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Review Article

Effect of Nitrogen Fertilization on the Growth and Seed Yield of Sesame (*Sesamum indicum* L.)

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Sesame (*Sesamum indicum* L.) is grown mainly in the tropics. It is typically grown by smallholders with nearly all of its production in developing countries. It is an important source of high-quality oil and protein. Inappropriate use of fertilizers and mono-cropping are among the major production constraints. The objective of this paper is therefore to review the effect of N fertilizers on sesame growth and productivity. Growth and yield of sesame are greatly influenced by the application of N fertilizer. In most of the sesame-producing countries, optimum seed yield of sesame was obtained from application of 46–100 kg·N/ha. Adequate nitrogen fertilization also improves uptakes of other nutrients, particularly P and K and some micronutrients. Preemergence application of mobile nitrogen (urea) is less efficient due to losses. Mobile form of N fertilizer became available within two days for the crop. Split N applications where the N fertilizer is applied at different growth stages of the crop increases productivity. Side-dress application is one of the easiest ways to maximize nitrogen use efficiency. N fertilizers should be placed 3–5 cm deeper than the seeds and 5–10 cm apart from the plant for side dress but not far than 20 cm. Under optimal environmental conditions, nitrogen fertilizer has no effect on phonological traits but on the growth parameters. In the potential areas, application of 46–100 kg·N/ha gives maximum yield and lowering the application of N to less than 46 kg·N/ha in marginal areas is economical.

1. Introduction

Sesame (*Sesamum indicum* L.) is very important and one of the most ancient oilseed crops in the tropics, where Ethiopia is considered to be the centre of cultivation [1]. Origin of sesame has been a matter of discussion for more than a century among many scholars. Sesame is presumed to have originated in Africa and later spread to India, China, and Japan [2]. On the other hand, investigations of Bedigian et al. [3] show domestication on the Indian subcontinent based on the formation of fully fertile hybrids, NMR spectroscopy, and common lignan constituents. Similarly, the origin of sesame has been disputed for more than a century and now it is well established that sesame was domesticated on the Indian subcontinent, where it was taken to Mesopotamia during the Early Bronze Age [4]. Sesame is an important source of high-quality oil and protein [5, 6]. The oil has excellent stability due to the presence of natural antioxidants such as sesamolin and sesamin [3], and these lignans protect the oil from oxidative rancidity. The oil offers low cholesterol and a high proportion of polyunsaturated fat (about 80% unsaturated fatty acids), and sesame proteins are rich in the essential sulphur-containing amino acids methionine and tryptophan [7, 8]. The ideal growing condition for sesame is 11° to 35°C of temperature and soil pH of 4.3 to 8.7 [7]. It is very sensitive to day length and waterlogging [9]. Sesame cultivars have long maturity spectrum (4 weeks to 6 months) and it requires only 500–650 mm rainfall per annum [7]. Sesame, the chief source of "queen oil," has the capacity to set seed and yield remarkably well under high temperatures, and it has a deep taproot for extracting moisture and nutrient from lower soil layers and succeeding on as little as 200–400 mm of rain during the growing season [7]. The same author added that sesame is an effective control method for striga, *Striga hermonthica* (Delile); one season of crop rotation with sesame diminishes the population of striga seeds in a field. In Ethiopia, sesame is the main source of foreign currency of the agricultural commodities next to coffee. The order of leading sesame producer countries varies year after year, but when the five-year total production is summed, Ethiopia is the seventh largest sesame producer in the world following Tanzania, Myanmar, India, China, Nigeria, and Sudan [10]. Inappropriate use of fertilizers is one of the major production constraints in Ethiopia [11–13]. In addition, poor "Hila" stacking method and poor storage facilities also cost the producers. Fertilizer application to sesame in either organic or inorganic form is a key component to good growth, high yield, high seed quality, and oil content [14]. The use of fertilizers for sesame is a notorious issue in most parts of the developing countries, particularly in Ethiopia. Therefore, this work is helpful to review the effect of N fertilizers on sesame growth performance and productivity.

