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Bioactive phytochemicals, pharmacological potential, and nanotechnological developments of *Plectranthus amboinicus* (Lour.) Spreng: A comprehensive review

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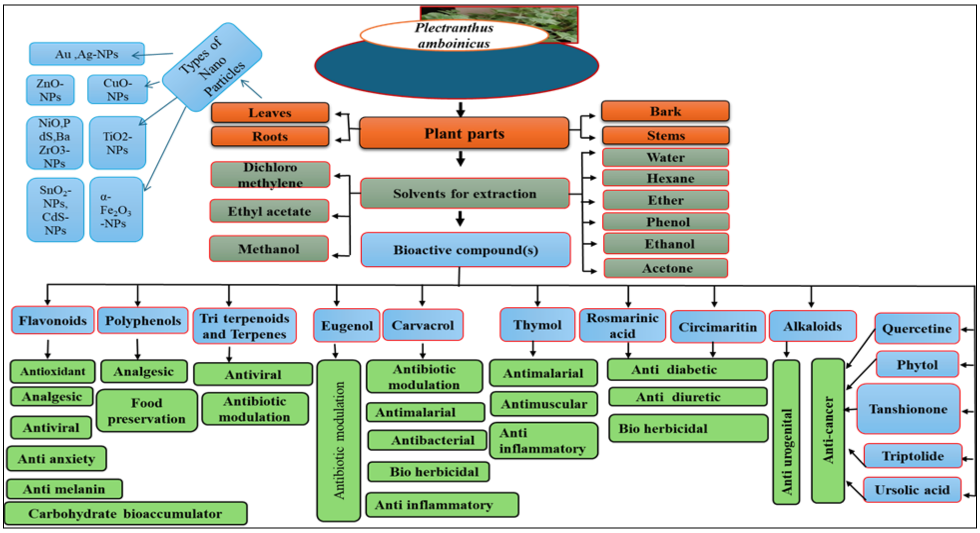
Abstract
Plectranthus amboinicus (Lour.) Spreng., has emerged as prominent medicinal plant due to its abundance of therapeutically active constituents. The plant's leaves, stems, roots, bark, and petioles are abundant in vital elements utilised in traditional medicine. A wide variety of essential oils and bioactive substances such as flavonoids, terpenoids, polyphenols, phytols, thymol, apigenin, rosmarinic acid, quercetin, carvacrol, and abietane diterpenes—are present in the plant, highlighting its medicinal significance. Additionally, trace amounts of compounds like ursolic acid, cinnamine, ladalein, caryophyllene oxide, and circimaritin contribute to its chemical complexity. A wide range of pharmacological actions, such as anti-cancer, anti-viral, antioxidant, anti-malarial, anti-fungal, anti-bacterial, anti-diabetic, and anti-inflammatory effects have been shown by *Plectranthus amboinicus* extracts.These extracts are effective in treating conditions such as wound healing, rheumatoid arthritis, epilepsy, nephroprotection, bio-herbicidal activities, bioaccumulation, nutrient mobilization, hemorrhagic and ischemic conditions, bacterial biofilm inhibition, nephron crystal formation, and pain management. Furthermore, the plant's antioxidant and antimicrobial properties are enhanced when formulated into green synthesized metal and non-metal-based nanoparticles. The potential applications of these nanoparticles extend to various health industries, pharmaceutical and beauty product manufacturing, and the decontamination of polluted waste sites. This review emphasizes the therapeutic benefits, phytochemical properties, green nanoparticle formulations (using leaf extracts), and synthetic applications of *Plectranthus amboinicus*-derived nanoparticles.

Keywords: Anti-cancer, nanoparticle, bioactive compound(s), essential oils, medicinal plant, *Plectranthus amboinicus*

