Mekelle University

Effect of Sowing Methods and Seed Rates on Growth, Yield and Yield Component of Black Cumin (*Nigella sativa L.)* at Endamekony district, Southern Tigray, Ethiopia

By:

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College of Dry Land Agriculture and Natural Resource

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DECLARATION

I, Birhanu Reda, here by present for consideration by the Plant and Horticultural Sciences Department within the College of Dryland Agriculture and Natural Resources at Mekelle University, my thesis in partial fulfillment of the requirement for the degree of Masters in Horticulture is entitled as Effect of sowing methods and seed rates on growth, yield and yield components of black cumin (*Nigella Sativa L.*) at Endamekony District, Southern Tigray, Ethiopia. I sincerely declare thathis thesis is my own work and that all sources of materials used for writing it has been accordingly acknowledged. No other person has published a similar study which I might have copied, and at no stage will this be published without my consent and that of the Plant and Horticultural Sciences Department.

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ABSTRACT

Black cumin (*Nigella sativa L.*) *is an important medicinal and commercial crop in Ethiopia. However, its productivity remains low due to lack of appropriate agronomic practices, particularly sowing methods and seed rates. A field experiment was conducted using a randomized complete block design (RCBD) in a factorial arrangement with three replications to evaluate the effects of sowing methods and seed rates on growth, yield and yield components of black cumin. The factors were; sowing methods and seed rates (5, 7.5, 10 & 12.5 kg ha^{-1} for row sowing) and (12.5, 15, 17.5, 20 & 22.5 kg ha^{-1} for broadcasting). DE, DF, DM, PH, NBPP, NCPP, NSPC, 1000 seed weight, YPP and YPH was collected and analyzed using GenStat 18 software. Result showed that, sowing method and seed rate for row sowing was statistically significant (at $p < 0.05$) on most yield and yield components except in days to maturity. In addition, in broadcast sowing with different seed rates on PH, NBPP, NCPP, NSPC, 1000 SWT and YPH were significant. In row sowing, yield increased from 1383 to 2137 kg ha^{-1} as seed rate increased from 5 to 10 kg ha^{-1}, then declined to 1647 kg ha^{-1} at 12.5 kg ha^{-1}. In broadcast sowing, yield increased from 1232 to 1714 kg ha^{-1} as seed rate increased from 12.5 to 20 kg ha^{-1}, but declined to 1549 kg ha^{-1} at 22.5 kg ha^{-1}. The interaction effect was significant on NBPP, DM, NCPP and YPH.* The highest yield (2137 kg/ha) was obtained from sr3 and followed by sr2 under row sowing (2122 kg/ha). *The study concludes that row sowing with a seed rate of 10 kg ha^{-1} as a main effect and interaction effect and broadcast sowing with 20 kg ha^{-1} as a main effect are optimal for maximizing black cumin yield. These findings provide practical recommendations for improving black cumin productivity and support evidence-based decision-making for farmers, researchers, and policymakers. However, further research across different agro-ecological zones and seasons is recommended to validate and fine-tune these agronomic practices.*

Keywords: Black Cumin, Seed Rate, Sowing Method, Yield

DEDICATION

This thesis is dedicated to the memory of my beloved family.

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LIST OF ABBRIVATIONS

ATVET	Agricultural Technical Vocational Education And Training
DAP	Di-ammonium phosphate
EIAR	Ethiopian institute of agricultural research
FAO	Food And Agricultural Organization Of The United Nations
NGO	None Governmental Organizations
NPK	Nitrogen, Phosphoros and Potassium fertilizers
Kg ha^{-1}	Killo Gram per Hectare
LSD	Least Significance Difference
M.A.S.L	Meter Above Sea Level
MARC	Mekelle Agricultural Research Center
MOA	Ministry of agriculture
RCBD	Randomized Complete Block Design

BIOGRAPHICAL SKETCH

The author, Birhanu Reda, was born on March 10, 1989 in Ofla Wereda, Southern Zone of Tigray, North Ethiopia from his mother w/ro Sindayo Girmay and his father Ato Reda Fantay. He attended his elementary schools (grade one to eight) at Fala elementary school from 1998-2003, and high school education at Korem comprehensive secondary school from 2004-2007. After successful completion of high school education, he joined Mekelle University in 2008 and graduated with the degree of Bachelor of science (BSc) in Horticulture in 2010.

Then after, he graduated he was employed by Ofla wereda Agricultural and Rural Development office as development agent (DA) for plant science in November 2012 and he worked for one year. In December 2013, he joined Maichew Agricultural Technical Vocational Education and Training Collage until he joined the School of Graduate Studies of Mekelle University in 2019 to pursue a study leading to the degree of Master of Science (MSc.) in Horticulture.

