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Exploring the potential of Neem (*Azadirachta indica* A. Juss.) as a sustainable biopesticide: Opportunities in Sudan

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Abstract

Sudan's escalating issue of insecticide pollution poses significant environmental and public health risks, emphasizing the need for sustainable alternatives. This review highlights the neem tree (*Azadirachta indica* A. Juss.), globally renowned for its applications in medicine, agriculture, and pest control, as a viable biopesticide solution. Despite the tree's broad distribution in Sudan, data on its adaptability, optimal cultivation techniques, and efficacy as a biopesticide in varying ecological zones remain limited. The review provides an in-depth examination of neem's botanical and ecological characteristics, propagation methods, and genetic diversity, with a focus on the need for enhanced selection of high-yield provenances suited to Sudan's climatic conditions. This research aims to bridge knowledge gaps and encourage the development of neem-based solutions to improve agricultural sustainability in arid regions.

1. Introduction

In recent years, Sudan's agricultural sector has expanded rapidly, heightening the need for effective pest control. This expansion has led to a heavy reliance on chemical insecticides, resulting in widespread soil and water contamination, loss of biodiversity, and significant health risks for humans and animals (Ali and Khan, 2020). Studies reveal that chemical residues are frequently detected in soil samples across Sudan, with concentrations often exceeding safe levels, signalling an urgent need for sustainable and environmentally friendly pest control alternatives (World Bank Report, 2021).

One promising solution is the neem tree (*Azadirachta indica* A. Juss.) (Figure 1), a species renowned globally for its pesticidal, medicinal, and agricultural uses. The active compound in neem; azadirachtin, offers strong insecticidal properties while remaining environmentally benign, making it a viable option to address Sudan's pesticide-related environmental issues. Although, neem is already present in Sudan, research on optimal cultivation practices, pest control efficacy, and application methods tailored to Sudan's diverse ecological zones remains scarce. This review provides a detailed examination of neem's potential as a biopesticide and emphasizes the importance of targeted cultivation practices to foster agricultural sustainability in Sudan's arid environments.

Figure 1: Photograph of *Azadirachta indica* A. Juss. (neem tree).

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Sudan's dependence on chemical insecticides has brought severe repercussions for biodiversity, soil quality, and human health, with pollution affecting water sources and food chains (Smith and Jones, 2020). In contrast, the neem tree is increasingly valued for its pest-resistant properties and sustainable nature, offering an alternative with significantly reduced ecological impacts. Neem tree exhibits a remarkable ability to adapt to various climates, making it especially suitable for Sudan's environmental conditions. as described in Table 1.

Table 1: Key ecological characteristics of neem

Parameter	Details
Scientific name	*Azadirachta indica* A. Juss.
Family	Meliaceae
Growth habitat	Arid, semi-arid tropical, and subtropical zones
Soil pH	6.2-7.0 (neutral to alkaline)
Rainfall	300-1500 mm annually
Temperature range	Thrives up to 40°C, sensitive to frost
Altitude	0 - 1500 meters
Tolerance	High drought tolerance, intolerant to water logging

The neem tree is adaptable to a range of challenging conditions which include temperatures up to 40°C, annual rainfall between 300 mm to 1500 mm, and neutral to alkaline soils (pH 6.2 - 7.0) and positions it well for Sudan's climate (Table 1). The tree's drought tolerance and requirement for well-drained soils make it suitable especially for where water scarcity is prevalent in Sudan's arid regions. However, its sensitivity to frost and intolerance of waterlogged soils highlight the need for region-specific cultivation practices to optimize its growth and effectiveness as a biopesticide.

By utilizing neem's natural resilience and pesticidal properties, Sudan can reduce its dependency on chemical insecticides, promoting a healthier ecosystem and safeguarding public health. This review underscores the critical need for further research to enhance neem cultivation and application as a sustainable biopesticide, offering a pathway toward ecological balance and agricultural productivity.

