IJNRD.ORG ISSN : 2456-4184
INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD) | IJNRD.ORG
An International Open Access, Peer-reviewed, Refereed Journal

The Multifaceted Antimicrobial Properties Of *Terminalia Arjuna*: A Comprehensive Review And Future Opportunities

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Abstract
The rise of antimicrobial resistance (AMR) poses a critical threat to global public health, rendering conventional antibiotics increasingly ineffective. This necessitates the exploration of alternative therapeutics, particularly from plant sources. While plant-derived antimicrobials offer promise, challenges remain in standardizing extraction protocols, addressing seasonal variations in phytochemical composition, and establishing safety margins through in vivo studies. *Terminalia arjuna* (T. arjuna), a cornerstone of Ayurvedic medicine for over 3,000 years, presents a potential solution due to its rich composition of bioactive compounds, including triterpenoids, flavonoids, tannins, and polyphenols. In vitro studies have demonstrated the significant antimicrobial efficacy of T. arjuna extracts against a broad spectrum of Gram-positive and Gram-negative bacteria and fungi, evidenced by pronounced zones of inhibition. This efficacy is attributed to the synergistic action of its multifaceted phytochemicals, which disrupt microbial membranes, inhibit virulence factors, and interfere with essential metabolic pathways. Future research should prioritize the isolation of individual bioactive constituents, elucidate their mechanisms of action at the genetic level, and explore synergistic combinations with existing antimicrobial agents to combat multidrug-resistant pathogens. Furthermore, investigating its potential as a biodegradable disinfection agent warrants exploration.
Keywords: Antimicrobial, *Terminalia arjuna*, Bark, Disinfectant, Zone of Inhibition.

1. INTRODUCTION

The rise of antimicrobial resistance (AMR) poses a major challenge to global public health, rendering conventional antibiotics increasingly ineffective against common bacterial pathogens. This has caused a paradigm shift in pharmaceutical research, with global health agencies advocating for the exploration of plant-derived therapeutics as alternatives to conventional antibiotics. [1]

In ancient India, medicinal plants were used to treat and prevent different chronic diseases and they used to be the best source for a variety of drugs. In today's era, a huge variety of species are available for treatment of various ailments but in the modern medical system, very few species are utilized. In the last decade, use of natural or herbal supplements increased from 2.5% to over 12%. According to WHO, over 75% of the world's population depends upon traditional medicine [2, 3]. The traditional knowledge system has shown critical importance in perspective with sustainable growth, protection and search for new potential usage patterns of plant resources. [3]

The medicinal properties of these plants are due to presence of some organic compounds which are synthesised by primary or secondary metabolism of living organisms. These organic compounds are known as secondary metabolites and provide definite physiological action in human body. They are chemically and taxonomically diverse and have obscure functions. In fact, many phytochemicals belonging to several chemical classes have been shown to have inhibitory effects on all types of microorganism in vitro. These bioactive compounds include phenols, flavonoids, tannins, terpenes, alkaloids, steroids, etc [4].

Among these medicinal plants, one indigenous to India is *Terminalia arjuna* (Roxb.) Wight and Arn., (T. arjuna). *Terminalia arjuna* has been a cornerstone of Ayurvedic medicine for over 3,000 years, traditionally employed for cardiovascular ailments, wound healing, and gastrointestinal disorders [5]. It is commonly known as Arjun (Hindi), TellMaddi/Yella maddi (Telugu), Marudhu (Tamil and Malyalam), TellMaddi/Yella maddi (Telugu), Arjhan (Bengali), Sadado/ Sadad (Gujrati). Its therapeutic efficacy is attributed to a rich composition of bioactive compounds, including triterpenoids (arjunolic acid, arjungenin), flavonoids (quercetin, luteolin, kaempferol), tannins, and polyphenols [2, 3].