2. Major Fertilizers for Sesame

Research on the nutrition of sesame in the tropics shows significant yield increase due to application of N P K fertilizers in India, Pakistan, and Tanzania (N P) [15]. In Ethiopia, N P fertilizers are commonly applied [16]. Nitrogen is the most dynamic nutrient element and the most important nutrient that is required for the survival of all living things [17–21]. Increases in N supply within limits are associated with increase in leaf area, carboxylases, and chlorophyll content, all of which determine the photosynthetic activities of leaf and ultimately dry matter production and allocation to the various organs of a plant [20, 22]. Similarly, good supply of P is usually associated with increased root density and proliferation, which aid in extensive exploration and supply of nutrients and water to the growing plant [23]. N contributes up to 50% of all the nutrient inputs, and therefore, nitrogen is the determinant of farmers' crop yield [22]. A general rule of thumb is that N is for leafy top growth, phosphorus is for root and fruit production, and potassium is for cold hardiness, disease resistance, drought tolerance, and general durability (http://aggiehorticulture.tamu.edu/vegetable/guides/texas-vegetable-growers-handbook).

2.1. N Application Rate. The rates of N fertilizer vary with soils, climate conditions, and local farming practices [24]. Higher morphological performance and seed yield (1333.3 kg/ha) were recorded by applying 46 kg·N/ha in Nigeria[1] (note: the superscript numbers 1–4 given with the country names indicate the land suitability for sesame production) [8]. Steady increase in yield was observed when the application rate of N was increased from 20 to 80 kg·N/ha [22]. In China[1], application of 123 kg·N/ha and 60 kg·P/ha has produced the maximum economic return [25]. In India[1], higher net returns of sesame were found with application of 60 kg·N/ha and 30 kg·P/ha [26]. Moreover, a five-year research by Motaka et al. [27] professed that higher yield of sesame (706 kg/ha) was recorded from application of 75 kg·N/ha. El-Sherif [28] concluded that application of 142 kg/ha·N was economical in Egypt[4]. In Sudan[4], higher seed yield of sesame (769 kg/ha) was recorded when 44 kg·N/ha was applied [26]. And Bahar et al. [29] reported that application of 100 kg·N/ha produced higher seed yield in Sudan[1]. In Ethiopia[3] (Humera area), application of 100 kg/ha DAP and 50 kg/ha urea (41 kg/ha·N) gave higher seed yield (744.3 kg/ha) [30]. Recently, higher seed yield (800 kg/ha) was recorded due to application of 69 kg·N/ha plus 46 kg·P/ha in Humera, Ethiopia[2] [31]. In general, optimum N fertilizer application for the potential areas varies from 46 to 100 kg·N per ha based on the soil type and moisture availability status.

2.2. Duration of N Availability in the Plant Root Zone. The applied N fertilizer can be either taken up by the crop or lost to the environment [32–34]. According to Nielsen [35] and Rosolem et al. [17], nitrogen use efficiency is primarily influenced by two factors: health of the crop and nitrogen losses (leaching, denitrification, and volatilization). All applied N fertilizers eventually convert to the nitrate-N form. This form of N held not tightly by soil particles. Urea can convert to nitrate-N in less than two weeks and thereafter is susceptible to leaching loss [35]. Mobile form of N becomes available for absorption within two days, and immobile ammonium forms of N move into the root system within 7–20 days based on soil temperature [36]. About 20% of the N applied to clay soil is lost through leaching [37]. Similarly, Fu et al. [38] stated that urea-derived N remaining in the soil was lower (around 60%) after the application of heavy rainfall-simulated irrigation in the first two weeks. UAN applied in sandy loam soil had a total N leaching loss of 66% when measured after a month [34]. In general, sandy soils are more vulnerable to leaching losses than clay soils, where more than 60% and 20–30% can leachate under heavy rainfall events within a month in sandy and clay soils, respectively.

Urea-based N fertilizer products are susceptible to volatilization losses if surface applied and not incorporated [37]. Urease enzymes and plant residues in the soil convert the urea component to free ammonia gas [39]. After conversion occurs at the soil surface and if accompanied by warm sunny days, up to 20% of the N may volatilize within a week. However, if a shower of rain occurs within 24 hours or if the N incorporated, the risk of volatilization could be minimized (https://www.extension.umn.edu/agriculture/nutrient-management/nitrogen/fertilizer-urea/). The volatility of urea depends to a great extent on soil temperature and soil pH; 20% of the surface-applied urea will be volatilized if the temperature is 32°C within 10 days and 40% if soil pH is more than 7 (https://www.extension.umn.edu/agriculture/nutrient-management/nitrogen/fertilizer-urea/). Peng et al. [34] stated that broadcasting urea-based N fertilizer might volatilize 30 to 60% of applied N. Moreover, Turner et al. [40] found that 12% of the applied N in dry soil was lost via ammonia volatilization within a week. Soil temperature is the main factor influencing the rate of nitrification in agricultural soils [35, 41]. In saturated soils, N can be converted to N gas within few days through denitrification process [40–52]. When N was applied on heavy clay soils, 2 to 20% denitrification losses ha^{-1} $week^{-1}$ was recorded [33]. Generally, Weier [33] reviewed that urea is the most widely used form of N fertilizer with about 50% of the applied N often lost via ammonia volatilization, denitrification, and leaching in the subtropics. Hence, timing of N, split application, methods, and depths of N applications are the key issues, which have to be considered for maximized N use efficiency.