2. Botanical and ecological characteristics of neem

2.1 Botanical and bioactive properties

The neem tree (*Azadirachta indica* A. Juss.), part of the Meliaceae family, is a small to medium-sized evergreen species renowned for its resilience, medicinal applications, and pest-resistant properties. Known to reach heights of up to 20 meters, the tree is identifiable by its pale grey-brown bark, compound leaves, fragrant white flowers, and greenish-yellow fruits. Neem's adaptability allows it to thrive in challenging climates, particularly in tropical and subtropical regions.

One of the defining characteristics of neem is its diverse profile of bioactive compounds, or secondary metabolites, which give it unique insecticidal and antifungal properties along with properties that help to maintain oral health and germ-free mouth. Neem is also very famous for use as a toothbrush (Mohammad *et al.,* 2023) and key among these is azadirachtin, a potent bioactive compound that disrupts the growth and feeding cycles of more than 200 insect species. This compound acts as both an effective pest repellent and an insect growth regulator, making neem an invaluable resource in the development of biopesticides. Other notable compounds include nimbolide and salannin, each contributing additional antifungal and antimicrobial benefits.

The neem fruit, which ripens over a period of 12 weeks, is dispersed by birds and bats, facilitating the tree's natural spread across ecosystems. Within each fruit is a seed, rich in azadirachtin-particularly within the kernel. This high concentration of azadirachtin in neem seeds has made the tree a globally recognized source for sustainable biopesticide production (Malakar and Mandal, 2025). The versatility and effectiveness of neem as a natural pest control solution underscore its potential as a sustainable alternative to chemical pesticides, enhancing agricultural productivity while preserving environmental health.

3. Propagation and cultivation practices

Neem can be propagated through seed germination and various vegetative methods, each offering unique benefits depending on growth goals and genetic needs. Seed germination; for instance, is ideal for rapid growth under optimal conditions; while vegetative propagation techniques like air layering help preserve specific genetic traits, essential for producing uniform plant characteristics. According to El-Hawary *et al.* (2018), fresh neem seeds demonstrate high germination rates of 75-90% within two to three weeks when sown under ideal conditions. However, neem seeds are recalcitrant, meaning they lose viability within three to four months, making immediate planting crucial for effective cultivation.

Among neem propagation methods, direct seed sowing is popular for its simplicity, though it requires fresh seeds to achieve optimal results. In contrast, air layering and other vegetative approaches, such as root and shoot cuttings, allow for the cloning of genetically identical plants, but demand more labour and specific environmental conditions. Table 2 provides a detailed comparison of these propagation methods, including germination rates, optimal growing conditions, and practical remarks (Prakash *et al.,* 2021).

Table 2: Comparison of neem propagation methods

Propagation technique	Germination rate (%)	Optimal conditions	Remarks
Direct seed sowing	75-90	Well-drained, shaded areas	Viability drops, if seeds stored >3 months
Air layering	80-85	High humidity, 25-30°C	Preserves genetic traits, suitable for clones
Root and shoot cuttings	60-70	Moist soil, shaded areas	Moderate success can produce clones
Somatic embryogenesis	85-90	Controlled lab environment	High success in retaining desired characteristics

Each propagation method has its advantages and limitations as shown in Table 2. Direct seed sowing offers simplicity and cost-effectiveness, yet it requires prompt planting since neem seeds lose viability quickly. Air layering, with an 80-85% success rate, is favourable for maintaining genetic integrity, making it suitable for producing clones with specific traits. Root and shoot cuttings provide moderate success in moist, shaded environments and allow for plant cloning, though success rates are lower than air layering. Somatic embryogenesis, a laboratory-based technique, ensures the highest success rate (85-90%) in retaining desired genetic characteristics, making it ideal for large-scale neem propagation.

These propagation techniques collectively offer flexibility to adapt neem cultivation based on resource availability, environmental conditions, and desired genetic uniformity. By carefully selecting an appropriate propagation method, neem cultivation can be optimized to meet the demands of sustainable agriculture in various ecological settings (Prakash *et al.,* 2021).