CHAPTER 1. INTRODUCTION

1.1. Background Information

Black cumin (*Nigella sativa* L.) is an annual seed spice and medicinal herb from the Ranunculaceae family, originally native to Egypt and the East Mediterranean. Later it spreads to Europe, Asia, and Africa (Zohary et al., 2012). Although native to the Mediterranean region, it is now extensively grown in various parts of the world, including Ethiopia (Kahaliw et al., 2021). Ethiopia is a significant producer and exporter of black cumin, alongside countries like India, Sri Lanka, Bangladesh, Afghanistan, Pakistan, Egypt, Iran, Iraq, Syria, and Turkey (Samima et al., 2018). Ethiopian black cumin exports predominantly go to Arabic countries, constituting 98% of the national exports (Orgut, 2007). According to the Ethiopian Investment Agency Report, Ethiopia produced 18 thousand metric tons of black cumin seeds in the 2015 cropping year (EIC 2016). The main producing regions in Ethiopia include Amhara, Oromia, SNNP, and Gambella (Teshome and Anshiso, 2019). In Dembia, South Gonder, Shirka in Arsi Zone, and Goro in Bale Zone, black cumin is a major crop (Alemaw et al., 2010). The plant is known as black seeds or 'Tikur azmud' in Amharic (Habtewold et al., 2017) and is used to prepare 'Berbere' for traditional Ethiopian dishes like 'wot' and to preserve butter (Hedberge et al., 2003).

Black cumin grows in rain-fed conditions at altitudes between 1500 and 2400 meters above sea level on heavy black soils, similar to those used for growing teff, chickpeas, and lentils (Girma et al., 2015). It prefers loamy sand soils with a pH of 7.0 to 7.5 (Datta et al., 2001; Orgut, 2007).

Demand for black cumin seed and oil is rising in local and national markets, making it the second most important cash crop after ginger (Teshome and Anshiso, 2019). According to the Spice Sector Strategy

Committee (2010), the export value was 1.18 USD per kg, while imports were 5.80 USD per kg, highlighting a significant opportunity for increased production. Ethiopia holds approximately 12% of the global market share, but 99% of the produce is consumed domestically.

Black cumin seeds are also a valuable source of essential oils with applications in the food, cosmetic, and medicinal industries (Kahaliw et al., 2021). The plant is highly valued for its medicinal properties, with traditional uses in treating various diseases. Black cumin is considered a native crop in Ethiopia, where it has been used for centuries. It has demonstrated numerous biological activities, including antibacterial, antifungal, antioxidant, anticancer, and anti-inflammatory effects (Ahmad et al., 2013; Kahaliw et al., 2021).

The total area cultivated black cumin (*Nigella sativa L.*) production by subsistence farmers in Ethiopia is estimated to be 5,336 hectares, producing approximately 9,533 tons annually, with an average productivity of 0.79 tons per hectare. Black cumin is mainly grown in the Amhara**,** Oromia**,** and Southern Nations, Nationalities, and Peoples (SNNP) regions by smallholder farmers. Although the crop is likely cultivated in Tigray as well, detailed and region-specific data for Tigray is currently limited (Tsegay et al., 2022). According to the CSA's 2014/15 report on the area and production of major crops (private peasant holdings, Meher season), the total area cultivated in the SNNP, Oromia, and Amhara regions was 13,672.52 hectares, with a total production of 42,012 quintals. Nevertheless, the national average yield for black cumin is reported to be 0.79 t/ha (Kifelew et al., 2017), while Zigyalew Gashaw (2020) reported a lower yield of 0.64 t/ha, significantly below the global average and major producers like India (2.2 t/ha). High yields of up to 1.7 t/ha at Adet and 1.8 t/ha at Woreta have been achieved (Adam Abebe, 2006). Low yields are attributed to the limited productivity of varieties (Ermias Assefa et al., 2015) and poor agronomic practices (Hammo, 2008).

The key factors limiting black cumin production includes lack of improved seeds, inadequate fertilizer use, postharvest handling issues, poor agricultural practices and extension services, and marketing challenges (Yosef, 2008). Modern agricultural technologies such as row planting, inorganic fertilizers and improved seeds are underutilized (Chanyalew et al., 2010).

Proper planting methods and planting density are crucial for maximizing crop yield, as it ensures that environmental resources are fully utilized and minimizes competition among plants (Alizadeh & Koucheki, 1995). Given the rising demand for black cumin for local consumption, medicinal use, and export, optimizing production methods and technology is vital.

1.2. Statement of the Problem and Justifications

Black cumin is cultivated across various regions of Ethiopia at different altitudes, indicating its adaptability to diverse agro-ecological conditions. Its growing significance increased from the rising local demand, its medicinal uses, export potential, contribution to crop diversification, income generation, and its ability to mitigate crop failure risks. These factors position black cumin as a valuable crop for Ethiopia's smallholder farmers (Science Publishing Group, 2015; Springer Open, 2020).

Despite the favorable environmental conditions for its cultivation, black cumin is rarely grown as a sole crop in Ethiopia. It remains underutilized due to inadequate identification of suitable varieties, sowing methods, and seed rates. Additionally, there has been limited focus on pest management and overall agricultural practices. Even though, the production and area coverage of black cumin have been increasing, but its productivity is still very low in most production areas. The low yields are mainly due to the low productivity of the varieties (Ermias Assefa et al. 2015) and the poor agronomic practices used by the farmers (Hammo, 2008). Key challenges contributing to this low productivity include a lack of advanced technology, reliance on traditional methods, insufficient awareness of the crop's value, and a shortage of processing facilities and markets.

