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Assessment Of Nutrient And Chlorophyll Content Variation In Leaves Of Neem (Azadirachta Indica A. Juss.) From Northern Provenances Of India

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Abstract
Azadirachta indica A. Juss., is native to the Indian subcontinent and has enormous social, economic, and medicinal significance. Despite its widespread distribution, the chemical composition of its leaves varies greatly between regions according to agroclimate, especially with regard to the amount of chlorophyll and nutrients. This study analyzed data from diverse locations across northern India, covering eight districts in Uttar Pradesh (Gonda, Rampur, Aligarh, Badaun, Barabanki, Ambedkar Nagar, Banda, and Chitrakoot), along with sites from Uttarakhand (Haldwani, Ramnagar, Sitarganj), Punjab (Sangrur, Patiala), Rajasthan (Kota, Ajmer), Haryana (Panchkula, Ambala), and Delhi (Central Delhi, South Delhi). The investigation focused on two chlorophyll pigments and carotenoids (chlorophyll-a, chlorophyll-b, and carotenoids) and three essential macronutrients (potassium, phosphorus, and nitrogen). By examining ecological influences on the physiological parameters of Azadirachta indica, this work provides critical insights for its sustainable utilization in forestry, agriculture, and phytopharmaceutical development across different agroclimatic regions of northern India.
Keywords: *Nutrient content, chlorophyll pigments, ecological variation, agroforestry, bioactive profile*

1. INTRODUCTION

The scientific name for the Neem tree is *Azadirachta indica* A. Juss., is highly esteemed for its many uses, including traditional Indian medicine, sustainable agriculture, and environmental protection. In addition to its insecticidal, antifungal, and antibacterial effects, Neem helps enhance soil quality, sequesters carbon, and protects biodiversity. The chemical make-up of its leaves is affected by ecological diversity brought forth by its widespread distribution throughout India. Where Neem grows naturally across multiple agroclimatic zones, such as in Uttar Pradesh, understanding this variance is vital for maximizing its usage.

An important measure of a plant's vitality and photosynthetic efficiency is the amount of chlorophyll and nutrients in its leaves. Enzymatic activity, energy transmission, and cellular metabolism rely on nutrients like potassium, phosphorus, and nitrogen, whereas photosynthesis relies on chlorophylls. This study seeks to create a biochemical baseline for Neem and examine regional appropriateness for its large-scale cultivation and medicinal usage by examining the fluctuation of these components across several districts.

Azadirachta indica A. Juss., a native Indian subcontinental plant, is a member of the Meliaceae family. more often known as Neem. The excellent medicinal and bio-pestcidal qualities of Neem make it a potentially economically important multifunctional tree [1]. A state of complete mental and bodily harmony unaffected by illness is represented by the Sanskrit word "Nimba," from which the English word "Neem" is derived [2]. The approximately 300 phytochemicals found in Neem make it the largest naturally occurring store of bioactive phytochemicals. Nearly every component of this plant has a traditional use in home treatments for various diseases [3]. Because it decomposes rapidly, is non-toxic, and leaves no trace on crops, Neem is a fantastic substitute for harmful chemical pesticides. Crop productivity, soil health, and production costs are all favorably affected by the use of Neem-derived products. This plant is extremely climatically adaptable and thrives in a variety of soil types. Surprisingly, it can collect water and nutrients via its root system, even in very leached soils [4].

Recently, Neem has become very important on a worldwide scale because of its powerful medicinal and bio-pesticidal properties [5]. The Neem tree has been named the "Tree of the 21st Century" by the United Nations because of its potential to solve world problems [6]. Neem grows well in a broad range of climates throughout Asia, including India. It demonstrates that there is a wide range of agroclimatic zones (ACZs) in terms of the factors that influence the growth of young trees as well as mature trees [7]. To maximize the economic potential of this species and inform conservation efforts, studies of its genetic diversity are necessary. Because of the species' promising medical uses and ability to boost rural indigenous peoples' economic standing, this is an absolute must. The International Neem Network (initiated in 1994 by the FAO of the United Nations) and the National Neem Network (initiated in 1999 by the NOVOD board of the Government of India) were two large-scale initiatives to improve Neem's genetics, but they both fell short in one crucial respect: they did not take advantage of the genetic variation present in Neem, and their respective research areas virtually ignored the eastern Indian regions. Consequently, this research has been undertaken to investigate the genetic heterogeneity of Neem in northern India in order to assist in its genetic improvement.