4. Genetic diversity and provenance selection

The genetic diversity within neem (*A.indica*) is essential to maximizing its value as a biopesticide. The natural variation in neem's traits- such as seed yield, azadirachtin content, growth rate, and drought tolerance across its native and introduced ranges provides opportunities for targeted selection to enhance its effectiveness in specific environments. Provenance testing, which evaluates neem ecotypes from diverse geographic locations, identifies trees with high concentrations of desirable compounds like azadirachtin and oil. This variability is especially useful for biopesticide production, as it allows for the selection of ecotypes that perform best under specific environmental conditions. For example, studies from India revealed substantial variation across 39 neem seed sources, emphasizing the importance of high-yielding provenances suited to Sudan's unique climate (Gupta and Sharma, 2021).

As outlined in Table 3, neem ecotypes from regions such as East Africa and Southern India display differing levels of azadirachtin and oil content, both crucial for neem's pesticidal effectiveness. Research indicates that neem's oil content ranges from 30% to 45%, with higher azadirachtin levels typically associated with trees from arid regions. This correlation between region-specific traits and chemical composition underscores the value of selecting neem provenances best suited to Sudan's arid climate for biopesticide production (Elteraifi and Hassanali, 2011).

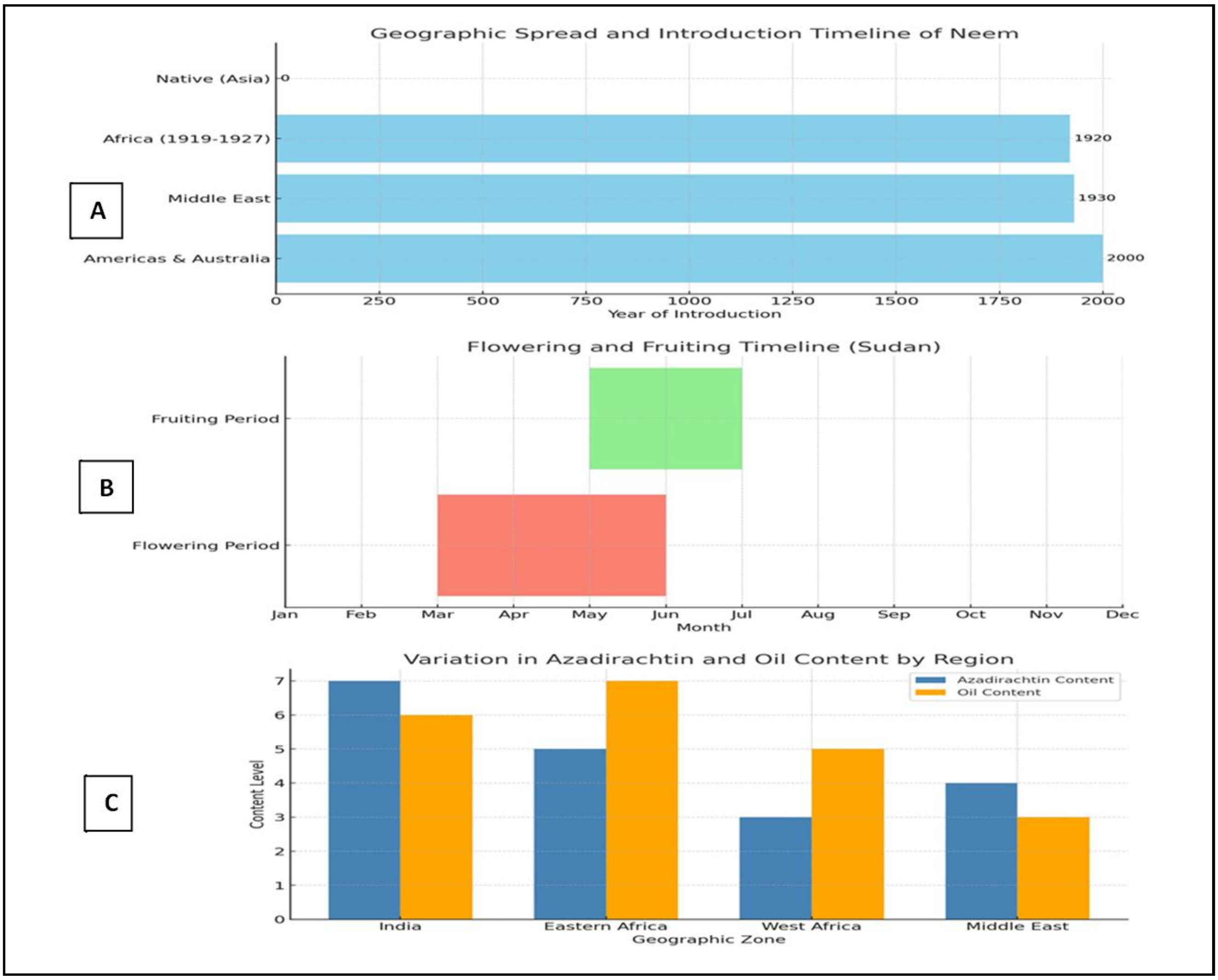

Figure 2: (A) Timeline, (B) Fruiting and flowering period, and (C) Illustrating differences in azadirachtin and oil content levels across regions, highlighting regional variations that may impact neem.

Table 3: Regional variation in neem composition

Region	Azadirachtin content (mg/g)	Oil content (%)	Suitability for Sudan
East Africa	2.1	38	High
Western India	1.8	32	Moderate
Southern India	2.5	40	Very High
Southeast Asia	1.7	30	Low

