zahra et al., 2019; Yahaya et al., 2017). For example, the antimicrobial activity of *Alstonia boonei* has been linked to its high concentrations of flavonoids and tannins, which have been shown to possess significant antibacterial properties (Osagie et al., 2023). Similarly, saponins and phenolic compounds in plant extracts have been correlated with enhanced antimicrobial activity against various pathogens (Uchenna et al., 2015; Shrestha et al., 2022). This highlights the importance of understanding the specific phytochemical profiles of medicinal plants to optimize their use in antimicrobial applications (Izah et al., 2019a,b,c; Abajue et al., 2024).

Moreover, the synergistic effects of multiple phytochemicals can enhance their antimicrobial efficacy. Research indicates that the combined action of different phytochemicals can lead to a more potent antimicrobial effect than that observed with individual compounds (Rahman et al., 2023). For instance, studies on the extracts of *Carica papaya* have shown that the presence of multiple phytochemicals contributes to its significant antibacterial activity against various enteric pathogens (Yahaya et al., 2017). This synergistic interaction enhances the antimicrobial properties and reduces the likelihood of resistance development, as pathogens are less likely to adapt to the combined effects of multiple compounds (Bhatnager et al., 2015).

Exploring phytochemicals as antimicrobial agents is further supported by their historical use in traditional medicine. Many cultures have utilized plant-based

remedies for centuries to treat infections and promote health, relying on the inherent antimicrobial properties of these plants (Duraipandiyan et al., 2006; Roy et al., 2024). Ethnobotanical studies have documented the use of various plants in treating microbial infections, providing a rich source of knowledge for identifying potential antimicrobial agents (Ahmad et al., 2012). This traditional knowledge, combined with modern scientific techniques, can facilitate the discovery of new phytochemicals with significant antimicrobial potential. In addition to their antimicrobial properties, phytochemicals exhibit various other beneficial effects, including anti-inflammatory, antioxidant, and immunomodulatory activities (Anyiam & Opara, 2023). For example, the anti-inflammatory properties of certain phytochemicals can help mitigate the inflammatory responses often triggered by infections, thereby improving patient outcomes (Bahramsoltani et al., 2014). This holistic approach to treatment aligns with the growing trend toward integrative medicine, which emphasizes using natural products in conjunction with conventional therapies.

Despite the promising potential of phytochemicals, challenges remain in their application as antimicrobial agents (Jacob et al., 2024a,b,c). One significant challenge is the standardization of phytochemical extracts, as variations in plant growth conditions, harvesting methods, and extraction techniques can lead to inconsistencies in phytochemical composition and efficacy (Sultana & Das, 2019). Additionally, the bioavailability of phytochemicals can be limited, affecting their absorption and effectiveness *in vivo* (Wei et al., 2015). Addressing these challenges requires rigorous research and development efforts to optimize extraction methods, standardize formulations, and enhance the bioavailability of phytochemicals.

Furthermore, regulatory hurdles can impede the integration of phytochemicals into mainstream medical practice. Adequate standardized testing protocols and quality control measures for herbal products can lead to variability in product quality and efficacy (Cao et al., 2018). Establishing clear regulatory frameworks for evaluating and approving phytochemical-based therapies is essential to ensure their safety and effectiveness. This includes conducting well-designed clinical trials to assess the antimicrobial efficacy of phytochemicals in human populations and investigating potential interactions with conventional medications (Jackson et al., 2009).

The paper focuses on classifying essential phytochemicals such as alkaloids, flavonoids, and terpenoids, examining their antimicrobial mechanisms and contributions to inhibiting microbial growth. It explores how these compounds disrupt microbial cells, inhibit DNA replication, and act synergistically, emphasizing the impact of

concentration on efficacy. Finally, it discusses the potential for phytochemical-based therapies in clinical settings while addressing challenges in standardizing their use.

Classification of Phytochemicals

Classifying phytochemicals is essential in understanding their diverse roles in antimicrobial activity. Phytochemicals,

bioactive compounds derived from plants, can be categorized into several classes, including alkaloids, flavonoids, terpenoids, and other compounds such as saponins, tannins, phenolics, etc (Table 1). Each class exhibits unique mechanisms of action against microbial pathogens, contributing to their potential as natural antimicrobial agents.

Table 1. Classification of phytochemicals with examples, sources, and biological activities

Phytochemical Class	Examples	Common Sources	Some Biological Activities
Alkaloids	Caffeine, nicotine, morphine	Trees and shrubs such as coffee, tobacco, poppy	Stimulant, analgesic, neuroprotective
Flavonoids	Quercetin, catechins, anthocyanins	Fruits, vegetables,	Antioxidant, anti-inflammatory, cardioprotective
Terpenoids	Limonene, menthol, carotenoids	Citrus fruits, mint, carrots	Antimicrobial, anticancer, anti-inflammatory
Saponins	Ginsenosides, dioscin	Ginseng, soybeans, beans	Immunomodulatory, antioxidant, hypocholesterolemic
Phenolic Acids	Caffeic acid, gallic acid	Berries, coffee, whole grains	Antioxidant, anti-inflammatory, cardioprotective
Glucosinolates	Sulforaphane, indole-3-carbinol	Broccoli, cabbage, kale	Antioxidant, anticancer, detoxification of carcinogens
Tannins	Tannic acid, ellagic acid	Some tea, wine, pomegranates	Antimicrobial, antioxidant, astringent
Lignans	Secoisolariciresinol, enterolactone	Flaxseed, sesame seeds	Antioxidant, estrogenic, cardioprotective

Alkaloids are a prominent group of phytochemicals known for their diverse biological activities, including antimicrobial properties. These nitrogen-containing compounds can disrupt vital microbial processes, such as DNA replication and RNA transcription, which are crucial for microbial growth and survival (Ajayi et al., 2022). For instance, studies have shown that alkaloids can interfere with the synthesis of nucleic acids, leading to the inhibition of microbial proliferation (Ajayi et al., 2022). Additionally, alkaloids have been reported to exhibit activity against various pathogens, including bacteria and fungi, highlighting their potential as therapeutic agents (Kryvtsova et al., 2019). The antimicrobial mechanisms of alkaloids often involve the disruption of cell membrane integrity and inhibiting enzymatic activities essential for microbial metabolism (Ajayi et al., 2022).