2. BOTANICAL DESCRIPTION

2.1 Scientific Classification

The species *Terminalia arjuna* (Roxb. ex DC.) Wight & Arn. belongs to the kingdom **Plantae**, more specifically within the vascular plants (Tracheobionta). Since it is flowering plant, it falls under the division **Magnoliophyta** (angiosperms) and subdivision **Spermatophyta** (seed-bearing plants). Taxonomically, it is classified under the class **Magnoliopsida** (dicotyledons), order **Myrtales** – an order characterized by woody plants with opposite leaves and hypanthium structures[2]. The species resides in the family **Combretaceae**, a pantropical family known for its trees and shrubs with simple leaves and inferior ovaries. Within this family, *Terminalia arjuna* is part of the genus *Terminalia*, which comprises approximately 100 species of tropical trees valued for their timber and medicinal properties. This taxonomic placement reflects its morphological characteristics, including its deciduous nature, spreading crown with drooping branches, new leaves appearing in hot season. It is about 20-30 meters tall, reasonably large, evergreen and can be found widely in India, most commonly around Delhi, UP and Bihar [2, 6].

Its leaves are 15-25cm long and 6-8cm wide, undivided with an obtuse base, has crenate margins and subacute apex. The fruit is 3-4 cm in diameter with 5-7 longitudinal lobes. It is drupe, woody and fibrous and often notched near the top. The bark is even, bright, and greenish grey externally and peeled off in large flat pieces regularly. Found in irregular pieces, and curved, not flat pieces. It is also of appreciable importance in Ayurveda[2, 7].

2.2 Historical Significance

The species epithet *arjuna* derives from the Sanskrit name of the mythical warrior-hero in the Mahabharata, alluding to the tree's cultural and therapeutic significance in South Asian traditions. In Rigveda, the word "Arjuna" is used in the Rigveda to signify silvery brightness or white colour. There are mentions of Arjuna in several ancient medicinal texts of India, including Charaka Samhita, Astang Hridayam and Sushruta Samhita. In Ayurveda, it is also mentioned to as Hridya (cardiac tonic).

Traditionally, all parts including leaf, stem bark, roots and fruit of T. arjuna are used to maintain one's health. A study by Gupta et al talked about the advocacy of juice of its leaves for earaches. The first documented use of stem bark powder to treat cardiac diseases was by Vegabhatta. As mentioned in a study by [8] arjuna bark powder is used to cure a large number of diseases, including injury or wound, emitiated condition, poison, styptic, diabetes, urinary diseases, and ulcer/wound also referred to a kshata, kshaya, visha, raktavikara, medaroga, prameha and vrana respectively in ayurveda. The bark has a somewhat sweet and cooling effects.

3 PHYTOCHEMICAL COMPOSITION

Although the chemical constituents of Arjuna are present throughout the plant, including the leaves and fruit, however the bark is considered most important constituent from a pharmacological standpoint as it exerts antioxidant, antimicrobal and medicinal action. It is highly rich in terpenoids, flavonoids, polyphenols, tannins, glycosides and minerals such as zinc, calcium, magnesium, etc as founded in a study by [7]. Some of the notable phytochemical isolated from the bark of T. arjuna include triterpenes such as arjungenin, arjunolic acid, arjunic acid; polyphenols such as arjunolone and arjunin and glucosides such as arjunetin, arjunoside I, arjunoside II, arjunoglucoside I-III and many more. Research is still ongoing to completely study the composition of T. arjuna tree.

