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Neem *(Azadirachta indica A. Juss.)* Leaf Extract as a Natural Biostimulant: Implications for Seed Germination, Plant Growth and Sustainable Crop Production

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ABSTRACT

The growing demand for environmentally sustainable crop production has increased interest in plant-derived biostimulants that improve plant growth while reducing dependence on synthetic agrochemicals. Among these, neem (Azadirachta indica A. Juss.) has emerged as one of the most promising botanical resources because of its diverse phytochemical composition and broad biological activities. Neem leaves contain limonoids, flavonoids, phenolic compounds, tannins, alkaloids, and terpenoids that exhibit antioxidant, antimicrobial, insecticidal, and growth-promoting properties. Experimental studies indicate that neem leaf extract can improve seed germination, seedling vigor, root and shoot development, chlorophyll synthesis, nutrient uptake, and tolerance to abiotic stresses. In addition, neem-derived compounds suppress numerous plant pathogens and insect pests, making neem an important component of sustainable crop protection. However, plant responses are strongly influenced by extract concentration, crop species, and application method, with excessive concentrations sometimes producing inhibitory effects. This review summarizes current knowledge on the phytochemical composition, physiological mechanisms, agricultural applications, and future prospects of neem leaf extract as a natural biostimulant for sustainable crop production.

***Keywords*:** Azadirachta indica, neem leaf extract, seed germination, biostimulant, antioxidant activity, stress tolerance, sustainable agriculture.

1. Introduction

The increasing demand for sustainable agricultural production has accelerated the search for environmentally friendly alternatives to synthetic fertilizers and pesticides. Intensive use of agrochemicals has undoubtedly improved crop yields; however, their long-term application has contributed to soil degradation, environmental pollution, biodiversity loss, and the development of pesticide resistance. Consequently, considerable attention has shifted toward plant-derived biostimulants that can enhance crop productivity while maintaining ecological sustainability (National Research Council, 1992). Neem (Azadirachta indica A. Juss.), belonging to the family Meliaceae, is widely recognized as one of the most valuable multipurpose trees in tropical and subtropical agriculture. For centuries, different parts of the plant have been utilized in traditional medicine, crop protection, and soil management. Modern scientific investigations have confirmed that neem contains numerous biologically active compounds responsible for its antimicrobial, antioxidant, insecticidal, antifungal, and growth-regulating properties (Biswas et al., 2002; Kumar & Navaratnam, 2013).Among the different plant parts, neem leaves have attracted increasing attention because they are abundant, renewable, and rich in bioactive phytochemicals including limonoids, flavonoids, phenolic compounds, tannins, and terpenoids. These metabolites contribute to improved physiological performance by enhancing antioxidant defense, reducing oxidative stress, suppressing pathogenic microorganisms, and supporting normal plant metabolism (Alzohairy,2016; Saleem et al., 2018). Recent studies have demonstrated that neem leaf extract can improve seed germination, seedling establishment, root and shoot growth, chlorophyll synthesis, nutrient acquisition, and tolerance to both biotic and abiotic stresses. Moreover, neem-based products are biodegradable and compatible with integrated pest management (IPM) and organic farming systems, making them attractive alternatives to conventional agrochemicals (Isman, 2020; Verma et al., 2021).Despite these promising findings, the biological response to neem leaf extract is highly concentration dependent. While low to moderate concentrations generally stimulate growth and physiological activity, excessive concentrations may inhibit germination and early seedling development because of allelopathic interactions (Khanam et al., 2020).

Therefore, understanding the mechanisms underlying these responses is essential for optimizing agricultural applications. This review critically examines the phytochemical composition, physiological functions, growth-promoting mechanisms, stress tolerance, and crop protection potential of neem leaf extract, highlighting its importance as a natural biostimulant for sustainable agriculture.

