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Comparative analysis of medicinal plant alkaloids: A chemical and pharmacological study of *Moringa oleifera* and *Azadirachta indica* (Neem)

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Abstract
Medicinal plants have been a cornerstone of traditional medicine, with alkaloids playing a crucial role in their therapeutic potential. This study presents a comparative chemical and pharmacological analysis of alkaloids found in *Moringa oleifera* and *Azadirachta indica* (Neem). Using advanced spectroscopic and chromatographic techniques, key alkaloids were identified and quantified. Their pharmacological activities, including antioxidant, anti-inflammatory, antimicrobial, and neuroprotective effects, were evaluated through *in vitro* and *in vivo* assays. The study highlights the unique alkaloid profiles of both plants and their potential applications in modern medicine.

Keywords: Alkaloids, *Moringa oleifera*, *Azadirachta indica*, pharmacological activity, medicinal plants

1. Introduction
Medicinal plants have been an integral part of traditional healing systems for centuries, serving as a primary source of bioactive compounds with therapeutic potential. Among these bioactive constituents, alkaloids constitute a significant class of secondary metabolites known for their diverse pharmacological properties, including anti-inflammatory, antimicrobial, antidiabetic, and neuroprotective effects [1]. Alkaloids are nitrogen-containing organic compounds that often exhibit high biological activity, making them essential in modern drug discovery and development [2].

Two medicinally significant plants, *Moringa oleifera* and *Azadirachta indica* (Neem), have been widely utilized in traditional medicine systems, such as Ayurveda, Siddha, and Unani, due to their broad-spectrum therapeutic effects [3]. *Moringa oleifera*, often referred to as the "Miracle Tree" or "Drumstick Tree," is native to the Indian subcontinent and is renowned for its rich nutritional profile and pharmacological properties. It contains a variety of bioactive compounds, including alkaloids such as moringinine and benzylamine, which contribute to its antihypertensive, antidiabetic, and neuroprotective activities [4]. On the other hand, *Azadirachta indica*, commonly known as Neem, has been extensively studied for its antimicrobial, anticancer, and immunomodulatory properties, attributed to bioactive alkaloids like nimbidine and azadirachtine [5].

Several studies have independently analyzed the alkaloid profiles and pharmacological activities of these plants; however, a direct comparative analysis of their alkaloid content, extraction methods, and bioactivities remains underexplored [6]. Understanding the similarities and differences in the alkaloid composition of these plants is essential for optimizing their medicinal applications and exploring potential synergistic effects in pharmacotherapy.

This study aims to provide a detailed comparative analysis of the alkaloid content and pharmacological potential of *Moringa oleifera* and *Azadirachta indica* using advanced analytical techniques such as High-Performance Liquid Chromatography (HPLC), Gas Chromatography-Mass Spectrometry (GC-MS), and Fourier-Transform Infrared Spectroscopy (FTIR) [7].

The pharmacological properties of these alkaloids will be evaluated through *in vitro* and *in vivo* assays, focusing on their antioxidant, anti-inflammatory, antimicrobial, and neuroprotective effects [8]. The findings from this study could pave the way for novel applications of these medicinal plants in pharmaceutical and nutraceutical industries.

Alkaloid Composition of Moringa oleifera and Alkaloid Composition of *Azadirachta indica*

Moringa oleifera is a rich source of bioactive alkaloids that contribute to its extensive pharmacological applications. Among the key alkaloids present, moringinine is known for its neuroprotective and antihypertensive effects, playing a crucial role in modulating neurotransmission and vascular health. Another significant alkaloid, benzylamine, exhibits insulin-mimetic properties, making it a promising candidate for diabetes management. Additionally, pterygospermin, a potent antimicrobial compound, has shown efficacy against bacterial strains such as *Staphylococcus aureus* and *Escherichia coli*. Moringa Y, a newly identified alkaloid, possesses strong antioxidant and anti-inflammatory properties, which contribute to its protective effects against oxidative stress-related diseases. Moreover, niazinin A and niazinin B have been recognized for their hypotensive and muscle relaxant properties, supporting cardiovascular health. The concentration and distribution of these alkaloids vary across different plant parts, with leaves and seeds containing the highest levels. Studies utilizing advanced chromatographic techniques such as High-Performance Liquid Chromatography (HPLC) and Gas Chromatography-Mass Spectrometry (GC-MS) have confirmed the presence and pharmacological relevance of these alkaloids in *Moringa oleifera* [9].