Table 3 depicts the variability in azadirachtin and oil content among neem ecotypes (Figure 2C), with Southern Indian ecotypes showing the highest potential due to their elevated levels of both azadirachtin (2.5 mg/g) and oil content (40%). These characteristics are highly desirable for biopesticide applications, as azadirachtin is the primary compound responsible for neem's insecticidal properties. In contrast, neem from regions like Southeast Asia demonstrates lower suitability for Sudan's biopesticide needs due to its comparatively low chemical content (Maheswari *et al.*,2023) and green technologies for sustainable management of invasive and transboundary pests.

Selecting optimal provenances, such as those from Southern India or East Africa, could enhance neem's resilience, yield, and bioactive compound production, making it a more potent alternative to synthetic pesticides in Sudan. Such selection strategies are not only advantageous for immediate biopesticide use, but are also critical to breeding programs aimed at improving neem's adaptability to arid conditions. Provenance selection; therefore, represents a strategic approach to harnessing neem's genetic diversity to support sustainable pest management and agricultural productivity in regions where environmental conditions pose significant challenges (Das *et al.,* 2014).

5. Neem as a sustainable biopesticide

Neemtree offers a sustainable solution to pest control due to its biopesticidal properties. These properties arise from a complex mix of compounds, most notably azadirachtin, nimbin, and salannin, which exert anti-feedant, repellent, and growth-inhibiting effects on various pest species. These bioactive compounds make neem an attractive alternative to conventional chemical pesticides, especially considering its low toxicity to non-target organisms, including humans and beneficial insects (Kambrekar *et al.,* 2022).

In Sudan, neem oil and leaf extracts have been effectively used to control pests such as aphids, mites, and caterpillars, which are common threats to crops. Neem's effectiveness; however, is influenced by several factors, including the concentration of azadirachtin, which varies depending on soil type, climate, and ecological adaptation. Given Sudan's diverse ecological zones, there is potential to select neem ecotypes with higher concentrations of bioactive compounds, thereby improving pest control efficacy while minimizing the environmental footprint.