Introduction

The plant *Plectranthus amboinicus* (Indian borage) has various uses in traditional medicine and cuisine, as well as potential applications in biotechnology. The plant produces a pungent oregano-like aroma and fleshy biomass that can be easily propagated *in vivo* or *in vitro* [1]. *Plectranthus amboinicus* has been used to treat respiratory diseases such as asthma and bronchitis by its expectorant effect [2]. The ethno-botanical uses of *Plectranthus* have been extensively described, under scoring its significance in traditional medicine across different cultures [3]. Given the rich phytochemical profile of *P. amboinicus,* it continues to be a vital tool for drug development and discovery. Green nanoparticles synthesis with plant decoctions is a novel approach that leverages the natural bioactive compounds of *P. amboinicus* to produce nanoparticles (NPs) with superior bioactivities [4]. NPs exhibit enhanced bioavailability and efficacy of the bioactive compounds, thereby amplifying their therapeutic benefits. For instance, metal and non-metal-based nanoparticles synthesized using *P. amboinicus* extracts have shown significant antimicrobial activities. In addition, nanoparticles also inhibit biofilm synthesis, making them effective in combating persistent infections. Additionally, the enhanced antioxidant properties of these nanoparticles make them valuable in preventing and treating oxidative stress-related diseases [4]. The potential applications of these nanoparticles extend beyond the medical field. The pharmaceutical industry can use their antimicrobial and antioxidant properties to develop more effective and safer products. These nanoparticles can be incorporated into creams, lotions, and other formulations to enhance product efficacy and safety. In the cosmetic industry, they offer promising applications in developing products with enhanced skin benefits and reduced side effects. Moreover, the environmental significance of *P. amboinicus* based nanoparticles cannot be overlooked. They hold promise in the decontamination of polluted waste sites, and soil can contribute to environmental cleanup efforts. This dual role in both healthcare and environmental sustainability underscores the multifaceted potential of *P. amboinicus* [4]. The current review focuses updated and concise pharmacological characteristics of *P. amboinicus* with many benefits for human health and well-being. It is also a source of novel bioactive compounds that can be exploited for drug discovery. NPs are promising tool for improving the delivery and action of these compounds by overcoming biological barriers such as pH sensitivity or low solubility. Therefore, this review aims to contribute to the advancement of knowledge on this plant by providing comprehensive information on its botanical characteristics, phytochemical constituents, pharmacological effects and nanotechnological applications.

Graphical abstract



Phyto morphological, Phytogeographical Distribution, and Vernacular Name(s)

Plectranthus amboinicus, commonly known as Indian borage belongs to the family Lamiaceae (200 genera and 3000-3200 species). The leaves of *P. amboinicus* are characterized as simple, young, massive, succulent shrub, and exhibit a round to sub-circular shape with tapering ends [5]. The upper leaf surface is covered with numerous glandular hairs, which gives it a white-milky appearance. The aromatic quality of the leaves is attributed to the presence of essential oils.

The fleshy stems of *P. amboinicus* attain a height of about 30-90 cm and are covered with soft, small, and erect hairs. The *Plectranthus* genus, to which *P. amboinicus* belongs, is characterized by its large and succulent herbaceous nature, ranging in height from 0.3 to 0.9 m. The plant exhibits thick, fleshy stems, and its leaves are highly branched. This succulent shrub can surpass one meter in height. However, due to the scarcity of distinctive physical or morphological characteristics for the identification of Plectranthus and its wild relatives, such as *Coleus*, *Solenostemon*, and *Englerastrum*, taxonomic challenges persist questions [6].

The *Plectranthus* genus comprises approximately 300 species distributed globally across warm and tropical regions, including Australia, Africa, and India [7]. The Northern and Southern regions of Africa exhibit an elevated level of endemism and biological variability in *Plectranthus* species. For instance, twenty-nine species of the genus are recorded on the sandstone of Glean Island [8].

In summary, limited data is available concerning the cultivation methods associated with the distribution of *Plectranthus* species. The vernacular names of *Plectranthus amboinicus* are provided in Tab.1 (www.cabidigitallibrary.org).

Table 1: Vernacular or common name(s) of *Plectranthus* genera concerning various countries.

S. No.	Vernacular Name(s)	Countries
1.	Pashanabhedi; Pathorchor; Karpooravalli; Indian Borage	India
2.	Can day la	Vietnam
3.	Kaloni; Pasiole	Tonga
4.	Kryddkarlbergare	Sweden
5.	orégano brujo; orégano de Espana	PuertoRico
6.	Suganda; toronjil de limón	Philippines
7.	Jamaika thymian	Germany
8.	Daun Kutjing; Torbangun	Indonesia
9.	Daun and pokak; bangun bangun	Malaysia
10.	Oregano; Oregano de Cartagena	Cuba
11.	French thyme, Indian mint, Mexican mint	USA

Medicinal properties

The specific uses and medicinal potential of Indian borage (*Plectranthus amboinicus*) have been extensively documented.

However, few bioactive compounds, derived from the plant PA have been thoroughly researched and utilized by the pharmaceutical industry. The plant produces bioactive substances that can be separated using a variety of solvents, including methanol, ethanol, acetone, hexane, dichloromethane, ethanol dimethyl sulfoxide, and ethyl acetate, and water [9].