Table 2.1: Phytochemical constituents of bark of *Terminalia arjuna* (Roxb.) Wight and Arn

Phytochemical Class	Chemical constituents	References
Triteropenoid	Arjunic acid	[34], [35]
	Arjungenin	[36]
	Arjunin	[34]
	Arjunolic acid	[37], [38]
Tannins	Punicallin	[39]
	Punicalagin	[40]
	Pyrocatechols	[41]
	Terchebulin	[42]
	Terflavin C	[43]
Glycosides	Arjunetin	[44], [45]
	Arjunolone	[45]
	Arjunolitin	[46]
	Arjunoside I	[47]
	Arjunoside II	[47]
	Terminoside A	[47]
Flavonoids and Phenolics	Luteolin	[25], [48]
	Ethyl gallate	[25], [48]
	Gallic acid	[25], [48]
	Arjunone	[25], [48]
	Kempferol	[25], [48]
Minute elements	Ca, Mg, Cu. Zn	[22]

The phytochemicals present in TAB extract can be classified into following major classes:

3.1 Terpenoids

The terpenoid constituents of *Terminalia arjuna* exhibit multifaceted antimicrobial mechanisms through distinct physiological disruptions. Arjunolic acid, a triterpenoid with amphiphilic properties, compromises microbial membrane integrity by integrating into lipid bilayers, increasing fluidity, and inducing potassium ion leakage (3.2 mM/hr at 50 μM) [7, 9]. Concurrently, ellagic acid glycosides interfere with virulence pathways by competitively inhibiting *Staphylococcus* sortase A (Ki: 8.9 nM), effectively blocking surface protein anchoring critical for pathogenicity. Biofilm formation is significantly inhibited through tannin glycosides like chebulagic acid, which reduce *Pseudomonas aeruginosa* alginate synthesis by 70% at 25 μg/mL, thereby diminishing biofilm biomass. Further modulation of microbial defense mechanisms occurs via terminoside A, which suppresses nitric oxide production and downregulates inducible nitric oxide synthase in lipopolysaccharide-activated macrophages [2, 3, 10, 11, 12]. Structural characterization of these bioactive compounds, including arjunic acid and arjungenin, has been confirmed through phytochemical studies conducted by Honda et al, with subsequent identification of additional glycosides such as arjunglucosides I-II and termiarjunosides I-II from ethanolic bark extracts. Alam et al isolated two more glycosides namely Olean-1a,3b,9a,22a-tetraol-12-en-28-oicacid-3b-D-glucopyranoside or Termiarjunoside I and Olean-3a,5a, 25-triol-12-en-23,28- dioicacid-3b-D-glucophyranoside or Termiarjunoside II from the ethanolic extract of TA bark. Arjunglucoside IV and V, Arjunasides A-E were isolated from the ethanolic extract of the stem bark of T. arjuna by Wang et al. These synergistic actions underscore *T. arjuna*'s potential as a broad-spectrum antimicrobial agent targeting both Gram-positive and Gram-negative pathogens through parallel physiological pathways [13, 14, 15, 16].

3.2 Tannins

The bark of T.arjuna contains tannins and their related compounds were isolated from it. Casuarinin, punicallin, terflavin C, punicalagin, pyrocatecols and terchebulin are some of the hydrolysable tannins that were isolated from TAB [3]. Tannins also demonstrate multifunctional biological activities, notably enhancing nitric oxide synthesis and inducing vasorelaxation in norepinephrine-pre-contracted vascular segments, while exhibiting antimicrobial, astringent, and wound-healing properties [17]. Structurally characterized through spectral analysis, these polyphenolic compounds further display antioxidant and anticancer potential through inhibition of LDL oxidation and platelet aggregation. Quantitative analysis via the Folin-Denis method reveals tissue-specific variation in tannin concentrations within *Terminalia arjuna*, with bark extracts containing 6.75–14.82% (67.5–148.2 mg/g dry weight) compared to lower levels in leaves and twigs (6.32–8.52 mg/g) [2, 7, 8]. The antimicrobial mechanisms of *T. arjuna* tannins involve three synergistic pathways:

- Membrane destabilization through chelation of Mg^{2+} and Ca^{2+} ions critical for bacterial envelope integrity,
- Potent inhibition of *Staphylococcus aureus* sortase A (Ki: 8.9 nM) to block virulence factor anchoring, and
- Biofilm disruption via 45% biomass reduction in *Enterococcus faecium* at 32 µg/mL through suppression of *esp* gene expression.

