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Effects of *Leucaena* Leaf Extract as a Liquid Organic Biostimulant and Harvest Timing on Yield and Seed Quality of Sesame (*Sesamum indicum*) in Dryland Systems

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ABSTRACT
Sesame productivity and seed quality in dryland systems are often constrained by low soil fertility and inappropriate harvest timing. This study aimed to evaluate the effects of *Leucaena leucocephala* leaf extract applied as a liquid organic biostimulant and different harvest timings on growth, yield, seed quality, and oil content of sesame cultivated under dryland conditions. The experiment was conducted using a factorial randomized complete block design with four extract doses (0, 100, 200, and 300 mL plant^{-1}) and three harvest timings (95, 102, and 109 days after planting). Vegetative growth parameters, yield components, seed physical and physiological quality, and oil content were measured and analyzed. The results showed that increasing extract doses significantly enhanced vegetative growth, capsule formation, seed weight, and total seed yield, with the highest yield obtained at 300 mL plant^{-1}. Harvest timing strongly influenced seed physiological quality and oil accumulation. Seeds harvested at 102 days after planting exhibited the highest germination performance and oil content, whereas earlier or later harvest reduced quality attributes. A moderate extract dose (200 mL plant^{-1}) combined with harvest at 102 days optimized seed quality and oil content, while higher doses favored yield maximization. These findings indicate that synchronizing organic nutrient management with appropriate harvest timing is essential to balance yield and quality in sustainable dryland sesame production systems.

Keywords: Dryland Agriculture; Germination; Legume Biostimulant; Organic Fertilization; Seed Oil Content

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INTRODUCTION
Sesame (*Sesamum indicum* L.) is one of the oldest oilseed crops cultivated worldwide and remains highly valued due to its exceptional oil quality, nutritional composition, and wide industrial applications (Langyan et al. 2022; Oboulbiga et al. 2023). Sesame oil is rich in unsaturated fatty acids, particularly oleic and linoleic acids, and contains unique lignans such as sesamin and sesamolin, which contribute to oxidative stability and health-promoting properties (Comini et al. 2023; Oboulbiga et al. 2023). These characteristics make sesame oil suitable for food, pharmaceutical, cosmetic, and nutraceutical industries (Langyan et al. 2022). In addition, the residual sesame meal after oil extraction contains a high protein content, providing potential value as animal feed (Norouzi et al. 2025). Owing to these advantages, global demand for sesame continues to increase, while production in many developing countries remains below its potential (Anyogu et al. 2024; Sanni et al. 2024).

In tropical and subtropical regions, including Indonesia and other parts of Southeast Asia, sesame is predominantly cultivated under dryland conditions. Dryland agroecosystems are characterized by low soil organic matter, limited nutrient availability, weak soil structure, and high vulnerability to erosion (Samijan et al. 2023; Al-Shammary et al. 2024; Usman 2024). These constraints frequently result in suboptimal crop growth, unstable yields, and low seed quality. Although sesame is relatively tolerant to drought compared with other oilseed crops, its productivity and seed performance are still highly dependent on soil fertility management and appropriate agronomic practices (kouighat et al. 2024; Baraki et al. 2025). Conventional reliance on inorganic fertilizers in dryland systems often fails to improve long-term soil quality and may exacerbate soil degradation, highlighting the need for sustainable nutrient management strategies (Al-Shammary et al. 2024; Liu et al. 2024; Kabato et al. 2025).

In recent years, increasing attention has been directed toward organic fertilizers and plant-based

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biostimulants as environmentally friendly alternatives to synthetic inputs (Boutahiri et al. 2024; Basar et al. 2025). Liquid organic fertilizers derived from plant biomass are of particular interest because they supply essential nutrients in readily available forms while simultaneously enhancing biological activity in the soil (Boutahiri et al. 2024; Fajdetić et al. 2025; Matthews et al. 2025). Leguminous plants represent an important source of organic inputs due to their ability to accumulate nitrogen and other macro- and micronutrients. Among them, *Leucaena leucocephala* is widely recognized as a fast-growing legume with high biomass production and rich nutrient composition. Extracts derived from *Leucaena* leaves contain nitrogen, phosphorus, potassium, calcium, magnesium, and bioactive compounds that may stimulate plant growth, improve nutrient uptake, and enhance soil biological processes (Yosilia et al. 2025).

Several studies have reported positive effects of legume-based organic fertilizers on crop growth, biomass accumulation, and yield components in various crops (Liu et al. 2024; Duri et al. 2025; Fajdetić et al. 2025; Prashar et al. 2025). Liquid formulations are considered particularly effective because nutrients are more rapidly absorbed by plants and more evenly distributed in the root zone compared with solid organic amendments. However, despite increasing interest in liquid organic biostimulants, scientific evidence regarding their optimal application rates and their interaction with crop management factors such as harvest timing remains limited, especially for sesame cultivated under dryland conditions (Liu et al. 2024; Neumann et al. 2024).

Seed yield alone is not sufficient to determine the success of sesame cultivation, particularly when the crop is intended for seed production. Seed quality, including germination capacity, vigor, and oil content, plays a crucial role in ensuring successful crop establishment and maintaining productivity in subsequent planting cycles. One of the most critical yet often overlooked factors influencing seed quality is harvest timing. Seeds harvested before reaching physiological maturity may exhibit poor germination and reduced vigor, whereas delayed harvest can result in seed shattering, weather damage, and quality deterioration. In sesame, determining the optimal harvest stage is particularly challenging due to its indeterminate growth habit and asynchronous capsule maturation.

Therefore, this study aimed to evaluate the effects of *Leucaena* leaf extract applied as a liquid organic biostimulant at different application rates and varying harvest times on yield components, seed quality, and oil content of sesame cultivated under dryland conditions. It was hypothesized that appropriate doses of *Leucaena* leaf extract would enhance plant growth and yield by improving nutrient availability and physiological performance, while optimal harvest timing would maximize seed maturity, germination capacity, and oil content. Furthermore, it was expected that the combination of an optimal biostimulant dose and appropriate harvest timing would produce synergistic effects, leading to superior yield and seed quality compared with conventional practices.