Several important biochemical compounds have been identified in Indian borage, including essential oils, flavonoids, carvacrol, eugenol, polyphenols, phytol, quercetin, ursolic acid, thymol, terpenes, rosmarinic acid, apigenin, abietane, cinnamine, triptolide, and circimaritins. These compounds, as listed in Tab. 2, provide numerous effective treatments for various serious diseases.

1. Anti-cancerous properties

The potent anti-tumor effects of Indian borage (*Plectranthus amboinicus*) have been evaluated on HeLa and Vero cell lines, which have shown significant cytotoxic properties against anti-metastasis using extracted bioactive compound [10]. The alcoholic extract of Indian borage demonstrated strong anti-neoplastic activity against MCF-7 oncogenic strains [11]. The application of bioactive components derived from medicinal plants is recommended to mitigate tumor growth [12]. Natural diterpenes, including carnesol, carnosic acid, tanshinones, and triptolide, plays a crucial role in these therapeutic effects. Milliradian, an intermediate product obtained from *P. barbatus*, is formed during diterpene synthesis and exhibits therapeutic effects [13]. (Tab. 2).

2. Modulation of antibiotic effects

Recent studies highlight the multifaceted applications of Indian borage (*Plectranthus amboinicus*), particularly due to its high essential oil content and utilized across various industries, including agriculture, food preservation, perfumery, food additives, and medicine [14].
(Tab.2). A study on the modulatory activity of direct contact antibiotic assays revealed that the presence of Indian borage extracts enhanced the antibiotic activity against aminoglycosides [15]. (Tab. 2).

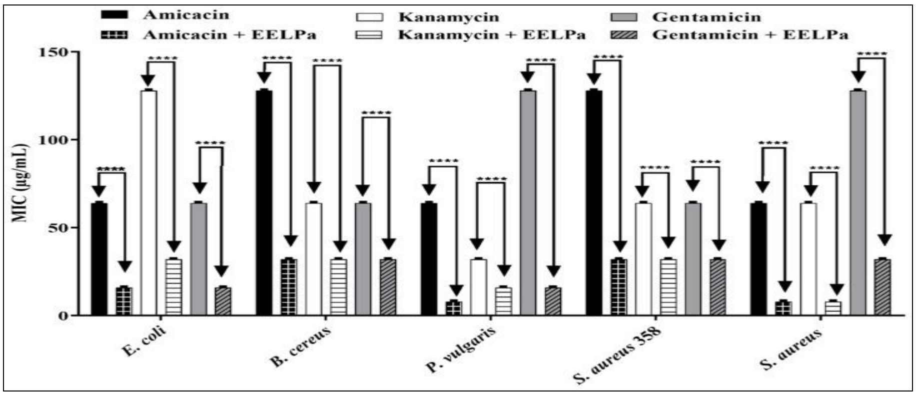


Fig 1: Modulating effect of ethanol extract of fresh *P. amboinicus* leaves on the antibiotic activity: $p < 0.0001$ [Adapted from (Rodrigues *et al*., 2020) [15]]

Further research and development could solidify its place in both medicinal and industrial applications, leveraging its bioactive compounds for improved health outcomes and innovative therapeutic solutions.

3. Starch suspending activity

Recent studies have evaluated that sodium carboxy methyl cellulose (CMC), starch derived from Vatke (*Plectranthus* spp.), has undergone evaluation as a suspending agent. Recent experimental findings suggest that the *Plectranthus* genus holds promise as an alternative to Na-CMC for this purpose. Notably, the suspension formulations exhibit stability during all storage conditions, indicating its potential for broader application in pharmaceuticals and food industries [16]. (Tab.2).

4. Anti-psychiatric activity

Recent research suggests that religious and cultural practices are gaining traction as complementary approaches to supporting mental health patients. Studies have shown that incorporating these practices into treatment plans may improve patient well-being and reduce anxiety. For instance, they have reported that psychiatric patients receiving *P. amboinicus* (Table 2) alongside traditional care exhibited positive outcomes, including a decrease in fear and an overall improvement in their emotional state [17]. (Tab. 2).

5. Anti-inflammatory properties

The ethanolic extracts of *P. amboinicus* leaves have been found to increase lysozyme activity and improve antibody production in rats, thereby enhancing immunity [18]. (Tab.2).
The role of rosmarinic acid in the inhibitory mechanism is crucial, highlighting the powerful medicinal characteristics of Indian borage as a unique therapeutic agent against inflammatory osteoclast cells. The combined action of these bioactive compounds makes *P. amboinicus* a promising candidate for developing anti-inflammatory therapies [19]. (Tab.2).