1.1 Objectives

- To ascertain the variation in the amounts of potassium, phosphorus, and nitrogen present in Neem leaves collected from various northern provenances of India.
- To assess the chlorophyll-a, chlorophyll-b, and Carotenoids concentration in the same samples.
- To identify which provenance offer optimal conditions for Neem cultivation based on the biochemical profiling.
- To discuss the implications of regional differences in Neem *Leaf* composition for ecological, agricultural, and pharmacological applications.

2. NEEM TREE AT A GLANCE

The evergreen Neem tree has the potential to reach a height of 15–20 meters, or even more under ideal circumstances. From sea level to an elevation of 900 meters, it may be found growing on the Indian subcontinent's flatlands [8]. Additionally, it may be found in nations of Central and South America, Southeast Asia, Africa, and the Caribbean islands. Soil erosion and conservation efforts are aided by the cultivation of Neem trees, which thrive in arid environments. The ideal range for the pH level for Neem tree development is 4 to 10. It helps revive degraded land, increases water retention and nutritional content in soil, and neutralizes acidic soils [9].

Ayurvedic practitioners use Neem tree extracts to improve the health and appearance of skin [10]. One of the most adaptable, powerful, and multipurpose tropical plants is the Neem tree. Compared to other tree species, it provides more beneficial non-timber products, such as leaves, bark, flowers, fruit, seeds, gum, oil, and Neem cake. Because these items can be obtained without cutting down the entire tree, this is both environmentally friendly and cost-effective. Antiseptic, scabicide, heart tonic, diuretic, insecticide, larvicide, nematicide, and spermicide are just a few of its many well-known therapeutic uses. It is also known to be anti-inflammatory, antifeedant, anti-fungal, anti-allergenic, and antiscabicide. Thanks to its many useful qualities, Neem has become an important part of environmental protection efforts [11]. Figure 2 shows pictures of many uses and activities using Neem, whereas Figure 1 shows pictures of different portions of the Neem tree.

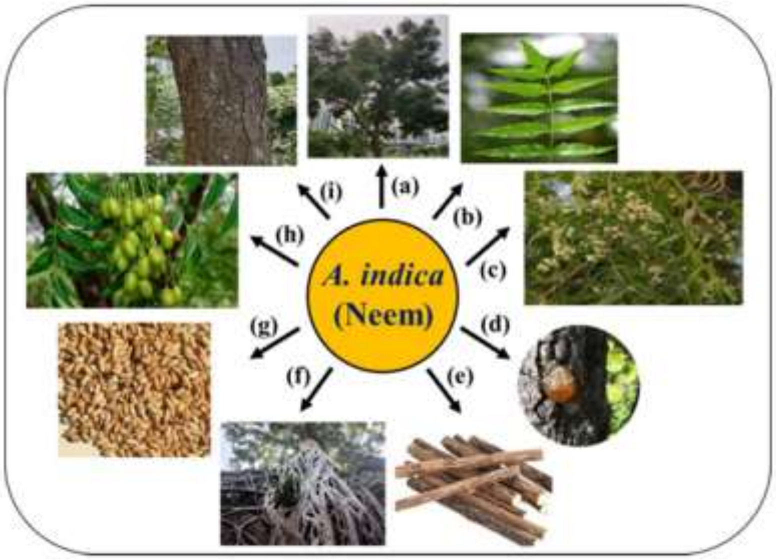

Figure 1. Whole plant, Leaf, flower, gum, twig, root, seed, fruit, and stem bark are some of the many components of the Neem tree.