MATERIALS AND METHODS

Plant Materials

Sesame (*Sesamum indicum* L.) seeds of the variety Sumberrejo 1 were used in this study. Fresh leaves of *Leucaena leucocephala* were used as the raw material for preparing the liquid organic extract. Additional materials included clean water, granulated sugar, and Effective Microorganisms-4 (EM4) as a bioactivator. Standard field equipment such as sprayers, measuring cylinders, weighing balances, cutting tools, and fermentation containers were used throughout the experiment.

Preparation of *Leucaena* Leaf Extract

The liquid organic extract was prepared through a controlled fermentation process. Fresh *Leucaena* leaves were chopped into small pieces (approximately 2 cm in length) to increase surface area and facilitate decomposition. A sugar solution was prepared by dissolving granulated sugar in water, which served as an energy source for microbial activity. The solution was mixed with EM4 at a ratio of 1:5 (EM4:water), stirred thoroughly, and allowed to activate for approximately 30 minutes.

Chopped *Leucaena* leaves were then placed into nylon bags and submerged in water-filled containers. The activated EM4 solution was evenly applied to the leaf material before submersion. The containers were tightly sealed and kept in a shaded area to prevent direct sunlight and contamination. Fermentation was carried out for 20 days, during which the mixture was stirred weekly to ensure uniform decomposition. After fermentation, the liquid extract was filtered and used as a liquid organic fertilizer for field application.

Experimental Design and Treatments

The experiment was arranged in a factorial randomized complete block design (RCBD) with two factors and three replications.

The first factor was the dose of *Leucaena* leaf extract, consisting of four levels:

- **L0**: 0 cc plant^{-1} (control, no extract)
- **L1**: 100 cc plant^{-1}
- **L2**: 200 cc plant^{-1}
- **L3**: 300 cc plant^{-1}

The second factor was harvest timing, consisting of three levels:

- **H1**: 95 days after planting (DAP)
- **H2**: 102 days after planting
- **H3**: 109 days after planting

In total, twelve treatment combinations were evaluated.

Field Layout and Crop Establishment

Each experimental plot measured 4.0 m × 3.6 m. Sesame was planted at a spacing of 60 cm × 25 cm, resulting in approximately 90 plants per plot. Seeds were sown directly into the field at a rate of two seeds per planting hole and later thinned to one plant per hole after establishment.

Application of *Leucaena* Leaf Extract

The liquid *Leucaena* leaf extract was applied as a soil drench near the base of each plant using a backpack sprayer. Applications were conducted at two-week intervals, starting from early vegetative growth, for a total of six applications during the growing season. The extract was applied according to the assigned treatment dose for each plot.

Harvesting and Post-Harvest Handling

Plants were harvested by cutting the stems approximately 15–20 cm below the lowest capsule. Harvested plants were bundled and air-dried in an upright position for seven days to allow capsule opening. Seeds were then manually threshed, cleaned, and dried prior to analysis.

Measured Variables

Observations were made on five randomly selected plants per plot.
Plant height (measured weekly)
Leaf area index (measured at 60 DAP using the gravimetric method)
Relative growth rate (calculated at 30, 60, and 90 DAP)
Dry biomass per plant
Number of capsules per plant
Capsule weight per plant
Number of seeds per capsule
Seed weight per plant
Seed yield per plot
Weight of 1,000 seeds
Germination percentage (top-of-paper method)
Germination rate
Seed oil content (determined using Soxhlet extraction)

Statistical Analysis

All collected data were subjected to analysis of variance (ANOVA) appropriate for a factorial RCBD, mean separation was performed using Duncan's Multiple Range Test (DMRT) at a 5% significance level..

RESULTS AND DISCUSSION

Effects of *Leucaena* Leaf Extract and Harvest Timing on Vegetative Growth of Sesame

Vegetative growth of sesame responded significantly to the application of *Leucaena* leaf extract, whereas harvest timing did not directly affect vegetative parameters. Plant height increased progressively with increasing extract dose throughout the growing period. At 11 weeks after planting, plants treated with 300 mL plant^{-1} of *Leucaena* leaf extract reached the greatest height (approximately 132 cm), which was significantly higher than that of untreated control plants (Table 1). Intermediate doses of 100 and 200 mL plant^{-1} also increased plant height relative to the control, although the magnitude of the response was lower than that observed at the highest dose. Differences among treatments were not significant during early growth stages but became pronounced during later vegetative development (Table 1).

Table 1. Effect of *Leucaena* leaf extract dose on plant height of sesame at different growth stages.

***Leucaena* leaf extract dose (mL plant^{-1})**	Plant height (cm)			
	3 WAP	6 WAP	9 WAP	11 WAP
Control	7.11 a*)	52.98 a	97.15 a	104.27 a
100 mL plant^{-1}	7.26 a	62.01 b	112.00 b	117.31 b
200 mL plant^{-1}	7.46 a	62.15 b	119.22 bc	127.89 c
300 mL plant^{-1}	7.66 a	65.22 b	120.27 c	131.84 c

Leaf area index (LAI) was significantly influenced by *Leucaena* leaf extract application. The highest LAI value (0.78) was recorded under the 300 mL plant^{-1} treatment, followed by the 200 mL plant^{-1} treatment, while the control and 100 mL plant^{-1} treatments did not differ significantly from each other (Table 2). Harvest timing did not significantly affect LAI, and no interaction between extract dose and harvest timing was detected for this parameter.

Relative growth rate (RGR) showed a clear positive response to increasing extract dose. Plants receiving 300 mL plant^{-1} exhibited the highest RGR values, followed by those receiving 200 mL plant^{-1}, whereas control plants showed the lowest growth efficiency (Table 3). Harvest timing did not significantly affect RGR, indicating that growth efficiency was primarily governed by nutrient availability during the vegetative phase.

Dry biomass accumulation per plant increased markedly with increasing extract dose. The highest dry biomass was recorded in plants treated with 300 mL plant^{-1}, followed by those receiving 200 and 100 mL plant^{-1}, while control plants produced the lowest biomass (Table 2). In contrast to plant height and LAI, dry biomass showed a significant interaction between extract dose and harvest timing, with higher extract doses maintaining greater biomass accumulation up to later harvest stages.

Table 2. Effects of *Leucaena* leaf extract dose and harvest timing on leaf area index and dry biomass of sesame.