Limited research has been conducted to assess black cumin’s yield potential and to develop optimal agricultural practices. Evidence shows that different planting methods can increase seed yield by up to 38% compared to traditional broadcasting (Mahmood et al., 2012). Optimal plant density ensures that plants can fully utilize environmental resources and minimize competition (Alizadeh & Koucheki, 1995).

In Southern Tigray, particularly at Endamekony district, there is a significant research gap concerning black cumin, especially aspects such as improved varieties, planting techniques, seed rates, and related agronomic practices. Furthermore, no studies have been done on seed rate and sowing methods for black cumin production in this area. Therefore, it is essential to investigate the appropriate seed rate, sowing method to enhance black cumin yields. Thus, the study was conducted to evaluate the effects of sowing methods and seed rates on the yield and yield components of black cumin.

1.3. Research Hypothesis

Null Hypothesis (H0): Sowing methods and seed rates not significantly affects yield and yield components of black cumin.

1.4. Objectives

1.4.1. General Objective:

To evaluate the effect of sowing methods and seed rates on growth, yield and yield components of black cumin.

1.4.2. Specific Objectives:

To investigate the effect of sowing methods on growth, yield and yield components of black cumin.

To determine the effect of seed rate on growth, yield and yield component of black cumin.

To evaluate the interaction effect of sowing method and seed rate on yield and yield component of black cumin.

1.5. Significance of the study

Black cumin is a crucial crop valued for its various uses, including household consumption, economic benefits, and medicinal purposes. In Ethiopia, smallholder farmers in the highlands benefit from black cumin cultivation under both irrigated and rain-fed conditions. However, this does not apply to the highlands of southern Tigray, particularly in the Endamekony District. Research into black cumin, specifically identifying optimal planting methods and seed rates, is essential to enhancing production and productivity for small-scale farmers.

This study provides additional insights into how planting methods and seed rates affect black cumin yield, benefiting small-scale farmers, researchers, investors, and NGOs. By establishing the best practices for plant density and planting techniques, this research aimed to boost black cumin production and productivity in the region. Furthermore, the findings serve as a reference for future studies at the Woreda, regional, and even national levels.

1.6. Scope and Limitations of the Study

This study specifically evaluated the effects of sowing methods and seed rates on the yield of black cumin, among the various crops cultivated in the study area. The focus is restricted to vegetables and cereal crops, as there is a limited understanding of the importance and agronomic practices associated with spice crops, particularly black cumin. Although the research could have been extended to different locations within the southern zone of Tigray, it was confined to Maichew and its surrounding areas due to financial constraints.

Despite these constraints, the findings of this study may serve as a valuable reference for similar studies in other areas.

CHAPTER 2. LITERATURE REVIEW

2.1. Origin and Distribution of Black Cumin

Black cumin (Nigella sativa L.) has a rich history of cultivation across the world. Its exact origin is debated, with various scholars proposing different regions, such as North Africa, South and Southwest Asia, and Southern Europe (Kulloli, 2016; Lal, 2018; Sultana et al., 2015). Some sources suggest that South and Southwest Asia is its primary native area (Kulloli, 2016; Sultana et al., 2015). In Ethiopia, black cumin cultivation is believed to date back to the era of the Queen of Sheba (Habtewold et al., 2017). Although the precise date of domestication is unclear, the plant was already cultivated over 3000 years ago, with black cumin seeds discovered in the tomb of Egyptian King Tutankhamun (Hammond, 2012). Black cumin spread to North Africa, the Middle East, and South Asia, where it became an integral part of traditional medicine. The plant was later introduced to Europe, North America, and Eastern Europe (Kulloli, 2016), where it has been used as a spice in bread and cakes (Heiss and Oeggl, 2005). The plant is commonly known by various names worldwide, including black cumin, fennel flower, and Roman coriander, and in Ethiopia, it is called "Gurraa" (Afan Oromo), "Tikur Azmud" (Amharic), and "Awoseda" (Tigrigna) (Habtewold et al., 2017).

2.2. Growth and Development of Black Cumin

Black cumin is an upright, annual herb that grows between 20 to 60 cm tall, with a branching stem (Girma et al., 2016). The flowers are hermaphroditic and are typically cross-pollinated, with the flowering process starting at the top of the plant and moving downward. Germination occurs 10 to 15 days after sowing, and flowering generally begins around 100 days after planting in temperate regions. The plant’s flowering is protandrous, with pollination primarily by insects (Miheretu, 2016). Black cumin’s seeds are triangular, rough on the surface, black on the outside, and white inside, with a mild odor and bitter taste (Qaiser, 2006). Cultivars exhibit considerable morphological and physiological diversity (Shariq et al., 2015).

2.3. Economic Significance of Black Cumin

Black cumin has been recognized for its economic value throughout human history, serving as a spice, traditional herb, food preservative, and flavor enhancer in baked goods (Ermumucu & Sanlier, 2017). Its local consumption and various uses—including medicinal oil and oleoresin—along with its role in crop diversification, income generation, and export markets, make black cumin an ideal crop for Ethiopia's smaller landholdings (Dessalegn & Wubeshet, 2018).