A comparison of neem biopesticides with synthetic pesticides further illustrates their environmental advantages. As shown in Table 4, while synthetic pesticides often exhibit high efficacy in pest control, they come with significant environmental costs, including toxicity to non-target organisms and long-term soil and water contamination. In contrast, neem biopesticides, although slightly less effective in pest control (85-82%), have a considerably lower environmental impact, making them a more sustainable option (Mandal, 2019).

Table 4: Efficacy of neem biopesticides vs. synthetic pesticides

Pest type	Synthetic pesticide efficacy (%)	Environmental impact	Neem biopesticide efficacy (%)	Environmental impact
Aphids	90	High	85	Low
Locusts	92	High	80	Low
Beetles	88	High	82	Low

As the table demonstrates, neem biopesticides exhibit a lower environmental impact compared to their synthetic counterparts, making them a promising option for sustainable agriculture, especially in regions like Sudan.

5.1 Provenance testing and neem's bioactive compounds

Provenance testing plays a crucial role in identifying neem strains that possess higher concentrations of bioactive compounds, which are essential for the plant's effectiveness as a biopesticide. As neem is grown across various geographical regions, genetic variation in the plant's chemical composition can significantly impact its pest control properties. Given Sudan's diverse environmental conditions, selecting neem ecotypes with optimal levels of bioactive compounds, particularly azadirachtin, nimbin, and salannin, is critical for improving pest control efficacy (Harrewijn, 2000).

Studies have shown that the concentrations of key bioactive compounds in neem, such as azadirachtin, nimbin, and salannin, vary across different geographical populations. For instance, research by Akinmoladun *et al.* (2018) revealed that neem trees from tropical regions, like those in Nigeria, exhibited higher azadirachtin levels compared to those from arid zones, found significant variance in neem extracts from different locations, with some populations showing higher concentrations of bioactive compounds that are crucial for pest control.

Table 5 summarizes the variation in key bioactive compounds found in neem extracts from different geographical populations as reported by various researchers. This data supports the idea that provenance testing can help identify neem strains with the most effective bioactive profiles for use in sustainable pest management, especially under Sudan's unique environmental conditions.

Table 5: Various bioactive compounds found in neem extracts

S. No.	*A. indica* phytoconstituents	Class of compound	Part	Potential therapeutic effects	Reference
1.	2',3'-dihydronimbolide	Terpenoid	Leaf	Anticancer	Mahapatra *et al.* (2011); Wu *et al.* (2014)
2.	2',3'-dehydrosalannol	Triterpenoid	Leaf	Antifeedant, anticancer	Srivastava *et al.* (2012)
3.	28-deoxonimbolide	Terpenoid	Seed	Anticancer	Mahapatra *et al.* (2011), Wu *et al.* (2014)
4.	6-deacetylnimbinene	Limonoid	Bark	Antiangiogenic, anticancer	Rupani and Chavez (2018)
5.	Azadirachtin	Limonoid	Seed	Anticancer	Kharwar *et al.* (2020)
6.	Azadiradione	Limonoid	Fruit	Neuroprotective	Hummel *et al.* (2014)
7.	Azadiramide	Limonoid	Seed	Anticancer	Alzohairy (2016)
8.	Azadirone	Limonoid	Seed	Anticancer	Patel *et al.* (2018)
9.	Catechin	Flavonoid	Bark	Antioxidant, anti-inflammatory	Elumalai and Arunakaran (2014)
10.	Epicatechin	Flavonoid	Bark	Antioxidant, anti-inflammatory	Ahmad *et al.* (2018)
11.	EAD	Limonoid	Fruits, seeds	Anti-inflammatory, anticancer	Zingue *et al.* (2019); Patel *et al.* (2016)
12.	Gedunin	Limonoid	Leaf, seed	Anticancer, antiallergic	Sharma *et al.* (2017)
13.	Isomargolonone	Diterpenoid	Bark	Antibacterial	Goswami *et al.* (2016)
14.	Margolonone	Diterpenoid	Bark	Antibacterial	Paul *et al.* (2011); Bandyopadhyay *et al.* (2004); Lin *et al.* (2019)

