Effect of Fulvic Acid Application on Nutrient Uptake Efficiency in Grossundnut

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Received: 31 May 2024
Revised: 13 Jun 2024
Accepted: 01 Jul 2024
Published: 22 Jul 2024

E-ISSN: 2989-5340
DOI: https://doi.org/10.54660/jafi.2024.4.2.35-40

ABSTRACT

Background: Groundnut (*Arachis hypogaea L.*) is a globally important oilseed-cum-legume crop that contributes substantially to edible oil production, protein nutrition, and farm income in tropical and semi-arid agro-ecosystems. Persistent nutrient deficiencies, declining soil organic matter, and suboptimal fertilizer use efficiency continue to constrain productivity, necessitating sustainable nutrient management approaches. Fulvic acid, a low-molecular-weight fraction of humic substances, has emerged as a promising bio-stimulant capable of enhancing nutrient solubility, root proliferation, and physiological efficiency in leguminous crops.

Objective: This study was undertaken to evaluate the influence of varying fulvic acid concentrations and application methods on nutrient uptake efficiency, growth, yield, and quality attributes of groundnut.

Methods: A field experiment was conducted following a Randomized Complete Block Design comprising five treatments (control, low, medium, and high fulvic acid concentrations applied through soil, and a combined soil plus foliar treatment) replicated four times. Growth parameters, nodulation, macro- and micronutrient uptake, yield attributes, and quality traits (oil and protein content) were recorded and subjected to analysis of variance followed by mean separation at $P \leq 0.05$.

Results: Fulvic acid application significantly improved plant height, root length, nodulation, and dry matter accumulation compared with the control. The combined soil plus foliar treatment recorded the highest nitrogen, phosphorus, potassium, and micronutrient uptake, along with the greatest pod yield, oil content, and protein content, followed by the high soil-application treatment. Nutrient use efficiency and benefit-cost ratio also increased progressively with increasing fulvic acid concentration.

Conclusion: Fulvic acid application, particularly through combined soil and foliar delivery, enhances nutrient uptake efficiency and physiological performance in groundnut, offering a practical and environmentally sound strategy for sustainable nutrient management in legume-based cropping systems

Keywords: Fulvic acid; groundnut; nutrient uptake efficiency; bio-stimulant; sustainable agriculture; nodulation

1. Introduction

Groundnut (*Arachis hypogaea* L.) ranks among the most economically significant oilseed and legume crops worldwide, providing edible oil, protein-rich food, and industrial raw material across more than 100 countries [1]. As a self-pollinated, nitrogen-fixing legume, groundnut plays a dual role in agricultural systems by supplying high-quality vegetable oil (approximately 48–52%) and digestible protein (25–28%), while simultaneously enriching soil fertility through symbiotic biological nitrogen fixation [2]. Its cultivation supports the livelihoods of millions of smallholder farmers in semi-arid and tropical regions, where it is often grown under resource-constrained, rainfed conditions.

Despite its agronomic and nutritional importance, groundnut productivity remains considerably below its genetic potential owing to widespread nutrient deficiencies, particularly of nitrogen, phosphorus, and micronutrients such as zinc, iron, and boron [3]. Continuous intensive cultivation, imbalanced fertilizer application, and inadequate replenishment of organic matter have accelerated soil fertility degradation, reducing the efficiency with which applied fertilizers are converted into plant-available nutrients [4]. Low nutrient use efficiency not only constrains crop yield and quality but also contributes to environmental problems such as nutrient runoff, leaching, and greenhouse gas emissions, underscoring the urgent need for sustainable nutrient management strategies that minimize input losses while maximizing crop uptake.

Among the emerging approaches to improve nutrient use efficiency, the application of humic substances—particularly fulvic acid—has attracted considerable scientific attention. Fulvic acid is a low-molecular-weight, water-soluble fraction of humic substances formed during the microbial decomposition of organic matter, characterized by a high density of carboxyl, phenolic, and hydroxyl functional groups [5]. These functional groups confer strong chelating capacity, enabling fulvic acid to form stable yet bioavailable complexes with essential macro- and micronutrients, thereby enhancing their solubility, mobility, and subsequent absorption by plant roots [6].

