International Journal of Allied Medical Sciences and Clinical Research (IJAMSCR)

IJAMSCR |Vol.13 | Issue 3| Jul - Sept -2025

www.ijamscr.com

ISSN: 2347-6567

DOI : https://doi.org/10.61096/ijamscr.v13.iss3.2025.453-462

Review

A Comprehensive Review of Neem (*Azadirachta Indica*): Extraction Methods, Properties, and Diverse Applications

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Published on: 22 Jul 2025

Published by:
Futuristic Publications

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Abstract

Azadirachta indica, commonly known as Neem, is a highly versatile tree with a rich history of traditional use in various cultures, particularly in India, for over two millennia. Scientific investigations have consistently validated its broad spectrum of biological activities, classifying it as one of the most adaptable plants due to the myriad of bioactive compounds present in all its parts, including leaves, seeds, fruits, roots, bark, and flowers.This review compiles recent research on Neem, focusing on efficient extraction methodologies, physicochemical properties of its extracts, and a diverse range of applications spanning medicinal, agricultural, and environmental sectors. Studies highlight the efficacy of solvents like ethanol and methanol in yielding high extract percentages from leaves and seeds. Neem extracts exhibit significant antibacterial, antidiabetic, anti-inflammatory, antioxidant, and antiproliferative properties, supporting their use in wound healing, disease management, and as natural larvicides. Agriculturally, Neem formulations prove effective as nematicides and insecticides, demonstrating systemic effects and persistence against pests like root-knot nematodes. Environmentally, Neem root extracts show promise in crude oil degradation in polluted soils, and innovative mechanical systems are being developed for efficient fruit collection, addressing economic and labor challenges. This review underscores Neem's potential as a sustainable and eco-friendly source for developing novel products and solutions.

Keywords: Neem leaves, Seed, Fruit, Extraction, Insecticidal, larvicidal, Anti-diabetic, Anti-proliferation, Anticoccidial

INTRODUCTION

Azadirachta indica A. Juss (Neem), belonging to the Meliaceae family, is revered as a "wonder tree" and has been utilized for over 2000 years in India and neighboring countries for its profound medicinal and therapeutic properties. Every part of the Neem tree from its seeds, flowers, twigs, barks, roots, and leaves possesses medicinal potential for humans. For instance, Neem leaves are traditionally incorporated into medicinal preparations for

their anti-inflammatory, antibacterial, antiviral, antioxidant, and hepatoprotective effects. The seeds are particularly rich in oil, containing approximately 45% oil, including oleic, linoleic, palmitic, stearic, and arachidic acids, and are functional as anti-malarial, antipyretic, and antifungal agents. Neem flowers contain aromatics, fatty acids, steroids, hydrocarbons, and sesquiterpenes, which are utilized in treating intestinal worms and for phlegm and bile suspension. While seeds and flowers are seasonal, Neem leaves are available year-round, making them a consistent subject for research [12,13]

Beyond its traditional medicinal uses, scientific validation has expanded the understanding of Neem's broad biological activity. Researchers have explored its efficacy in various modern applications, driven by the increasing demand for natural, eco-friendly, and sustainable alternatives to synthetic compounds. The plant's complex composition, characterized by over 300 different bioactive compounds, contributes to its multidirectional activities, including anticancer potential [5].

This review aims to consolidate current knowledge from recent research articles on *Azadirachta indica*, covering the methodologies employed for extracting its valuable compounds, characterizing their physicochemical properties, and evaluating their diverse applications. It highlights how different parts of the Neem tree and various extraction techniques yield compounds with significant impacts across health, agriculture, and environmental remediation [3,4].

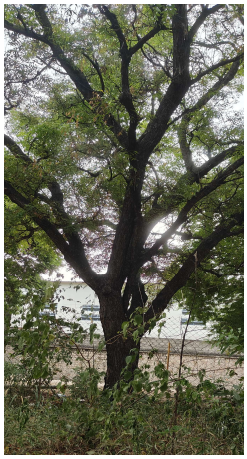

Fig 1: NeemTree

MATERIALS AND METHODS

Plant Material Collection and Preparation

Neem plant materials were collected from various geographical locations and prepared for extraction and analysis.