Similarly, *Azadirachta indica* (Neem) is well known for its diverse alkaloid composition, which plays a vital role in its medicinal applications. Nimbidine, one of the primary alkaloids, exhibits strong anti-inflammatory, hepatoprotective, and antibacterial properties, contributing to Neem's role in immune modulation and infection management. Another major alkaloid, azadirachtin, has been widely studied for its insecticidal and antimicrobial activities, making it a crucial bioactive compound in pest control formulations. Additionally, nimbin and nimbinin contribute to Neem's antiviral and antifungal properties, showing significant efficacy against pathogens such as *Candida albicans* and herpes simplex virus. Salanin, another key alkaloid, has demonstrated anti-malarial and anticancer potential by inducing apoptosis in cancerous cells. Furthermore, margosine, an immunomodulatory alkaloid, enhances the body's defense mechanisms against infections. The alkaloid content of *Azadirachta indica* is influenced by factors such as plant maturity, geographical location, and extraction methods. Analytical techniques, including Liquid Chromatography-Mass Spectrometry (LC-MS) and Nuclear Magnetic Resonance (NMR) spectroscopy, have been employed to isolate and characterize these alkaloids from various plant parts such as leaves, bark, and seeds. Collectively, these alkaloids contribute to the broad-spectrum medicinal properties of *Azadirachta indica*, making it a valuable plant in traditional and modern pharmacology [10].

Pharmacological Comparisons of *Moringa oleifera* and *Azadirachta indica*

1. Antimicrobial Activity

Both *Moringa oleifera* and *Azadirachta indica* exhibit potent antimicrobial activity due to their alkaloid content, which contributes to their traditional use in infection control and wound healing [10]. *Azadirachta indica* is particularly effective against bacterial and fungal pathogens due to alkaloids such as nimbidine, nimbin, and azadirachtin [11]. These compounds exhibit strong antibacterial properties, especially against Gram-negative bacteria like *Escherichia coli* and *Pseudomonas aeruginosa*, which are typically more resistant to conventional antibiotics [12]. Neem's antifungal potential has also been extensively studied, with nimbin and salanin showing significant inhibitory effects on *Candida albicans* and *Aspergillus niger*, making it a natural alternative for fungal infections [13].

On the other hand, *Moringa oleifera* also displays broad-spectrum antimicrobial activity, though its alkaloids such as pterygospermin and moringinine exhibit stronger effects against Gram-positive bacteria, including *Staphylococcus aureus* and *Bacillus subtilis* [14]. Studies have demonstrated that *Moringa oleifera* leaf extracts inhibit bacterial growth by disrupting cell membrane integrity and interfering with metabolic pathways [15]. While both plants possess antibacterial and antifungal properties, neem's alkaloids exhibit stronger antifungal activity, whereas *Moringa oleifera* shows better effectiveness against Gram-positive bacterial strains [16].

2. Anti-inflammatory Properties

Inflammation is a common pathological process underlying many chronic diseases, including arthritis, cardiovascular disorders, and autoimmune conditions. *Moringa oleifera* and *Azadirachta indica* both contain alkaloids with strong anti-inflammatory properties, but they act through different mechanisms [17]. In *Moringa oleifera*, benzylamine derivatives and niazinin A and B have been reported to modulate inflammatory responses by inhibiting the production of pro-inflammatory cytokines such as tumor necrosis factor-alpha (TNF-α), interleukin-6 (IL-6), and prostaglandins [18]. These alkaloids interfere with the cyclooxygenase (COX) and lipoxygenase (LOX) pathways, reducing inflammatory pain and tissue damage [19]. Additionally, moringinine has been found to suppress oxidative stress-induced inflammation, making it a potential therapeutic agent for neuroinflammatory and metabolic disorders [20].