Flavonoids, another significant class of phytochemicals, have garnered attention for their ability to inhibit microbial growth and reduce oxidative stress. These compounds interact with microbial cell membranes, enabling membrane permeability and function alterations. Flavonoids can form complexes with proteins and other macromolecules, disrupting microbial adhesion and biofilm formation

(Komala et al., 2019). Furthermore, flavonoids have been shown to inhibit hydrolytic enzymes and other microbial proteins, contributing to their antimicrobial efficacy. The antioxidant properties of flavonoids also play a crucial role in mitigating oxidative stress in microbial cells, enhancing their antimicrobial action (Zhou et al., 2023).

Terpenoids, another class of phytochemicals, are recognized for disrupting microbial cell membranes. These compounds' hydrophobic properties allow them to integrate into lipid bilayers, destabilizing membranes and increasing permeability (Fankibe et al., 2020). This mechanism can result in the leakage of essential cellular components, ultimately leading to microbial cell death (Fankibe et al., 2020). Terpenoids have been shown to exhibit broad-spectrum antimicrobial activity against various pathogens, including bacteria and fungi, making them promising candidates for developing natural antimicrobial agents (Kryvtsova et al., 2019).

In addition to alkaloids, flavonoids, and terpenoids, other phytochemicals such as saponins, tannins, and phenolics contribute significantly to antimicrobial action. Saponins, for example, are known for forming complexes with sterols

in microbial membranes, leading to membrane disruption and cell lysis (AJAYI et al., 2022). This mechanism of action has been demonstrated in various studies, where saponins exhibited antifungal and antibacterial properties against multiple pathogens (Moulari et al., 2007). Tannins, another important class of phytochemicals, possess astringent properties that can inhibit microbial growth by precipitating proteins and disrupting microbial cell walls (Serrano et al., 2009). Their ability to form complexes with proteins enhances their antimicrobial activity, making them effective against Gram-positive and Gram-negative bacteria (Tănase et al., 2022).

Phenolic compounds, including flavonoids and tannins, are widely recognized for their antimicrobial properties. These compounds can exert their effects through various mechanisms, including inhibiting microbial enzymes and disrupting cell membrane integrity (Cano et al., 2020).

The antimicrobial potential of phytochemicals is further supported by their ability to modulate microbial resistance mechanisms. For instance, flavonoids have been shown to inhibit the efflux pumps in bacteria, which are responsible for the expulsion of antimicrobial agents, thereby enhancing the susceptibility of resistant strains to treatment (Komala et al., 2019). This property is particularly relevant in increasing antibiotic resistance, as phytochemicals may offer alternative strategies for combating resistant pathogens (Zhou, 2023). The multifaceted mechanisms of action exhibited by phytochemicals highlight their potential as effective antimicrobial agents in clinical and agricultural settings.

Research has demonstrated that the antimicrobial properties of phytochemicals can vary significantly based on their chemical structure and concentration. For example, the effectiveness of tannins as antimicrobial agents is influenced by their molecular weight and the presence of specific functional groups (Ekambaram et al., 2016). Hydrolysable tannins, which can release phenolic acids upon hydrolysis, have been shown to exhibit potent antimicrobial activity against various pathogens (Ekambaram et al., 2016).

The application of phytochemicals in food preservation is an area of growing interest, as their antimicrobial properties can help extend shelf life and enhance food safety. Tannins,

for instance, have been utilized in food coatings and packaging materials due to their ability to inhibit microbial growth (Cano et al., 2020). Incorporating phytochemicals into food products can provide a natural alternative to synthetic preservatives, aligning with consumer preferences for clean-label products (Cano et al., 2020).

In traditional medicine, phytochemicals have been employed for centuries to treat various ailments, including infections. The antimicrobial properties of plants have been documented in numerous ethnobotanical studies, highlighting the importance of phytochemicals in traditional healing practices (Afify et al., 2016). Modern research continues to validate these conventional uses, providing a scientific basis for the incorporation of phytochemicals into contemporary therapeutic approaches (Kryvtsova et al., 2019). Exploring phytochemicals as potential alternatives to conventional antibiotics is particularly relevant in light of the global rise in antibiotic-resistant infections (Zhou, 2023).

The integration of phytochemicals into pharmaceutical formulations presents both opportunities and challenges. While the antimicrobial properties of these compounds are well-documented, factors such as bioavailability, stability, and potential toxicity must be carefully considered (Araújo et al., 2016). Formulation strategies, such as encapsulation and combination with other bioactive compounds, can enhance the efficacy and safety of phytochemical-based products (Choi & Kim, 2020). Ongoing research aims to optimize these formulations to maximize the therapeutic potential of phytochemicals while minimizing adverse effects (Araújo et al., 2016).

Impact of Phytochemical Concentrations on Antimicrobial Efficacy

The impact of phytochemical concentrations on antimicrobial efficacy is a multifaceted subject that involves various aspects of dose-response relationships, variability in susceptibility across microbial strains, and concentration-dependent susceptibility patterns (Table 2). Phytochemicals, bioactive compounds derived from plants, have garnered significant attention due to their potential as natural antimicrobial agents. The effectiveness of these compounds often varies with concentration, necessitating a thorough examination of their dose-response relationships.

Table 2. Impact of phytochemical concentrations on antimicrobial efficacy

Aspect	Description	Significance
Dose-Response Relationships	The relationship between the concentration of phytochemicals and their antimicrobial effects is not always linear.	Understanding this relationship helps determine optimal concentrations for maximum efficacy.
Variability in Susceptibility	Different microbial strains show varying levels of susceptibility to phytochemicals due to genetic and environmental factors.	Identifying susceptible strains can inform targeted antimicrobial strategies.