2. Phytochemical Composition and Bioactive Constituents of Neem Leaf Extract

The remarkable biological activity of neem leaf extract originates from its complex mixture of secondary metabolites. These compounds collectively contribute to the antioxidant, antimicrobial, insecticidal, and plant growth-promoting properties that have made neem an important resource in sustainable agriculture (Govindachari, 1992; Biswas et al., 2002). Limonoids constitute the major bioactive group present in neem. Compounds such as azadirachtin, nimbin, nimbidin, salannin, and gedunin are widely recognized for their insecticidal, antifungal, antibacterial, and growth-regulating activities. Among these, azadirachtin is considered the most biologically active constituent because it interferes with insect feeding, development, and reproduction, thereby reducing pest populations without causing extensive environmental contamination (Mordue & Nisbet, 2000; Isman, 2020). Neem leaves are also rich in flavonoids and phenolic compounds, including quercetin, rutin, catechin, gallic acid, caffeic acid, and chlorogenic acid. These phytochemicals possess strong antioxidant properties and help protect plant tissues from oxidative damage by scavenging reactive oxygen species generated during environmental stress. Consequently, they play an important role in maintaining cellular integrity and improving plant resilience (Subapriya & Nagini, 2005; Alzohairy, 2016) In addition, neem leaves contain tannins, alkaloids, terpenoids, saponins, and essential mineral nutrients such as nitrogen, potassium, calcium, magnesium, iron, zinc, and manganese. Although neem leaf extract is not primarily used as a fertilizer, these nutrients may support plant metabolism and contribute to improved physiological performance (National Research Council, 1992). The concentration of these bioactive constituents varies with genotype, geographical location, environmental conditions, leaf maturity, and extraction method. Such variation partly explains the inconsistent responses reported among different studies and emphasizes the importance of standardized extraction and application protocols (Saleem et al., 2018; Islas et al., 2020).Overall, the synergistic interaction among these phytochemicals forms the biochemical basis for the diverse agricultural applications of neem leaf extract, including seed treatment, growth promotion, stress tolerance, and biological crop protection.

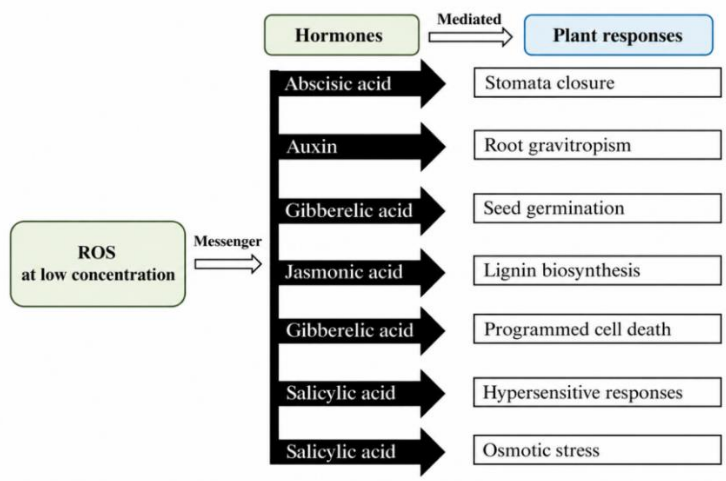

Figure 1. Reactive oxygen species (ROS) as second messengers in several plant hormone responses.

Source: Sharma, P., Jha, A. B., Dubey, R. S., & Pessarakli, M. (2012).

Phytochemical Group	Major Compounds	Reported Biological Functions
Limonoids	Azadirachtin, Nimbin, Nimbidin, Salannin, Gedunin	Insecticidal, antimicrobial, antifungal, growth regulation
Flavonoids	Quercetin, Kaempferol, Rutin, Catechin	Antioxidant activity, ROS scavenging, stress tolerance
Phenolic Compounds	Gallic acid, Caffeic acid, Chlorogenic acid, Ferulic acid	Antioxidant, antimicrobial, membrane protection
Terpenoids	Various triterpenoids	Plant defence and physiological regulation
Tannins	Condensed and hydrolysable tannins	Antimicrobial activity and pathogen suppression
Alkaloids	Various alkaloids	Defense response and biological activity
Saponins	Plant saponins	Antifungal and antimicrobial properties

Table 1. Major Phytochemical Constituents of Neem (Azadirachta indica) Leaf Extract and Their Reported Biological Functions

***Source*:** Compiled from Govindachari (1992), Biswas et al. (2002), Alzohairy (2016), Saleem et al. (2018), Islas et al. (2020), and Isman (2020).