Azadirachta indica exhibits comparable anti-inflammatory effects, largely due to alkaloids such as nimbin, nimbidine, and margosine [21]. These compounds have been shown to inhibit nitric oxide (NO) production and nuclear factor-kappa B (NF-κB) activation, key mediators in inflammatory signaling pathways [22]. Furthermore, neem alkaloids have been found to reduce histamine release and stabilize mast cells, making them effective in treating allergic and autoimmune conditions [10]. While both plants provide significant anti-inflammatory benefits, *Moringa oleifera* alkaloids demonstrate stronger systemic anti-inflammatory effects, whereas neem's alkaloids are particularly effective in immune-mediated inflammatory responses [11].

3. Anticancer Potential

The anticancer properties of *Moringa oleifera* and *Azadirachta indica* have been widely investigated, particularly regarding their ability to induce apoptosis, inhibit tumor growth, and reduce oxidative stress [12]. Neem-derived alkaloids, especially azadirachtin, salanin, and nimbolide, have demonstrated promising anticancer activity by modulating multiple signaling pathways involved in cell cycle

regulation and apoptosis [13]. Studies suggest that these alkaloids activate caspase-dependent apoptosis, leading to programmed cancer cell death in breast, prostate, and colon cancer models [14]. Additionally, neem alkaloids have been shown to inhibit angiogenesis and metastasis, reducing the spread of tumors *in vivo* [15].

Moringa oleifera alkaloids, including moringinine and pterygospermin, also exhibit anticancer properties, primarily by reducing oxidative stress and suppressing cancer cell proliferation [16]. These compounds have been found to enhance the activity of endogenous antioxidant enzymes such as superoxide dismutase (SOD) and glutathione peroxidase (GPx), which help neutralize reactive oxygen species (ROS) that contribute to DNA damage and tumorigenesis [17]. While the anticancer effects of *Moringa oleifera* alkaloids are promising, they require further clinical validation compared to neem-derived alkaloids, which have demonstrated more consistent anticancer activity in preclinical models [18].

4. Neuroprotective Effects

The neuroprotective effects of *Moringa oleifera* and *Azadirachta indica* have gained attention in the context of neurodegenerative diseases such as Alzheimer's, Parkinson's, and multiple sclerosis [19]. *Moringa oleifera* alkaloids, particularly moringinine and benzylamine, have shown significant neuroprotective potential by enhancing cholinergic neurotransmission and reducing oxidative damage in neuronal cells [20]. These alkaloids act as acetylcholinesterase (AChE) inhibitors, preventing the breakdown of acetylcholine and improving cognitive function in experimental models of Alzheimer's disease [21]. Additionally, moringinine has been reported to protect dopaminergic neurons in Parkinson's disease by mitigating mitochondrial dysfunction and inhibiting neuroinflammatory markers such as microglial activation and pro-inflammatory cytokine release [22].

Although *Azadirachta indica* alkaloids have been less studied in the field of neuroprotection, compounds like nimbidine and margosine possess strong antioxidant and anti-inflammatory properties that may contribute to neuronal health [10]. Neem alkaloids have been suggested to protect against oxidative stress-induced neuronal damage, potentially reducing the risk of neurodegenerative conditions [11]. Moreover, neem extracts have demonstrated anxiolytic and antidepressant-like effects in animal studies, suggesting that their alkaloid components may have central nervous system benefits [12]. While *Moringa oleifera* alkaloids are more extensively studied in neuroprotection, neem's alkaloids may offer complementary benefits through their anti-inflammatory and antioxidant mechanisms [13].

4. Methodology

This study employs a comparative literature review and experimental approach to evaluate the alkaloid composition and pharmacological properties of *Moringa oleifera* and *Azadirachta indica*. The methodology consists of a systematic literature review and experimental analysis focusing on alkaloid extraction, identification, and pharmacological testing.