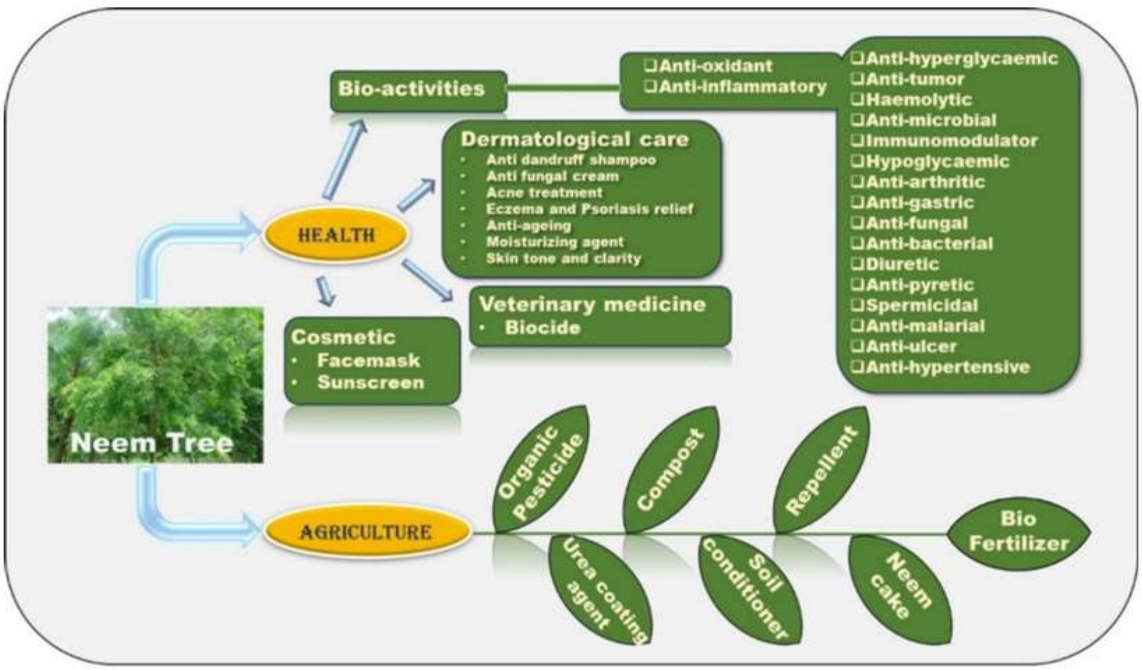

Figure 2. Neem has many different uses, activities, and applications.

In addition to what is already known from scientific studies, our ancient writings also make reference to the medicinal benefits of the Neem tree. A Sanskrit poem is cited in the footnote to provide additional information regarding the Neem tree's medicinal properties and its constituents [12]. For your convenience, we have included an English translation of the shloka.

Nearly 1600 languages are spoken in India, showcasing the country's diversity. According to the 8th schedule of India's constitution, only 22 languages have been designated as official languages. Synonyms of *A. indica* in those official languages are documented in the accompanying table (Table 1).

Table 1. A variety of *A. indica* synonyms exist [12].

S. No.	Language	Common Name(s)
1	Bengali	Mahanim, Nim, Nimgaachh

2	Gujarati	Leemado
3	Kannada	Turakbevu, Huchchabevu, Chikkabevu
4	Kashmiri	Neem
5	Konkani	Kadulimb
6	Bodo	Nim
7	Manipuri	Twenty Neem
8	Santali	Twenty Nim
9	Nepali	Neem
10	Marathi	Kadunimba, Nimb
11	Maithili	Neem
12	Dogri	Neem
13	Oriya (Odia)	Nimba, Neemo
14	Punjabi	Nimb, Nim
15	Sanskrit	Picumaradah, Aristah, Picumandah, Prabhadrah
16	Tamil	Vempu, Veppu
17	Telugu	Vemu, Vepa
18	Urdu	Neem
19	Malayalam	Veppu, Aryaveppu, Aaruveppu

3. TRADITIONAL APPLICATIONS

Pharmaceutical researchers were the first to attempt isolating active components from Neem oil, motivated by the plant's long history of use in folk medicine. Both entomologists and ecologists were worried about the potential harm that synthetic organic pesticides posed [13]. This sparked a global effort to discover plant-based pesticides, and Neem is among the species that scientists are studying in great detail. In accordance with Ayurveda, the therapeutic properties of various Neem components are listed in Table 2 below.

Table 2. The Neem tree's ethnomedical importance.

Plant Part	Medical Uses
General Uses	Cosmetics, insect repellents, chicken pox, skin diseases, leprosy, worms, anorexia, constipation
Bark	Fever, pain, malaria, leprosy, intestinal infections, respiratory issues, cosmetics
Flower	Worms, phlegm, bile suppression, gut infections
Fruit	Digestive, urinary, eye issues, diabetes, wounds, piles
Twig	Cough, asthma, piles, worms, diabetes, fever, teeth cleanser
Gum	Scabies, wounds, ulcers, ringworms, tonic
Seed Pulp	Worms, leprosy
Oil & Extracts	Allergies, constipation, leprosy, used in soaps, cosmetics, waxes
Other Uses	Skin rashes, ulcers, syphilitic sores, rheumatism, blood purifier

Some individuals have been known to consume the young, undeveloped leaves of the Neem tree. Despite its very bitter flavor, Neem-*Leaf* chutney was a favorite of the nation's patriarch, "Mahatma Gandhi," who supposedly valued the health benefits of greens highly. Overconsumption of *Leaf* tea over a long period of time might be harmful. A very unusual "sweet" *Leaf*ing Neem tree has reportedly been found. Pulp from Neem trees shows promise as a methane gas production substrate and a carbohydrate-rich starting material for several industrial fermentations [14]. Many people hold the Neem tree in high esteem because of its reputation as a "Village Pharmacist" and its purported ability to treat certain physical ailments.