Historical and traditional references to black cumin are well-documented in ancient texts and historical records (Botnick et al., 2012). Its medicinal significance is particularly notable, with ancient herbalists referring to it as a “miracle herb,” “universal healer,” “holy herb,” and “herb from heaven” (Aftab et al., 2018; Dubey et al., 2016; Tariq, 2008; Yarnell & Abascal, 2011). Scholars highlight its value as a natural remedy for various ailments, including its effectiveness as an antimicrobial agent, antioxidant, and cognitive enhancer (Abdallah, 2017; Paseban et al., 2020; Sahak et al., 2016; Tavakkoli et al., 2017). Black cumin oil is prized in nutritional and pharmaceutical applications for its active components, such as tocopherol, phenolic compounds, and thymoquinone, which contribute to its health benefits, including antioxidant properties (Rohman et al., 2019).

Black cumin plays a crucial role in supporting immune and pulmonary health, as well as in managing conditions like diabetes mellitus, breast cancer, dermatological issues, dyspepsia, osmotic balance, and dehydration. Research on its gastroprotective effects shows that its benefits are largely due to its antioxidant activity and its ability to stimulate gastric mucus secretion and enhance total hexose in the gastric mucosa (Paseban et al., 2020). Beyond its flavor, black cumin is valued for its nutritional content. Studies reveal that its essential oil contains significant amounts of carbohydrates, proteins, and lipids (Dubey et al., 2016). The fixed oil is rich in fatty acids, including myristic, myristoleic, palmitic, stearic, oleic, linoleic, linolenic, eicosenoic, arachidonic, behenic, and dihomolionolenic acids, along with various saturated, monounsaturated, and polyunsaturated fatty acids (Margout et al., 2013; Sultan et al., 2009). Key active constituents in black seed essential oil include thymoquinone, dihydro-thymoquinone, t-anethole, α-thujene, thymol, and secondary compounds such as α-pinene and β-pinene (Khalid, 2018). The seed oil is also rich in essential nutrients like magnesium, phosphorus, calcium, and potassium, with smaller amounts of sodium, manganese, zinc, iron, and copper (Sultan et al., 2009).

2.4. Agro-Ecological Requirements of Black Cumin

The growth and development of black cumin are significantly influenced by environmental factors such as climate and soil conditions. These factors affect plant physiology, the production of active compounds, and the yield and quality of essential oils (Malhotra, 2008). For medicinal and aromatic plants like black cumin, the quality of the crop is as crucial as the quantity; plants that do not meet specific quality standards are not viable even if they yield abundantly. Therefore, black cumin should only be cultivated in regions where the local ecological conditions are suitable (Girma et al., 2016).

In Ethiopia, black cumin is typically grown at elevations between 1750 and 2200 meters above sea level in the mid- to highland areas (Gezahegn and Sintayehu, 2016). It performs well in semi-arid regions with well-drained black vertosols that retain some moisture, even during drought periods (Ermias et al., 2015). An optimal growing season would include rainfall between 120 and 400 millimeters. Black cumin prefers temperatures ranging from 0 to 25°C, with 12-14°C being ideal (Malhotra, 2008). While it requires warm temperatures for rapid growth and full sun for maximum flowering, it can tolerate partial shade, though flowering will be reduced (Killinger, 2018). Consistent water availability throughout the growth period is crucial for timely flowering and seed development, despite the plant's low water needs (Habtewold et al., 2017). Black cumin thrives in well-drained soil but can adapt to various soil types, with sandy loam enriched with microbiological activity being particularly ideal (Killinger, 2018). The plant prefers areas with heavy rainfall and sloping soils or moderate rainfall with flat, well-drained soils. It requires a soil PH of 7.0 to 7.5 (Shariq et al., 2015). Black cumin's germination is highly sensitive to temperature, with 23°C being optimal, though it can also germinate in highly saline conditions due to its halophytic nature (Alshammari, 2017).

2.5. Crop Establishment and Agronomic Practices

Effective cultivation practices are crucial for enhancing yield and profitability (Willer and Yussef, 2007). Key crop management tasks for black cumin include site preparation, land tillage, sowing, weeding, thinning, supplemental irrigation, fertilization, and pest and disease control (Zapotoczny et al., 2019).

Land preparation for black cumin should begin at least a month before sowing. The soil should be plowed 2-3 times, depending on its characteristics (Ermias et al., 2015). Beds should be spaced 120-130 cm apart to facilitate water drainage and reduce disease risks such as wilt and damping-off (Habtewold et al., 2017). Sowing is done directly, considering factors like sowing timing, method, and seed rate. The recommended seed rate is 15-20 kg/ha for broadcasting and 5-7.5 kg/ha for drilling. Seeds are typically sown directly in the field due to their fragility, but they can also be started in peat blocks. Row spacing of 15-40 cm is common, and sowing can be done by broadcasting, in rows, or on beds. Bed sowing generally results in the highest yields (Mahmood et al., 2012). Seeds should be soaked overnight to aid germination. Black cumin is usually drilled and then thinned to the recommended spacing (Zapotoczny et al., 2019).

Propagation is by seed, with sowing times varying based on local conditions. It can be sown during the rainy season from August to September or through irrigation from April to May. The recommended seed rate is 5-7.5 kg/ha at a depth of 2 cm. Germination takes 10-15 days in temperate climates, with thinning to 20 cm recommended after 20 days. Flowering starts about 100 days after sowing, with seed maturity occurring 50 days later. In warmer climates, flowering may begin 8-10 weeks post-germination.