***Leucaena* leaf extract (mL.plant^{-1})**	**Leaf Area Index**	**Dried Biomass (g)**
Control	0.32 a	9.60 a
100 mL plant^{-1}	0.33 a	14.15 b
200 mL plant^{-1}	0.56 b	21.10 c
300 mL plant^{-1}	0.78 c	29.84 d

The enhancement of sesame vegetative growth observed in this study demonstrates the effectiveness of *Leucaena* leaf extract as a liquid organic biostimulant under dryland conditions. Increased plant height, LAI, RGR, and dry biomass at higher extract doses indicate improved nutrient availability and physiological performance, which are critical determinants of crop establishment and productivity in nutrient-limited dryland soils.

Table 3. Effect of *Leucaena* leaf extract dose on relative growth rate of sesame.

***Leucaena* leaf extract dose (mL plant⁻¹)**	**Relative Growth Rate 60 and 30 days ($g.g^{-1}.d^{-1}$)**
Control	0.009 a
100 mL plant⁻¹	0.015 ab
200 mL plant⁻¹	0.020 bc
300 mL plant⁻¹	0.029 c

The significant increase in plant height under the 300 mL plant⁻¹ treatment reflects improved nitrogen and phosphorus supply from the *Leucaena* extract. Nitrogen plays a central role in chlorophyll synthesis, protein formation, and cell division, while phosphorus is essential for energy transfer and meristematic activity. The liquid formulation of the extract likely accelerated nutrient diffusion and root uptake compared with solid organic amendments, enabling plants to respond more efficiently during the active vegetative growth phase. Similar growth-promoting effects of legume-derived organic fertilizers have been reported in sesame and leafy vegetables, where improved nutrient solubility enhanced vegetative development (Liu et al. 2024; Lee et al. 2025).

The delayed appearance of significant height differences among treatments during early growth stages suggests that the biostimulant effect was mediated through microbial mineralization processes. Organic inputs generally require time for decomposition and nutrient release before becoming plant-available. Organic materials typically begin releasing nutrients effectively several weeks after application. This mineralization-driven response highlights the importance of appropriate application timing when using organic biostimulants.

Leaf area index is a key determinant of canopy photosynthetic capacity and radiation interception. The increase in LAI with increasing extract dose indicates enhanced leaf expansion and canopy development, which directly supports higher photosynthetic rates and biomass accumulation. Optimal LAI allows crops to maximize light capture without excessive self-shading (Zhang et al. 2020; Al-Shammary et al. 2024). Under dryland conditions, improved canopy development is particularly advantageous because it enhances radiation use efficiency while maintaining balanced water use. The absence of a harvest timing effect on LAI confirms that canopy formation was largely completed before the onset of physiological maturity.

Relative growth rate reflects the efficiency with which plants convert assimilates into new biomass. Higher RGR values under increasing *Leucaena* extract doses indicate improved growth efficiency, likely resulting from enhanced nutrient availability and increased photosynthetic enzyme activity. Nutrient-sufficient plants generally exhibit higher RGR due to improved carbon assimilation per unit biomass (Liu et al. 2024). Comparable increases in RGR have been reported in sesame and other oilseed crops receiving organic nutrient inputs, particularly those derived from leguminous biomass (Baraki et al. 2025).

Dry biomass accumulation integrates the combined effects of photosynthesis, nutrient uptake, and assimilate partitioning. The strong positive response of dry biomass to *Leucaena* extract application confirms that the biostimulant not only enhanced vegetative growth but also sustained biomass production throughout the growth cycle. The significant interaction between extract dose and harvest timing suggests that higher nutrient availability delayed senescence and maintained biomass integrity until later harvest stages. This finding is particularly relevant for dryland systems, where nutrient stress often accelerates leaf senescence and limits assimilate supply to reproductive organs (Kabato et al. 2025).

The superior performance of the 300 mL plant⁻¹ dose indicates that sesame cultivated on Alfisol dryland soils requires relatively high organic nutrient input to overcome inherent fertility constraints. Alfisols are typically characterized by low nitrogen availability and limited exchangeable potassium and magnesium. *Leucaena* leaf extract contains not only nitrogen and phosphorus but also calcium and magnesium, which may have contributed to improved nutrient balance and enhanced microbial activity in the rhizosphere (Usman 2024; Kabato et al. 2025). *Leucaena* biomass decomposes rapidly and releases substantial quantities of essential nutrients, particularly nitrogen, supporting sustained vegetative growth (Sofian et al. 2025).

Compared with previous studies using solid organic amendments, the vegetative growth response observed in this study was relatively pronounced. This difference may be attributed to the liquid nature of the extract, which facilitates faster nutrient mobility and uptake. Liquid organic fertilizers have been reported to be more effective than solid forms in improving early plant vigor, particularly in soils with low nutrient diffusion capacity (Liu et al. 2024; Lee et al. 2025). In addition, bioactive compounds present in *Leucaena* leaves may have contributed biostimulant effects beyond basic nutrient supply, including enhanced root development and improved nutrient acquisition efficiency (Basar et al. 2025).

In contrast, harvest timing did not significantly affect vegetative growth parameters such as plant height, LAI, or RGR. This outcome aligns with crop developmental theory, as vegetative growth in sesame largely concludes before physiological maturity. Harvest timing primarily influences reproductive and seed quality attributes rather than vegetative traits. Similar findings have been reported in sesame and other oilseed crops, where harvest stage affects seed development and quality but has minimal impact on vegetative growth parameters (Berhane et al. 2024; Baraki et al. 2025).

Yield Components and Yield Formation of Sesame

Yield formation in sesame was significantly affected by *Leucaena* leaf extract application and harvest timing, with a clear interaction between both factors for several yield components. The number of capsules per plant increased significantly with increasing extract dose. Plants treated with 300 mL plant^{-1} produced the highest number of capsules, followed by those receiving 200 and 100 mL plant^{-1}, while the control treatment resulted in the lowest capsule number (Table 4). Harvest timing also significantly influenced capsule number, with the highest values recorded at 109 days after planting (DAP).

Capsule weight per plant responded strongly to extract dose and harvest timing. The highest capsule weight was observed in plants treated with 300 mL plant^{-1} and harvested at 109 DAP, whereas the lowest values were recorded in control plants harvested at 95 DAP (Table 4). A significant interaction between extract dose and harvest timing indicated that improved nutrient availability enhanced capsule filling, particularly when harvest was delayed to allow full reproductive development.