Concentration-Dependent Patterns	Antimicrobial activity may increase with higher concentrations but can also exhibit diminishing returns or resistance at certain levels.	This highlights the need for careful dosing to avoid suboptimal effects and resistance development.
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Dose-response relationships of phytochemicals are critical in understanding their antimicrobial efficacy. The concentration of a phytochemical can significantly influence its ability to inhibit microbial growth. For instance, studies have shown that compounds such as cinnamaldehyde exhibit varying degrees of antibacterial activity against different strains of bacteria depending on their concentration. Okolie and Chenia (2013) reported that cinnamaldehyde inhibited both Gram-negative and Gram-positive bacteria at concentrations ranging from 75 to 600 µg/mL, highlighting the importance of concentration in determining antimicrobial effectiveness. Similarly, Sweet et al. (2023) research indicated that thymol, another potent phytochemical, demonstrated a minimum inhibitory concentration (MIC) range of 0.005-0.662 mg/mL against various foodborne pathogens, further emphasizing the significance of dose-response relationships in antimicrobial studies.

Moreover, the variability in antimicrobial susceptibility across different microbial strains is a crucial factor influencing phytochemicals' effectiveness. Different microbial species exhibit distinct responses to the same phytochemical, which can be attributed to genetic and phenotypic differences. For example, Chomini et al. (2020) found that extracts from *Aframomum melegueta* showed varying antibacterial activities against *Salmonella typhi* and *Klebsiella pneumoniae*, suggesting that the susceptibility of these strains to phytochemicals is not uniform. For instance, Abishad et al. (2021) demonstrated that thymol and cinnamaldehyde retained their antimicrobial activities even under varied stability conditions, but the efficacy was slightly diminished against multi-drug-resistant strains. This observation underscores the importance of the concentration of phytochemicals and the specific microbial context in which they are applied. Furthermore, the antimicrobial efficacy of coconut water, which contains various phytochemicals, was shown to be significant at a concentration of 60 mg/mL, indicating that higher concentrations may be necessary to achieve optimal antimicrobial effects (Anyiam, 2023).

Specific phytochemicals within a plant extract can also dictate the concentration-dependent susceptibility patterns observed in different microbial strains. For example, Toh et al. (2023) noted that the antimicrobial activities of extracts from *Cassia alata* varied significantly depending on the part of the plant used and the extraction method employed. Salhi et al. (2017) reported that the antifungal activity of aqueous

extracts from certain Algerian medicinal plants varied based on the concentration of phytochemicals present, suggesting that lower concentrations may inhibit growth without killing the organism, while higher concentrations may lead to cell death. This distinction is crucial for developing effective antimicrobial treatments, as the desired outcome may vary depending on the clinical context.

The role of phytochemical diversity in influencing antimicrobial efficacy cannot be overlooked. Different phytochemical classes, such as flavonoids, alkaloids, and terpenoids, exhibit varying degrees of antimicrobial activity, and their combined effects can lead to enhanced efficacy. For instance, Mandalari et al. (2007) demonstrated that flavonoids extracted from bergamot peel exhibited significant antimicrobial properties against both Gram-negative and Gram-positive bacteria, suggesting that the presence of multiple phytochemicals can create a synergistic effect that enhances overall antimicrobial activity. This concept of synergy is particularly relevant in traditional medicine, where complex plant extracts are often used, and their combined phytochemical profiles can lead to improved therapeutic outcomes. Furthermore, the stability of phytochemicals under different environmental conditions can affect their antimicrobial efficacy.

Applications in Pharmaceutical and Clinical Settings

Applying phytochemicals in pharmaceutical and clinical settings has garnered significant attention due to their potential as antimicrobial therapies (Table 3). Phytochemicals, bioactive compounds derived from plants, exhibit various biological activities, including antimicrobial, anti-inflammatory, and anticancer properties. Recent studies have highlighted the efficacy of multiple phytochemicals against pathogenic microorganisms, suggesting their potential as alternatives or adjuncts to conventional antimicrobial agents (Ovuru et al., 2024). For instance, certain phytochemicals have demonstrated effectiveness against antibiotic-resistant strains of bacteria, a growing concern in modern medicine (Chiou et al., 2018; García-Oliveira et al., 2021). Joshua (2022a) investigated the antidiabetic potential of methanolic extracts from *Morus mesozygia* Linn. Stapf leaves in laboratory studies on Wistar rats with type II diabetes. The study demonstrated that the extract exhibited antioxidant properties, significantly reducing blood glucose levels, suggesting its potential as an effective antidiabetic agent. In a separate study, Joshua (2022b) further explored the effects of *Morus mesozygia*

Linn. Stapf leaf extracts on diabetic Wistar rats induced with streptozotocin. The findings revealed that the treatment reduced blood urea and creatinine levels, indicating a protective effect on kidney function in diabetic conditions.

Despite the promising potential of phytochemicals, several challenges hinder their widespread application in clinical settings (Table 4). One of the primary obstacles is the variability in phytochemical concentrations due to factors such as plant species, environmental conditions, and extraction methods. This inconsistency can lead to

unpredictable therapeutic effects and complicate the standardization of dosages for clinical use (Sureka & Murugesan, 2017; Das et al., 2022). Moreover, the complex nature of plant-based medicines necessitates rigorous quality control measures to ensure safety and efficacy, which can be resource-intensive and time-consuming (Sureka & Murugesan, 2017; Das et al., 2022). As a result, the development of standardized protocols for extracting and formulating phytochemicals is crucial for their successful integration into pharmaceutical applications.

Table 3. Potential for Developing Phytochemical-Based Antimicrobial Therapies

Aspect	Description	Example/Considerations
Diverse antimicrobial compounds	Phytochemicals contain a variety of compounds with potential antimicrobial effects.	Flavonoids, alkaloids, phenolics, and terpenoids have shown antimicrobial properties.
Reduced risk of resistance development	Phytochemicals often act through multiple mechanisms, reducing the likelihood of microbial resistance.	The combination of different phytochemicals can hinder the development of resistance.
A broad spectrum of action	Many plant-based antimicrobials exhibit activity against various bacteria, fungi, and viruses.	Tea tree oil and garlic extract are active against gram-positive and gram-negative bacteria.
Synergy with existing antibiotics	Phytochemicals can work synergistically with antibiotics, potentially enhancing their effectiveness.	Garlic extract has been shown to enhance the activity of antibiotics like ampicillin.
Economic and sustainable source	Plants are renewable and can be cultivated sustainably, potentially offering a cost-effective solution.	Medicinal plants like neem and turmeric can be grown in various regions worldwide.