Fig 2: Neem leaves

Neem Leaves: Leaves were collected from areas around university campuses or from the Punjab region in India [5]. They were thoroughly washed with distilled water, sun-dried for three days or air-dried under shade for one week until a constant weight was achieved. The dried leaves were then ground into powder form using a hammer

mill or electric grinder, often with an 8-mm sieve size. The homogeneous powder was stored in amber glass bottles or airtight containers to protect contents from UV rays and humidity [5,7].
Neem Seeds and Kernels: Neem seeds were purchased from local markets. Dirt, shells, and hulls were removed by washing in clean water and then sun-drying for 2-3 days. The kernels were subsequently ground into powder form for oil extraction [2].
Neem Fruits: Ripe Neem fruits were collected from local areas. They were washed thoroughly and dried in shady places at room temperature, then manually crushed into powder using hammer mill with 8-mm sieve size. For animal feed studies, dried Neem fruits were milled and further processed by water-washing. For mechanical collection studies, fruit geometry and physical properties were determined [6].
Neem Root Bark: Neem roots were collected from university campuses. The root bark was separated, shade-dried, and then Alcoholic extract of bark was obtained by continuous extraction in percolator using 70%ethanol [8].

Solvents Used
A wide array of solvents, varying in polarity, was employed across the studies to extract different bioactive compounds from Neem. These included:
Alcohols: Methanol (MeOH), ethanol (EtOH), 70% ethyl alcohol, 50%-aqueous EtOH, 80%-aqueous EtOH, and absolute (99.8%) EtOH. Methanol is suitable for extracting both polar and non-polar substances, while ethanol is a polar solvent that readily mixes with water and breaks down water-soluble molecules [1,2,4,5,8,11].
Esters: Ethyl acetate (EAc). Ethyl acetate has medium polarity and minimum toxicity [1].
Hydrocarbons: Hexane (Hex), petroleum ether, and n-hexane. Hexane is non-polar, allows for simple recovery, and has high selectivity [1,2,11].
Water: Distilled water (DW). Distilled water was often used to study its potential as a cost-effective and environmentally friendly medium [1,2,9].
Other: Carbon tetrachloride, dichloromethane, and acetone [11,12].

Extraction Methods
Several extraction techniques were utilized to obtain Neem extracts, depending on the plant part and desired compounds:
Soxhlet Extraction: This method was commonly used for extracting oil from Neem leaves and seeds. It involves continuous extraction, ensuring high yield [1,2,4].
Immersion/Shake Flask Method: This technique involved soaking plant powder in a solvent for a specified period with or without agitation or heating [2,5,9].
Percolator/Continuous Extraction: Used for obtaining alcoholic extract from Neem root bark [8].
Water Soaking/Washing: Specifically for Neem fruits, this method was used to reduce bitter components while retaining beneficial properties for animal feed [6].
Manual Crushing/Grinding: Used as a preliminary step for all plant parts to increase surface area for solvent interaction [2,5,11].

Analysis and Evaluation Methods
After extraction, various analyses were conducted to characterize the extracts and evaluate their properties and applications:
Physicochemical Properties: Visual observation (appearance, color, odor), pH measurement, viscosity studies, washability, spreadability, and solubility in water [1,2,4].
Yield Percentage and Sedimentation: Calculated based on weight ratio of extracted material to initial sample. Sedimentation analysis by centrifuging at different speeds [1,2].
Spectrophotometric and Chromatographic Analyses:

- **UV-Vis Analysis:** Used to identify the formation of extract and absorption bands of functional groups [1].
- **High Performance Liquid Chromatography (HPLC):** Used for standardization of extracts and formulations, and identification of marker compounds [4].
- **HPLC-Mass Spectrometry (HPLC-MS):** Used for identification and quantification of phenolic compounds in extracts, providing a detailed phenolic profile [5].
- **Total Phenolic Content (TPC), Total Flavonoid Content (TFC), Total Condensed Tannin Content (TCTC):** Quantified using spectrophotometric methods [5].