2.3. N Application Times. Daily N uptake is influenced by plant age, soil N supply, pest infestation, climatic variation, and soil moisture status. The maximum potential rate of N uptake is determined by plant growth stage [36, 42] and lower N uptake occurs during the seedling stage and preharvest periods, while the vegetative growth and flower initiation demand higher N supply [36]. Urea can transform into ammonium (NH^+) within two days, with almost complete conversion of ammonium into nitrate (NO_3^-) within a week or two weeks of application [38]. Applying all the fertilizer up front can lead to leafy tall plants that will not yield as well as they look [43], because the moisture and fertility end up being used in the stems and leaves instead of filling seed. Loss of N from broadcast urea (left on surface) and soil incorporation were 28% and 26%, respectively, whereas the loss from split band application was only 6% [44]. In US[1], N was applied in two split forms [45], and 33–60% of the applied N (67 kg·N/ha) was taken up during the reproductive growth phase of sesame. The same authors added that 31–66% of aboveground accumulated N (70–99 kg·N/ha) was remobilized to capsules and seeds (29–49 kg/ha in seeds). In Iran[2], higher seed yields (1315 kg/ha) were noted with three split applications: 25% at planting, 50% at 8-leaf stage, and 25% at flower initiation, and the lowest seed yield (554 kg/ha) was with two spilt applications of 70% at planting and 30% at 8-leaf stage [46]. In Bangladesh[4], higher yield (1386 kg/ha) was harvested when urea was applied in two split forms: half of N during planting and the remaining half of N top-dressed at 30 days after sowing [47]. In Ethiopia[3], sesame plant produced higher yield (799.9 kg/ha) with two split applications: 50% of the recommended at first branching and the remaining half at early flower initiation or 50% of the recommended dose at planting time and 50% of the recommended dose at early flower initiation [48]. The same author added that full dose application of the recommended N has 45.5% yield reduction compared to the split application. In Egypt[4], application of N in split form at three equal doses produced higher yields: after thinning and 35 and 50 days from sowing [49]. Application of urea/N to growing crops during warm periods (above 20°C) is not advisable, as urea in contact with vegetative material will tend to give off ammonia (https://www.extension.umn.edu/agriculture/nutrientmanagement/nitrogen/fertilizer-urea/). N application should be made during the coolest period of the day, especially when broadcasting in dry periods. In conclusion, for the higher seed yield, N should be applied in a split form 2-3 times and applied not in a one-time full dose.

2.4. N Placement Depth and Methods. Narrow bands of fertilizer can apply in furrows 5 to 8 cm to the side of the planting area and 3 to 5 cm deeper than the seeds. Placement of the fertilizer band too close to the seeds can burn the roots of the seedlings (http://aggie-horticulture.tamu.edu/vegetable/guides/texas-vegetable-growers-handbook/chapter-iii-soils-fertilizers/). N fertilizer applied in the sesame seed furrow can disintegrate the seeds. Hence, applying the fertilizer below the seeds or to the side of the seed line is recommended [43]. N fertilizers are very soluble and move readily in moist soil [50, 51]. Placement with or very near the seed is not desirable [52]. The same authors added that relative efficiencies of the various methods such as broadcast, preplant band, side band at planting, side dress, and seed row placement depend on the plant growth stage, soil moisture, soil type, type of fertilizer, row spacing, and spread of seed and fertilizer. Broadcast application is less effective than banded/side-dress or seed row application [53, 54]. Fertilizer placed in the seed row can delay or severely reduce crop emergence [55]. Banding or side dress (≥5 cm deep) is a common method of applying N fertilizers, and fertilizer applied on both sides of the row no more than 20 cm from the plants is fruitful [54]. Side dress of soil-incorporated applications at the young growth stage minimizes root pruning (http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex621). Banding particularly satisfies the P need of many crops as the first roots develop [56]. Broadcast application of P should be 2–4 times the recommended rates for row application [57]. K moves in the soil more readily than P. However, for annual crops, K fertilizers are more efficient when drilled or banded to a side of the seeds [56] and broadcast applications can be used at about twice the rate used for drill application. S in the sulphate form moves readily in moist soils. Therefore, soluble sulphate fertilizers provide an available sulphur source as either broadcast or band applications, and elemental sulphur and gypsum can be used as sulphur fertilizers (http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/agdex621).