6. Anti-plasmodial properties

Essential oils from PA, including selinene, terpineol, caryophyllene oxide, undecanal, humulene, thymol, and carvacrol, have been well-documented for their bioactive properties [20]. (Tab. 2).

7. Anti fungal properties

Indian borage demonstrates considerable antifungal properties. The essential oil from *P. amboinicus* leaves significantly inhibits the growth of broad-spectrum fungal mycelia from various genera, including *Candida* and *Fusarium*, showcasing its potential as a fungicidal agent against such invasive diseases. This essential oil offers a promising therapeutic application when combined with specific antimicrobials, enhancing the efficacy of medication strategies [21]. The integration of clinically advantageous plant extracts with targeted antimicrobials could lead to more effective treatments, leveraging the natural antifungal properties of *P. amboinicus* for better clinical outcomes [22]. (Tab.2).

8. The bactericidal property

Indian borage (*Plectranthus amboinicus*) possesses significant bactericidal properties. Streptococcus mutans and Staphylococcus aureus are two bacteria associated with halitosis. Interestingly, ethanol isolates from Indian Borage leaves exhibit potent antimicrobial effects against these bacteria, making it a viable option for use as a mouthwash [23]. The Carvacrol and essential oils found in the stem and leaves of *P. amboinicus* have demonstrated antibacterial properties. Notably, carvacrol, a compound isolated from Indian Borage leaves, even confers resistance to vancomycin in *Staphylococcus aureus* [24]. (Tab. 2).

9. Virus-resistant characteristics

Indian borage (*Plectranthus amboinicus*) has shown significant antiviral properties, which various studies have supported. The plant's aqueous isolates have demonstrated immunological modulation and cytotoxic-free action. Notably, the flavonoids in karpuratulasi exhibit strong anti-HIV effects by inhibiting HIV-1 protease enzymes [25]. (Tab. 2).

10. Free radical-scavenging properties

Indian borage (*Plectranthus amboinicus*) exhibits significant antioxidant properties, as demonstrated by various studies. Methanolic extracts of Indian borage contain polyphenol components with high anti-oxidation activity, effectively combating early aging and skin pigmentation [26]. (Tab. 2).

Table 2: Reveals different solvent type(s), Bioactive compound(s), and Medicinal attributes

S. No.	Solvents	Bioactive Compounds	Medicinal Properties	References
1.	Acetone, Hexane, Methanol, Water	Triterpenoids, Cinnamine, Quercetin, Phytol, Ursolic acid, α/β-Amyrin, Essential oils, Tanshionone, Triptolide, α-terpenes, Carnasol, Carnosic.	Anti-cancerous	10-13
2.	Water, Ethanol	Eugenol, Thymol, Terpenes, Carvacrol.	Antibiotic modulation	14-16
3.	Water	Suspension formulations	Starch suspending	16
4.	Water	Suspension formulations	Anti psychiatric	17
5	Methanol, CH_3CH_2OH. H_2O, Hexane	Rosmarinic acid, Thymoquinone, Carvacrol, Salvigenin, Circimaritin, Flavonoids	Anti- inflammatory	18-19
6.	Ethyl acetate, H_2O, CH_3CH_2OH, CH_2Cl_2, H2O (1:1), CH_3OCH_3	β-Selenine, α-Humulene, Carvacrol, Abietane diterpenes, Caryophyllene oxide, Un-decanal, γ-terpines, α-terpineols, Thymol	Anti-plasmodium or Anti-malarial	20
7.	Methanol, Sucrose Containing Yeast (SCY).	Essentialoils	Anti-fungal	21-22
8.	H_2O, CH_3CH_2OH, Acetone, Ethyl acetate	Carvacrol	Anti-bacterial	23-24
9.	H_2O, CH_3CH_2OH	Flavonoids	Anti-viral	25
10.	Phenol, Acetone, Methanol, Ethyl-acetate, Ethanol.	Flavonoids	Anti-oxidant or Premature aging	26
11.	Methanol	Flavonoids	Muscle integrity, Anti-preaging or Anti-melanin	26
12.	H_2O, CH_3CH_2OH, Methanol	Cirsimaritin, Rosmarinic acid, Ladanein.	Anti-diabetic, Antihyperglycemic, Antidiuretic or Antilipidogenic,	27
13.	Ethanol	Suspension-formulation	Carbohydrate- Bio-accumulator	28
14.	Methanol, H_2O	Flavonoids	Bio-herbicidal potential	28
15.	H_2O, CH_3CH_2OH	Thymol, Carvacrol	Prophylactic or curative activity	29
16.	H_2O	Stem Suspension- Formulation	Anti-ischemic or anti-cardiac arrest potential	30
17.	Ethanol	Essential oils	Antibiofilm activity	31
18.	Methanol	Suspension-formulation	Kidney stone preventive characteristics	32
19.	H_2O, H_2O+ Ethanol	Combinatorial Formulations	Analgesic property	19
20.	H_2O, Acetic acid	Flavonoids, Polyphenols	Food preservative characteristics	33
21.	Acetone, Ethyl-acetate	Polyphenols	Anti-hypertension property	27
22.	H_2O, Ethanol, Methanol	Apigenin, Flavonoids	Antiurogenital tract ailments properties	34
23.	H_2O, Ethanol	Phenol, Flavonoids, Alkaloids	Milk-enhancing properties	18
24.	Ethyl alcohol	Aqueous- suspension Formulations	Anti-rheumatic or anti-arthritic potential	19,35
25.	H_2O	Rosmarinic acid	Antimuscular disease activity	35
26.	H_2O	Essential oils, Thymol	Nutrient mobilization properties	28
27.	H_2O	Aqueous suspension formulations	Antiseptic potential	36
28.	H_2O, Ethanol	Essential oils	Wound repairing action	31