Antioxidant and Radical-Scavenging Activity: Assessed using various assays such as Ferric-Reducing Antioxidant Power (FRAP), Trolox-Equivalent Antioxidant Capacity (TEAC), Oxygen Radical Absorbance Capacity (ORAC), and DPPH Radical-Scavenging Activity [4,5].
Stability Studies: Observed changes in physical properties (color, odor, viscosity, pH) and fungal growth over time, often under accelerated conditions [1,4].

Biological Activity Assays

- **Antibacterial Activity:** Evaluated against various bacterial strains (e.g., *E. coli, Klebsiella sp., S. aureus, Pseudomonas sp., M. luteus, S. paratyphi*) using agar well diffusion and broth dilution methods, determining minimum inhibitory concentration (MIC) [2,4,5,9].
- **Insecticidal Activity:** Tested on insects like gram pod borer, spider mites, and cockroaches by recording death time [2].
- **Larvicidal Bioassay:** Evaluated against mosquito larvae (e.g., *Culex quinquefasciatus*) by noting mortality response after exposure to extracts [11].
- **Antiproliferative Activity:** Assessed against cancer cell lines (e.g., HepG2, HeLa, MCF-7) using MTT assay to determine cell viability reduction [5].
- **Antidiabetic Activity:** Evaluated using glucose tolerance tests and alloxan-induced diabetes models in rats, measuring blood sugar levels [8].
- **Anticoccidial Efficacy:** Determined by fecal egg counts and percentage efficacy of coccidia egg reduction in animals [6].
- **Nematicidal Activity:** Assessed against root-knot nematodes (*Meloidogyne javanica*) through seedling dip, split-root techniques, and evaluation of galling index and egg masses [7].

Agricultural and Environmental Parameters

- **Feed Intake and Growth Performance:** Measured in animals (e.g., rams) to assess the impact of Neem inclusion in diets [6].
- **Nutrient Digestibility and Metabolism:** Determined crude protein, hemicellulose digestibility, and nitrogen retention in animals [6].
- **Crude Oil Degradation:** Investigated the biodegradability of total petroleum hydrocarbon (TPH) in loamy soil amended with Neem root extracts, alongside changes in physicochemical properties of soil (pH, EC, MC, TOC, TN, P) and total bacteria count [10].
- **Mechanical Ground Collection System:** Design, fabrication, and evaluation of a pneumatic system based on fruit properties for efficient collection [3].

Procedure of extraction

The extraction of bioactive compounds from *Azadirachta indica* is a critical step in harnessing its diverse properties. Various methods are employed, each tailored to the specific plant part and the desired compounds. Generally, the process involves sample preparation followed by solvent-based extraction, and subsequent purification steps.

General Sample Preparation

Regardless of the plant part, initial preparation steps are essential for effective extraction:

Collection: Neem leaves, seeds, fruits, or roots are collected from their respective sources [1,2,4,5,8,11].

Washing: The collected materials are thoroughly washed, typically with distilled water, to remove dirt, debris, and any foreign particles. For Neem fruits, shells and hulls may also be removed during this step [1,2,5,9].

Drying: Samples are dried to reduce moisture content, which prevents microbial growth and enhances the efficiency of subsequent grinding. Drying methods include sun-drying (e.g., for 2-3 days for seeds or 3 days for leaves), shade-drying at room temperature (for fruits or root bark), or air-drying under shade for a week (for leaves) [1,2,5,8,11].

Grinding/Milling: The dried plant materials are then ground into a fine powder. This is achieved using a grinder, hammer mill (e.g., with an 8-mm sieve size for fruits for animal feed), or manually with a mortar and pestle. This increases the surface area for efficient solvent penetration [1,2,5,6,11].