The number of seeds per capsule was primarily influenced by harvest timing rather than extract dose. Capsules harvested at 109 DAP contained significantly more seeds per capsule than those harvested at 95 and 102 DAP (Table 5). Although extract dose showed a positive trend, differences among extract treatments were not statistically significant for this parameter.

Seed weight per plant increased significantly with increasing extract dose and later harvest timing. The highest seed weight per plant (approximately 21 g plant^{-1}) was obtained under the combination of 300 mL plant^{-1} extract and harvest at 109 DAP, representing an increase of approximately 31% compared with the control treatment (Table 5).

At the plot level, seed yield followed a similar pattern. Application of 300 mL plant^{-1} resulted in the highest seed yield per plot (approximately 2.7 kg plot^{-1}), whereas the control treatment produced the lowest yield (Table 6). Harvest timing significantly affected yield, with the highest yields recorded at 109 DAP.

Table 4. Effect of *Leucaena* leaf extract dose and harvest timing on number of capsules and capsule weight per plant of sesame.

***Leucaena* leaf extract dose (mL plant^{-1})**	**Number of Capsules per Plant**	**Capsule Weight per Plant (g)**
Control	26.18 a	6.59 a
100	35.02 a	8.34 a
200 mL plant^{-1}	53.49 b	11.82 b
300 mL plant^{-1}	74.02 c	14.50 c

The significant improvement in yield components observed in this study confirms that enhanced vegetative growth induced by *Leucaena* leaf extract translated effectively into reproductive success and yield formation. Yield formation in sesame is largely determined by the number of capsules per plant and the efficiency of seed filling within each capsule. The increase in capsule number with increasing extract dose indicates that improved nutrient availability during the vegetative and early reproductive phases promoted the initiation and retention of reproductive structures (Baraki et al., 2025; Berhane et al., 2024).

Table 5. Effect of harvest timing on number of seeds per capsule and seed weight per plant of sesame.

***Leucaena* leaf extract dose (mL plant^{-1})**	**Number of Seeds per Capsules**	**Seed Weight per Plant (g)**
Control	76.89 a	6.48 a
100 mL plant^{-1}	82.38 a	7.58 a
200 mL plant^{-1}	84.33 a	10.95 b
300 mL plant^{-1}	92.02 b	15.26 c

Table 6. Effect of *Leucaena* leaf extract dose on seed yield per plot of sesame.

***Leucaena* leaf extract dose (mL plant^{-1})**	**Seed Yield per Plot (g)**
Control	1166.00 a
100 mL plant^{-1}	1365.44 a
200 mL plant^{-1}	1970.64 b
300 mL plant^{-1}	2747.80 c

Nitrogen availability plays a critical role in determining the number of reproductive nodes and capsules in sesame. Adequate nitrogen supply enhances branching, flower initiation, and capsule retention, thereby increasing sink capacity. The superior capsule number observed under the 300 mL plant^{-1} treatment suggests that *Leucaena* leaf extract provided sufficient nitrogen to support reproductive organ differentiation and reduce flower abortion. Similar increases in capsule number have been reported in sesame fertilized with organic nutrient sources, including poultry manure and legume-based amendments (Tang et al. 2023; Baraki et al. 2025).

Capsule weight per plant is an integrative indicator of assimilate partitioning and reproductive sink strength. The strong interaction between extract dose and harvest timing observed for this parameter indicates that nutrient availability alone was insufficient to maximize capsule filling unless adequate time was allowed for assimilate translocation. Delayed harvest at 109 DAP allowed prolonged photosynthate accumulation and translocation into developing capsules, resulting in heavier capsules, particularly under high nutrient availability. This interaction highlights the importance of synchronizing nutrient management with harvest timing to optimize yield formation (Smith et al. 2018; Berhane et al. 2024).

The relatively minor influence of extract dose on the number of seeds per capsule suggests that this trait is more strongly governed by genetic and developmental factors than by nutrient availability. In sesame, ovule number and seed set per capsule are largely determined during early reproductive development and are less responsive to post-flowering nutrient inputs. However, harvest timing significantly affected seed number per capsule, indicating that premature harvest may result in incomplete seed development and reduced seed set. Similar findings have been reported in recent sesame studies, which demonstrated that delayed harvest increased seed number and reduced the proportion of underdeveloped seeds (Seadh et al. 2007; Berhane et al. 2024).

Seed weight per plant is the most direct indicator of yield performance at the individual plant level. The substantial increase in seed weight under the combined treatment of 300 mL plant⁻¹ extract and harvest at 109 DAP reflects the cumulative effects of enhanced vegetative growth, increased capsule number, and improved assimilate translocation. The 31% increase in seed weight relative to the control underscores the agronomic potential of *Leucaena* leaf extract as a liquid organic biostimulant in dryland sesame production. This yield gain is comparable to or higher than those reported in previous studies using solid organic fertilizers or integrated organic–inorganic nutrient management systems (Tang et al. 2023; Baraki et al. 2025).

At the plot scale, seed yield per plot mirrored trends observed at the plant level, confirming the consistency of treatment effects across spatial scales. The higher yield recorded under the 300 mL plant⁻¹ treatment demonstrates that individual plant responses were sufficiently uniform to translate into meaningful yield gains at the field level. This finding is particularly important for practical adoption, as yield stability across plots is a key consideration for farmers operating under variable dryland conditions (Tang et al. 2023).

The superiority of later harvest timing (109 DAP) for yield formation can be attributed to the attainment of physiological maturity and complete assimilate translocation. In oilseed crops, premature harvest often interrupts the seed-filling process, leading to reduced seed weight and yield losses. Recent seed physiology studies confirm that maximum dry matter accumulation occurs at physiological maturity, after which further delay primarily affects moisture content rather than dry weight (Borreani et al. 2007; Gesch & Johnson 2012). The present results corroborate this principle, demonstrating that harvest at 109 DAP allowed seeds to reach maximum dry matter accumulation.

Seed Physical and Physiological Quality of Sesame

Seed physical and physiological quality of sesame was significantly influenced by harvest timing and, to a lesser extent, by *Leucaena* leaf extract application. Thousand-seed weight was significantly affected by extract dose, whereas harvest timing showed no significant interaction with extract dose for this parameter. The highest thousand-seed weight (2.86 g) was recorded in plants treated with 300 mL plant⁻¹ of *Leucaena* leaf extract, while the lowest value was observed in the control treatment (Table 7). Intermediate extract doses resulted in moderate increases in seed weight, indicating a positive dose-dependent response.