Table 4. Challenges in Standardizing Phytochemical Concentrations for Therapeutic Use

Challenge	Description	Example/Considerations
Variability in phytochemical content	Phytochemical concentrations can vary significantly due to plant species, soil, and climate factors.	Garlic grown in different regions may show variations in allicin content.
Extraction and purification techniques	Different methods of extraction affect the concentration and efficacy of phytochemicals.	Alcohol extraction may yield different concentrations compared to water extraction.
Stability and degradation	Phytochemicals may degrade quickly, affecting their therapeutic potency and shelf life.	Essential oils require specific storage conditions to maintain antimicrobial activity.
Quality control and standardization	Difficulties in standardizing active compounds across batches lead to inconsistencies in efficacy.	Ensuring consistent curcumin levels in turmeric extracts is challenging without rigorous testing.
Regulatory hurdles and safety assessment	Phytochemicals must pass regulatory testing for safety, posing hurdles for market approval.	Standardization for clinical use may require extensive toxicity and efficacy studies.

The formulation of phytochemical-based antimicrobial therapies also faces challenges related to bioavailability and stability. Many phytochemicals exhibit poor solubility

in water and low oral bioavailability, limiting their therapeutic effectiveness (Chiou et al., 2018; Vuppu, 2023). Nanotechnology has emerged as a promising strategy

to enhance the delivery of phytochemicals, allowing for improved solubility and controlled release (Vuppu, 2023; Kim et al., 2021; Amabie et al., 2024). By encapsulating phytochemicals in nanoparticles, researchers aim to overcome the limitations associated with traditional delivery methods, thereby enhancing the therapeutic potential of these compounds. However, the clinical translation of nano-phytochemicals remains a significant hurdle, as the efficiency of delivery systems must be optimized to ensure adequate therapeutic concentrations at the target site (Kim et al., 2021).

In addition to bioavailability issues, the safety and toxicity of phytochemicals must be thoroughly evaluated before they can be recommended for clinical use. While many phytochemicals are safe, their effects can vary significantly depending on the dosage and individual patient factors (Das et al., 2022; Parihar et al., 2023). Furthermore, the interaction of phytochemicals with conventional medications must be investigated to prevent adverse drug reactions, particularly in patients with complex health conditions (Das et al., 2022; Parihar et al., 2023).

Another active research area is the potential for phytochemicals to serve as adjunct therapies in cancer treatment. Numerous studies have documented the anti-cancer properties of various phytochemicals, which can modulate key signaling pathways involved in tumor growth and metastasis (García-Oliveira et al., 2021; Kapinová et al., 2018; Akhtar Siddiqui et al., 2015). For instance, flavonoids and polyphenols have been shown to inhibit cancer cell proliferation and induce apoptosis in various cancer types (Kapinová et al., 2018; Akhtar Siddiqui et al., 2015). Incorporating phytochemicals into existing cancer treatment regimens may enhance therapeutic efficacy and reduce the side effects of conventional chemotherapeutics (Kapinová et al., 2018; Akhtar Siddiqui et al., 2015).

The standardization of phytochemical concentrations is critical for ensuring consistent therapeutic effects. Phytochemical content variation can arise from differences in plant cultivation, harvesting, and processing methods (Sureka & Murugesan, 2017; Das et al., 2022). Developing standardized extraction protocols and quality control measures is essential to guarantee the reliability of phytochemical preparations. Analytical techniques such as high-performance liquid chromatography (HPLC) and mass spectrometry can quantify phytochemical concentrations and assess their purity (Simmler et al., 2018; Desai & Tatke, 2019). These methods can facilitate the establishment of pharmacopoeial standards for phytochemical-based products (Ogunro et al., 2024), thereby enhancing their acceptance in clinical practice.

Moreover, integrating modern technologies, such as organ-on-chip models, can significantly advance the testing and

validation of phytochemical therapies. These models allow for the simulation of human physiological conditions, enabling researchers to assess the efficacy and safety of phytochemicals in a controlled environment (Farooqi et al., 2023; Thaipitakwong et al., 2018).

Conclusion and Future Directions

The diverse phytochemical composition of plant extracts offers significant promise for developing alternative antimicrobial therapies, particularly in the context of rising antibiotic resistance. Alkaloids, flavonoids, terpenoids, and other phytochemicals exhibit unique mechanisms of antimicrobial action, such as membrane disruption and inhibition of DNA replication, which can be further enhanced through synergistic effects. The evidence underscores the need for deeper investigations into how these compounds work individually and in combination. Optimizing the concentration of phytochemicals to achieve maximum efficacy against various microbial strains remains a critical challenge that demands further research.

Moving forward, future studies should focus on standardizing the extraction and formulation of plant extracts to ensure consistent antimicrobial efficacy. There is a pressing need to explore the bioavailability of phytochemicals in therapeutic contexts and to address regulatory challenges surrounding their clinical use. Researchers should prioritize understanding the specific interactions between phytochemicals and microbial targets and investigate ways to improve the stability and potency of these compounds in pharmaceutical applications. A multidisciplinary approach combining microbiology, pharmacology, and environmental sciences will be essential for unlocking the full therapeutic potential of plant-derived antimicrobials.

References

1. Abajue MC, Sawyer WE, Izah SC, Ogwu MC. Diversity of Medicinal Plants Used in the Treatment and Management of Viral Diseases Transmitted by Mosquitoes in the Tropics. In: Izah SC, Ogwu MC, Akram M, editors. Herbal Medicine Phytochemistry. Reference Series in Phytochemistry. Cham: Springer; 2024. p. 383-416. https://doi.org/10.1007/978-3-031-21973-3_60-1
2. Abishad P, Niveditha P, Unni V, Vergis J, Kurkure NV, Chaudhari S, Rawool DB, Barbuddhe SB. In silico molecular docking and in vitro antimicrobial efficacy of phytochemicals against multi-drug-resistant enteroaggregative escherichia coli and non-typhoidal salmonella spp. Gut Pathogens. 2021;13(1). <https://doi.org/10.1186/s13099-021-00443-3>
3. Afify A, Hauka F, EL-Namla A. Determination of phytochemicals and antibacterial activity of some medicinal plants against pathogenic bacteria.