2.5. N Application Effect on Sesame Seed Quality. Urea application significantly enhances the uptake of nutrients N, P, K, Ca, Mg, Na, Fe, Cu, Mn, and Zn [22]. Furthermore, application of N has positive interactions with P, K, S, Ca, Mg, Zn, Cu, Mn, and Fe [19]. Since N is the most dynamic nutrient and building block of all plant structures [20], its inclusion in the sesame production is critically important. Seed quality in sesame is determined by seed color, seed size, aroma, oil, and protein contents. Therefore, oil and protein are mostly made up of N and the seed size is also influenced by oil and protein contents to some extents. According to Couch et al. [45], of the N absorbed by the plant, 31–66% remobilizes to capsules and seeds. Hence, application of N fertilizer has great impacts on the quality of sesame seeds.

2.6. Urea/N Blending and Storage. Urea is neither combustible nor explosive. It can be stored safely with no loss of quality under normal circumstances. Urea particles are generally soft and abrasive (https://extension.umn.edu/nitrogen/fertilizer-urea). Urea should not mix with ammonium nitrate, ammonium calcium nitrate, KCl, SSP, TSP, and most of the micronutrients. The critical relative

Table 1: Effects of soil type, annual rainfall, temperature, soil pH, and N rates on sesame productivity.

S. No.	Country	Soil type/texture	Annual rainfall (mm)	Average temperature (°C)	Soil pH	Altitude (m)	Environment/ land suitability (1–4)	Fertilizer rate, N (kg/ha)	Country average yield (kg/ha) [10]	Yield (kg/ ha)	Reported by
1	China		642	14.2 (8–27)		100	2	N123, P60	1555.7	762.5	Wei et al. [25]
2	India	Sandy loam	787–1172		8.1		1	N75, P–	419.8	706	Motaka et al. [27]
3	Sudan	Calcareous matrix	<200	29.8	Alkaline	380	3	N44, P44	245.9	919	El Mahdi [26]
		Sandy loam	650	25.7		900	1	N100		762	Bahar et al. [62]
4	Tanzania	Sandy clay	400–500	25.7	5.5–7	1140	1	N45, P20	1044.7	889.7	Sanga [62]
5	Ethiopia	Verisol/clay	400–620	27–37	8.4	600	3	N41, P46	792.7	675	Gebrelibanos [48]
		Sandy clay loam	150–340	23–35	8.3	300	2	N46, P46		1633.3	Mekonnen et al. [11]
6	Nigeria	Ultisol/sandy clay loam	1570	18–32	6.3	1000	1	N46, P–	1056.9	1333.3	Ogundare et al. [8]
		Loam	600–800	20–23		696	1	N75, P45		850	Shehu et al. [15]
		Sandy loam	600–800				1	N50, P–		888	Haruna [14]
7	Uganda	Sandy loam	1000	18–29	5.4	1128	1	P30, P25, K40	619	946	Anguria [63]
8	Bangladesh		Irrigated				4	N125, P150	915.7	1386	Sarkar et al. [47]
9	Egypt	Sandy loam	Irrigated				4		1406.3	1534	El-Sherif [28]
10	Iran	Clay loam	536.71		7.8	20	1	N150, P60	901	1199.62	Amin and Alireza [46]

Environment/land suitability: potential (1), suitable with some limitations (2), marginal (3), and irrigated (4).

humidity at which urea can absorb moisture from the air is above 75%. However, when mixed with ammonium nitrate, it can absorb moisture at a relative humidity of 18%. Otherwise, urea can blend with most of the fertilizers (DAP, NPS, etc.), but the mixtures containing urea should apply immediately after mixing (http://seap.ipni.net/article/SEAP-3024). Therefore, a mixture of urea fertilizer should not be stored for more than 24 hours.