Beyond its chelating role, fulvic acid functions as a genuine bio-stimulant, promoting root elongation, increasing cell membrane permeability, activating key metabolic enzymes, and stimulating chlorophyll biosynthesis, all of which collectively enhance nutrient assimilation and photosynthetic efficiency [7].

Given the pressing need to reconcile crop productivity with environmental sustainability, understanding how fulvic acid modulates nutrient uptake physiology in groundnut is of substantial scientific and practical relevance. While fulvic acid and related humic substances have been extensively studied in cereals and vegetable crops, comparatively limited research has systematically examined their influence on nutrient uptake efficiency, nodulation, and quality parameters in groundnut under field conditions. The present investigation was therefore designed with the specific objectives of (i) evaluating the effect of varying fulvic acid concentrations and application methods on growth, nodulation, and biomass accumulation in groundnut; (ii) quantifying macro- and micronutrient uptake efficiency under different fulvic acid regimes; and (iii) assessing the consequent impact on pod yield, oil content, protein content, and economic returns, thereby generating evidence to support the practical adoption of fulvic acid as a sustainable nutrient management tool in groundnut cultivation.

2. Related Work

Extensive research has documented the nutritional requirements of groundnut, emphasizing its high demand for calcium during pod development, together with adequate nitrogen, phosphorus, potassium, and micronutrients such as zinc and boron for optimal pod filling and oil synthesis [8]. Deficiencies in these nutrients, especially under low organic matter conditions, have been repeatedly associated with reduced pod yield, poor kernel quality, and diminished shelling percentage [9].

Humic substances, comprising humic acid, fulvic acid, and humin, have been widely investigated as organic soil amendments capable of improving soil structure, cation exchange capacity, and microbial activity [10]. Among these fractions, fulvic acid is distinguished by its lower molecular weight and greater water solubility, which facilitate rapid root and foliar absorption compared with the larger, less soluble humic acid molecules [11]. Studies on the chemistry of fulvic acid have characterized its abundant oxygen-containing functional groups, which underlie its strong metal-chelating and ion-exchange properties [12].

A growing body of literature classifies fulvic acid among plant bio-stimulants, a category of substances that enhance nutrient use efficiency, abiotic stress tolerance, and crop quality independent of their nutrient content [13]. Research on nutrient use efficiency has shown that bio-stimulant application can substantially reduce the proportion of applied fertilizer lost to leaching or fixation, thereby improving the agronomic efficiency of nitrogen and phosphorus fertilizers [14]. Investigations into root physiology have further demonstrated that fulvic acid stimulates lateral root formation and root hair proliferation, increasing the absorptive root surface area available for nutrient interception [15].

Soil microbial interactions have also been implicated in fulvic acid-mediated nutrient enhancement, with several studies reporting increased populations of plant growth-promoting rhizobacteria and mycorrhizal associations following fulvic acid application, which indirectly augment nutrient mineralization and availability [16]. Comparative studies on foliar versus soil application methods indicate that foliar delivery provides rapid physiological responses, whereas soil application offers more sustained improvements in root-zone nutrient dynamics, suggesting that combined application strategies may be agronomically superior [17].

Prior investigations in other legumes, including chickpea, soybean, and mungbean, have reported that fulvic acid application enhances nodulation, biological nitrogen fixation, and grain yield through improved rhizosphere conditions and enzyme activity [18, 19]. However, despite these encouraging findings in related legumes, systematic field-level evidence quantifying the effect of fulvic acid on nutrient uptake efficiency, nodulation dynamics, and quality parameters specifically in groundnut remains limited. Existing studies have often focused narrowly on yield outcomes without adequately characterizing the underlying nutrient uptake mechanisms or economic feasibility, representing a clear knowledge gap that the present study seeks to address.