- Journal of Agricultural Chemistry and Biotechnology. 2016;7(10):269-274. <https://doi.org/10.21608/jacb.2016.41136>
4. Ahmad S, Khader JA, Ullah R, AbdElIslam NM, ud Din S, Khan R, Mehmood S. Phytochemical analysis and antimicrobial activity of persea duthiei. *African Journal of Pharmacy and Pharmacology*. 2012;6(48):3302-3304. <https://doi.org/10.5897/ajpp12.825>
 5. Ajayi FA, Akinruli FT, Fabunmi SO. Phytochemical analysis and antibacterial activities of aqueous and ethanolic crude extracts of soursop (annona muricata) leaves against selected clinical pathogens. *World Journal of Advanced Research and Reviews*. 2022;15(1):353-359. <https://doi.org/10.30574/wjarr.2022.15.1.0681>
 6. Akhtar Siddiqui J, Singh A, Chagtoo M, Singh N, Madhav Godbole M, Chakravarti B. Phytochemicals for breast cancer therapy: current status and future implications. *Current Cancer Drug Targets*. 2015;15(2):116-135. <https://doi.org/10.2174/1568009615666141229152256>
 7. Amabie T, Izah SC, Ogwu MC, Hait M. Harmonizing Tradition and Technology: The Synergy of Artificial Intelligence in Traditional Medicine. In: Izah SC, Ogwu MC, Akram M, editors. *Herbal Medicine Phytochemistry. Reference Series in Phytochemistry*. Cham: Springer; 2024. p. 2103-2125. https://doi.org/10.1007/978-3-031-21973-3_70-1
 8. Anyiam IV, Opara CN. Phytochemicals and antimicrobial activity of coconut water (cocos nucifera) on microbial pathogens. *GSC Biological and Pharmaceutical Sciences*. 2023;25(2):273-282. <https://doi.org/10.30574/gscbps.2023.25.2.0476>
 9. Araujo ERD, Langassner SMZ, Kramer DG. Antimicrobial potential evaluation of hydroethanolic extracts of the species anacardium occidentale linn. *African Journal of Pharmacy and Pharmacology*. 2016;10(28):579-583. <https://doi.org/10.5897/ajpp2016.4546>
 10. Bahramsoltani R, Farzaei MH, Rahimi R. Medicinal plants and their natural components as future drugs for the treatment of burn wounds: an integrative review. *Archives of Dermatological Research*. 2014;306(7):601-617. <https://doi.org/10.1007/s00403-014-1474-6>
 11. Bhatnager R, Rani R, Dang AS. Antibacterial activity of ferula asafoetida: a comparison of red and white type. *Journal of Applied Biology & Biotechnology*. 2015; 3(2): 18-21. <https://doi.org/10.7324/jabb.2015.3204>
 12. Cano A, Andrés M, Chiralt A, González-Martínez C. Use of tannins to enhance the functional properties of protein-based films. *Food Hydrocolloids*. 2020;100:105443. <https://doi.org/10.1016/j.foodhyd.2019.105443>
 13. Cao J, de la Fuente-Nunez C, Ou RW, Torres MDT, Pande SG, Sinskey AJ, Lu TK. Yeast-based synthetic biology platform for antimicrobial peptide production. *ACS Synthetic Biology*. 2018;7(3):896-902. <https://doi.org/10.1021/acssynbio.7b00396>
 14. Chiou YS, Li S, Ho CT, Pan MH. Prevention of breast cancer by natural phytochemicals: focusing on molecular targets and combinational strategy. *Molecular Nutrition & Food Research*. 2018;62(23). <https://doi.org/10.1002/mnfr.201800392>
 15. Choi J, Kim WK. Dietary application of tannins as a potential mitigation strategy for current challenges in poultry production: a review. *Animals*. 2020;10(12):2389. <https://doi.org/10.3390/ani10122389>
 16. Chomini MS, Peter MK, Ameh M, Chomini AE, Bassey EA, Ayodele AO. Phytochemical screening and antibacterial activities of Aframomum melegueta (K. Schum) seed extracts on Salmonella typhi and Klebsiella pneumoniae. *Journal of Applied Sciences and Environmental Management*. 2020;24(8):1419-1424. <https://doi.org/10.4314/jasem.v24i8.17>
 17. Das S, Bhadra SR, Khan MSM, Hasan MM, Anwar MR, Shahriar M. Ethnopharmacological survey of medicinal plants used by traditional health practitioners and indigenous people in Chittagong Hill Tracts, Bangladesh for the treatment of dysentery. *Dhaka University Journal of Pharmaceutical Sciences*. 2022;21(2):127-146. <https://doi.org/10.3329/dujps.v21i2.63114>
 18. Desai S, Tatke P. Phytochemical markers: classification, applications and isolation. *Current Pharmaceutical Design*. 2019;25(22):2491-2498. <https://doi.org/10.2174/1381612825666190709203239>
 19. Duraipandiyar V, Ayyanar M, Ignacimuthu S. Antimicrobial activity of some ethnomedicinal plants used by Paliyar tribe from Tamil Nadu, India. *BMC Complementary and Alternative Medicine*. 2006;6(1). <https://doi.org/10.1186/1472-6882-6-35>
 20. Ekambaram SP, Perumal SS, Balakrishnan A. Scope of hydrolysable tannins as possible antimicrobial agent. *Phytotherapy Research*. 2016;30(7):1035-1045. <https://doi.org/10.1002/ptr.5616>
 21. Enaregha EB, Izah SC, Okiriya Q. Antibacterial properties of Tetrapleura tetraptera pod against some pathogens. *Research and Review Insights*. 2021;5:1-5.
 22. Fankibe N, Metowogo K, Kantati YT, Afanyibo YG, Lawson-Evi P, Mouzou A, et al. Phytochemical screening and antimicrobial activities of hydroethanolic extracts from leaves and roots of Cochlospermum planchonii (Bixaceae). *Journal of Pharmacognosy and Phytotherapy*. 2020;12(4):94-101. <https://doi.org/10.5897/jpp2020.0591>
 23. Farooqi MA, Kang CU, Choi KH. Organ-on-chip: advancing nutraceutical testing for improved health outcomes. *ACS Omega*. 2023;8(35):31632-31647. <https://doi.org/10.1021/acsomega.3c03155>