Though black cumin requires relatively low water, sufficient water supply during the growing season is crucial for flower development, seed setting, and yield (Ariafar and Forouzandeh, 2017). Ceasing irrigation during budding can increase essential oil, carvone, and thymoquinone content, though it does not affect total yield. Hence, full irrigation is critical for maximizing seed yield (Hadi et al., 2016).

While black cumin has low fertilizer needs, inadequate fertilization can reduce yield. In Ethiopia, applying 60 kg/ha of nitrogen has been shown to enhance yield. For optimal results, NPK applications of 50, 40, and 20 kg/ha, along with 10-15 tons/ha of farmyard manure, are recommended (Habtewold et al., 2017). Fertilizer application positively impacts various plant parameters (e.g., plant height, branch number, chlorophyll content) and yield (e.g., capsule count, seed count, yield per hectare). The highest yields are achieved with a combination of organic and inorganic fertilizers (Sen et al., 2019; Yousuf et al., 2018).

Effective weed, disease, and pest management is also essential for maximizing yield. Regular weeding, about 3-5 times every 20-25 days using a hand hoe, is necessary to prevent weed competition, which can reduce yields by 60-85% (Datta et al., 2012; Habtewold et al., 2017). Proper management of diseases and pests is crucial for optimal yields (Merga et al., 2019).

Black cumin requires 58-62 days from sowing to flower bud initiation and 78-87 days for flower opening. Harvesting should occur before seed shattering, typically 135-150 days after sowing, when capsules turn brown (Habtewold et al., 2017). Black cumin matures determinately, and harvesting involves uprooting plants, bundling, drying them upright, threshing, and winnowing to separate seeds from impurities (Tiru et al., 2017). Seeds should be dried and stored in cool, dry conditions (Datta et al., 2012).

2.6. Production and Productivity of Black Cumin

Black cumin is cultivated across various regions worldwide, including the Middle East, Europe, Asia, Syria, Turkey, and Saudi Arabia (Thilakarathna et al., 2018). Ethiopia has a long history of growing black cumin, with around 21,550 hectares dedicated to its cultivation in 2007, yielding an estimated 17,072 tons annually (Habtewold et al., 2017). Ethiopian black cumin seeds are exported to numerous countries, such as Saudi Arabia, Israel, Malaysia, France, Pakistan, Austria, Tanzania, Germany, and Indonesia. The export of dry seeds or essential oils contributes to the country's foreign revenue, enhancing its economy through both import substitution and export activities (Girma et al., 2016). Ethiopian black cumin seeds are notable for their high thymol content, up to 50%, which makes them valuable for the healthcare and medicinal sectors (Ebrahim et al., 2019). The essential oil's high thymoquinone content also presents significant opportunities for use in the cosmetics industry (Thilakarathna et al., 2018).

Despite its historical significance, the production of black cumin in Ethiopia has been relatively low, especially when compared to other countries. For instance, in 2012, Ethiopia produced 9,533 tons from 5,336 hectares of land across small-scale farmers' fields, resulting in lower overall production compared to other black cumin-producing nations (MoA,2012).

Although there has been an increase in the area cultivated and production of black cumin, productivity remains below 0.64 tons per hectare (EIAR, MoA, FAO, 2014). Some studies have reported higher yields under optimal management, with figures reaching 1.5 tons per hectare (Girma et al., 2008) and up to 1,716.15 kg/ha at Adet and 1,869.56 kg/ha at Woreta (Adam, 2006). However, these yields are still lower compared to countries like India, where productivity can reach 2.2 tons/ha. Contributing factors to low productivity include the use of low-yielding genotypes, less productive released varieties (such as Dirishaye, Eden, and Deribera), poor crop management, high weed prevalence, disease and insect damage, insufficient planting density, and inadequate postharvest handling, marketing, and processing techniques (Yosef, 2008; Ermias et al., 2015).

Among the factors influencing yield, plant density is crucial. Optimal plant density allows plants to fully utilize environmental resources (water, air, light, and soil) while minimizing intra-specific competition. Ideal plant spacing ensures complete resource use and limits both intra- and inter-species competition (Alizadeh and Koucheki, 1995). Different planting methods have been shown to improve seed yields by up to 38% compared to direct sowing methods (Mahmood et al., 2012).

2.7. Role of Seed Rate on Yield and Yield Components of Black Cumin

Seed rates directly influence plant density, which has a cascading effect on other growth parameters of black cumin. Increased seed rates typically lead to higher plant population density but may result in competition for light, water, and nutrients. This can reduce individual plant growth but may increase the overall seed yield per unit area if managed well.

Plant Height: Studies have shown that seed rate can affect plant height in black cumin. At higher seed rates, competition for resources can lead to reduced plant height, as plants may grow taller in an attempt to outcompete neighboring plants for light (Mohammed et al., 2018). However, optimal seed rates often result in well-balanced growth with moderate plant height and better yield potential (Shrestha et al., 2022).

Number of Branches: The number of branches is another important yield determinant in black cumin. Higher seed rates generally lead to a reduction in the number of branches per plant due to increased competition for nutrients and space (Mekonnen et al., 2021). However, this trade-off is offset by the increase in plant population density, which may result in a higher total yield per hectare.