These coordinated actions position tannins as multi-target therapeutic agents against Gram-positive pathogens and biofilm-mediated infections [18, 19].

3.3 Flavonoids and Polyphenol

Bark of T. arjuna is rich in flavonoids, which include kempferol, flavones, arjunolone, quercetin, luteolin and baicalein. The aqueous extract contains flavonols, such as (þ)-gallocatechin, (þ)-catechin and epigallocatechin; derivatives of gallic acid and ellagic acid such as 3-O-methyl ellagic acid 4-O-b-Dxylopyranoside and 3-O-methyl ellagic acid 3-O-rhamnoside.

Flavonoids exhibit multifaceted biological activities primarily attributed to their structural capacity to interact with cellular components. The antioxidant properties of flavonoids arise through multiple mechanisms, including direct free radical scavenging and metal ion chelation. The arrangement of hydroxyl groups, particularly the ortho-dihydroxy configuration in the B-ring, enables electron delocalization that stabilizes reactive oxygen species (ROS) [20, 21]. These compounds further inhibit enzymatic ROS generators like NADH oxidase and glutathione S-transferase through structural interactions. The degree of polymerization and hydroxyl group density amplifies antioxidant capacity, as seen in proanthocyanidins which demonstrate superior radical neutralization compared to monomeric forms [22, 23, 24].

The antimicrobial effects stem from interactions with extracellular proteins and bacterial cell walls, disrupting membrane permeability and inhibiting biofilm formation. The polyphenolic compounds also demonstrate synergistic effects with conventional antibiotics by reversing microbial resistance mechanisms, enhancing therapeutic potential against multidrug-resistant pathogens. Structural features such as hydroxylation patterns significantly influence bioactivity, where C3 hydroxylation in ring C enhances antibacterial potency, while methylation at specific positions can either potentiate or reduce antimicrobial effects depending on substitution patterns [22, 25].

Recent investigations into *Terminalia arjuna* extracts reveal significant correlations between flavonoid content and bioactivity. Methanolic extracts exhibit potent free radical scavenging capacity through DPPH and ABTS assay systems, which can be attributed to high concentrations of flavonoid aglycones. These extracts demonstrate broad-spectrum antimicrobial activity against Gram-positive and Gram-negative pathogens, with efficacy linked to specific hydroxylation patterns and the presence of electron-withdrawing substituents that enhance membrane interaction.

4 ANTIMICROBIAL EFFICACY

The most used method for quantification of antimicrobial activity is agar well diffusion method. The same was done for the study conducted by Baqir et al which estimated the activity of TAB extract against isolated bacterial and fungal strains [26].

In this method, cotton swabs are used to uniformly spread bacterial and fungal strains on nutrient agar plates. Using cork borer, wells were punched in the agar. Approximately 50 µL of the extract of bark, fruit and leaves were added into the wells and allowed to incubate for two hours at 37ºc. After 24h of incubation, the zone of inhibition was measured.

In case of gram-positive bacteria

- In case of E. faecalis, ethanol bark extract showed maximum zone of inhibition, i.e. 28.33±0.88mm against E. faecalis while aqueous fruit extract showed least zone of inhibition, i.e.,7.67±0.42mm. Moreover, it was observed that ethanol extract from leaf also remained significantly better than other extracts for having antibacterial potential against E. faecalis. No significant change was noted among the aqueous extract from leaf and fruit, ethanol extract from fruit, chloroform extract from leaf and fruit and n-Hexane extract from bark of *Terminalia arjuna* for antibacterial potential against E. faecalis [26, 27].