11. Anti-aging and hyper-chromaticity properties

The extract of *Plectranthus amboinicus* has been shown to inhibit the tyrosinase and collagenase enzymes significantly. Tyrosinase is involved in melanin production and inhibiting it can help regulate skin pigmentation and prevent hyper-chromaticity. Collagenase breaks down collagen, a crucial protein for skin structure and elasticity. By inhibiting it, it helps maintain skin firmness and prevent premature aging. The methanolic extracts of Indian borage is responsible for the effectiveness of collagenase enzyme suppression activities and potential use in making pharmaceutical formulations and as a biologically active dietary supplement [26]. (Tab. 2)

12. Anti-diabetic and di-uretic properties

The presence of flavonoids such as cirsimaritin, ladanein, and rosmarinic acid in the aqueous and methanolic isolates enhances the potential of *P. amboinicus* as an effective treatment for diabetes [27]. (Tab. 2).

13. Carbohydrate bio-accumulator potential

Indian borage contains carbohydrate bio accumulators, which serve as a significant source of energy for the body and have medicinal value. The high carbohydrate content in Indian borage contributes to its ability to support metabolic functions and provide sustained energy. This herb is particularly adept at accumulating and storing carbohydrates, especially in the form of polysaccharides such as starches and sugars. Its high carbohydrate content is due to its unique enzymatic activity, which aids in the synthesis and accumulation of these compounds. This attribute not only enhances its nutritional value but also suggests potential applications in bioenergy production and as a dietary supplement for carbohydrate intake [28]. (Tab. 2).

14. Bio-herbicidal potential

Plectranthus amboinicus has shown promising bio-herbicidal potential due to its rich phytochemical composition. The plant’s bioactive properties, including anti-microbial, anti-bacterial, and anti-fungal effects, contribute to its effectiveness as a natural herbicide. This makes Indian borage a valuable resource for sustainable agricultural practices, reducing the reliance on synthetic chemicals [28]. (Tab. 2).

15. Prophylactic or curative activity

It has shown that the stem isolate of Indian borage has been tested on platelet-rich plasma, revealing its potential as a natural anti-thrombotic agent. The study found that ATP acts as an antagonist in platelet utilization, indicating that platelet production is a dose-dependent process. Given the primary role of platelets in blood composition, these findings suggest that Indian borage could be an effective natural remedy for preventing thrombosis [29]. (Tab. 2)

16. Anti-ischemic or anti-cardiac arrest potential

The plant’s bioactive compounds, particularly carvacrol, have been studied for their cardioprotective effects. Carvacrol is known to modulate oxidative stress markers and enhance antioxidant enzyme activities, which can mitigate the damage caused by ischemic conditions [30]. (Tab. 2).

17. Antibiofilm activity

Biofilms, which are networks of pathogenic colonies, represent populations of microorganisms encased in an exterior coating. The biofilm prevention capabilities of *Streptococcus mutans* have been observed in leaf isolates from *Plectranthus amboinicus* (PA). An increasing the titer of Indian borage isolates enhances their effectiveness. The methanol extracts of PA have demonstrated antiquorum sensing and antibiofilm properties against *Vibrio* and *Pseud omonas* species [31]. (Tab. 2).

18. Kidney stone preventive characteristics

Kidney has the highest serum lipid profile and significant levels of calcium oxalate. Furthermore, another study indicates that PA extracts may offer additional benefits for kidney health. It was observed that rats with induced kidney stones displayed significantly lower cholesterol and lipid levels after PA administration [32]. (Tab. 2). This finding suggests that PA may contribute to overall kidney health beyond just preventing stone formation.