3. Physiological Mechanism of Fulvic Acid in Nutrient Uptake

Fulvic acid is chemically characterized by a complex, heterogeneous structure rich in carboxylic, phenolic hydroxyl, and quinonic functional groups, which confer both acidity and strong chelating capacity [20]. Its comparatively low molecular weight, typically below 2000 Da, allows rapid penetration through root cell walls and stomatal openings, distinguishing it functionally from the larger humic acid fraction [5]. The principal functional groups of fulvic acid and their corresponding physiological roles in nutrient uptake are summarized in Table 1.

3.1. Chelation and Nutrient Mobility

The carboxyl and hydroxyl groups of fulvic acid form soluble metal-organic complexes with polyvalent cations such as iron, zinc, manganese, copper, calcium, and magnesium. This chelation prevents nutrient precipitation and fixation in the soil matrix, maintaining these elements in plant-available forms and substantially increasing their mobility toward the root surface [6, 20].

3.2. Membrane Permeability and Root Architecture

Fulvic acid interacts with root plasma membranes, increasing their permeability and facilitating passive and carrier-mediated ion transport. Concurrently, it stimulates auxin-like activity that promotes lateral root initiation, root hair elongation, and overall root biomass, thereby expanding the absorptive surface area available for nutrient and water uptake [7, 15].

3.3. Microbial Stimulation and Nodulation

By improving soil aeration and organic carbon availability, fulvic acid fosters proliferation of beneficial rhizosphere microorganisms, including *Rhizobium* species essential for nodule formation in groundnut. Enhanced nodulation increases biological nitrogen fixation capacity, reducing dependency on external nitrogen fertilizer while improving overall nitrogen economy of the crop [16, 18].

3.4. Enzyme Activation and Photosynthetic Enhancement

Fulvic acid application has been associated with elevated activity of key enzymes, including nitrate reductase and carbonic anhydrase, which govern nitrogen assimilation and carbon fixation, respectively. Improved magnesium uptake supports chlorophyll biosynthesis, while enhanced potassium and calcium availability strengthen stomatal regulation and water-use efficiency, collectively translating into greater photosynthetic output and assimilate translocation toward developing pods [7, 21].

Collectively, these interconnected mechanisms—chelation-driven mobility, membrane permeability, root proliferation, microbial stimulation, and enzymatic activation—operate synergistically to enhance the uptake efficiency of nitrogen, phosphorus, potassium, calcium, magnesium, sulfur, and micronutrients including iron, zinc, manganese, copper, and boron, ultimately supporting superior vegetative growth, nodulation, and reproductive performance in groundnut.

Table 1: Key Functional Groups of Fulvic Acid and Their Physiological Role in Nutrient Uptake

Functional Group / Property	Chemical Role	Physiological Effect on Nutrient Uptake
Carboxyl (-COOH) groups	Metal chelation via ion exchange	Solubilizes Fe, Zn, Mn, Cu; prevents fixation
Phenolic hydroxyl (-OH)	Weak acid dissociation, pH buffering	Maintains rhizosphere nutrient availability
Low molecular weight (<2000 Da)	High water solubility, membrane penetration	Rapid root and foliar absorption
Quinonic structures	Redox activity	Facilitates Fe(III) to Fe(II) reduction for uptake
Polysaccharide-like moieties	Root membrane interaction	Increases membrane permeability and ion flux
Auxin-like bioactivity	Hormonal stimulation	Promotes lateral root and root hair proliferation