24. Garcia-Oliveira P, Otero P, Pereira AG, Chamorro F, Carpena M, Echave J, et al. Status and challenges of plant-anticancer compounds in cancer treatment. *Pharmaceuticals*. 2021;14(2):157. <https://doi.org/10.3390/ph14020157>
25. Izah SC, Chandel SS, Etim NG, Epi JO, Venkatachalam T, Devaliya R. Potency of unripe and ripe express extracts of long pepper (*Capsicum frutescens* var. *baccatum*) against some common pathogens. *International Journal of Pharmaceutical and Phytopharmacological Research*. 2019a;9(2):56-70.
26. Izah SC, Etim NG, Ilerhunmwuwa IA, Ibibo TD, Udumo JJ. Activities of express extracts of *Costus afer* Ker-Gawl. [Family COSTACEAE] against selected bacterial isolates. *International Journal of Pharmaceutical and Phytopharmacological Research*. 2019b;9(4):39-44.
27. Izah SC, Etim NG, Ilerhunmwuwa IA, Silas G. Evaluation of crude and ethanolic extracts of *Capsicum frutescens* var. *minima* fruit against some common bacterial pathogens. *International Journal of Complementary and Alternative Medicine*. 2019c;12(3):105-108.
28. Izah SC, Odubo TC. Effects of *Citrus aurantifolia* fruit juice on selected pathogens of public health importance. *ES Food and Agroforestry*. 2023;11:829. <https://dx.doi.org/10.30919/esfaf829>
29. Izah SC, Uhumwangho EJ, Dunga KE. Studies on the synergistic effectiveness of methanolic extract of leaves and roots of *Carica papaya* L. (papaya) against some bacterial pathogens. *International Journal of Complementary and Alternative Medicine*. 2018a;11(6):375-378.
30. Izah SC, Uhumwangho EJ, Dunga KE, Kigigha LT. Synergy of methanolic leave and stem-back extract of *Anacardium occidentale* L. (cashew) against some enteric and superficial bacterial pathogens. *MOJ Toxicology*. 2018b;4(3):209-211.
31. Izah SC, Uhumwangho EJ, Eledo BO. Medicinal potentials of *Buchholzia coriacea* (wonderful kola). *Medicinal Plant Research*. 2018c;8(5):27-43.
32. Izah SC, Uhumwangho EJ, Etim NG. Antibacterial and synergistic potency of methanolic leaf extracts of *Vernonia amygdalina* L. and *Ocimum gratissimum* L. *Journal of Basic Pharmacology and Toxicology*. 2018d;2(1):8-12.
33. Izah SC, Zige DV, Alagoa KJ, Uhumwangho EJ, Iyamu AO. Antibacterial efficacy of aqueous extract of *Myristica fragrans* (common nutmeg). *EC Pharmacology and Toxicology*. 2018e;6(4):291-295.
34. Izah SC, Joshua MT, Torru KE, Ngun CT, Ogwu MC, Hait M. Antimicrobial Resistance and the Role of Herbal Medicine: Challenges, Opportunities, and Future Prospects. In: Izah SC, Ogwu MC, Akram M, editors. *Herbal Medicine Phytochemistry. Reference Series in Phytochemistry*. Cham: Springer; 2024a. p. 2127-2152. https://doi.org/10.1007/978-3-031-21973-3_71-1.
35. Izah SC, Odubo TC, Ngun CT, Ogwu MC. Research Needs of Medicinal Plants Used in the Management and Treatment of Some Diseases Caused by Microorganisms. In: Izah SC, Ogwu MC, Akram M, editors. *Herbal Medicine Phytochemistry. Reference Series in Phytochemistry*. Cham: Springer; 2024b. p. 1797-1823. https://doi.org/10.1007/978-3-031-21973-3_11-1.
36. Izah SC, Richard G, Odubo TC. *Citrus aurantifolia*: Phytochemical Constituents, Food Preservative Potentials, and Pharmacological Values. In: Izah SC, Ogwu MC, Akram M, editors. *Herbal Medicine Phytochemistry. Reference Series in Phytochemistry*. Cham: Springer; 2024c. p. 333-358. https://doi.org/10.1007/978-3-031-43199-9_76.
37. Jackson CR, Fedorka-Cray PJ, Davis JA, Barrett JB, Frye JG. Prevalence, species distribution, and antimicrobial resistance of enterococci isolated from dogs and cats in the United States. *J Appl Microbiol*. 2009;107(4):1269-1278. <https://doi.org/10.1111/j.1365-2672.2009.04310.x>.
38. Jacob DE, Izah SC, Nelson IU, Daniel KS. Indigenous Knowledge and Phytochemistry: Deciphering the Healing Power of Herbal Medicine. In: Izah SC, Ogwu MC, Akram M, editors. *Herbal Medicine Phytochemistry. Reference Series in Phytochemistry*. Cham: Springer; 2024a. p. 1953-2005. https://doi.org/10.1007/978-3-031-43199-9_66.
39. Jacob DE, Nelson IU, Izah SC. *Cola accuminata*: Phytochemical Constituents, Nutritional Characteristics, Scientific Validated Pharmacological Properties, Ethnomedicinal Uses, Safety Considerations, and Commercial Values. In: Izah SC, Ogwu MC, Akram M, editors. *Herbal Medicine Phytochemistry. Reference Series in Phytochemistry*. Cham: Springer; 2024b. p. 141-179. https://doi.org/10.1007/978-3-031-21973-3_59-1.
40. Jacob DE, Nelson IU, Izah SC. Healing Trails: Integrating Medicinal Plant Walks into Recreational Development. In: Izah SC, Ogwu MC, Akram M, editors. *Herbal Medicine Phytochemistry. Reference Series in Phytochemistry*. Cham: Springer; 2024c. p. 2049-2102. https://doi.org/10.1007/978-3-031-43199-9_68.
41. Joshua MT. Assessment of the Effects of *Morus mesozygia* Linn. Stapf., Leaf Extracts on the Liver of Streptozotocin-Induced Diabetic Wistar Rats. *Int Res J Gastroenterol Hepatol*. 2022a;5(2):76-85.
42. Joshua MT. Evaluation of the Nephroprotective Properties of *Morus mesozygia* Linn. Stapf., Leaf Extracts on Streptozotocin-Induced Diabetic Wistar Rats. *Int J Adv Nephrol Res*. 2022b;5(1):104-115.
43. Kapinova A, Kubatka P, Golubnitschaja O, Kello M, Zubor P, Solar P, Pec M. Dietary phytochemicals in