Table 7. Effect of *Leucaena* leaf extract dose on thousand-seed weight of sesame.

Leucaena leaf extract dose (mL plant⁻¹)	1000 Seed Weight (g)
Control	2.55 a
100 mL plant⁻¹	2.62 a
200 mL plant⁻¹	2.78 b
300 mL plant⁻¹	2.86 b

Seed physiological quality, as indicated by germination percentage and germination rate, was strongly influenced by harvest timing. Seeds harvested at 102 days after planting (DAP) exhibited the highest germination percentage (approximately 89%), whereas seeds harvested at 95 DAP showed significantly lower germination (Table 8). Germination percentage declined slightly when harvest was delayed to 109 DAP, although values remained higher than those recorded at 95 DAP. Germination rate followed a similar trend, with the fastest germination observed in seeds harvested at 102 DAP. In contrast, seeds harvested at 95 DAP exhibited slower and less uniform germination. *Leucaena* leaf extract dose did not significantly affect germination percentage or germination rate, and no interaction between extract dose and harvest timing was detected for these parameters (Table 8).

Table 8. Effect of harvest timing on germination percentage and germination rate of sesame seeds.

Days After Planting	Germination Percentage (%)	Germination Rate (d)
95	83.87 a	0.72 ab
102	89.12 b	0.79 b
109	82.12 c	0.63 a

Seed physical and physiological quality are critical attributes determining the agronomic value of sesame, particularly when the crop is intended for seed production or high-quality oil extraction. The present results demonstrate that nutrient management through *Leucaena* leaf extract application primarily influenced seed physical traits, whereas harvest timing played a dominant role in determining seed physiological quality.

The increase in thousand-seed weight with increasing *Leucaena* extract dose reflects improved assimilate availability during seed filling. Seed weight is largely determined by the rate and duration of dry matter accumulation in developing seeds, which in turn depends on photosynthetic capacity and nutrient supply during the reproductive phase. The superior seed weight observed under the 300 mL plant⁻¹ treatment suggests that enhanced vegetative growth and improved nutrient status, as discussed in Sections 3.1 and 3.2, provided sufficient assimilates to support more complete seed filling. Phosphorus and potassium supplied by the *Leucaena* extract likely played key roles in carbohydrate translocation and starch synthesis, which are essential for seed mass accumulation (Wang et al. 2023; Shah et al. 2024; Wei et al. 2025).

The absence of a significant harvest timing effect on thousand-seed weight indicates that seed mass had largely stabilized by the earliest harvest stage evaluated. This finding suggests that physiological processes governing seed filling were completed before 95 DAP, even though other aspects of seed quality continued to change. Similar observations have been reported in oilseed crops, where seed dry weight reaches a plateau prior to full physiological maturity, after which moisture content declines without substantial changes in dry matter (Sripathy & Groot 2023; Moreno et al. 2024).

In contrast to seed weight, seed physiological quality was strongly influenced by harvest timing. The highest germination percentage and germination rate recorded at 102 DAP indicate that this harvest stage closely corresponded to physiological maturity of sesame seeds. At physiological maturity, seeds attain maximum viability and vigor, characterized by fully developed embryos, optimal reserve accumulation, and functional membrane systems. Seeds harvested prematurely at 95 DAP likely had incomplete embryo development and insufficient reserve accumulation, resulting in reduced germination capacity and slower germination. Kishk (2024), reported that early-harvested sesame seeds exhibited lower germination and vigor due to incomplete physiological development, supporting the present findings.

The slight decline in germination percentage observed at 109 DAP may be attributed to post-maturity deterioration processes. Once seeds reach physiological maturity, prolonged field exposure can lead to quality degradation due to fluctuations in temperature and humidity, oxidative stress, and mechanical damage during capsule dehiscence. In sesame, delayed harvest increases the risk of seed exposure to environmental stressors, which may impair membrane integrity and reduce germination performance. Seed deterioration is widely recognized to begin after physiological maturity and is accelerated by unfavorable moisture–temperature conditions (Alemayehu et al. 2023; Gebregergis et al. 2024).

The lack of a significant effect of *Leucaena* leaf extract on germination percentage and germination rate indicates that seed physiological quality was primarily determined by developmental timing rather than by nutrient availability. This finding suggests that while improved nutrition enhances seed size and yield, it does not necessarily alter the intrinsic physiological processes governing seed viability and vigor once basic nutrient requirements are met. Similar conclusions have been reported in studies examining the effects of organic fertilization on seed quality, where nutrient inputs improved seed yield and size but had limited influence on germination characteristics (Balouchi et al. 2025).

Seed Oil Content and Integrated Interpretation of Quality Attributes

Seed oil content of sesame was significantly influenced by the interaction between *Leucaena* leaf extract application and harvest timing. The highest oil content (54.26%) was recorded in seeds obtained from plants treated with 200 mL plant^{-1} of *Leucaena* leaf extract and harvested at 102 days after planting (DAP) (Figure 1). Oil content was slightly lower in seeds harvested at 109 DAP and markedly lower in seeds harvested at 95 DAP across all extract treatments.

Extract dose alone showed a moderate effect on oil content. Seeds from plants treated with 200 mL plant^{-1} consistently exhibited higher oil content than those from the control and the highest extract dose (300 mL plant^{-1}). Although the 300 mL plant^{-1} treatment maximized vegetative growth and yield, oil content did not increase proportionally and, in some cases, declined slightly relative to the 200 mL plant^{-1} treatment.

Harvest timing exerted a stronger influence on oil content than extract dose. Seeds harvested at 102 DAP exhibited significantly higher oil content than those harvested at 95 DAP, while a slight decline in oil content was observed when harvest was delayed to 109 DAP. This pattern was consistent across extract treatments, indicating that oil accumulation was closely associated with the physiological maturity stage of the seeds.