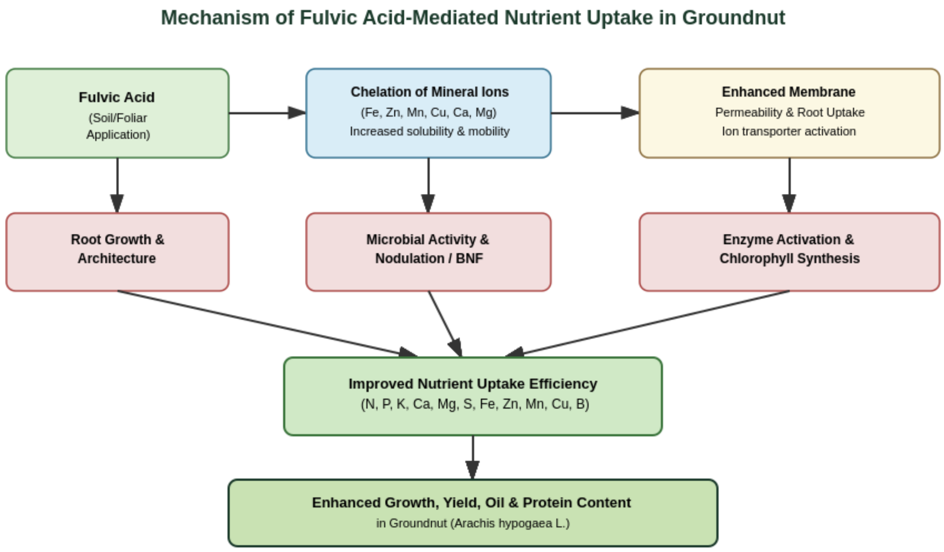

Fig 1: Mechanism of Fulvic Acid-Mediated Nutrient Uptake in Groundnut.

4. Materials and Methods

4.1. Experimental Site and Agro-climatic Conditions

The field experiment was conducted at a research farm situated in a semi-arid agro-climatic zone characterized by a mean annual rainfall of approximately 750 mm, predominantly received during the monsoon season. Mean maximum and minimum temperatures during the cropping period ranged from 32°C to 38°C and 21°C to 25°C, respectively, representing conditions typical of major groundnut-growing regions.

4.2. Soil Characteristics

Pre-sowing composite soil samples were collected from the 0–15 cm layer and analyzed for physicochemical properties. The soil was sandy loam in texture with a pH of 7.4 (neutral to slightly alkaline) and an electrical conductivity of 0.32 dS/m, indicating a non-saline status. Organic carbon content (0.48%) and available potassium (182 kg/ha) were rated medium, whereas available nitrogen (218 kg/ha) was rated low. Available phosphorus (16.2 kg/ha) was medium, while DTPA-extractable zinc (0.62 mg/kg) was marginal, justifying the relevance of micronutrient uptake assessment in this study.

4.3. Experimental Design and Treatments

The experiment was laid out in a Randomized Complete Block Design (RCBD) with five treatments replicated four times, resulting in twenty experimental plots, each measuring 5 m × 4 m (20 m²). Treatments comprised a control (no fulvic acid) and four fulvic acid regimes differing in concentration and application method, applied at 30 and 45 days after sowing, as detailed in Table 2.

4.4. Crop Management

A high-yielding, medium-duration groundnut variety was sown at a spacing of 30 cm × 10 cm using the dibbling method at a seed rate of 100 kg/ha. A basal fertilizer dose of 20:40:40 kg NPK/ha was applied uniformly to all plots at sowing, with fulvic acid treatments superimposed as per the experimental design. Irrigation was provided at critical growth stages (flowering, pegging, and pod development) through supplementary irrigation during dry spells. Weeds were controlled through pre-emergence herbicide application followed by one manual hand-weeding at 30 days after sowing, while need-based plant protection measures were adopted against foliar diseases and sap-sucking insect pests.

4.5. Data Collection

Growth parameters including plant height, number of branches per plant, root length, number of nodules per plant, and dry matter accumulation were recorded at 60 days after sowing from five randomly tagged plants per plot. Yield attributes—pods per plant, pod weight, seed weight, shelling percentage, pod yield, and haulm yield—were assessed at harvest. Quality parameters, namely oil content and protein content, were determined using standard analytical procedures. Nutrient concentrations of nitrogen, phosphorus, potassium, calcium, magnesium, iron, and zinc in plant tissue were estimated using standard digestion and spectrophotometric or atomic absorption spectroscopy methods, and nutrient uptake was computed as the product of nutrient concentration and corresponding dry matter yield.