The data provided in Table 5 further supports the importance of provenance testing to optimize neem's bioactive compound content, which varies depending on geographical origin. By conducting detailed analyses of different neem populations in Sudan, it is possible to identify strains with higher concentrations of azadirachtin and other bioactive compounds. This will help enhance neem's effectiveness as a biopesticide, tailored to Sudan's environmental conditions, leading to better pest control and sustainable agricultural practices.Thus, ongoing research and selection of neem ecotypes through provenance testing are essential for improving the agricultural and environmental benefits of neem biopesticides (Raguraman *et al.,* 2004).

6. Research gaps and future directions

Despite the considerable potential of neem (*A. indica*) as a sustainable solution for pest management and environmental protection in Sudan, several research gaps need to be addressed to optimize its application. While neem's efficacy as a biopesticide is well-documented, much remains to be explored regarding its adaptability to Sudan's unique ecological conditions. A major gap in the literature concerns the interaction between neem's genetic traits and environmental stressors such as drought, high soil salinity, and temperature fluctuations, which are prevalent in Sudan. Studies by Ali *et al.* (2018) highlight that few research efforts have focused on how these factors influence neem's growth, bioactive compound production, and overall pest control effectiveness. This knowledge is crucial for optimizing neem cultivation and its use as a biopesticide in Sudan's arid and semi-arid regions.

In accumulation to genetic-environment interactions, more research is needed to determine the optimal application rates, formulations, and compatibility of neem-based biopesticides with other pest control methods within Sudan's diverse ecosystems. While neem has shown efficacy against a range of pests, understanding how to maximize its impact in different crop systems, and determining the best methods for its integration with other biocontrol agents, is essential. Furthermore, a better understanding of neem's physiological responses to Sudanese soil types and climate conditions could provide valuable insights into optimizing plantation density, irrigation schedules, and soil management practices. For example, the identification of neem ecotypes that are more resilient to environmental stresses and have higher concentrations of bioactive compounds like azadirachtin would significantly improve its efficiency as a biopesticide.

A key area for future research is genetic studies on drought-tolerant neem ecotypes and those that produce high levels of azadirachtin. Selective breeding based on these traits could enhance neem's adaptability and effectiveness as an eco-friendly pesticide, offering long-term benefits for agricultural sustainability in Sudan. By understanding the genetic diversity of neem and its relationship to environmental factors, targeted breeding programs could be developed to produce high-yielding neem strains, better suited to the harsh climatic conditions of Sudan.

7. Conclusion

The neem tree offers a promising solution for sustainable agriculture in Sudan by reducing reliance on harmful chemical insecticides, enhancing soil quality, and providing drought-resistant vegetation cover in arid regions. Neem's rich chemical profile, particularly its bioactive compounds, and its adaptability to harsh climates make it a valuable resource for both agricultural productivity and environmental protection. However, realizing the full potential of neem in Sudan requires a comprehensive, multidisciplinary approach that combines genetic, ecological, and agronomic research to address existing challenges in cultivation and application.

To optimize neem's use in Sudan, it is necessary to:

i. **Establish propagation protocols**: Tailoring propagation techniques to Sudan's specific climate and soil conditions will be essential. Research should focus on identifying the most efficient methods for neem seed propagation and vegetative reproduction, with an emphasis on enhancing germination rates and seedling growth under local conditions.

ii. **Explore neem's role in integrated pest management**: A national-scale strategy for integrating neem into pest management practices could help reduce the environmental impact of synthetic pesticides. By evaluating neem's compatibility with other biopesticides and its efficacy in diverse agricultural systems, Sudan can adopt neem as a key component in sustainable pest control.

iii. **Genetic and ecological research**: Further genetic studies on neem's adaptation to local environmental stressesparticularly drought, soil salinity, and temperature variation are crucial. Research should also focus on the identification of neem ecotypes that produce high concentrations of azadirachtin and other bioactive compounds.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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