19. Analgesic property

Indian borage leaves showed promise as a natural pain reliever. Studies in rats suggest that PA extracts can alleviate muscle cramps and acetic acid-induced pain. This potential analgesic effect is likely linked to the plant's rich content of phenols and flavonoids, which also possess antioxidant properties [19]. (Tab. 2).

20. Food preservative characteristics

Indian borage leaves extract show promises as natural food preservatives. According to studies, these extracts may be able to stop dangerous bacteria from These extracts disrupt potential bonds or arrangements in cell wall elements, altering the leakage of genetic material and resulting in cell wall disorganization, which hinders the expansion of pathogens in the food sector [33]. (Tab. 2).

21. Anti-hypertension property

The aqueous and methanol extracts of Indian borage (*Plectranthus amboinicus*) exhibits significant potential in synthesizing flavonoid-carbohydrate-rich conjugates, which are effective in reducing anxiety levels [27]. (Tab. 2).

22. Antiurogenital tract ailments properties

Indian borage has shown promising potential in treating urogenital tract ailments. Studies have suggested its antimicrobial and anti-inflammatory, and antioxidant activities, which are beneficial in managing infections and inflammation of the urinary tract. Additionally, bioactive compounds isolated from *P. amboinicus* leaves have been shown to dissolve fine kidney stone crystals [34]. (Tab. 2).

23. Milk-enhancing properties

Indian borage (*Plectranthus amboinicus*) is known for its significant milk-enhancing properties. The leaves of this plant are believed to stimulate the mammary glands and enhance the secretion of antibodies such as Ig-A, which are crucial for post-delivery lactation. This effect is attributed to the bioactive compounds present in the leaves, which may activate the mammary glands and support milk production. Studies have shown that the consumption of Indian borage leaves can be beneficial for nursing mothers, potentially improving both the quantity and quality of breast milk [18]. (Tab. 2).

24. Anti-rheumatic or anti-arthritic potential

Indian borage has shown significant potential in treating chronic inflammation and arthritis. The plant’s bioactive compound, rosmarinic acid, plays a crucial role in reducing bone degradation by negatively regulating RANKL-stimulated NFATc1 expression. This mechanism helps block the mature cellular pathway responsible for bone destruction [19]. The leaf exudates of *P. amboinicus* has been reported to reduce inflammation and swelling in arthritic rats by stimulating collagen synthesis, indicating its potential in treating rheumatoid arthritis symptoms [35]. Overall, Indian borage exhibits promising anti-rheumatic and anti-arthritic properties, making it a valuable candidate for further research and therapeutic use. (Tab. 2).

25. Antimuscular disease activity

Studies have shown that when doses ranging from zero to around three percent of *P. amboinicus* isolates are applied, there is a decline in muscle fibroblast cell count, indicating its potential in managing muscle-related conditions. The aqueous extracts of *P. amboinicus* have been found to control fibroblast density in dermal tissues, suggesting its usefulness in treating skin conditions as well [35]. (Tab. 2).

26. Nutrient mobilization properties

The leaves of Indian borage are rich in essential nutrients, including zinc, which acts as a co-factor for numerous enzymatic activities involved in metabolism and serves as a hormonal precursor like auxin. This nutrient profile supports the plant's ability to effectively mobilize essential elements from soil to plant tissues. Recent studies have highlighted high concentration of zinc and other vital nutrients in Indian borage leaves, suggesting their potential in enhancing nutrient uptake and utilization in plants [28]. (Tab. 2).

27. Antiseptic potential

Several studies have investigated the antimicrobial properties of Indian borage (*Plectranthus amboinicus*), but specific clinical trials focusing on its efficacy as an antiseptic agent are limited. Indian borage leaf extracts exhibit significant antimicrobial activity against various pathogens, including *Pseudomonas aeruginosa* and *Staphylococcus aureus*, by disrupting bacterial cell membranes and reducing catalase activity, which protects bacteria against oxidative stress [36] (Tab. 2).

28. Wound repairing action

Indian borage has demonstrated significant wound-healing properties. The Leaf extracts of Indian borage have been shown to promote wound closure by enhancing the granulation tissue synthesis and stimulating collagen formation, which is crucial for tissue repair. Studies in mice have revealed that topical application of these extracts accelerates the healing process by increasing the tensile strength of the skin and improving epithelial regeneration. Additionally, the plant exhibits anti-biofilm activity, which helps mitigate delayed inflammatory responses that often impede healing [31]. (Tab. 2).