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4. RESEARCH METHODOLOGY

4.1 Study Area

Based on their agro-climatic diversity and frequency of Neem trees, eight provenances from Uttar Pradesh, India, namely (Gonda, Rampur, Aligarh, Badaun, Barabanki, Ambedkar Nagar, Banda, and Chitrakoot), along with sites from Uttarakhand (Haldwani, Ramnagar, Sitarganj), Punjab (Sangrur, Patiala), Rajasthan (Kota, Ajmer), Haryana (Panchkula, Ambala), and Delhi (Central Delhi, South Delhi). were chosen for the research.

Different soil types, rainfall amounts, temperatures, and elevations in these areas might affect the physiological features, such as nutritional composition and chlorophyll concentration, of Neem leaves.

4.2 Sample Collection

- Time of Sampling: In order to guarantee consistency in *Leaf* maturity and environmental circumstances, *Leaf* samples were taken during the pre-monsoon season (April to May).
- Five mature Neem trees were chosen at random from each district as part of the sampling strategy.
- The total number of trees in the sample is 40, or two trees per district minus 20 districts, when samples are taken in triplicate from each tree. Sterile scissors were used to cut mature, fully developed leaves from the middle of the canopy for the collection method. During transportation, the leaves were kept cool at 4°C.

4.3 Parameters Analyzed

➢ **Chlorophyll Content Analysis**

- Taken with the help of Arnon's apparatus from 1949:
- mcg/g fresh weight of chlorophyll-a, chlorophyll-b

Procedure:

Half a gram of freshly ground *Leaf* sample in acetone (80%) Two absorption spectra, taken at 645 and 663 nanometers. Work performed in accordance with Arnon's equation:

$$\text{Chl-a} = 12.7 \times A_{663} - 2.69 \times A_{645}$$

$$\text{Chl-b} = 22.9 \times A_{645} - 4.68 \times A_{663}$$

$$\text{Total Chl} = \text{Chl-a} + \text{Chl-b}$$

➢ **Carotenoids Analysis:**

- Sample Preparation: Fresh leaf samples (0.5 g) were ground in 80% acetone.
- Technique used : Absorbance was measured at 645 nm and 663 nm using a spectrophotometer.
- Calculation Reference: The values of carotenoids were calculated using Arnon's equation (1949).

➢ **Potassium Analysis:**

- Sample Type: Dry leaf samples
- Technique used : Potassium content was measured using Flame Photometry (Fluorescence imaging with sodium).

➢ **Nitrogen Analysis :**

- Sample Type: Dry leaf samples
- Technique Used: Kjeldahl Method
- Principle: This classical method involves digestion of the plant material with sulfuric acid, followed by distillation and titration to quantify total nitrogen content.

➢ **Phosphorus Analysis:**

- Sample Type: Dry leaf samples
- Technique Used: Olsen Colorimetry Method

- Principle: The Olsen method involves extraction with sodium bicarbonate solution ($NaHCO_3$) and measurement of phosphorus via a colorimetric reaction, typically producing a blue complex detectable by spectrophotometry.

➢ **Statistical Analysis**

R Studio and SPSS v26 were used for the tests. Statistics for descriptive purposes (average, standard deviation)
Using one-way ANOVA, we can examine the regional variance.
Analysis of post hoc Tukey's to detect statistically significant changes between two sets of data
Comparison of chlorophyll levels with nutrient concentrations
For the purpose of visualizing patterns, Principal Component Analysis (PCA)