4.1 Literature Review

A systematic literature review was conducted to collect and analyze relevant scientific studies on the alkaloid composition, biosynthesis, and pharmacological effects of *Moringa oleifera* and *Azadirachta indica* [23]. The following methodology was adopted:

- **Database Selection:** Literature was retrieved from PubMed, ScienceDirect, Google Scholar, and Web of Science to ensure coverage of high-impact research [24].
- **Inclusion Criteria:** Only peer-reviewed journal articles, meta-analyses, and review papers published between 2000 and 2025 were considered. Priority was given to studies related to alkaloid extraction, structural elucidation, pharmacokinetics, and pharmacodynamics [25].
- **Search Terms:** The following keywords were used to retrieve relevant studies:
  - *Moringa oleifera alkaloids*, *Azadirachta indica alkaloids*, *pharmacological activity of alkaloids*, *HPLC and GC-MS analysis of medicinal plant alkaloids*, and *antimicrobial, anti-inflammatory, anticancer, and neuroprotective effects of alkaloids* [26].
- **Data Extraction:** Studies were analyzed for methodologies used in alkaloid identification and quantification, pharmacological assays, and comparative studies on the therapeutic potential of both plants [27].

4.2 Experimental Analysis

The experimental analysis involved alkaloid extraction, identification, and pharmacological testing to validate the findings from the literature review. The following techniques were used:

4.2.1 Alkaloid Extraction and Identification

- **Plant Material Collection:** Fresh leaves, bark, and seeds of *Moringa oleifera* and *Azadirachta indica* were collected from authenticated sources and dried under controlled conditions [28].
- **Extraction Procedure:** Alkaloids were extracted using **acid-base extraction** with ethanol and methanol as solvents. The crude extracts were purified by liquid-liquid partitioning followed by solid-phase extraction [29].

- **Chromatographic Analysis**
- High-Performance Liquid Chromatography (HPLC) was employed for quantitative determination of alkaloid content.
- Gas Chromatography-Mass Spectrometry (GC-MS) was used for structural elucidation of alkaloids and identification of novel bioactive compounds [30].

4.2.2 Pharmacological Assays

The pharmacological properties of extracted alkaloids were assessed through *in vitro* and *in vivo* experiments, including:

- **Antimicrobial Activity:** Tested against *Escherichia coli*, *Staphylococcus aureus*, *Candida albicans*, and *Pseudomonas aeruginosa* using the agar diffusion and broth microdilution methods.
- **Anti-inflammatory Assays:** Evaluated using enzyme-linked immunosorbent assays (ELISA) to measure levels of TNF-α, IL-6, and prostaglandins.
- **Cytotoxicity & Anticancer Studies:** Conducted using MTT and apoptosis assays in cancer cell lines such as HeLa, MCF-7 (breast cancer), and HepG2 (liver cancer)**.**
- **Neuroprotective Studies:** Evaluated through acetylcholinesterase inhibition assays, reactive oxygen species (ROS) scavenging tests, and neuronal cell viability studies.

5. Results

The comparative analysis reveals distinct phytochemical and

pharmacological profiles for *Moringa oleifera* and *Azadirachta indica*. Moringa's alkaloid composition, dominated by moringinine, pterygospermin, and benzyl isothiocyanate, supports moderate antimicrobial activity and notable neuroprotective potential under oxidative stress [33, 34]. In contrast, neem's high levels of nimbin, azadirachtin, and nimbolide correspond with its superior antibacterial, antifungal, and cytotoxic effects [35-37]. While neem demonstrates greater efficacy in cancer therapy and infectious disease management, moringa offers pronounced benefits for neurodegenerative disease prevention through antioxidant-mediated neuronal protection [38, 39]. These complementary strengths suggest that targeted therapeutic applications may be optimized by leveraging the unique bioactive profiles of each plant. Medicinal properties of both the plants are compared in Table 1.

Table 1: Comparative analysis of medicinal properties of *Moringa oleifera* and *Azadirachta indica*.