4.6 Statistical Analysis

Data recorded for all parameters were subjected to analysis of variance (ANOVA) appropriate for the Randomized Complete Block Design. Treatment means were compared using Duncan's Multiple Range Test (DMRT) at a significance level of $P \leq 0.05$. All statistical computations were performed using standard agricultural statistical software (SPSS/OPSTAT), and correlation analysis was carried out to examine relationships between nutrient uptake and yield parameters [22].

Table 2: Treatment Details and Experimental Design

Treatment	Description	Fulvic Acid Dose	Application Method
T0	Control (No fulvic acid)	0%	—
T1	Low concentration	0.1%	Soil application
T2	Medium concentration	0.2%	Soil application
T3	High concentration	0.3%	Soil application
T4	Combined application	0.2% + 0.1%	Soil + Foliar (twice)

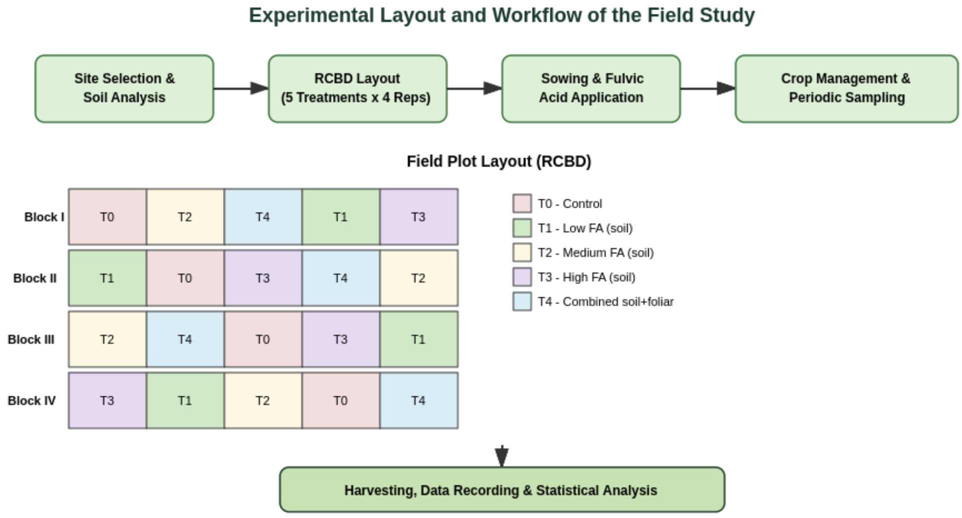

Fig 2: Experimental Layout and Workflow of the Field Study.

5. Results and Performance Evaluation

5.1. Growth, Root Development, and Nodulation

Fulvic acid application significantly influenced vegetative growth and nodulation relative to the control (Table 3). Plant height increased progressively with increasing fulvic acid concentration, rising from 32.4 cm under the control to 45.2 cm under the combined soil plus foliar treatment (T4), representing an improvement of approximately 39.5%. Root length followed a similar trend, increasing from 14.2 cm in T0 to 21.8 cm in T4, reflecting enhanced root proliferation. Nodule number per plant increased substantially from 18.6 in the control to 32.6 under T4, indicating a marked stimulation of rhizobial symbiosis and biological nitrogen fixation potential.

5.2. Nutrient Uptake Efficiency

Nutrient uptake exhibited a consistent and statistically significant treatment-dependent pattern. Nitrogen uptake increased from 48.3 kg/ha under the control to 74.5 kg/ha under T4, corresponding to a 54.2% enhancement. Phosphorus and potassium uptake improved by approximately 67.0% and 52.2%, respectively, under the combined application relative to the control. Micronutrient uptake, exemplified by zinc, increased from 62.4 g/ha in T0 to 101.6 g/ha in T4, an improvement of 62.8%, underscoring the pronounced chelation-driven enhancement of micronutrient bioavailability under fulvic acid treatment.

5.3. Yield Attributes and Quality Parameters

Pod yield increased significantly with increasing fulvic acid dose, from 1842 kg/ha in the control to 2718 kg/ha under T4, an improvement of 47.6%. This yield enhancement was underpinned by significant increases in pods per plant (21.3 to 34.5) and was accompanied by qualitative improvements: oil content rose from 47.8% to 51.2%, while protein content increased from 24.6% to 27.6% under the combined treatment (Table 3).