- For Staphylococcus aureus, Ethanol bark extract showed maximum zone of inhibition, i.e.,27.33±0.88mm while chloroform fruit and n-Hexane leaf extracts showed east zone of inhibition for S. aureus, i.e.,6.67±0.58mm and 7.33±0.95mm, respectively. It was also observed that ethanol extract from leaf, aqueous and chloroform extracts from bark also remained significantly efficient as compared to others for having antibacterial potential against S. aureus. No significant change for antibacterial action was noted among the aqueous extract from leaf and fruit, ethanol extract from fruit and n-Hexane extract from bark and fruit against S. aureus [26, 28, 29].

In case of gram-negative bacteria

- Against Klebsiella pnuemoniae, ethanol bark extracts of the plant showed maximum zone of inhibition, i.e.,20.33±0.22mm whereas aqueous, n-Hexane and chloroform fruit extracts showed least zone of inhibition measured as 12.33±0.12mm, 12.67±0.48mm and 13.33±0.33mm respectively for K. pnuemoniae. It was observed that ethanol extract from fruit and leaf also remained better over other extracts against K. pnuemoniae. No significant change was noted among the aqueous extracts from leaf and fruit, chloroform and n-Hexane extracts from bark, leaf and fruit for antibacterial potential against K. pnuemoniae [26, 30, 31].
- For Burkholderia cepacian, ethanol bark extract showed maximum, i.e.,30.67±0.33mm while minimum zone was formed by n-Hexane bark, i.e.,0.8±0.58mm. Following to that, ethanol and aqueous extracts from bark remained better over other extracts for antibacterial potential against B. cepacia. However, no significant change was noted among the aqueous and ethanol extracts from fruit against B. cepacian [26].

The extracts of *Terminalia arjuna* showed remarkable antifungal potential as well

- Against Trichoderma viridae, chloroform bark extract showed maximum zone of inhibition, i.e.,36.33±0.34mm while chloroform fruit and aqueous leaf extracts showed least zone of inhibition, i.e.,13±0.23mm and 15.67±0.42 respectively for T. viridae. It was observed that n-Hexane and chloroform extracts from bark and leaf also remained better over other extracts for antibacterial potential against T. viridae. No significant change was noted among the aqueous and n-Hexane extracts from leaf and fruit against T. viridae [26, 29].
- In the case of Rhizopus stolonifera, ethanol fruit extract showed maximum zone of inhibition, i.e.,36.67±0.33mm while n-Hexane bark extract showed least zone of inhibition, i.e.,15.33±0.33mm against R. stolonifer. It was observed that ethanol bark extract and n-Hexane leaf extract also remained better over other extracts for antibacterial potential against R. stolonifer. No significant change was noted for the aqueous fruit extract and n-Hexane extract from leaf and fruit against R. stolonifera [26, 28, 32].

Table 3.1: Zone of inhibition of tree extracts against specific strains

Part of plant	**Strain**	**Type of extract**	**Zone of inhibition**	**References**
Bark	E. faecalis	Ethanolic extract	28.33±0.88mm	[26]
	Staphylococcus aureus	Ethanolic extract	27.33±0.88mm	[26]
	Klebsiella pnuemoniae	Ethanolic extract	20.33±0.22mm	[26]
	Burkholderia cepacian	Ethanolic extract	30.67±0.33mm	[26]
	Burkholderia cepacian	n-Hexane extract	0.8±0.58mm	[26]
	Rhizopus stolonifera	n-Hexane extract	15.33±0.33mm	[26]
	Trichoderma viridae	Chloroform extract	36.33±0.34mm	[26]
Fruit	E. faecalis	Aqueous extract	7.67±0.42mm	[26]
	Staphylococcus aureus	Chloroform extract	6.67±0.58mm	[26]
	Klebsiella pnuemoniae	Aqueous extract	12.33±0.12mm	[26]
	Klebsiella pnuemoniae	n-Hexane extract	12.67±0.48mm	[26]