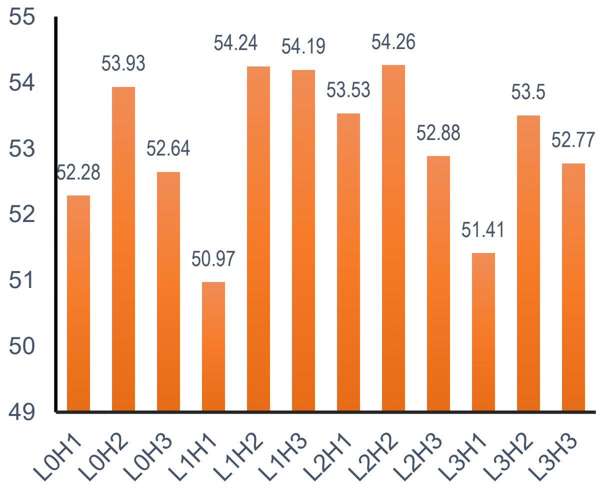

Figure 1. Interaction effects of *Leucaena* leaf extract dose and harvest timing on oil content of sesame seeds.

Seed oil content is a defining quality attribute of sesame, influencing its economic value and suitability for food and industrial applications. The results of this study demonstrate that oil accumulation in sesame seeds is regulated by a complex interaction between nutrient availability and harvest timing, with physiological maturity playing a dominant role.

The highest oil content observed at 102 DAP indicates that this harvest stage closely corresponds to the period of maximum lipid biosynthesis in sesame seeds. Oil accumulation in oilseed crops generally occurs during the latter stages of seed development, when assimilates are actively converted into storage lipids. At physiological maturity, enzymatic activity involved in fatty acid synthesis reaches its peak, resulting in maximal oil concentration. Harvesting prior to this stage, as observed at 95 DAP, interrupts lipid biosynthesis and leads to reduced oil content. Similar trends have been reported in sesame and other oilseed crops, where premature harvest significantly lowers oil concentration due to incomplete seed maturation (Gebregergis et al. 2024; Moreno et al. 2024).

The slight decline in oil content observed at 109 DAP suggests the onset of post-maturity processes that may dilute or degrade oil concentration. After physiological maturity, continued field exposure can result in seed respiration, oxidative reactions, and potential mobilization of storage compounds. In sesame, prolonged exposure to fluctuating temperature and humidity after capsule maturation may also increase lipid oxidation, reducing measurable oil content. Recent studies confirm that delayed harvest can negatively affect oil quality through oxidative deterioration despite stable seed dry weight (Alemayehu et al. 2023; Balouchi et al. 2025).

The differential response of oil content to extract dose provides important insights into nutrient–quality relationships. While moderate application of *Leucaena* leaf extract (200 mL plant^{-1}) enhanced oil accumulation, further increases in extract dose did not result in proportional increases in oil content. This pattern suggests that excessive nutrient availability may favor vegetative growth and yield formation at the expense of oil concentration, a phenomenon commonly described as a dilution effect. High nitrogen availability, in particular, is known to promote protein synthesis and vegetative biomass, potentially reducing the relative allocation of carbon to lipid biosynthesis (Shah et al. 2024; Wei et al. 2025).

Comparatively, the oil content values obtained in this study fall within the upper range reported for sesame varieties cultivated under field conditions. Recent sesame studies report oil contents commonly ranging between 45% and 55%, depending on cultivar, environment, and management practices (Oboulbiga et al. 2023; Tang et al. 2023). The maximum oil content of 54.26% achieved in this study demonstrates that high-quality oil production is attainable even under dryland conditions when nutrient management and harvest timing are optimized.

Collectively, the results demonstrate that *Leucaena* leaf extract functions effectively as a liquid organic biostimulant in dryland sesame cultivation, enhancing vegetative growth, yield formation, and seed physical quality. Harvest timing emerged as the dominant factor controlling seed physiological quality and oil content. Optimal outcomes were achieved through the synchronization of nutrient management and harvest timing, emphasizing the need for integrated agronomic strategies to balance productivity and quality in sustainable sesame production systems.

CONCLUSIONS AND SUGGESTIONS

This study demonstrates that the application of *Leucaena leucocephala* leaf extract as a liquid organic biostimulant effectively improves sesame growth, yield, and seed quality under dryland conditions. Increasing extract doses enhanced vegetative growth and yield components, with the highest seed yield achieved at 300 mL plant^{-1}, indicating that sufficient organic nutrient supply is essential for overcoming fertility constraints in dryland soils. Harvest timing played a decisive role in determining seed physiological quality and oil accumulation. Seeds harvested at 102 days after planting exhibited the highest germination performance and oil content, reflecting harvest at physiological maturity, whereas earlier or later harvest reduced quality attributes. A moderate extract dose (200 mL plant^{-1}) combined with harvest at 102 days optimized seed quality and oil content, while higher doses favored yield maximization. These findings reveal a functional trade-off between yield and quality in sesame production. Therefore, management strategies should be adjusted according to production objectives. Further studies are suggested to assess long-term soil health impacts of repeated *Leucaena* extract application and to explore its integration with other sustainable inputs to enhance productivity and resilience in dryland sesame systems

REFERENCES

Al-Shammary AAG, Al-Shihmani LSS, Fernández-Gálvez J, Caballero-Calvo A. 2024. Optimizing sustainable agriculture: A comprehensive review of agronomic practices and their impacts on soil attributes. J Environ Manage. 364:121487. doi:10.1016/j.jenvman.2024.121487. https://linkinghub.elsevier.com/retrieve/pii/S0301479724014737.

Alemayehu S, Abera FA, Ayimut KM, Darnell R, Mahroof R, Harvey J, Subramanyam B. 2023. Effects of Storage Duration and Structures on Sesame Seed Germination, Mold Growth, and Mycotoxin Accumulation. Toxins (Basel). 15(1):39. doi:10.3390/toxins15010039. https://www.mdpi.com/2072-6651/15/1/39.

Anyogu A, Somorin YM, Oladipo AO, Raheem S. 2024. Food safety issues associated with sesame seed value chains: Current status and future perspectives. Heliyon. 10(16):e36347. doi:10.1016/j.heliyon.2024.e36347. https://linkinghub.elsevier.com/retrieve/pii/S240584402412378X.

Balouchi H, Soltani Khankahdani V, Piri R, Moradi A, Gholamhoseini M, Heydari SZ, Ahmed LQ, Escobar-Gutiérrez AJ, Dedicova B. 2025. Deciphering the Germination Behavior of Sesame Cultivars: The Interplay of Hydrothermal Time Model Parameters and Seed Fatty Acid Profiles. Plants. 14(22):3422. doi:10.3390/plants14223422. https://www.mdpi.com/2223-7747/14/22/3422.