5.4 Economic Analysis

The benefit-cost ratio improved progressively with fulvic acid concentration, from 1.82 under the control to 2.62 under the combined soil plus foliar treatment, indicating that the additional input cost of fulvic acid was more than offset by the corresponding yield and quality gains.

5.5. Correlation Analysis

Correlation analysis revealed strong positive associations between nodule number and nitrogen uptake ($r = 0.94$), between root length and phosphorus uptake ($r = 0.89$), and between total nutrient uptake and pod yield ($r = 0.92$), all significant at $P \leq 0.05$, confirming that fulvic acid-induced improvements in root development and nodulation were mechanistically linked to enhanced nutrient acquisition and ultimately to yield formation.

Table 3: Effect of Fulvic Acid on Growth, Nutrient Uptake, Yield, and Quality Parameters of Groundnut

Parameter	T0 (Control)	T1 (Low)	T2 (Medium)	T3 (High)	T4 (Combined)	CD (P≤0.05)
Plant height (cm)	32.4	36.1	40.8	42.5	45.2	1.8
Nodules/plant	18.6	22.3	27.1	29.4	32.6	1.4
Root length (cm)	14.2	16.5	18.9	20.1	21.8	0.9
N uptake (kg/ha)	48.3	56.7	64.2	68.9	74.5	2.6
P uptake (kg/ha)	9.1	10.8	12.6	13.9	15.2	0.7
K uptake (kg/ha)	41.2	47.6	54.3	58.1	62.7	2.1
Zn uptake (g/ha)	62.4	74.8	86.5	93.2	101.6	3.8
Pods/plant	21.3	24.6	28.9	31.2	34.5	1.2
Pod yield (kg/ha)	1842	2103	2387	2549	2718	68
Oil content (%)	47.8	48.9	49.7	50.4	51.2	0.6
Protein content (%)	24.6	25.4	26.3	26.9	27.6	0.5
B:C ratio	1.82	2.04	2.31	2.48	2.62	—

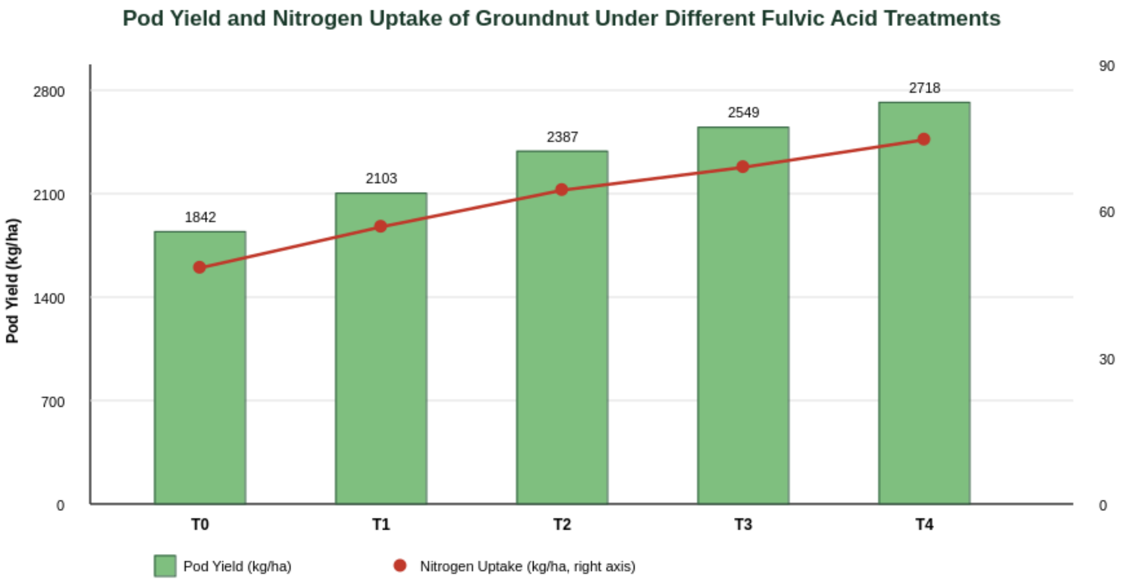

Fig 3: Pod Yield and Nitrogen Uptake of Groundnut Under Different Fulvic Acid Treatments.