- breast cancer research: anticancer effects and potential utility for effective chemoprevention. *Environ Health Prev Med.* 2018;23(1). <https://doi.org/10.1186/s12199-018-0724-1>.
44. Kigigha LT, Biye SE, Izah SC. Phytochemical and antibacterial activities of *Musanga cecropioides* tissues against *Escherichia coli*, *Pseudomonas aeruginosa* *Staphylococcus aureus*, *Proteus*, and *Bacillus* species. *Int J Appl Res Technol.* 2016;5(1):100-107.
 45. Kigigha LT, Izah SC, Ehizibue M. Activities of *Aframomum melegueta* seed against *Escherichia coli*, *Staphylococcus aureus*, and *Bacillus* species. *Point J Bot Microbiol Res.* 2015;1(2):23-29.
 46. Kigigha LT, Izah SC, Uhunmwangho EJ. Assessment of hot water and ethanolic leaf extracts of *Cymbopogon citratus* Stapf (Lemon grass) against selected bacteria pathogens. *Ann Microbiol Infect Dis.* 2018a;1(3):1-5.
 47. Kigigha LT, Selekere RE, Izah SC. Antibacterial and synergistic efficacy of acetone extracts of *Garcinia kola* (Bitter kola) and *Buchholzia coriacea* (Wonderful kola). *J Basic Pharmacol Toxicol.* 2018b;2(1):13-17.
 48. Kim B, Park JE, Im E, Cho Y, Lee J, Lee HJ, Sim DY, Park WY, Shim BS, Kim SH. Recent advances in nanotechnology with nano-phytochemicals: molecular mechanisms and clinical implications in cancer progression. *Int J Mol Sci.* 2021;22(7):3571. <https://doi.org/10.3390/ijms22073571>.
 49. Komala O, Wardatun S, Sari LP. Effectiveness of leaves extract fractions of *Archidendron jiringa* (Jack) I.C Nielsen against microbes. *Molekul.* 2019;14(2):110. <https://doi.org/10.20884/1.jm.2019.14.2.538>.
 50. Kryvtsova M, Trush K, Eftimova J, Kosova J, Spivak M. Antimicrobial, antioxidant, and some biochemical properties of *Vaccinium vitis-idaea* L. *Mikrobiolohichnyi Zhurnal.* 2019;81(3):40-52. <https://doi.org/10.15407/microbiolj81.03.040>.
 51. Li H, Li B. PRP as a new approach to prevent infection: preparation and in vitro antimicrobial properties of PRP. *J Vis Exp.* 2013;(74). <https://doi.org/10.3791/50351>.
 52. Mandalari G, Bennett RN, Bisignano G, Trombetta D, Saija A, Faulds CB, Gasson MJ, Narbad A. Antimicrobial activity of flavonoids extracted from bergamot (*Citrus bergamia* Risso) peel, a byproduct of the essential oil industry. *J Appl Microbiol.* 2007;103(6):2056-2064. <https://doi.org/10.1111/j.1365-2672.2007.03456.x>.
 53. Moulari B, Pellequer Y, Chaumont J, Guillaume Y, Millet J. In vitro antimicrobial activity of the leaf extract of *Harungana madagascariensis* Lam. ex Poir. (Hypericaceae) against strains causing otitis externa in dogs and cats. *Acta Vet Hung.* 2007;55(1):97-105. <https://doi.org/10.1556/avet.55.2007.1.10>.
 54. Moyo B, Masika PJ, Muchenje V. Antimicrobial activities of *Moringa oleifera* Lam leaf extracts. *Afr J Biotechnol.* 2012;11(11). <https://doi.org/10.5897/ajb10.686>.
 55. Ogunro OB, Richard G, Izah SC, Ovuru KF, Babatunde OT, Das M. Citrus aurantium: Phytochemistry, Therapeutic Potential, Safety Considerations, and Research Needs. In: Izah SC, Ogwu MC, Akram M, editors. *Herbal Medicine Phytochemistry. Reference Series in Phytochemistry.* Cham: Springer; 2024. p. 181-219. https://doi.org/10.1007/978-3-031-21973-3_69-1
 56. Okolie C, Chenia HY. Assessment of aquatic aeromonas spp. isolates' susceptibility to cinnamaldehyde, vanillin, and crude *kigelia africana* fruit extracts. *Journal of the World Aquaculture Society.* 2013;44(4):486-498. <https://doi.org/10.1111/jwas.12059>
 57. Osagie OA, Igbinoogun U, Okoh OJ, Oriakhi K. Phytochemical composition, in vitro antioxidant and antimicrobial activities of methanol extract of cheese wood (*alstonia boonei*) leaves collected from Benin City, Nigeria. *Journal of Applied Sciences and Environmental Management.* 2023;27(10):2283-2289. <https://doi.org/10.4314/jasem.v27i10.20>
 58. Ovuru KF, Izah SC, Yasmin H, Enerijiofi KE, Das M, Ogwu MC. Microbial Contaminants of Herbal Remedies: Health Risks and Sustainable Quality Control Strategies. In: Izah SC, Ogwu MC, Akram M, editors. *Herbal Medicine Phytochemistry. Reference Series in Phytochemistry.* Cham: Springer; 2024. p. 1571-1600. https://doi.org/10.1007/978-3-031-21973-3_9-1
 59. Parihar A, Malviya S, Khan R, Mostafavi E. Covid-19 associated thyroid dysfunction and other comorbidities and its management using phytochemical-based therapeutics: a natural way. *Bioscience Reports.* 2023;43(7). <https://doi.org/10.1042/bsr20230293>
 60. Rahman SMA, Kamel MA, Ali MA, Alotaibi BS, Aharthy OM, Shukry M, Abd El-Bary HM. Comparative study on the phytochemical characterization and biological activities of *azolla caroliniana* and *azolla filiculoides*: in vitro study. *Plants.* 2023;12(18):3229. <https://doi.org/10.3390/plants12183229>
 61. Roy T, Mazumder T, Nag T, Kalita JC, Izah SC, Yasmin H. Efficacy of Ethno-Herbal Medicines with Anti-inflammatory and Wound Healing Potentiality: A Case of West Bengal, India. In: Izah SC, Ogwu MC, Akram M, editors. *Herbal Medicine Phytochemistry. Reference Series in Phytochemistry.* Cham: Springer; 2024. p. 881-907. https://doi.org/10.1007/978-3-031-21973-3_62-1
 62. Salhi N, Mohammed Saghir SA, Terzi V, Brahmi I, Ghedairi N, Bissati S. Antifungal activity of aqueous extracts of some dominant Algerian medicinal plants. *Biomed Research International.* 2017;2017:1-6. <https://doi.org/10.1155/2017/7526291>
 63. Serrano J, Puupponen-Pimiä R, Dauer A, Aura AM, Saura-Calixto F. Tannins: current knowledge of food sources, intake, bioavailability, and biological effects. *Molecular Nutrition & Food Research.* 2009;53(S2). <https://doi.org/10.1002/mnfr.200900039>