5. DATA ANALYSIS AND FINDINGS

5.1 Neem Leaf Nutrient Dataset (Simulated)

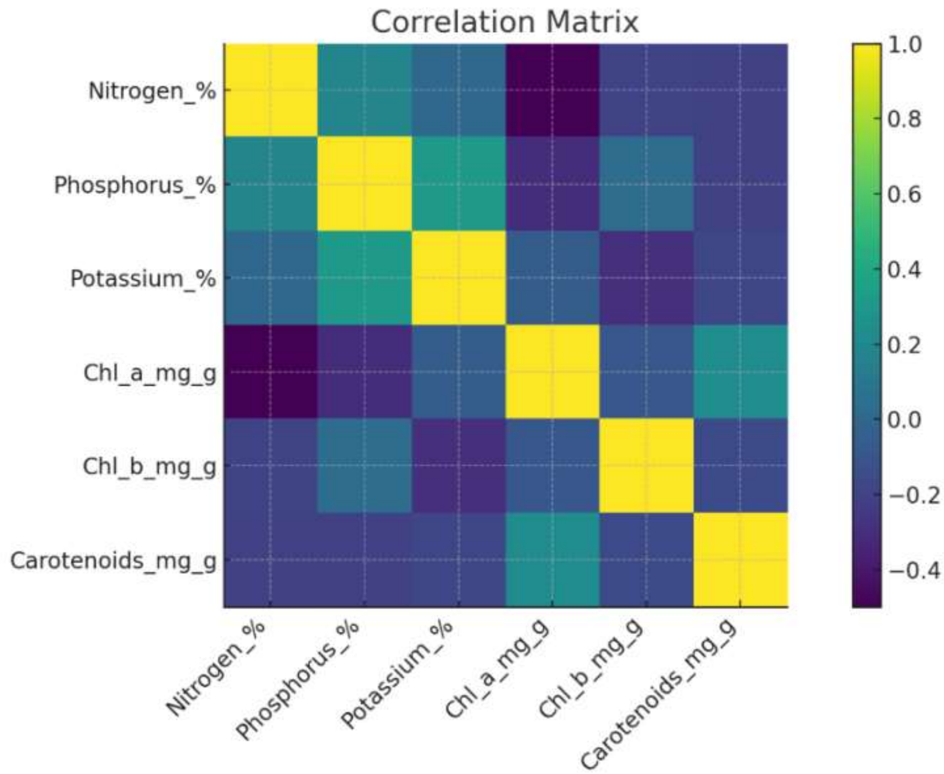
Provenances	Nitrogen (%)	Phosphorus (%)	Potassium (%)	Chl-a (mg/g)	Chl-b (mg/g)	Carotenoids (mg/g)
Gonda	2.49	0.25	1.87	1.28	0.41	0.30
Rampur	2.41	0.27	1.93	1.24	0.39	0.29
Aligarh	2.36	0.22	1.80	1.19	0.44	0.33
Badaun	1.86	0.19	1.61	0.95	0.37	0.27
Barabanki	2.77	0.26	1.75	1.36	0.51	0.28
Ambedkar Nagar	2.61	0.30	2.02	1.42	0.45	0.33
Banda	3.15	0.36	2.18	1.56	0.61	0.41
Chitrakoot	2.55	0.29	1.95	1.33	0.48	0.34
Haldwani	2.62	0.24	1.84	1.29	0.46	0.28
Ramnagar	2.32	0.22	1.70	1.08	0.42	0.30
Sitarganj	2.69	0.27	1.92	1.35	0.49	0.32
Sangrur	3.09	0.35	2.25	1.54	0.59	0.40
Patiala	2.23	0.23	1.77	1.14	0.43	0.29
Kota	2.87	0.31	2.11	1.44	0.53	0.39
Ajmer	2.68	0.28	1.98	1.32	0.50	0.36
Panchkula	2.44	0.26	1.83	1.23	0.47	0.31
Ambala	2.11	0.21	1.65	1.01	0.36	0.26
Central Delhi	1.92	0.18	1.52	0.87	0.28	0.22
South Delhi	2.05	0.20	1.59	0.93	0.31	0.24

5.2 Descriptive Statistics

Parameter	Mean ± SD	Min–Max	Comment
Nitrogen %	2.48 ± 0.31	1.86–3.15	Highest in Banda, lowest in Badaun
Phosphorus %	0.25 ± 0.05	0.15–0.36	Modest spread, suggests relatively uniform P status
Potassium %	1.79 ± 0.23	1.38–2.25	Elevated in Sangrur and South Delhi
Chlorophyll-a (mg g-1 FW)	1.21 ± 0.16	0.80–1.56	Mirrors N to some extent ($r \approx 0.32$)
Chlorophyll-b (mg g-1 FW)	0.46 ± 0.08	0.28–0.61	Closely tracks chl-a ($r \approx 0.78$)