Number of Seeds per Plant: A key component of seed yield is the number of seeds produced per plant. Studies indicate that lower seed rates result in fewer plants per unit area but higher seed production per plant, whereas higher seed rates may lead to lower seed numbers per plant due to overcrowding (Alemayehu et al., 2020). Optimal seed rates should balance seed production per plant with overall plant density to maximize yield.

Seed Weight: Seed weight, often considered a measure of seed quality, is also influenced by seed rate. At higher seed rates, the plants may produce lighter seeds due to limited space and resources for seed development (Abd El-Latif et al., 2018). Conversely, lower seed rates allow plants to develop larger, heavier seeds due to reduced competition. However, excessive reductions in seed rate may lead to underutilization of land area and lower overall yield.

Seed yield in black cumin is a function of both the number of plants per unit area and the yield per plant. Research has shown that there is an optimal seed rate range that maximizes yield while minimizing negative competition effects. At optimum rate, plants have enough space to develop well while still maintaining a sufficiently high plant population density to enhance overall yield.

However, it is essential to note that the ideal seed rate can vary based on environmental factors such as rainfall, soil fertility, and altitude. For example, in more fertile soils, slightly higher seed rates may be beneficial, while in less fertile soils, lower seed rates may help reduce competition for nutrients (Tsegaye et al., 2020).

2.8. Role of sowing methods (Row sowing vs Broadcasting) on growth, yield and yield components of black cumin

One of the key agronomic practices that influence the yield of black cumin is the planting method. The two most common planting methods row planting and broadcasting differ in their impact on seed germination, plant growth, and ultimately seed yield. The choice of planting method can influence several yield components, such as plant height, number of branches, number of seeds per plant, seed weight, and ultimately, the total seed yield per unit area. In Ethiopia, studies have suggested that optimizing planting methods could significantly enhance black cumin productivity, but the effects vary across different agro-ecological zones. This paper reviews the findings of recent studies conducted in Ethiopia to compare these planting methods.

The sowing method plays a significant role in influencing plant growth dynamics and resource utilization. The spacing between plants in row sowing ensures that each plant has adequate access to sunlight, water, and nutrients, whereas broadcasting often results in uneven plant distribution and higher competition for these resources. The following are key aspects of how planting methods affect black cumin yields and yield components.

Plant Population and Growth: Row sowing generally results in a more controlled plant population, allowing for better spacing between plants, which promotes healthier growth. Studies have shown that row planting encourages more vigorous growth in black cumin, with plants growing taller, having more branches, and better seed development compared to broadcasting (Alemayehu et al., 2022). Broadcasting, on the other hand, often leads to overcrowding, where plants may be stunted due to competition for light and nutrients.

Seed Germination and Establishment: Seed germination rates are typically higher in row planting because seeds are placed at optimal depths and distances, reducing the risk of uneven germination. In contrast, broadcasting can result in poor seed-to-soil contact, leading to lower germination rates, especially if seeds are dispersed unevenly or too deep (Abd -Latif et al., 2018). Additionally, broadcasting may cause seeds to be sown too densely in some areas, leading to poor establishment in those spots.

Plant Height: The height of black cumin plants is often influenced by the planting method. Row planting encourages taller plants due to better resource allocation and reduced competition for light (Mekonnen et al., 2021). In contrast, broadcasting can result in shorter plants due to overcrowding and competition for light and space, which restricts upward growth. This reduction in plant height under broadcasting is also linked to the limited ability of plants to expand their root systems properly (Mohammed et al., 2020).

Number of Branches: In row planting, each plant has more room to develop additional branches, which are crucial for increasing seed production. A study conducted by Tsegaye et al. (2020) showed that row-planted black cumin had a higher number of branches per plant compared to broadcasted plants. More branches generally translate into more flower heads and seeds, contributing to higher yields.

Seed Yield and Seed Quality: Overall seed yield is significantly higher in row planting compared to broadcasting. This is due to the more efficient use of resources, such as sunlight, water, and nutrients, as well as a reduction in plant-to-plant competition (El-Beltagy et al., 2019). Row planting also results in higher-quality seeds due to better plant health, as plants are not stressed by overcrowding. Broadcasting tends to lead to reduced seed yield and smaller seeds due to the limitations imposed by overcrowded conditions.

Number of Seeds per Plant: The number of seeds per plant is generally higher in row planting because of reduced competition for resources. Black cumin plants in rows can develop fuller seed heads with more seeds per plant (Mekonnen et al., 2021). In contrast, broadcasting often results in fewer seeds per plant, as the plants are not able to grow to their full potential due to overcrowding and resource limitations.