Nanoparticle synthesis from *Plectranthus amboinicus* with Pharmacological applications

The production of NPs from natural plant sources has drawn a lot of interest because it is biocompatible, economical, and environmentally benign. Among various medicinal plants, Indian borage has emerged as a promising candidate for the green synthesis of nanoparticles with potent pharmacological applications. The synthesis of nanoparticles using PA offers a sustainable approach to harnessing the plant's bioactive compounds for biomedical applications, particularly in drug delivery, antimicrobial activity, and anticancer therapy.

1. Synthesis of plant-based ZnO-NPs

Traditional nanoparticle synthesis methods are often hazardous to both human health and the environment due to the pollution they generate. In contrast, green synthesis approaches offer a safer alternative, with plant-based nanoparticles emerging as a viable substitute for conventional physical and chemical methods. Specifically, plant-derived materials, such as leaves, are beneficial in the formulation of zinc oxide nanoparticles (ZnO-NPs). These ZnO-NPs can be characterized using such as photoluminescence, scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR) [37]. The bio-synthesized ZnO-NPs from *P. amboinicus* demonstrate superior electrochemical responses compared to those synthesized through conventional chemical methods [38]. These plant-derived ZnO-NPs demonstrated significant antimicrobial activity in contrary to *Staphylococcus aureus* and *Escherichia coli*. These modified ZnO-NPs are to be more effective in reducing mosquito larvae and protozoa populations [39].

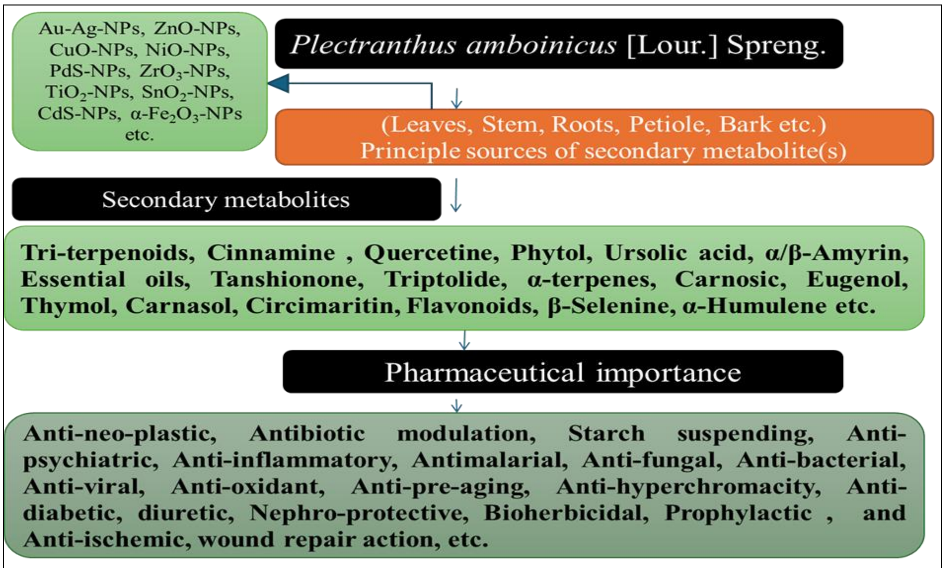


Figure- 2. A Schematic representation of the plant secondary metabolite(s) and their nano particles assisted pharmacological importance

The creation of nanocomposites is gaining attention due to its possible uses as medicines and photocatalysts. Moreover, Indian borage has been utilized in environmentally friendly formulations of immobilized chitosan, extracted from the shells of the crab *Paratelphusa hydrodromous* based on ZnO-NPs, which are beneficial in agricultural applications like rice fields. In another study, it has been reported that light-dependent photosynthesized numerous metal oxide nanoparticles, including ZnO-NPs, are effective against drug-resistant foodborne pathogens [40]. Furthermore, because of their tiny size and high specific surface area, ZnO nanoparticles are useful adsorbents for azo dye removal in the textile industry [41]. The diverse functions of zinc nanoparticles may offer a different approach to treating the undiagnosed illness. The simplicity, dependability, and environmental friendliness of the green synthesis process highlight the significance of ZnO-NPs generated from plants.