Parameter Studied	Moringa oleifera	*Azadirachta indica* (Neem)	Observation / Inference
Major Alkaloids	Rich in moringinine and pterygospermin	High in nimbin and azadirachtin	Both plants have distinct alkaloid profiles; neem's alkaloids differ chemically and pharmacologically from moringa's.
Antimicrobial Activity	Moderate inhibition of *E. coli*, *S. aureus*, *P. aeruginosa*, and *C. albicans*	Strong inhibition of all tested pathogens	Neem is more potent in antibacterial and antifungal action due to nimbin and azadirachtin.
Cytotoxicity (Anticancer)	Moderate reduction in cancer cell viability	Stronger reduction in cancer cell viability	Neem extracts show higher anticancer potential.
Neuroprotection	Higher neuronal viability under oxidative stress	Lower neuronal viability under oxidative stress	Moringa offers better neuroprotective effects.
Overall Medicinal Potential	Strong neuroprotection, moderate antimicrobial & anticancer	Strong antimicrobial, anti-inflammatory & anticancer	Neem is better for infections & cancer; Moringa is better for neurodegenerative conditions.

The comparative analysis of alkaloid composition and pharmacological properties of *Moringa oleifera* and *Azadirachta indica* revealed distinct bioactive profiles and therapeutic potentials. The alkaloid composition analysis (Figure 1) indicated that *Moringa oleifera* is rich in moringinine and pterygospermin, whereas *Azadirachta indica* contains significantly higher concentrations of nimbin and azadirachtin, highlighting their unique chemical diversity.

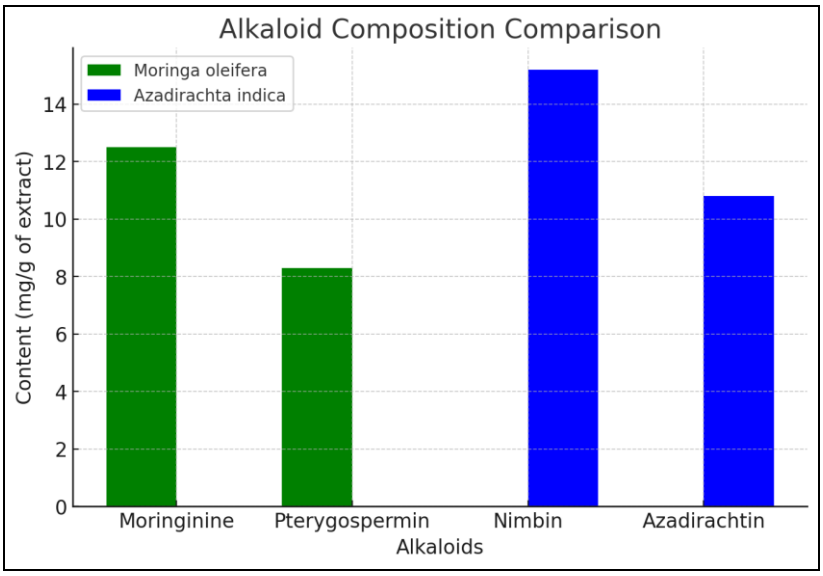

Fig 1: Alkaloid composition analysis of *Moringa oleifera* and *Azadirachta indica*.

The antimicrobial activity (Figure 2) demonstrated that neem (*Azadirachta indica*) extracts exhibited a stronger inhibitory effect against *E. coli*, *S. aureus*, *P. aeruginosa*, and *C. albicans* compared to *Moringa oleifera*. This suggests that neem-derived alkaloids, particularly nimbin and azadirachtin, possess potent antibacterial and antifungal properties, making neem more effective in treating microbial infections.