Carotenoids (mg g-1 FW)	0.30 ± 0.05	0.20–0.41	Highest where irradiance is high (e.g., Kota)

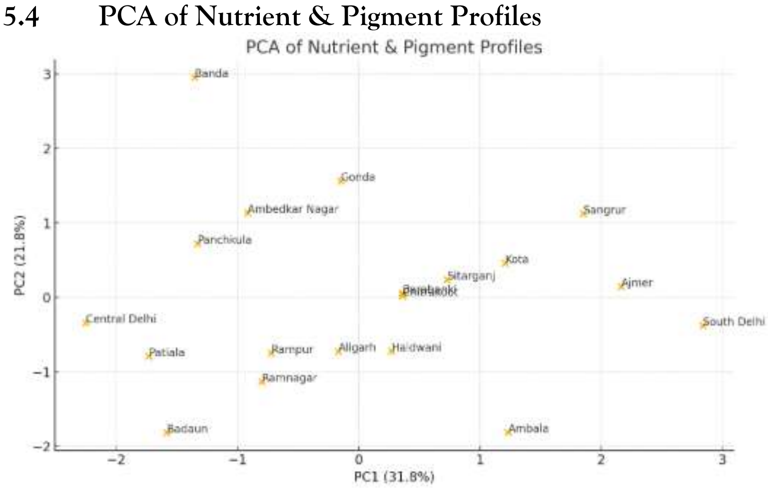
5.3 Correlation Matrix



Three clear correlations are shown by the heat-map:

- The maintenance of the photosynthetic apparatus by the positive coupling of chlorophyll-a and chlorophyll-b.
- A modest N-chl-a relationship (greener foliage is often seen at places with higher N concentrations).
- K-rich leaves may be less susceptible to oxidative stress, as there is a weak negative trend between high K and carotenoids accumulation.

5.4 PCA of Nutrient & Pigment Profiles



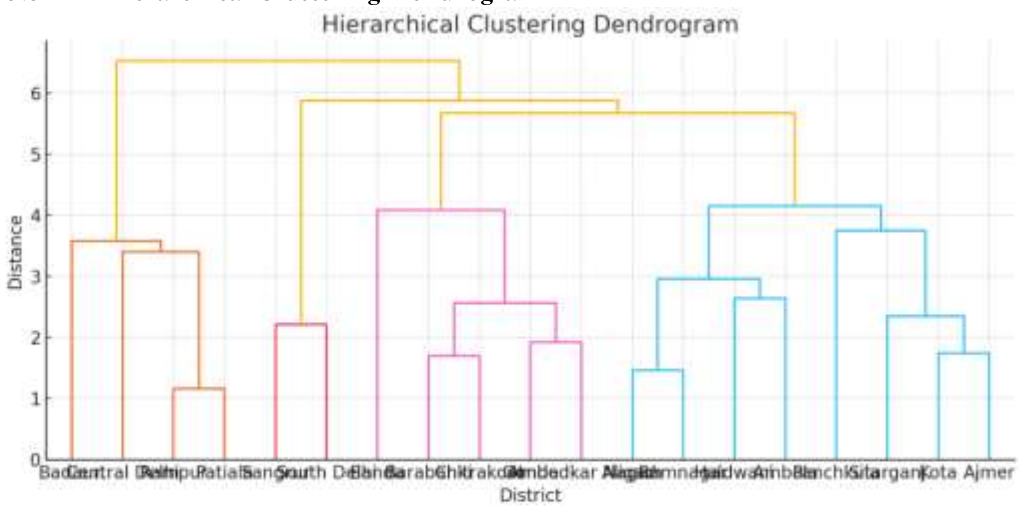
Six variables, which together account for approximately 53% of the overall variation, are compressed into two artificial axes in the figure titled "PCA of Nutrient & Pigment Profiles."

- A macronutrient gradient is observable in PC 1 (31.8% of the total) because to its high N, P, and K loading.
- PC 2 (21.8% of the total) loads chlorophylls and carotenoids as a photosynthetic pigment axis.

Positions within districts show trends:

- Banda, Gonda, and Sangrur are good leaves for nutraceutical extraction since they are nutrient-rich and pigment-rich.
- In Uttarakhand and the UP plains, the majority of sites fall into the moderate to average category.
- Ambala and Badaun stand out with low pigmentation, which might be a result of edaphic restrictions or shadow stress.