Storage: The powdered material is typically stored in airtight containers, such as amber glass bottles, at low temperatures (e.g., 4°C) or in desiccators to protect it from light, moisture, and degradation until further use [5,7].

Solvent-Based Extraction Methods

Soxhlet Extraction

Soxhlet extraction is a preferred method for its efficiency in yielding high amounts of oil and other compounds due to continuous solvent cycling. This method is suitable for solid-liquid extraction of compounds that have limited solubility in a solvent and for samples containing large amounts of impurities [2].

For Neem Leaves

- 26.0 grams of ground neem leaves powder is placed into a Soxhlet extractor.
- 300 ml of a chosen solvent (e.g., methanol, ethanol, ethyl acetate, or hexane) is added to the distillation flask.

- The setup is heated, allowing the solvent to vaporize, condense into the thimble containing the leaf powder, and then drip back into the flask, continuously extracting compounds for 2 hours.
- After extraction, the crude extract is filtered.
- The solvent is evaporated completely using a rotary vacuum evaporator (e.g., BUCHI R-215) to obtain the crude extract.
- The same steps are repeated for other solvents [14].

For Neem Seed Oil

- 50 grams of neem seeds powder is mixed with 250 ml of methanol in a Soxhlet extraction kit.
- The mixture is heated at 60°C for six hours.
- The extracted oil-solvent mixture is transferred to a vacuum evaporator to remove solvent residue.
- The extracted oil is then centrifuged at 5000 rpm for 20 minutes to remove any suspended particles.
- The process is repeated until a sufficient quantity of oil is obtained [15].

For Neem Fruit Extracts

- Dried neem fruits are prepared and ground.
- A methanolic extract is obtained by continuous extraction (Soxhlet method). The most effective extract is identified for further formulation [4].

Immersion / Shake Flask Extraction

This method is simpler than Soxhlet and can be adapted for various temperatures and agitation conditions.

For Neem Leaves

- 26.0 grams of neem leaves powder is weighed and placed into a polytetrafluoroethylene (PTFE) bottle.
- 300 ml of a chosen solvent (e.g., methanol, ethanol, ethyl acetate, or hexane) is added to the bottle.
- The bottle is tightly closed and placed in an oven at a specific temperature (e.g., 100°C) for 2 hours.
- The solution is then filtered.
- The solvent is evaporated using a rotary vacuum evaporator to obtain the extract.
- For distilled water, the immersion method is also used at various temperatures (25°C, 50°C, 70°C, and 90°C) for 2 hours to assess its potential as a cost-effective medium [1].

For Neem Seed Oil (Shake Flask Method)

- 250 grams of neem seed kernel powder is soaked in 1 liter of petroleum ether.
- The mixture is placed on a shaker for approximately 72 hours.
- The mixture is then filtered using a muslin cloth, and the solid cake is separated.
- The filtrate undergoes distillation to separate the extracted oil from the solvent [16].

For Neem Root Bark Extract

- Shade-dried and powdered root bark is used.
- An alcoholic extract is obtained by continuous extraction in a percolator using 70% ethyl alcohol.
- A fresh solution is prepared by dissolving the extract in distilled water before each experiment [8].

For Neem Leaf Extract (Antibacterial/Antiproliferative studies)

- 1 gram of dry powdered leaves is mixed with 20 ml of ethanol (at concentrations like 50% aqueous EtOH, 80% aqueous EtOH, or absolute EtOH).
- The mixture is subjected to extraction for 24 hours at 4°C with constant stirring using a multi-position magnetic stirrer.
- Samples are then centrifuged at 1500×g for 10 minutes.
- The supernatant is filtered using Whatman filter paper N°1.
- The filtrate is lyophilized for two days to obtain dry extracts.
- For antibiofilm studies, fresh neem leaves are ground with 10 mL sterile distilled water, allowed to stand for 4 hours, and then filtered [5,9].

Water-Washing for Neem Fruit (Animal Feed Application)

This specific preparation aims to reduce undesirable components while retaining beneficial ones for livestock.