2. Synthesis of silver nanoparticles (Ag-NPs)

Ag-NPs are synthesized by reducing $AgNO_3$ with leaf extract. These particles exhibit potent antibacterial properties against pathogens such as *Escherichia coli* and *Penicillium* spp [42]. Silver nanoparticle-based graphene nanocomposites are widely used in various sectors, including medicine, material science, and environmental applications [43]. The primary aim of *P. amboinicus*-mediated synthesis of Ag-NPs is to characterize biological molecules from natural sources and provide a foundational synthesis route for creating non-toxic materials [44]. Additionally, an efficient green synthesis of Ag-NPs has been developed to cure many opportunistic bacterial infections [45] (Fig. 2).

3. Synthesis of cupric oxide nanoparticles

Green formulations are superior to synthetic nanoparticles in reducing pollution. Green synthesis methods have also been employed to produce cadmium and cupric sulfide-based NPs, which significantly reduce cytotoxicity and are promising for enhanced bio-imaging applications [46] (Fig. 2).

4. Synthesis of gold (Au), Titanium dioxide (TiO_2), and Barium zirconate ($BaZrO_3$) nanoparticles

The Au-NPs synthesized from *Plectranthus amboinicus* (Indian borage) have demonstrated significant antioxidant and anti-carcinogenic properties, particularly against human lung adenocarcinoma [47]. Titanium dioxide nanoparticles (TiO_2-NPs), treated with *P. amboinicus* on a nanoscale, have shown potent anti-cancer, antibacterial and photocatalytic activities. In addition, synthetically produced spherical TiO_2-NPs have demonstrated enhanced solar-to-electrical energy conversion efficiency [48]. TiO_2-ZnO-NP composites have proven to be effective in both antibacterial applications and environmental phytochemical cleanups [49]. Leaf extracts of *P. amboinicus* have been found to synthesize barium zirconate nanoparticles ($BaZrO_2$-NPs), which possess antimicrobial, photocatalytic, and magnetic properties [50]. The synthesis process involves the reduction of barium nitrate (Ba $(NO_3)_2$) and zirconium oxychloride ($ZrOCl_2$) using plant extract. The resulting $BaZrO_3$-NPs exhibit a perovskite structure, which is known for its stability and multifunctional properties (Fig.2). The green-synthesized NPs have encouraging promise in a number of areas, such as energy applications, environmental remediation, and medicine.

Conclusion

Plectranthus amboinicus (Lour.) Spreng., has emerged as a plant of significant pharmacological interest due to its diverse bioactive compounds and traditional medicinal uses. *P. amboinicus's* extensive phytochemical composition, which includes phenolics, terpenoids, flavonoids, and essential oils, is responsible for its pharmacological uses. The traditional uses of *P. amboinicus* in treating respiratory ailments, skin disorders, and digestive issues have been validated by modern scientific studies, further emphasizing its therapeutic relevance. Nanoparticle-assisted bioactivities have opened new avenues for enhancing the efficacy and delivery of *P. amboinicus*-derived compounds. The green synthesis of nanoparticles using *P. amboinicus* extracts has demonstrated significant potential in improving bioactive compounds' stability, bioavailability, and targeted delivery. Silver nanoparticles (Ag-NPs) and silver oxide nanoparticles (AgO-NPs) synthesized using *P. amboinicus* have shown remarkable antibacterial and anticancer activities, highlighting their potential in developing novel therapeutic agents.

Future perspectives

Future research on *Plectranthus amboinicus* should focus on several key areas to maximize its therapeutic potential and address current knowledge gaps. Advanced methods like HPLC, MS, and NMR should be employed to identify and characterize individual bioactive compounds, potentially uncovering novel compounds with therapeutic relevance. To confirm *P. amboinicus's* efficacy and safety in people, especially for illnesses, thorough clinical researches are necessary- such as diabetes, cancer, and inflammatory conditions. To evaluate the safety profile of *P. amboinicus* and its nanoparticle formulations, thorough toxicological investigations are required. These studies should evaluate cytotoxicity, genotoxicity, and long-term effects to ensure its safe clinical application.

Sustainable cultivation and harvesting practices are also vital to ensure a continuous supply of high-quality *P. amboinicus*. Research into optimized cultivation methods, pest management, and post-harvest processing will support sustainable production. Efforts should be made to integrate *P. amboinicus*-based therapies into modern medicine. This includes the development of standardized guidelines, educating healthcare professionals about its benefits, and promoting its acceptance within mainstream healthcare systems. Exploration of the synergistic interactions between *Plectranthus amboinicus* and other medicinal plants or conventional pharmaceuticals may facilitate the development of more effective combination therapies, with the potential to improve therapeutic efficacy while minimizing adverse effects. The biotechnological approaches, such as genetic engineering and tissue culture, can be utilized to enhance the production of bioactive compounds in *P. amboinicus* and to create new varieties with improved pharmacological properties.

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