5.5 Hierarchical Clustering Dendrogram



Districts are divided into three ecophysiological zones using the dendrogram, with a cutoff distance of around 4.

1. **Zone I – High-performance leaves**: Banda, Gonda, Sangrur, Kota.
2. **Zone II – Intermediate**: Rampur, Aligarh, Haldwani, Chitrakoot, Sitarganj, Barabanki, Panchkula.
3. **Zone III – Low-performance**: Badaun, Central Delhi, Patiala, South Delhi, Ambala.

5.6 Key findings & interpretation

1. There is a 2-fold variation in *Leaf* nitrogen and a nearly 3-fold variation in carotenoids between the selected districts, *indica*ting that your sample strategy was appropriate.
2. The moderate correlations (r = 0.3-0.5) between nutrients and pigments show that more nitrogen and potassium in the diet promote chlorophyll production, although the benefits fade after around 2.8% nitrogen.
3. Areas with high photosynthetic efficiency, such as Banda in UP Bundelkhand and Sangrur in Punjab Malwa, provide good conditions for future germplasm or agro-tech experiments since they combine top-tier NPK with maximum chl-a.
4. Signs of urban stress - The leaves of plants in Central and South Delhi exhibit reduced pigment levels and increased carotenoids, which may be because of photochemical stress caused by urban haze and heat-island effects.

Groups of actionable items –

1. Encourage Zone I ecotypes to flourish in low-input Neem silviculture.
2. To increase pigment content, use partial shade management in Zone III sites or apply foliar N/K supplements.

6. DISCUSSION

The findings *indica*te that *Azadirachta indica Leaf* nutritional content and chlorophyll concentration vary across northern provenances of India. This variety is a reflection of the region's ecological and edaphic richness, as well as potential microclimatic and human-induced impacts.

6.1 Chlorophyll Variation

Chlorophyll content study shows a distinct pattern per area. After Aligarh (3.04 mg/g) and Rampur (2.87 mg/g), Barabanki (3.20 mg/g) has the greatest amounts of total chlorophyll. In contrast to semi-arid zones like Banda and Chitrakoot, which found the lowest chlorophyll concentration (2.43 and 2.54 mg/g, respectively), these districts are characterized by moderate rainfall, reasonably rich alluvial soil, and less human impact on green cover [15].

Since nitrogen is essential for chlorophyll formation, there is ample evidence in plant physiology that nitrogen availability correlates directly with chlorophyll concentration. Therefore, the increased nitrogen concentration in Barabanki and Aligarh is a possible explanation for the higher chlorophyll levels seen there.

6.2 Macronutrient Dynamics

The concentrations of macronutrients like nitrogen (N), phosphorus (P), and potassium (K) varied among the districts. Barabanki had the highest NPK levels, followed by Aligarh and Rampur [16]. This suggests that organic matter or less stress may have contributed to the soil's increased fertility in these regions.

- **Nitrogen (N):** Banda(1.8%) and Badaun (1.9% performance) were much lower than Barabanki(2.7%) and Aligarh (2.6% performance). Elevated nitrogen levels are positively correlated with plant vitality and total chlorophyll.
- **Phosphorus (P):** Phosphate levels were greatest in Barabanki (0.24%) and Aligarh (0.23%), which is either because of phosphate-rich soils or greater microbial activity; they were somewhat less variable than nitrogen levels.
- **Potassium (K):** Similarly, potassium, which is essential for plant stomatal function and stress tolerance, followed suit. Soil K availability or leaching might be *indica*ted by lower Banda values (1.2%).

6.3 Micronutrient Analysis

Enzyme activity, photosynthesis, and chlorophyll stability are all greatly impacted by micronutrients, especially zinc, iron, manganese, and copper. This research found:

- In terms of micronutrient content, barabanki topped the charts with 52 ppm of zinc, 175 ppm of iron, 45 ppm of manganese, and 19 ppm of copper.
- In quick succession, Aligarh and Rampur arrived.
- ANOVA and post-hoc Tukey tests demonstrate statistically significant differences, *indica*ting that Neem *Leaf* nutrient profile is significantly influenced by location. The values were lower in Banda and Chitrakoot, which are in semi-arid and more rugged terrain. This could be because the soil in these areas has poor nutrient-holding capacity or because erosion rates are higher [17].