For Water-Washed Neem Fruit for Animal Feed

- Dried neem fruit is acquired and milled using a hammer mill with an 8-mm sieve size.
- A known quantity of the milled samples is put into bags and soaked in a drum containing water at a ratio of 1.2 L of water per kg of fruit.
- After 24 hours of soaking, the water is decanted.
- Fresh water is added to top up the drum to the mark.

- After another 24 hours, the processed fruits are removed (without straining) and sun-dried.
- The prepared water-washed fruit samples are collected and stored in airtight containers [6].

RESULTS AND DISCUSSION

Neem (Azadirachta indica) has demonstrated remarkable versatility across various applications, driven by the rich array of bioactive compounds found in its different parts. The efficacy of Neem largely depends on the extraction method and the solvent used, which influence the yield and the profile of extracted compounds.

Extraction Yields and Physicochemical Properties

The efficiency of extraction varies significantly with the method and solvent employed. For Neem leaves, the immersion method with ethanol yielded the highest percentage (22.0%), closely followed by Soxhlet extraction with ethanol (21.5%). Methanol also provided good yields (16.0% via Soxhlet, 18.0% via immersion), while ethyl acetate consistently yielded 15.0% for both methods. Hexane extraction resulted in lower yields (15.0% Soxhlet, 13.0% immersion). Interestingly, for Neem leaves, 50%-aqueous ethanol emerged as the best solvent, yielding 25.14% extract, outperforming 80%-aqueous ethanol (19.04%) and absolute ethanol (12.89%). This highlights the effectiveness of mixed solvents in enhancing the extraction of particular phenolic compounds due to varied polarity requirements and improved cell tissue permeability [1,5].

For Neem seed oil, Soxhlet extraction using methanol achieved a high yield of 28%, which was significantly better than the 14.06% obtained from the shake flask method using petroleum ether. This suggests Soxhlet is generally preferred for its high oil yield from seeds [2].

Physicochemical observations of crude Neem extracts revealed a consistent dark brown to light brown color, a strong to light garlic-like odor, and a high viscosity. Most crude oil extracts were liquid at room temperature, though hexane extracts tended to solidify after a while due to the volatility of hexane. Sedimentation analysis showed that centrifuging at 3000 rpm was more efficient in eliminating Neem leaf sediment, reducing it to less than 5%, compared to 1500 rpm which left less than 2%. The pH of extracts typically started as low acidic (5.6–5.9 after 4 weeks) and became neutral (7.0–7.2 after 8 weeks), making them suitable for use in cosmetic products such as lotions and cleansers. Stability tests indicated that extracts stored at room temperature showed a gradual lightening of color and reduction in smell over 8 weeks, with increased viscosity. However, distilled water extracts at lower temperatures (25°C and 50°C) exhibited fungus growth after 7 days, indicating unsuitability as an extraction medium without proper storage conditions like refrigeration, unlike those prepared at 70°C and 90°C. [1,2].

Medicinal and Therapeutic Applications

Neem's rich array of bioactive compounds, including azadirachtin, nimbin, nimbidin, and various phenolic compounds (phenolic acids, flavonoids, terpenoids), underpins its extensive medicinal applications [2,5,7] Shown on figure :3.