CHAPTER 3. MATERIAL AND METHODS

3.1. Description of the study area

The study was conducted at Maichew Agricultural Poly Technique College experimental field site in the off season with irrigation from February to June 2024. The study area is geographically located approximately 662 km from Addis Ababa and 120 km from Mekelle at an latitude of 12°47' N and longitude of 39°32' E, with an elevation of 2432 meters above sea level. The annual rainfall of the area ranges between 600 and 800 mm, with annual minimum and maximum temperatures recorded at 12.07°C and 24.96°C, respectively (Mekelle meteorology station, 2008). The dominant soil type is Lithosols, with a clay loam texture and pH of 7.64 (Hayelom, 2011). In the southern highlands of Tigray, the traditional system of mixed subsistence farming is common practice, in which the livelihoods of rural farming communities depend on both livestock and crop production. Crop production is mainly dependent on rainfall. However, due to the irregular distribution of rainfall, there is an increasing trend of using irrigation water as the area has high groundwater potential. The main crops grown in the study area include maize (*Zea mays.)*, teff *(Eragrotis tef)*, wheat *(Triticum* ***aestivum****)*, barley *(Hordium vulgare)*, onions (*Allium cepa.)*, garlic *(Allium sativum)* and Tomatoes *(Lycopersicum esculantum)*, *etc.*

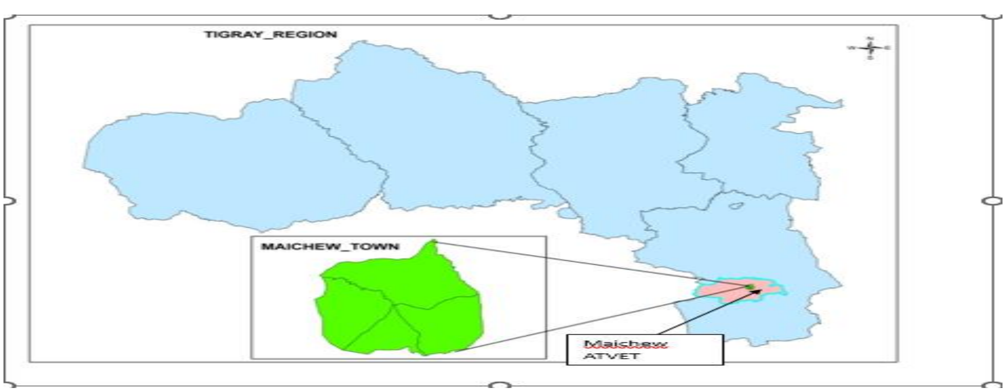

Figure 1. Map of the study area Maichew Agricultural Poly Technique College

3.2. Experimental Design and Treatments

The field experiment was carried out in factorial arrangement using Randomized Complete Block Design (RCBD) with three replications. There were two factors with a total of 9 treatments in this experiment with a total of 27 experimental units. The factors were two sowing methods (row and broadcast) and seeding rates (5, 7.5, 10 and 12.5 for row spacing and 12.5, 15, 17.5, 20, and 22.5 for broadcasting) methods. Black cumin Habru variety has been used as planting material for this study. It was obtained from the Mekelle Agricultural Research Center (MARC). This variety was selected as it was commonly used and available in that center.

Table 1**:** Description of Treatments

Treatment Codes	Seed rate kg ha^{-1}	sowing methods
(T1) = Rsr1	5	Row sowing (R)
(T2) = Rsr2	7.5	
(T3) = Rsr3	10	
(T4) = Rsr4	12.5	
(T5) = Bsr1	12.5	Broadcasting (B)
(T6) = Bsr2	15	
(T7) = Bsr3	17.5	
(T8) = Bsr4	20	
(T9) = Bsr5	22.5	

Rsr = row sowing with seed rates and **Bsr** = broadcasting sowing with seed rates

3.3. Experimental Procedures

The study site was ploughed three times using oxen to achieve the desired tilth, leveled and then divided into sub-plots. The total area of the experimental field was 363 m² (33m *11m), divided into three equal blocks, each containing nine plots. The spacing between blocks and plots was 1 m * 0.75 m respectively. Seeds were sowed using two methods and different seed rates (5, 7.5, 10, 12.5 $kgha^{-1}$ for row and 12.5, 15, 17.5, 20, 22.5 $kgha^{-1}$ for broadcast sowing). The row sowing method involved spacing each row 40 cm apart. Each plot had seven (7) rows in row sawing and the area of each plot was 3m * 3m ($9m^2$). All cultural practices were carried out according to recommendations for black cumin production. Weeding, hoeing was performed manually and the crop was harvested when fully physiological mature.

3.4. Data Collection

Data was collected from the central rows of each plot, with five randomly selected plants per plot (each plot had seven rows from these five central rows was selected) for days to emergence, days to 50% flowering, plant height, number of branches per plant, number of capsules per plant, number of seeds per capsule, days to maturity and 1000 seed weight being counted and measured

Growth and Phenological Parameters:

Days to 50% Emergence (DE): Emergence date was recorded as the number of days from sowing until 50% of seedlings emerged in each plot.

Days to 50% Flowering (DF): The date of 50% flowering was recorded when 50% of the plants in a plot had opened flowers and the period required in days from the date of sowing and date of 50% flowering was calculated and expressed as average number of days to flowering.

Days to 90% Maturity (DM): Measured from sowing to when 90% of the plants in a plot showed physiological maturity (drying of leaves and capsules).

Plant Height (PH): Plant height was measured in centimeter at physiological maturity from the ground level to the tip of plant from five randomly selected plants in each plot and mean value was calculated and expressed in centimeter.

Number of Branches per Plant (NBPP): Number of branches per plant was counted from the randomly selected five plants before physiological maturity and mean value of data were calculated and recorded for each treatment.