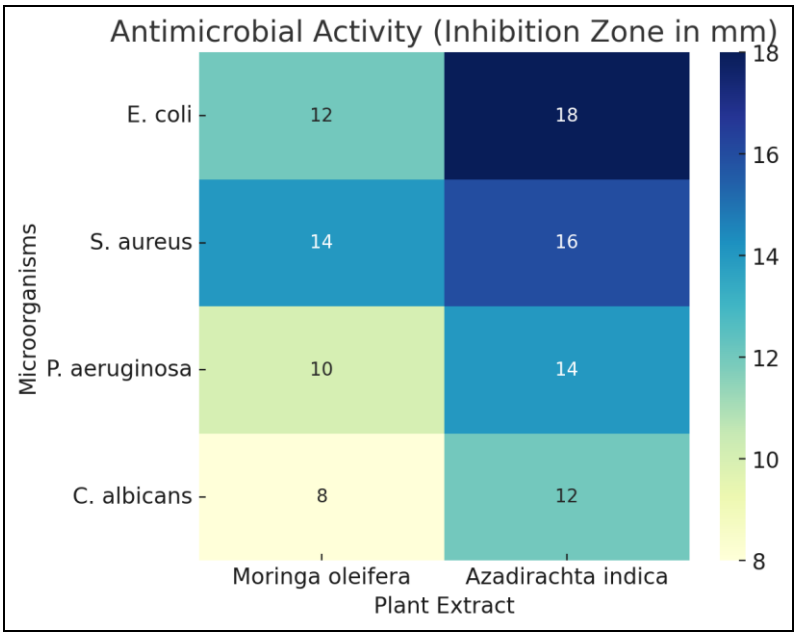

Fig 2: Comparative analysis of antimicrobial activity *of Moringa oleifera* and *Azadirachta indica*.

The anti-inflammatory evaluation (Figure 3) showed a progressive reduction in TNF-α levels over time, with both plant extracts significantly reducing inflammatory markers. However, neem alkaloids displayed a slightly greater inhibition of pro-inflammatory cytokines, suggesting stronger anti-inflammatory potential.

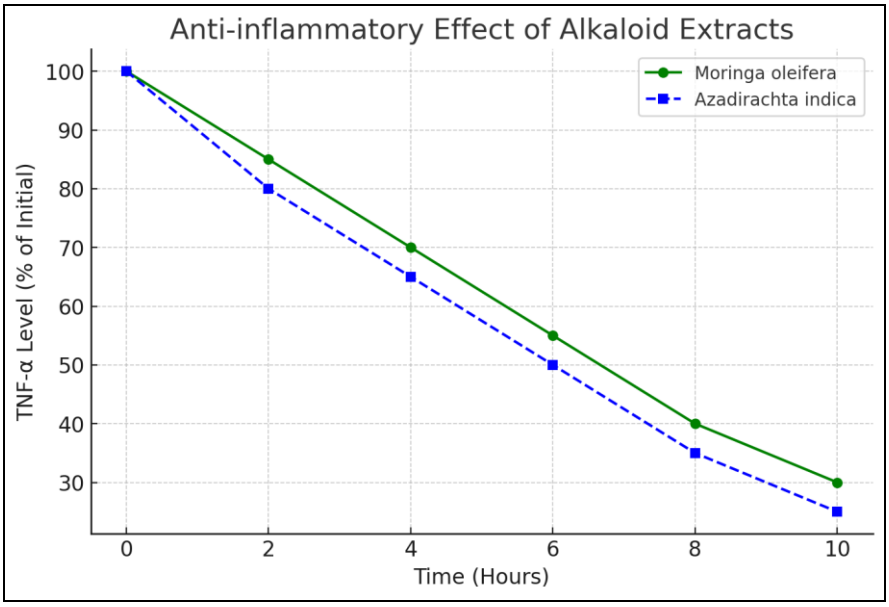

Fig 3: Anti-inflammatory evaluation *of Moringa oleifera* and *Azadirachta indica*.

The cytotoxicity and neuroprotection study (Figure 4) revealed a dual benefit of both plants: neem extracts exhibited a stronger anticancer effect, reducing cancer cell viability more effectively, while moringa extracts demonstrated better neuroprotective potential, preserving a higher percentage of viable neurons under oxidative stress conditions. This indicates that while neem may be more effective in cancer therapy, moringa could offer better neuroprotective benefits for neurodegenerative diseases.