Antibacterial and Anti-biofilm Activity

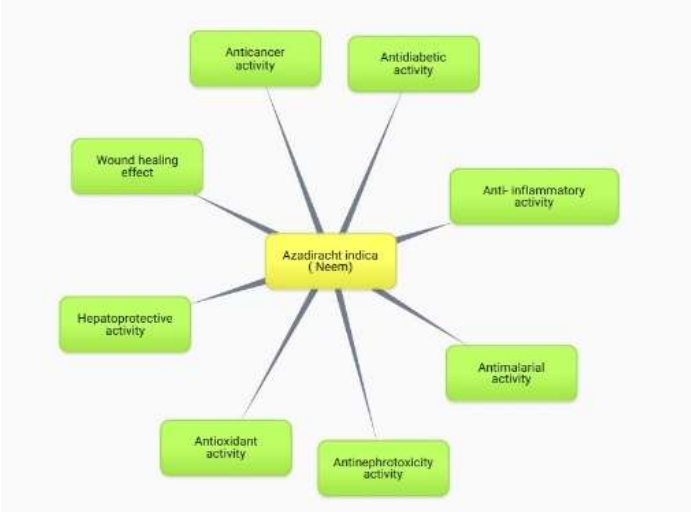

Fig 3: Neem activities

Neem oil and leaf extracts demonstrate significant antibacterial properties against various pathogens. Neem seed oil showed notable antibacterial activity against *Staphylococcus aureus* and *Pseudomonas sp.*, yielding a 13 mm zone of inhibition in agar well diffusion assays, though it did not affect *E. coli* growth. Neem leaf extract (50%-aqueous EtOH) exhibited better antibacterial activity against *S. aureus* and *E. coli* strains (MIC 0.50 mg/mL) compared to penicillin [2,5].

Crucially, Neem leaf extract has been identified as a potential anti-biofilm agent against *Pseudomonas aeruginosa*. It significantly reduced biofilm formation, altered biofilm architecture (resulting in a thinner biofilm with less exopolysaccharide), and decreased factors contributing to adherence, such as total polysaccharides, alginate, and cell surface hydrophobicity. This suggests its potential as a standalone or adjuvant treatment for biofilm-associated infections that are typically resistant to conventional antibiotics [9].

Antidiabetic Activity

The 70% alcoholic extract of Neem root bark has demonstrated antidiabetic activity. n an oral glucose tolerance test (OGTT) in albino rats, a dose of 800 mg/kg of the root bark extract significantly reduced blood sugar levels by 54% after 4 hours, showing antihyperglycemic activity. In alloxan-induced diabetic rats, the same dose (800 mg/kg, administered twice daily for 15 days) led to a maximum blood sugar reduction of 76% by the 15th day, indicating hypoglycemic activity. While effective, its potency was less significant than glibenclamide, a standard antidiabetic drug. Nimbidin, a terpenoid present in Neem, is suggested to be responsible for these antidiabetic effects. This research supports Neem root bark's potential as a prophylactic or adjuvant agent in diabetes management [8].

Wound Healing Properties

Neem fruit extracts have been successfully formulated into topical semisolid dosage forms like ointments and gels for wound healing. A 3% methanolic extract of dried Neem fruits, prepared by continuous (Soxhlet) extraction, was incorporated into polyethylene glycol ointment and carbopol gel bases. These formulations demonstrated compliance with official pharmacopeia requirements for appearance, pH, viscosity, spreadability, and drug content uniformity. They were found to be non-irritant and stable under accelerated stability conditions. The Neem ointment and gel exhibited antimicrobial activity against *Staphylococcus aureus* (18–20 mm inhibition zone) and possessed antioxidant activity (DPPH radical scavenging), primarily due to phenolic compounds such as flavonoids, alkaloids, and terpenoids. These phenolic compounds contribute astringent and antimicrobial properties, promoting wound contraction and increased epithelialization, thus supporting the traditional use of Neem for wound management [4].

Antiproliferative Activity against Cancer Cells

Neem leaf extract (50%-aqueous EtOH) has shown significant antiproliferative activity against various human cancer cell lines, including breast adenocarcinoma (MCF-7), cervical adenocarcinoma (HeLa), and hepatocellular carcinoma (HepG2). Higher concentrations of the extract (7% v/v) were more effective, with reductions in viable cells ranging from 85.43% (HepG2) to 96.26% (MCF-7) after 48 hours of treatment. The efficacy was particularly pronounced against MCF-7 and HeLa cells. The phenolic compounds, particularly phenolic acids and flavonoids (such as sinapinic acid, caffeic acid, p-coumaric acid, myricetin, luteolin C-hexoside, and cyanidin 3-O-galactoside) identified in the extract, are believed to contribute to these anticancer effects. These findings reinforce Neem's potential as a source for natural therapeutic agents in cancer treatment [5].