Baraki F, Hadgu F, Berhe G. 2025. Soil fertility management on sesame (*Sesamum indicum* L.) production in Northern Ethiopia: A review. Heliyon. 11(2):e41618. doi:10.1016/j.heliyon.2024.e41618. https://linkinghub.elsevier.com/retrieve/pii/S2405844024176499.

Basar NU, Shahid MA, Primo ASB, Kadyampakeni DM. 2025. Synergies between biostimulants and plant nutrients: a review of ecofriendly nutrient management in crop production. Discov Agric. 3(1):150. doi:10.1007/s44279-025-00345-x. https://link.springer.com/10.1007/s44279-025-00345-x.

Berhane A, Abrha B, Worku W, Hadgu G. 2024. Modeling the response of sesame (*Sesamum* *indicum* L.) to different soil fertility levels under rain-fed conditions in the semi-arid areas of western Tigray, Ethiopia. Heliyon. 10(17):e36084. doi:10.1016/j.heliyon.2024.e36084. https://linkinghub.elsevier.com/retrieve/pii/S2405844024121159.

Borreani G, Peiretti PG, Tabacco E. 2007. Effect of harvest time on yield and pre-harvest quality of semi-leafless grain peas (*Pisum sativum* L.) as whole-crop forage. F Crop Res. 100(1):1–9. doi:10.1016/j.fcr.2006.04.007. https://linkinghub.elsevier.com/retrieve/pii/S0378429006001067.

Boutahiri S, Benrkia R, Tembeni B, Idowu OE, Olatunji OJ. 2024. Effect of biostimulants on the chemical profile of food crops under normal and abiotic stress conditions. Curr Plant Biol. 40:100410. doi:10.1016/j.cpb.2024.100410. https://linkinghub.elsevier.com/retrieve/pii/S2214662824000926.

Comini E, Rubiales D, Reveglia P. 2023. Variability of Fatty Acid Composition and Lignan Content in Sesame Germplasm, and Effect of Roasting. ACS Food Sci Technol. 3(10):1747–1758. doi:10.1021/acsfoodscitech.3c00304. https://pubs.acs.org/doi/10.1021/acsfoodscitech.3c00304.

Duri LG, Paradiso R, Di Mola I, Cozzolino E, Ottaiano L, Marra R, Mori M. 2025. Organic Fertilization and Biostimulant Application to Improve Yield and Quality of Eggplant While Reducing the Environmental Impact. Plants. 14(6):962. doi:10.3390/plants14060962. https://www.mdpi.com/2223-7747/14/6/962.

Fajdetić NR, Božić Ostojić L, Benković R, Zima D, Blažinkov M, Mirosavljević K, Popović B, Benković-Lačić T. 2025. Effects of Three Organic Fertilizers and Biostimulants on the Morphological Traits and Secondary Metabolite Content of Lettuce. Horticulturae. 11(11):1288. doi:10.3390/horticulturae11111288. https://www.mdpi.com/2311-7524/11/11/1288.

Gebregergis Z, Baraki F, Fiseseha D. 2024 May 22. Effects of environmental factors and storage periods on sesame seed quality and longevity. CABI Agric Biosci. doi:10.1186/s43170-024-00247-w. http://www.cabidigitallibrary.org/doi/10.1186/s43170-024-00247-w.

Gesch RW, Johnson BL. 2012. Seed moisture at physiological maturity in oilseed and confectionary sunflower hybrids in the northern U.S. F Crop Res. 133:1–9. doi:10.1016/j.fcr.2012.03.012. https://linkinghub.elsevier.com/retrieve/pii/S0378429012001050.

Kabato W, Hailegnaw N, Mutum L, Molnar Z. 2025. Managing soil health for climate resilience and crop productivity in a changing environment. Sci Total Environ. 1000:180460. doi:10.1016/j.scitotenv.2025.180460. https://linkinghub.elsevier.com/retrieve/pii/S004896972502100X.

Kishk AM. 2024. Effect of plant biostimulants, harvesting dates, and storage periods on Sesame (*Sesamum indicum* L.) seed quality in newly reclaimed soils. Egypt J Agron. 46(2):329–341. doi:10.21608/agro.2024.304521.1464. https://agro.journals.ekb.eg/article_387308.html.

kouighat M, Kettani R, El Fechtali M, Nabloussi A. 2024. Exploring mechanisms of drought-tolerance and adaptation of selected sesame mutant lines. J Agric Food Res. 15:100911. doi:10.1016/j.jafr.2023.100911. https://linkinghub.elsevier.com/retrieve/pii/S2666154323004180.

Langyan S, Yadava P, Sharma S, Gupta NC, Bansal R, Yadav R, Kalia S, Kumar A. 2022. Food and nutraceutical functions of sesame oil: An underutilized crop for nutritional and health benefits. Food Chem. 389:132990. doi:10.1016/j.foodchem.2022.132990. https://linkinghub.elsevier.com/retrieve/pii/S0308814622009529.

Lee J, Jo N-Y, Shim S-Y, Le TYL, Jeong WY, Kwak KW, Choi HS, Lee B-O, Kim S-R, Lee M-G, et al. 2025. Impact of organic liquid fertilizer on plant growth of Chinese cabbage and soil bacterial communities. Sci Rep. 15(1):10439. doi:10.1038/s41598-025-95327-w. https://www.nature.com/articles/s41598-025-95327-w.

Liu Y, Lan X, Hou H, Ji J, Liu X, Lv Z. 2024. Multifaceted Ability of Organic Fertilizers to Improve Crop Productivity and Abiotic Stress Tolerance: Review and Perspectives. Agronomy. 14(6):1141. doi:10.3390/agronomy14061141. https://www.mdpi.com/2073-4395/14/6/1141.

Matthews S, Siddiqui Y, Ali A. 2025. Unleashing the power of bio-stimulants for enhanced crop growth, productivity, and quality: a comprehensive review. J Plant Nutr. 48(4):703–725. doi:10.1080/01904167.2024.2412736. https://www.tandfonline.com/doi/full/10.1080/01904167.2024.2412736.

Moreno L, Santos AF, Tubbs RS, Grey TL, Monfort WS, Lamb MC, Pilon C. 2024. Physiological components of seed quality in runner-type peanut during seed formation. Agron J. 116(1):189–201. doi:10.1002/agj2.21506. https://acsess.onlinelibrary.wiley.com/doi/10.1002/agj2.21506.