3. Effects of Neem Leaf Extract on Seed Germination and Early Seedling Establishment

Seed germination is the first and one of the most critical stages of the plant life cycle because it directly influences crop establishment and final productivity. Successful germination depends on rapid water uptake, activation of metabolic pathways, reserve mobilization, and protection against biotic and abiotic stresses. Owing to its diverse phytochemical composition, neem (Azadirachta indica) leaf extract has attracted considerable interest as a natural seed treatment capable of enhancing these physiological processes (Biswas et al., 2002; Alzohairy, 2016). Several studies have demonstrated that neem leaf extract improves germination percentage, germination rate, seedling vigor, and uniform crop establishment when applied at appropriate concentrations. These beneficial responses are attributed to the antioxidant and antimicrobial properties of neem, which reduce oxidative damage and suppress seed-borne pathogens during the early stages of germination (Verma et al., 2021). Neem-derived phenolics and flavonoids also contribute to maintaining membrane integrity and improving metabolic efficiency during seed imbibition. Enhanced physiological activity promotes the mobilization of stored food reserves required for radicle emergence and early seedling growth. Consequently, seedlings originating from neem-treated seeds often exhibit greater vigor and improved establishment compared with untreated controls (Subapriya & Nagini, 2005). Despite these positive effects, neem leaf extract exhibits concentration-dependent responses. While low concentrations generally stimulate germination and early growth, higher concentrations may inhibit radicle emergence, reduce seedling length, and suppress overall development because of allelopathic interactions. Khanam et al. (2020) reported that excessive concentrations significantly reduced germination and seedling growth in several vegetable crops, highlighting the importance of optimizing application rates. Overall, current evidence suggests that neem leaf extract can serve as an effective natural seed treatment when applied at appropriate concentrations. Nevertheless, standardized protocols based on crop species and environmental conditions are essential to ensure consistent performance in agricultural systems.

4. Influence of Neem Leaf Extract on Root Growth, Shoot Development and Seedling Vigour

Following germination, rapid root and shoot development is essential for successful plant establishment and subsequent productivity. A vigorous root system improves water and nutrient absorption, whereas healthy shoot development enhances photosynthetic capacity and biomass accumulation. Neem leaf extract has been reported to positively influence both processes through its physiological and protective effects (Verma et al., 2021). Several investigations have demonstrated increased root length, shoot height, leaf expansion, and seedling biomass following neem-based treatments. Improved root architecture enables plants to exploit a larger soil volume for nutrient and water uptake, thereby supporting continued vegetative growth. Simultaneously, enhanced shoot development contributes to greater light interception and increased photosynthetic efficiency (Biswas et al., 2002). The growth-promoting effects of neem are primarily associated with improved nutrient acquisition, antioxidant protection, and reduced pathogen pressure around the developing root system. These factors collectively improve metabolic efficiency and promote vigorous seedling development under both normal and moderately stressful conditions (Saleem et al., 2018; Alzohairy, 2016). Seedling vigor is widely recognized as an important indicator of future crop performance because vigorous seedlings establish rapidly, compete more effectively with weeds, and tolerate environmental stress more successfully. Numerous studies indicate that neem-treated seedlings generally exhibit superior vigor compared with untreated controls, suggesting that neem leaf extract can improve early crop establishment (Verma et al., 2021). However, excessive concentrations may suppress root elongation and shoot growth because of phytotoxic or allelopathic effects. Therefore, careful optimization of extract concentration is necessary before large-scale agricultural application (Khanam et al., 2020). Overall, neem leaf extract contributes to improved root and shoot development, leading to healthier seedlings and greater potential for sustained crop productivity.

5. Effects of Neem Leaf Extract on Photosynthesis, Chlorophyll Synthesis and Nutrient Uptake

Photosynthesis is the primary physiological process responsible for biomass production and crop yield. Its efficiency depends largely on chlorophyll concentration, nutrient availability, and the functional integrity of the photosynthetic apparatus. Research indicates that neem leaf extract can positively influence these factors, thereby improving overall plant performance (Alzohairy, 2016). Several studies have reported increased chlorophyll content and improved leaf greenness following neem application. Enhanced chlorophyll synthesis improves light harvesting and carbon assimilation, resulting in greater photosynthetic efficiency and biomass production. These responses are likely associated with the presence of antioxidant compounds and essential mineral nutrients in neem leaves (National Research Council, 1992). Improved root growth also enhances nutrient acquisition by increasing the absorption of nitrogen, phosphorus, potassium, and essential micronutrients required for photosynthesis and metabolic activity. Consequently, neem-treated plants frequently exhibit improved physiological performance, nutrient-use efficiency, and vegetative growth (Verma et al., 2021). The antioxidant properties of neem further protect chloroplasts and photosynthetic pigments from oxidative damage under stressful environmental conditions. By maintaining chlorophyll stability and reducing reactive oxygen species, neem leaf extract supports continued photosynthetic activity during drought, salinity, and other abiotic stresses (Saleem et al., 2018). Although most reports describe positive physiological responses, treatment effectiveness varies among crop species and environmental conditions. Therefore, standardized application protocols remain necessary for maximizing the benefits of neem-based biostimulants. Collectively, available evidence indicates that neem leaf extract enhances photosynthetic efficiency, chlorophyll synthesis, nutrient uptake, and overall plant productivity, supporting its use as a sustainable agricultural input.