Larvicidal Activity

Neem fruit extracts have demonstrated potent larvicidal activity against mosquito vectors like *Culex quinquefasciatus*, which transmits lymphatic filariasis. Among petroleum ether, carbon tetrachloride, and methanol extracts of *Azadirachta indica* fruits, the methanol extract proved most potent, with LC50 values of 74.04 ppm (24h) and 58.52 ppm (48h). This efficacy was superior to extracts from bitter gourd and castor seeds. Neem products, including azadirachtin, are known to produce multiple effects on insects, such as anti-feeding, growth regulation, fecundity suppression, and oviposition repellency, making insect resistance less likely due to varied mechanisms of action [11].

Agricultural Applications

Neem's natural insecticidal and nematicidal properties make it a valuable resource for sustainable agriculture, offering eco-friendly alternatives to synthetic pesticides.

Nematicidal Activity

Neem formulations exhibit significant nematicidal activity against plant-parasitic nematodes, particularly root-knot nematodes (*Meloidogyne javanica*). Aqueous extracts of crude neem leaves and neem cake, used as a seedling dip treatment, significantly reduced the number of female nematodes and egg masses in roots. A refined product, azadirachtin (aza), did not show a direct effect as a post-invasion seedling dip, suggesting it might not be directly toxic in this application, or not systemically absorbed.

However, using a split-root technique, it was demonstrated that active compounds from neem cake and aza were absorbed by plant roots and translocated to untreated root portions, where they still significantly reduced egg masses and eggs per egg mass. This indicates a systemic effect, though with reduced biological activity upon translocation.

The persistence of neem formulations in soil varies: 3% concentrations of neem leaf and cake persisted for up to 16 weeks, reducing galling index and egg masses. Neem cake's effect appeared to persist longer than leaves, possibly due to a slower release or sustained effectiveness of metabolites. Despite this, effectiveness generally declined over time, suggesting that repeated applications may be necessary to maintain nematode populations below economic thresholds. The efficacy of neem leaves and aza remained stable after 8 months of storage, while that of neem cake declined when stored in daylight [7].

Insecticidal Activity

Neem oil extracted from seeds shows significant insecticidal activity against various pests. Direct sprays of neem seed oil at concentrations of 50% and 100% demonstrated lethal properties against gram pod borer (*Helicoverpa armigera*) and spider mites, with higher concentrations leading to faster death times (e.g., 82 seconds for 100% oil on pod borer, and 1 minute 10 seconds for 100% oil on spider mites). These findings support the use of high-concentration neem seed oil as an effective insecticide for protecting crops like green gram plants [2].

Growth Promotion and Anticoccidial Effects in Livestock

Incorporation of water-washed neem fruit (WN) into the diets of West African Dwarf (WAD) rams has shown promising results as a growth promoter. The WN fruit, prepared by soaking in water to remove some bitter components, was included in feed at various percentages.

Anticoccidial Efficacy: WN inclusion linearly increased anticoccidial efficacy, significantly reducing fecal coccidial egg counts compared to the control group. The effect was notable within 14 days of administration, attributed to compounds like margosate, which powerfully act against protozoa.

Growth Performance: Feed intake and weight gain quadratically increased with up to 5.0% WN inclusion, with an optimal level of 5.1% for daily weight gain. This improved growth is attributed to enhanced efficiency in feed utilization, potentially by reducing energy loss through methane production and by eliminating parasites that hinder animal growth.

Nutrient Digestibility: Crude protein and hemicellulose digestibility linearly increased with WN inclusion (up to 7.5% and 5% respectively). This is thought to be due to increased efficiency in energy use for digestion and possibly increased beneficial rumen bacteria and fungi populations.

However, increasing WN inclusion beyond 5.0% led to a decline in average daily gain and intake, likely due to the inhibition of beneficial rumen microbes by higher concentrations of phytochemicals. Thus, while WN fruit can be an effective growth promoter and anticoccidial agent in sheep production, its inclusion should not exceed 5.0% [6].