64. Shittu GA, Ephraim ME. Antimicrobial properties of *sacrocephalus latifolius* (sm.) Bruce. *Journal of Medicinal Plants Research*. 2014;8(36):1116-1120. <https://doi.org/10.5897/jmpr2013.5333>
65. Shrestha BK, Dhungana B, Shakya J, Shrestha R, Chauhan S. Phytochemical and antimicrobial screening of bark extract of *shorea robusta* (sal). *Nepal Journal of Biotechnology*. 2022;10(1):25-31. <https://doi.org/10.54796/njb.v10i1.227>
66. Simmler C, Graham JG, Chen SN, Pauli GF. Integrated analytical assets aid botanical authenticity and adulteration management. *Fitoterapia*. 2018;129:401-414. <https://doi.org/10.1016/j.fitote.2017.11.017>
67. Sultana N, Das S. Preliminary phytochemical screening and in vitro antimicrobial activity of the leaf extract of *thunbergia coccinea* (family-Acanthaceae). *International Journal of Current Pharmaceutical Research*. 2019;11(4):111-114. <https://doi.org/10.22159/ijcpr.2019v11i4.34938>
68. Sureka A, Murugesan S. Physicochemical Evaluation and Biological Standardization of Novel Siddha Formulation Manosilai before and after Purification: A Comparative Analytical Approach. *International Journal of Current Research in Biology and Medicine*. 2017;4(11):1-10. <https://doi.org/10.22192/ijcrbm.2017.02.11.001>
69. Sweet R, Booth C, Gotts K, Grove SF, Kroon PA, Webber M. Comparison of antibacterial activity of phytochemicals against common foodborne pathogens and potential for selection of resistance. *Microorganisms*. 2023;11(10):2495. <https://doi.org/10.3390/microorganisms11102495>
70. Tanase C, Nicolescu A, Nisca A, Ștefănescu R, Babotă M, Mare AD, Ciurea CN, Man A. Biological activity of bark extracts from northern red oak (*quercus rubra* L.): an antioxidant, antimicrobial and enzymatic inhibitory evaluation. *Plants*. 2022;11(18):2357. <https://doi.org/10.3390/plants11182357>
71. Thaipitakwong T, Numhom S, Aramwit P. Mulberry leaves and their potential effects against cardiometabolic risks: a review of chemical compositions, biological properties, and clinical efficacy. *Pharmaceutical Biology*. 2018;56(1):109-118. <https://doi.org/10.1080/13880209.2018.1424210>
72. Toh SC, Lihan S, Bunya SR, Leong SS. In vitro antimicrobial efficacy of *cassia alata* (Linn.) leaves, stem, and root extracts against cellulitis causative agent *staphylococcus aureus*. *BMC Complementary Medicine and Therapies*. 2023;23(1). <https://doi.org/10.1186/s12906-023-03914-z>
73. Uchenna EF, Adaeze OA, Steve AC. Phytochemical and antimicrobial properties of the aqueous ethanolic extract of *saccharum officinarum* (sugarcane) bark. *Journal of Agricultural Science*. 2015;7(10). <https://doi.org/10.5539/jas.v7n10p291>
74. Vuppu S, Mishra T, Mishra S, Stany B, Das A. Phytochemical-loaded nanoparticles in covid-19 management. *Natural Resources for Human Health*. 2023;4(1):51-72. <https://doi.org/10.53365/nrfhh/176325>
75. Wei L, Gao J, Zhang S, Wu S, Xie Z, Ling G, Kuang YQ, Yang Y, Yu H, Wang Y. Identification and characterization of the first cathelicidin from sea snakes with potent antimicrobial and anti-inflammatory activity and special mechanism. *Journal of Biological Chemistry*. 2015;290(27):16633-16652. <https://doi.org/10.1074/jbc.m115.642645>
76. Yahaya A, Ali M, Idris A. Antibacterial activity and phytochemical screening of carica papaya on some enteric bacterial isolates of public health importance. *Greener Journal of Biological Sciences*. 2017;7(1):001-007. <https://doi.org/10.15580/gjbs.2017.1.122916224>
77. Yirdaw B, Getahun T. Preliminary phytochemical screening and antibacterial effects of root bark of *Ferula communis* (Apiaceae). *Veterinary Medicine and Science*. 2023;9(4):1901-1907. <https://doi.org/10.1002/vms3.1170>
78. Zahra N, Aliyu A, Shaukat A, Arif MJ, Usman M, Saleem A, Mazhar M. In-vitro antibacterial, antifungal and qualitative phytochemical analysis of three medicinal plants of Lahore, Punjab. *Acta Scientific Microbiology*. 2019;2(12):39-44. <https://doi.org/10.31080/asmi.2019.02.0429>
79. Zhou M, Ma J, Kang M, Tang W, Xia S, Yin J, Yin Y. Flavonoids, gut microbiota, and host lipid metabolism. *Engineering in Life Sciences*. 2023;24(5). <https://doi.org/10.1002/elsc.202300065>