Neumann G, Nawaz F, Weinmann M, Arbona V, Balestrini R, Pagliarani C, Gonzalez-Guzman M. 2024. Editorial: Enhancing sustainable crop production: biostimulants and biotechnological approaches in challenging climates. Front Plant Sci. 15. doi:10.3389/fpls.2024.1534774. https://www.frontiersin.org/articles/10.3389/fpls.2

024.1534774/full.

Norouzi Z, Nateghi L, Rashidi L, Movahhed S. 2025. Increasing the bioactive properties of sesame seed meal as a valuable protein source through the enzymatic hydrolysis. Food Biosci. 68:106790. doi:10.1016/j.fbio.2025.106790. https://linkinghub.elsevier.com/retrieve/pii/S2212429225009666.

Oboulbiga EB, Douamba Z, Compaoré-Sérémé D, Semporé JN, Dabo R, Semde Z, Tapsoba FW-B, Hama-Ba F, Songré-Ouattara LT, Parkouda C, et al. 2023. Physicochemical, potential nutritional, antioxidant and health properties of sesame seed oil: a review. Front Nutr. 10. doi:10.3389/fnut.2023.1127926. https://www.frontiersin.org/articles/10.3389/fnut.2023.1127926/full.

Prashar D, Singh A, Dhama V, Singh PK, Kumar M, Kumar S, Pandey D, Verma G. 2025. Effect of Organic and Inorganic Fertilizers on Crop Yield and Soil Fertility: A Comprehensive Review. J Exp Agric Int. 47(2):16–22. doi:10.9734/jeai/2025/v47i23261. https://journaljeai.com/index.php/JEAI/article/view/3261.

Samijan, Minarsih S, Jauhari S, Basuki S, Susila A, Nurwahyuni E, Hindarwati Y, Supriyo A, Aristya VE. 2023. Revitalizing sub-optimal drylands: Exploring the role of biofertilizers. Open Agric. 8(1). doi:10.1515/opag-2022-0214. https://www.degruyter.com/document/doi/10.1515/opag-2022-0214/html.

Sanni GBTA, Ezin V, Chabi IB, Missihoun AA, Florent Q, Hamissou Z, Niang M, Ahanchede A. 2024. Production and achievements of *Sesamum indicum* industry in the world: Past and current state. Oil Crop Sci. 9(3):187–197. doi:10.1016/j.ocsci.2024.06.006. https://linkinghub.elsevier.com/retrieve/pii/S2096242824000435.

Seadh SE, Badawi MA, EL-Abady MI, EL-Saidy A. 2007. How varieties and harvesting dates of sesame affect seed yield and quality. J Soil Sci Agric Eng. 32(12):10811–10823. doi:10.21608/jssae.2007.201811. https://jssae.journals.ekb.eg/article_201811.html.

Shah IH, Jinhui W, Li X, Hameed MK, Manzoor MA, Li P, Zhang Y, Niu Q, Chang L. 2024. Exploring the role of nitrogen and potassium in photosynthesis implications for sugar: Accumulation and translocation in horticultural crops. Sci Hortic (Amsterdam). 327:112832. doi:10.1016/j.scienta.2023.112832. https://linkinghub.elsevier.com/retrieve/pii/S0304423823010002.

Smith MR, Rao IM, Merchant A. 2018. Source-Sink Relationships in Crop Plants and Their Influence on Yield Development and Nutritional Quality. Front Plant Sci. 9. doi:10.3389/fpls.2018.01889. https://www.frontiersin.org/article/10.3389/fpls.2018.01889/full.

Sofian M, Raksun A, Handayani BS, Zulkifli L. 2025. Effect of NPK Fertilizer and Liquid Organic Fertilizer Lamtoro Leaves (*Leucaena* leucocephala spp. leucocephala) on The Growth of Cayenne Peppers (*Capsicum frutescens* L.). J Biol Trop. 25(3):4618–4633. doi:10.29303/jbt.v25i3.10031. http://jurnalfkip.unram.ac.id/index.php/JBT/article/view/10031.

Sripathy K V., Groot SPC. 2023. Seed Development and Maturation. In: Seed Science and Technology. Singapore: Springer Nature Singapore. p. 17–38. https://link.springer.com/10.1007/978-981-19-5888-5_2.

Tang Q, Wang G, Zhao L, Song Z, Li Y. 2023 Dec. Response of yield, root traits and plasticity of nitrogen-efficient cultivars of drip-irrigated rice to a nitrogen environment. J Integr Agric. doi:10.1016/j.jia.2023.12.014. https://linkinghub.elsevier.com/retrieve/pii/S2095311923004616.

Usman S. 2024. Soil and water management perspectives for tropical and dryland areas of Africa. Soil Stud. 13(2):104–118. doi:10.21657/soilst.1601786. http://dergipark.org.tr/en/doi/10.21657/soilst.1601786.

Wang J, Li H, Wang Q, Huang X, Hu W, Wang S, Zhou Z. 2023. Effects of phosphorus application on carbohydrate metabolism in cottonseed kernel during the key development period provided a new insight for phosphorus management in cotton production. Ind Crops Prod. 191:115972. doi:10.1016/j.indcrop.2022.115972. https://linkinghub.elsevier.com/retrieve/pii/S0926669022014558.

Wei J, Zhang X, Li G, Fu K, Yan M, Li Cheng, Li Chunyan. 2025. Phosphorus Alters the Metabolism of Sugars and Amino Acids in Elite Wheat Grains. Plants. 14(20):3152. doi:10.3390/plants14203152. https://www.mdpi.com/2223-7747/14/20/3152.

Yosilia R, Joevira AE, Winandari OP. 2025. The effect of liquid organic fertilizer (lof) derived from *leucaena* leaves (*Leucaena* leucocephala) and pineapple peels (*Ananas comosus* L.) on pak choi (Brassica rapa subsp. chinensis) Growth. J Agrotropika. 24(2):375–386. doi:10.23960/ja.v24i2.10407. https://jurnal.fp.unila.ac.id/index.php/JAT/article/view/10407.

Zhang Y, Wang X, Liu B, Liu Q, Zheng H, You X, Sun K, Luo X, Li F. 2020. Comparative study of individual and Co-Application of biochar and wood vinegar on blueberry fruit yield and nutritional quality. Chemosphere. 246:125699. doi:10.1016/j.chemosphere.2019.125699.