6. Physiological and Biochemical Mechanisms Underlying the Growth-Promoting Effects of Neem Leaf Extract

The growth-promoting effects of neem (Azadirachta indica A. Juss.) leaf extract arise from the coordinated action of its bioactive phytochemicals on several physiological and biochemical processes. Rather than functioning as a direct nutrient source, neem enhances plant performance by improving metabolic efficiency, antioxidant defense, nutrient utilization, and cellular protection (Alzohairy, 2016; Saleem et al., 2018). During seed germination, stored carbohydrates, proteins, and lipids are mobilized to support embryo development. Neem-derived compounds may enhance the activity of hydrolytic enzymes such as α-amylase, proteases, and lipases, promoting reserve mobilization and accelerating early seedling growth (Verma et al., 2021). This improved metabolic activity contributes to greater seedling vigor and more uniform crop establishment. Another important mechanism involves the regulation of reactive oxygen species (ROS). Although ROS participate in normal cellular signaling, excessive accumulation during environmental stress damages membranes, proteins, and nucleic acids. Neem leaves contain flavonoids, phenolics, and other antioxidant molecules that scavenge ROS, thereby reducing oxidative stress and maintaining cellular homeostasis (Subapriya & Nagini, 2005; Alzohairy, 2016). Neem treatments have also been associated with increased activity of antioxidant enzymes including superoxide dismutase (SOD), catalase (CAT), peroxidase (POD), and ascorbate peroxidase (APX). These enzymes strengthen the plant's antioxidant defense system, protect chloroplasts and membranes, and improve tolerance to adverse environmental conditions (Wylie et al., 2022) In addition, neem-derived phytochemicals help maintain membrane integrity by reducing lipid peroxidation, thereby supporting nutrient transport, water balance, and metabolic activity. Emerging evidence further suggests that neem may influence stress-responsive signaling pathways involved in plant defense and adaptation, although these molecular mechanisms require further investigation (Gupta et al., 2017). Overall, the growth-promoting effects of neem leaf extract result from the combined regulation of metabolism, antioxidant defense, membrane stability, and physiological adaptation, making neem a promising natural biostimulant for sustainable crop production.

7. Antioxidant Activity and Abiotic Stress Tolerance

Environmental stresses such as drought, salinity, heat, and heavy metal contamination significantly limit crop productivity by disrupting physiological processes and increasing oxidative stress. Neem leaf extract has gained considerable attention because of its ability to improve plant tolerance to these adverse conditions through antioxidant and protective mechanisms (Alzohairy, 2016; Wylie et al., 2022). Neem leaves are rich in flavonoids, phenolic compounds, tannins, and terpenoids that possess strong antioxidant activity. These phytochemicals reduce oxidative damage by scavenging reactive oxygen species and enhancing endogenous antioxidant enzyme systems, thereby protecting cellular structures under stress conditions (Subapriya & Nagini, 2005; Saleem et al., 2018). Under drought conditions, neem-treated plants often maintain higher chlorophyll content, improved water-use efficiency, and better physiological stability than untreated plants. Similarly, during salinity stress, neem supports membrane integrity, nutrient uptake, and antioxidant activity, reducing the harmful effects of salt-induced oxidative stress (Saleem et al., 2018). Neem-derived antioxidants also contribute to tolerance against temperature extremes by protecting photosynthetic pigments and preserving chloroplast function. Under heavy metal stress, these compounds help reduce oxidative injury and maintain normal metabolic activity, allowing plants to sustain growth despite unfavorable environmental conditions (Wylie et al., 2022). The ability of neem leaf extract to improve stress tolerance has important implications for climate-resilient agriculture. As climate change increases the frequency of environmental stresses, biodegradable plant-based biostimulants such as neem may offer sustainable alternatives for maintaining crop productivity while reducing dependence on synthetic agricultural inputs (National Research Council, 1992; Isman, 2020).Although current findings are encouraging, additional field-based studies are required to establish crop-specific application protocols and validate long-term performance under diverse agroecological conditions. Overall, the available evidence indicates that neem leaf extract enhances plant resilience through antioxidant protection, physiological regulation, and improved metabolic stability, reinforcing its value in sustainable crop production systems.