6. Discussion

The consistent and dose-dependent improvements in growth, nodulation, nutrient uptake, and yield observed in this study corroborate the proposed physiological mechanisms whereby fulvic acid enhances nutrient bioavailability through chelation and improves absorptive capacity through root proliferation [6, 20]. The superior performance of the combined soil plus foliar treatment (T4) over soil-only applications aligns with earlier reports indicating that foliar delivery provides immediate physiological stimulation while soil application sustains root-zone nutrient dynamics over a longer duration [17], suggesting that integrated application strategies maximize the agronomic benefits of fulvic acid.

The marked increase in nodulation and nitrogen uptake under fulvic acid treatments supports findings from related legume studies, where enhanced rhizosphere conditions and organic carbon availability favored *Rhizobium* proliferation and biological nitrogen fixation [16, 18]. This mechanism carries particular significance for sustainable nutrient management, as improved biological nitrogen fixation can reduce reliance on synthetic nitrogen fertilizers, thereby lowering both input costs and the environmental footprint associated with nitrogen losses through volatilization and leaching [14].

The pronounced enhancement in micronutrient uptake, particularly zinc, reflects the strong chelating affinity of fulvic acid for polyvalent cations, which prevents their fixation in alkaline soil conditions and maintains bioavailability in the root zone [12]. This finding is agronomically important given the widespread prevalence of zinc deficiency in groundnut-growing soils and its critical role in enzyme activation and reproductive development.

From a fertilizer efficiency standpoint, the observed improvements in nutrient uptake at a fixed basal fertilizer dose indicate that fulvic acid effectively enhances the efficiency with which applied nutrients are utilized by the crop, rather than merely supplying additional nutrients. This has direct implications for reducing fertilizer application rates without compromising yield, thereby minimizing nutrient losses to the environment and contributing to more sustainable input use [4, 14]. The improvement in oil and protein content further suggests that fulvic acid-mediated physiological enhancement extends beyond vegetative growth to influence reproductive and biochemical processes governing seed composition.

Despite these encouraging findings, certain limitations warrant consideration. The study was conducted over a single growing season at one location, and soil-specific and climatic variability may influence the magnitude of fulvic acid response under different agro-ecological conditions. Long-term, multi-location trials are therefore recommended to validate the consistency of these findings and to refine optimal dosage and application timing. Future research should also explore the molecular basis of fulvic acid-induced gene expression related to nutrient transporters, as well as its integration within precision nutrient management frameworks incorporating variable-rate application technologies.

7. Conclusion

This study demonstrates that fulvic acid application significantly enhances nutrient uptake efficiency, root development, nodulation, and overall physiological performance in groundnut, with the combined soil plus foliar application consistently producing the greatest improvements in nitrogen, phosphorus, potassium, and micronutrient uptake. These physiological gains translated into substantial increases in pod yield, oil content, and protein content, alongside improved economic returns as reflected in a higher benefit-cost ratio. The findings confirm that fulvic acid functions as an effective bio-stimulant capable of improving fertilizer use efficiency and reducing dependency on high fertilizer input rates, thereby offering clear agronomic and environmental advantages. Given its demonstrated capacity to enhance nutrient chelation, root proliferation, and biological nitrogen fixation, fulvic acid application particularly through integrated soil and foliar delivery at medium to high concentrations—can be recommended as a practical component of sustainable nutrient management programs in groundnut cultivation. Future work should prioritize long-term, multi-location field validation and the integration of fulvic acid application within precision nutrient management systems to optimize dosage, timing, and delivery method across diverse soil and climatic conditions.

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