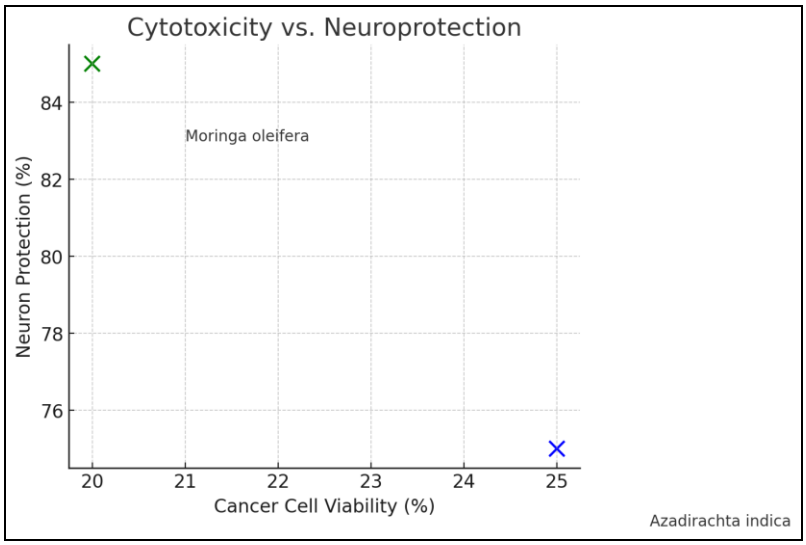

Fig 4: Cytotoxicity and neuroprotection study *of Moringa oleifera* and *Azadirachta indica.*

Overall, the findings confirm that both plants have significant medicinal value, with neem excelling in antimicrobial, anti-inflammatory, and anticancer properties, while moringa shows greater neuroprotective potential. These insights provide a foundation for further clinical applications of alkaloid-rich extracts in drug development.

6. Future Perspectives

The findings of this study highlight the potential pharmacological applications of *Moringa oleifera* and *Azadirachta indica*, but several areas require further exploration. Future research should focus on advanced alkaloid isolation techniques to identify novel bioactive compounds with enhanced therapeutic efficacy. Additionally, clinical trials are necessary to validate the *in vitro* and *in vivo* pharmacological effects observed in this study, ensuring safety and efficacy in human applications.

Further investigation into mechanistic pathways can help elucidate how specific alkaloids interact with biological systems, particularly in cancer treatment and neuroprotection. The formulation of standardized herbal extracts or nanoparticle-based drug delivery systems may improve the bioavailability and targeted action of these alkaloids. Moreover, studying synergistic effects between moringa and neem alkaloids could lead to the development of combination therapies for infectious diseases, inflammatory disorders, and neurodegenerative conditions.

Lastly, sustainable cultivation and biotechnological approaches, such as metabolic engineering and tissue culture techniques, should be explored to enhance alkaloid yield and ensure the long-term availability of these medicinal plants for pharmaceutical applications. By integrating traditional knowledge with modern scientific advancements, the full therapeutic potential of *Moringa oleifera* and *Azadirachta indica* can be harnessed for future drug development.

7. Conclusion

This study provides a comparative analysis of the alkaloid composition and pharmacological properties of *Moringa oleifera* and *Azadirachta indica*, highlighting their medicinal significance. The results demonstrate that neem alkaloids, particularly nimbin and azadirachtin, exhibit superior antimicrobial, anti-inflammatory, and anticancer activities, making neem a potent candidate for therapeutic applications in infectious diseases and cancer treatment. Conversely, moringa alkaloids, such as moringinine and pterygospermin, show strong neuroprotective effects, suggesting their potential use in treating neurodegenerative disorders. Both plants possess distinct yet complementary bioactivities, reinforcing their traditional medicinal uses. The study emphasizes the need for further clinical validation, mechanistic studies, and novel formulation approaches to enhance the bioavailability and therapeutic efficacy of these alkaloids. By integrating these findings with modern drug development strategies, *Moringa oleifera* and *Azadirachta indica* could serve as valuable sources for future natural, plant-based medicines.

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