3. Effect of N Fertilizer on Agronomic Traits of Sesame

Unfertilized plot was flowering 14% earlier than the 100 kg·N/ha treated plot in Nigeria[2] [14]. Similarly, higher (92 kg/ha) N application has delayed flowering compared to the unfertilized ones in the drought-prone parts of north Ethioipa[3] [30]. On the other side, an experiment carried out, in Nigeria[1], witnessed that emergence date, flowering date (52 days), and maturity date (89) were not affected by urea application rates [8]. Therefore, N fertilizer has no relation with sesame phonological traits under higher rainfall areas, whereas in drought-prone areas, zero fertilization might flower earlier than the fertilized one. Taller plants (116 cm), higher LAI (0.78), higher branches per plant (8.7), and TDM per plant (32.7 g) were obtained with the application of 100 kg·N/ha in Nigeria[1] [14]. However, the control plots produced the lowest values for all the growth characters measured. The maximum number of branches per plant in sesame was obtained from application of 75 kg·N/ha in India[1] [27]. Higher seed yield was obtained when 75 kg·N/ha was applied (56.09% increment over the control) [15, 58] in Nigeria[1]. Similarly, application of 50 kg·N/ha produced significantly higher number of capsules per plant (83.8) and seed yield (888 kg) compared with the controlled plots in Nigeria[1] [14]. In Iran, higher yield was obtained from 50 kg·N/ha compared to 150 kg·N/ha [59]. Research conducted in India[1] for five years noted that maximum seed yield of sesame was obtained under 75 kg·N/ha application [27]. Recent studies stated that higher seed yield (800 kg/ha) was recorded due to application of 69 kg·N/ha plus 46 kg·P/ha in Humera, Ethiopia[2] [31]. On the other side, Blal et al. [60] reported that higher seed yield of sesame was harvested when 95 kg·N/ha was applied in Egypt[4]. Higher seed yield of sesame (850 kg/ha) was recorded from application of 30 kg·N/ha than higher N rates in Vietnam[3] [61]. Hence, in the marginal/poor areas, N fertilizer application has to be limited (less than 46 kg·N/ha), whereas in the potential/suitable environments (Table 1) application of 46–100 kg·N per ha could be economical and fruitful. Application of 50–100 kg·N/ha gave a significant oil content enhancement in comparison with zero fertilization [22, 27].

4. Conclusion

N P K fertilizers have been extensively researched and proven to significantly increase sesame yield in the tropics. Particularly, growth and yield of sesame are greatly influenced by the application of N fertilizer. A general rule is that nitrogen is for leafy top growth, phosphorus is for root and fruit production, and potassium is for cold hardiness, disease resistance, and drought tolerance. As per the review, optimum seed yield of sesame was obtained from application rate of 46–100 kg·N/ha. Adequate nitrogen nutrition (46–100 kg·N/ha·N) is beneficial to improve uptakes of other nutrients, particularly P and K and some micronutrients. Preemergence application (at planting) of mobile nitrogen (urea) is less efficient due to losses. Urea can convert to plant available form of N (ammonium) within two days. Moreover, ammonium converts to nitrate-N in less than two weeks and thereafter becomes available for the crop again and/or to leaching loss. Urea/N is susceptible to volatilization and denitrification losses if surface applied and if waterlogging occurs, respectively. Split N applications, where some N is applied prior to crop emergence and the remaining after emergence, increase crop productivity. It should be applied in a split form of two to three times and not be applied in a one-time full dose. Sesame utilizes more N at the reproductive growth stage. Hence, when split N application was carried out, most of the recommended dose should be scheduled to be applied at the initial flowering stage. Side-dress application remains one of the easiest and least expensive ways to maximize nitrogen use efficiency. N fertilizers should be placed 3–5 cm deeper than the seeds at sowing and 5–10 cm apart from the seedlings for side dress and 10–20 cm apart from the plant at flower initiation. Urea is the widely used type of fertilizer, which about 50% of the applied N often lost via ammonia volatilization, denitrification, and leaching in the subtropics. Hence, the timing, split application, method of application, and depth applications have to be considered to maximize N use efficiency. Under optimal environmental conditions, nitrogen fertilizer has no effect on phonological traits but on the growth parameters and yield. In the optimal environment, application of 46–100 kg·N/ha gives maximum yield and application of less than 46 kg·N/ha is economical in marginal areas.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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