Environmental Applications

Neem's potential extends to environmental solutions, particularly in bioremediation and agricultural machinery innovation.

Crude Oil Degradation in Soil

Neem root extracts have been investigated for their ability to enhance the biodegradation of Total Petroleum Hydrocarbon (TPH) in crude oil-polluted loamy soil. When loamy soil was amended with Neem root extracts in a water solution, significant improvements in soil physicochemical properties were observed. Parameters such as density, electrical conductivity (EC), moisture content (MC), total organic carbon (TOC), total nitrogen (TN), and phosphorus (P) initially increased after pollution but decreased remarkably under treatment. Conversely, the pH of the loamy soil, which initially decreased after pollution, increased from acidity to neutrality with treatment.

The TPH degradation was higher in treated soil, with a more pronounced degradation when a higher volume of Neem root extract was used (e.g., NW-600 vs. NW-500 bioreactors). The total bacteria count, crucial for biodegradation, increased across treated soils for up to 56 days before declining due to nutrient depletion. These findings demonstrate that Neem root extracts offer a promising and effective approach for the bioremediation of crude oil-contaminated soils [10].

Ground Collection System for Neem Fruit

Addressing the challenges of manual Neem fruit collection, which is laborious, time-consuming, and uneconomical (costing ₹30 per kg against a selling price of ₹25 per kg), a mechanical ground collection system based on the principle of suction has been designed and developed. This mobile, engine-driven pneumatic system aims to enhance competitiveness in Neem cultivation.

The prototype consists of a 0.82 hp air-cooled engine, a centrifugal suction unit with a forward curved impeller, a flexible suction hose (80 mm diameter), a flat suction nozzle, and a storage bin with a 12 kg capacity. The machine achieved an estimated collection capacity of approximately 10 kg per hour with an efficiency of over 90%. Critically, the cost of collecting Neem fruit using this machine is significantly lower at ₹2.55 per kg, compared to the conventional manual method's ₹30 per kg. The projected payback period for the machine's investment cost (₹30,000) is estimated at 3.64 years, indicating a viable solution for improving the economics of Neem plantations [3].

CONCLUSION

Azadirachta indica remains a plant of immense scientific and practical interest, with research continuously uncovering and validating its diverse applications. This review highlights Neem's profound impact across medicinal, agricultural, and environmental domains, underpinned by its rich array of bioactive compounds.

From a medicinal standpoint, Neem extracts exhibit robust antibacterial, anti-biofilm, antidiabetic, wound-healing, and antiproliferative properties. The efficacy against antibiotic-resistant biofilms and various cancer cell lines, coupled with its role in traditional wound management and blood sugar regulation, positions Neem as a promising source for novel pharmaceuticals and nutraceuticals. In agriculture, Neem's value is evident in its potent nematicidal and insecticidal activities, offering sustainable alternatives to synthetic chemical inputs. Its ability to systemically protect plants from nematodes and act as an effective insecticide against common pests underscores its utility in integrated pest management. Furthermore, the inclusion of water-washed Neem fruit in animal feed improves growth performance and acts as an effective anticoccidial agent, demonstrating its potential in animal husbandry. Environmentally, Neem contributes to bioremediation efforts, with root extracts enhancing crude oil degradation in polluted soils. Innovative mechanical solutions for Neem fruit collection also offer significant economic and labor benefits, making Neem cultivation more viable.

The choice of extraction method and solvent is critical for optimizing the yield and specific properties of Neem extracts, with ethanol-based methods often yielding high percentages of potent compounds. While current research provides a strong foundation, further extensive field trials and in-depth investigations into the precise mechanisms of action of isolated bioactive compounds are necessary. Continued research into Neem's complex phytochemistry and the development of standardized, scalable formulations will be key to unlocking its full potential for a wide range of sustainable and eco-friendly applications globally.

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