8. Role of Neem Leaf Extract in Disease and Pest Management

Plant diseases and insect pests are major constraints to global agricultural productivity. Although synthetic pesticides remain widely used, their continuous application has raised concerns regarding environmental pollution, pesticide resistance, and risks to non-target organisms. Consequently, neem (Azadirachta indica A. Juss.) has become one of the most extensively investigated botanical alternatives for sustainable crop protection (National Research Council, 1992; Isman, 2020). Neem leaf extract contains limonoids, flavonoids, phenolics, and terpenoids with broad-spectrum antimicrobial and insecticidal properties. These compounds inhibit the growth of numerous fungal and bacterial pathogens while reducing infection during seed germination, seedling establishment, and vegetative growth (Biswas et al., 2002; Wylie et al., 2022). The insecticidal activity of neem is primarily attributed to azadirachtin, a limonoid that interferes with insect feeding, molting, reproduction, and development. Unlike conventional insecticides that often act through a single toxic mechanism, neem disrupts multiple physiological pathways, reducing the likelihood of resistance development (Mordue & Nisbet, 2000; Isman, 2020) Neem also exhibits antifeedant and nematicidal properties, further enhancing its value in integrated pest management (IPM). Because neem-based products are biodegradable and relatively safe for many beneficial organisms, they are increasingly incorporated into sustainable and organic farming systems.Overall, neem leaf extract provides an environmentally compatible approach to crop protection by combining antimicrobial, insecticidal, and growth-promoting activities within a single botanical resource

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9. Agricultural Applications of Neem Leaf Extract

The multifunctional properties of neem leaf extract have enabled its use in diverse agricultural practices, including seed treatment, seed priming, foliar application, crop protection, and stress management. These applications improve crop performance while reducing dependence on synthetic agricultural inputs (Verma et al., 2021).Neem-based seed treatments enhance germination, seedling vigor, and early crop establishment, whereas foliar applications improve chlorophyll content, physiological activity, and stress tolerance. In addition, neem-derived formulations effectively suppress insect pests and plant pathogens, making them suitable components of integrated crop management programs (Isman, 2020). Because neem products are biodegradable and compatible with organic farming systems, they represent sustainable alternatives for environmentally responsible crop production. Their combined effects on plant growth, stress tolerance, and biological crop protection highlight their increasing importance in modern agriculture.

Figure 2. Preparation of Fresh Neem (Azadirachta indica A. Juss.) Leaf Extract for Agricultural Applications

Source: Lucidcentral – Pacific Pests, Pathogens & Weeds Fact Sheets: Neem (preparation & use) (402).

10. Research Gaps and Future Perspectives

Despite extensive research, several limitations continue to restrict the broader agricultural use of neem leaf extract. Variability in extraction methods, leaf maturity, environmental conditions, and application protocols often results in inconsistent experimental outcomes (Saleem et al., 2018).Future studies should prioritize standardized extraction procedures, crop-specific concentration optimization, and large-scale field validation. Furthermore, advanced molecular approaches, including transcriptomics, proteomics, and metabolomics, may improve understanding of the genetic and biochemical mechanisms responsible for neem-induced plant responses (Gupta et al., 2017).The development of nano-formulations, controlled-release technologies, and integrated biostimulant formulations may further improve the stability and effectiveness of neem-derived products under practical agricultural conditions.

11. Critical Evaluation of Published Research

Current scientific evidence strongly supports the potential of neem leaf extract as a natural biostimulant and crop protection agent. Most studies report improvements in seed germination, seedling vigor, physiological performance, antioxidant activity, and resistance to biotic and abiotic stresses (Biswas et al., 2002; Alzohairy, 2016). However, plant responses vary according to crop species, environmental conditions, extraction methods, and treatment concentration. High concentrations may inhibit germination and seedling growth, emphasizing the importance of dose optimization and standardized application protocols (Khanam et al., 2020).Although laboratory and greenhouse studies provide encouraging results, additional multi-location field trials are required to validate the effectiveness of neem-based technologies under commercial farming conditions.

12. Conclusion

Neem (Azadirachta indica A. Juss.) leaf extract represents a valuable natural biostimulant with significant potential for improving sustainable crop production. Its diverse phytochemical composition contributes to enhanced seed germination, seedling establishment, root and shoot development, photosynthetic efficiency, nutrient uptake, antioxidant defense, and tolerance to environmental stresses.In addition to promoting plant growth, neem-derived compounds provide effective protection against numerous pathogens and insect pests, supporting integrated pest management and reducing reliance on synthetic agrochemicals. However, the biological response to neem leaf extract is highly dependent on concentration, crop species, and application method, making optimization essential for successful field application. Future research should focus on standardization, molecular characterization, and long-term field evaluation to facilitate the wider adoption of neem-based technologies. With continued scientific validation, neem leaf extract has considerable potential to contribute to environmentally sustainable and climate-resilient agricultural systems.

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