	Klebsiella pnuemoniae	Chloroform extract	13.33±0.33mm	[26]
	Trichoderma viridae	Chloroform extract	13±0.23mm	[26]
	Rhizopus stolonifera	Ethanolic extract	36.67±0.33mm	[26]
Leaf	Staphylococcus aureus	n-Hexane extract	7.33±0.95mm	[26]
	Trichoderma viridae	Aqueous extract	15.67±0.42	[26]

5 FUTURE POSSIBILITIES

The antimicrobial efficacy of *Terminalia arjuna* bark extract demonstrated significant potential in recent studies, as demonstrated by distinct increase in zones of inhibition (ZOI) across bacterial and fungal test samples. ZOI measurements, a standard metric for assessing antimicrobial activity, revealed dose-dependent inhibitory effects, with larger zones correlating to higher extract concentrations. This inhibitory activity proves *T. arjuna* bark as a potential candidate for alternative disinfection strategies, particularly in context of synthetic antimicrobial agents facing challenges such as microbial resistance or environmental toxicity. The extract's broad-spectrum efficacy can be attributed to its its complex phytochemical profile, which includes high concentrations of flavonoids (e.g., quercetin, kaempferol derivatives) and phenolic compounds such as gallic acid, ellagic acid, and arjunolic acid [33]. These secondary metabolites can disrupt microbial membranes through hydrophobic interactions, chelate essential metal ions, and interfere with enzymatic pathways critical for pathogen survival [27].

Flavonoids exhibit multifunctional antimicrobial mechanisms. Their molecular configurations give them the ability to show intercalation into bacterial cell membranes, increasing permeability and inducing osmotic instability. Similarly, phenolic acids act as potent pro-oxidants, generating reactive oxygen species (ROS) that overwhelm microbial antioxidant defences, leading to oxidative damage to lipids, proteins, and nucleic acids [20, 21]. Synergistic interactions between these compound classes likely increase the extract's overall antimicrobial potency, as observed in the supra-additive inhibition zones compared to isolated phytochemical benchmarks. Moreover, the bark's terpenoid constituents, including arjungenin and arjunglucoside, may contribute to antifungal activity by inhibiting ergosterol biosynthesis—an important component of fungal cell membranes.

These findings verify historical ethnopharmacological applications of *T. arjuna* while aligning with current research seeking natural antimicrobial alternatives. The bark's efficacy against drug-resistant microbial strains holds relevance against the rising threat of antibiotic resistance. Compared to conventional disinfectants like sodium hypochlorite or triclosan, *T. arjuna* extracts offer a natural
While the current research and findings highlight *T. arjuna*'s pharmacological promise, some challenges persist. Standardization of extraction protocols remains an issue, as antimicrobial efficacy fluctuates significantly with seasonal variations in bark phytochemistry. Additionally, in vivo toxicity profiling and pharmacodynamic studies are necessary to establish safety margins for human applications. Nevertheless, the current evidence substantiates *T. arjuna*'s potential as a multifaceted disinfecting agent, bridging traditional Ayurvedic medicine and modern antimicrobial discoveries.

6 CONCLUSION

Based on existing literature, this review showcases the importance of T. arjuna as an important therapeutic and antimicrobial agent due to its phytochemical and pharmacological properties. Plants and their extracts have been used for centuries to cure ailments, and this review aims to bridge the gap between ayurvedic science and modern therapeutics. Research should be focused on development of natural products derived from medicinal plants. Our community should incorporate modern techniques to streamline extraction and establish efficacy and safety of these medicinal plants and the bioactive compounds present in them.

ACKNOWLEDGEMENT

I genuinely appreciate Dr. Priyanka Shankar for their insightful advice and Department of Food and Nutrition, School of Home Science, Babasaheb Bhimrao Ambedkar University, Lucknow for supplying necessary materials. For their important contributions to the study, I also like to thank my colleagues for their thoughtful conversations. Finally, I want to sincerely thank my family and friends for their unwavering support.

CONFLICT OF INTEREST

The authors have declared no conflict of interest.

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