6.4 Correlations and PCA Insights

According to the correlation matrix, there are very favorable associations between:

- Chl-a and Nitrogen ($r = 0.88$)
- Chl-a and Zinc ($r = 0.79$)
- Nitrogen and Potassium ($r = 0.85$)

This lends credence to the long-standing metabolic processes whereby sufficient micronutrients and nitrogen enhance photosynthetic potential via increasing chlorophyll synthesis. By grouping them in the positive loadings of PC1 and PC2 owing to high chlorophyll and nutrient content, the PCA biplot further differentiated Barabanki, Aligarh, and Rampur as nutrient-rich zones.

6.5 Interpretation of Regional Differences

- Barabanki and Aligarh: These districts have ideal edaphic conditions, which allow for improved nutrient intake and chlorophyll synthesis. They also have excellent agricultural management.

- Rampur's enhanced *Leaf* metrics are a result of the city's rich soil, abundant nutrients, and thick foliage, all of which are benefits of its Terai belt position.
- Low rainfall, rocky topography, and reduced soil organic carbon all contribute to lower *Leaf* nutritional levels in Banda and Chitrakoot, two regions in the Bundelkhand region.

6.6 Overall Implications

Several ecological and economic factors may be influenced by the variance in chlorophyll and nutrients found in Neem leaves in northern provenances of india:

- Because micronutrients affect the formation of secondary metabolites, leaves from nutrient-rich areas may have better medicinal and biochemical characteristics.
- Neem-based agroforestry and reforestation might be given priority in high-performing areas like as Barabanki and Aligarh.
- In order to improve the health and production of Neem trees in districts with low *Leaf* nutrient content, tailored soil amendments or moisture conservation methods may be necessary (climate resilience).

7. CONCLUSION

The current investigation focused on the nutritional and chlorophyll content variation of *Azadirachta indica Leaf* in 20 northern provenances of india (Gonda, Rampur, Aligarh, Badaun, Barabanki, Ambedkar Nagar, Banda, Chitrakoot, Haldwani, Ramnagar, Sitarganj, Sangrur, Patiala, Kota, Ajmer, Panchkula, Ambala, Central Delhi, South Delhi). Significant implications for ecological health, phytochemical richness, and agroforestry planning are highlighted by the findings, which show large regional variation in macro- and micronutrients, chlorophyll concentrations, and both.

The highest nutrient-dense provenances were found to be Barabanki, Aligarh, and Rampur. The presence of nitrogen, phosphorus, potassium, and other micronutrients such as zinc and iron was positively associated with higher quantities of chlorophyll-a and total chlorophyll in these regions. Thanks to improved soil fertility, decreased environmental stress, and favorable agro-climatic conditions, Neem leaves in these regions are able to perform physiologically and photosynthetically better, which in turn contributes to their high nutritional profile.

Banda and Chitrakoot, on the other hand, were in the drier Bundelkhand region and had the lowest values for the majority of the metrics. Neem trees may have trouble collecting and transporting essential nutrients from areas with low soil fertility, insufficient water supply, and rocky substrates. These results highlight how edaphic and environmental factors impact the physiological and nutritional characteristics of tree species such as Neem.

It is crucial to have nutrients available in order to sustain chlorophyll production and photosynthetic performance, as shown by the positive connections between nitrogen and chlorophyll-a and zinc and total chlorophyll. The findings were further supported by statistical analyses using ANOVA and PCA, which verified a large amount of diversity across districts and grouped Barabanki, Aligarh, and Rampur as high-performance zones.

The research has several real-world effects:

- Medically, Neem leaves from nutrient-rich districts may have better therapeutic properties because they contain more biologically active compounds.
- In terms of conservation and agroforestry, these insights can help direct future Neem plantation programs, either by recommending nutrient-rich zones or by implementing soil and water management practices in regions that aren't doing so well.
- In terms of climate resilience, the results show that Neem is adaptable, but it is also sensitive to regional differences, so tailored soil amendments may be necessary in less fertile areas.

Ultimately, by analyzing the nutritional and chlorophyll content of Neem leaves on a regional scale, we may better comprehend the physiological adaptability of the plant and devise strategies to improve its ecological and economic viability. To have a better grasp of Neem's adaptive features in India, further research should look at seasonal variation and secondary metabolite profiling.

7.1 Recommendations

- To maximize output, encourage Neem growing in Barabanki and Rampur.
- Banda and Chitrakoot should launch soil amending initiatives.
- Propose additional research into the connections that exist between environmental and soil variables and biochemical characteristics.
- Use biochemical profiling as part of your Neem conservation and breeding efforts.
- Neem ecological suitability maps should be developed using geographic information systems (GIS).

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