Yield and yield component parameters:

Number of Capsules per Plant (NCPP): Number of capsules per plant was counted manually and calculated mean as per plant basis from the five randomly selected plants at maturity stage.

Number of Seeds per Capsule (NSPC): Number of seeds per capsule on well-matured, dried and normal size capsules selected from each of the five randomly selected plants was separated manually and their number was counted on individual capsule basis and average was expressed as number of seed per capsules.

1000 Seed Weight: A composite sample was taken from the yield of five plants and were recorded by counting and weigh 200 seeds first and then the results were converted into 1000 seeds. The 200-seeds of each plot were counted and weighed with a digital electric balance. The converted 1000- seed weight was recorded in gram.

Seed Yield per Plant (YPP): The separated seeds of five selected plant were collected, cleaned, dried and weighed properly. The seed weight per plant was then recorded in gram.

Seed Yield per Hectare (YPH): After drying, cleaning and threshing, total harvested seeds from the central rows of each plot were weighed and the total yield were converted it to kg/ha using the plot area and recorded.

3.5. Data Analysis

All the collected data were checked for normality and subjected to analysis of variance (ANOVA) using GenStat 18 computer software for statistical analysis. The differences among treatment means were compared using the Least Significant Difference (LSD) test at 5% level of significance, as described by Gomez and Gomez (1984).

CHAPTER 4. RESULTS AND DISCUSSION

4.1. Effect of Sowing Methods and Seed Rates on Growth and Phenology of Black cumin

4.1.1. Days to 50% emergence:

The ANOVA result on days to 50% emergence for row sowing with different seeding rates showed significant differences across the treatments, this indicates that seed rate has a significant effect on the number of days required for 50% emergence, which was statistically significant at $p < 0.05$) **(**appendix table 1).

The longest day (14.00 days) for days to 50% emergence was recorded on row sowing with seed rate of 12.5 kg ha^{-1}(Rsr4), while the shorter (12.00) days were recorded from 5 kg ha^{-1} (Rsr1) seeding rate on days to 50% emergence (Table 2).

This indicates as seed rates increase, the time to seedling emergence is often delayed due to factors such as intensified seed-to-seed competition, reduced soil aeration, uneven soil moisture availability, and physical impediments caused by dense planting, which collectively slow germination and early seedling growth. Similar observations have been reported in black cumin (*Nigella sativa*) and related species, where higher seed densities led to delayed emergence and reduced uniformity, largely attributed to overcrowding effects and altered microenvironmental conditions around the seed zone (Khan et al., 2020; Sharma and Kumar, 2018).

Thus, the delay in emergence with increasing seed rate is likely a result of both physical and physiological stress imposed by dense planting conditions. This competition may lead to delayed germination due to the increased density of seeds in the soil, which could reduce the space available for individual plants to germinate and establish themselves (Huang et al., 2020). The findings are in line with those of (Ahmed et al., 2022), who reported that increasing seed rates can delay the germination process due to seedling competition and environmental factors.

The result of the analysis of variance for days to 50% emergence indicated that the effect of seed rate treatments under broadcast sowing was not statistically significant at the 5% level of significance. These results showed that all seed rate treatments under broadcast sowing had similar means, with no significant differences observed between them. Despite some minor variations in the means, none of the seed rate treatments significantly affected the number of days to emergence. The mean days to emergence ranged from 10.67 to 11.67 days, with no notable differences between treatments (Table 2).

Although the seed rate treatments did not show a statistically significant effect on the days to emergence, the results indicate that emergence times were relatively consistent across different seed rates. This consistency suggests that variations in seed rate within the tested range did not considerably influence the time required for emergence. These findings are consistent with similar studies in the literature (Jones et al., 2018) and (Smith et al., 2020) who observed that seed rate variations in broadcast sowing systems did not significantly affect emergence times, supporting the conclusion that emergence is largely unaffected by seed rate within certain limits.

Additionally, Wang et al. (2017) found that seed rate did not influence emergence time in broadcast sowing systems, reinforcing the idea that factors other than seed rate, such as soil conditions or environmental variables, might play a more significant role in determining emergence. The consistency in emergence times across different seed rates also implies that farmers may not need to adjust seed rates dramatically to achieve uniform emergence, potentially simplifying management practices.

4.1.2. Days to 50% Flowering (D50%_F)

The result of analysis of variance for days to 50% flowering on different seed rates of row sowing revealed a significant effect at ($P < 0.05$) (Appendix Table 1).

The results showed that row sowing with seed rate of 12.5 kg ha^{-1} (Rsr4) resulted in the late flowering, with a mean of 81.67 days to reach 50% flowering, significantly different from the row with 5 kg ha^{-1} (Rsr1) and row with seed rates of 7.5 kg ha^{-1} (Rsr2), which had means of 80.00 days each. The row with 10 kg ha^{-1} (Rsr3) had a mean of 81.00 days, which was intermediate and statistically similar to 10 kg ha^{-1} (Rsr3) and 12.5 kg ha^{-1} (Rsr4) but significantly different from 5 kg ha^{-1} (Rsr1) and 7.5 kg ha^{-1} (Rsr2) in (Table 2).

This finding suggests that as the seed rate increases, the time to reach 50% flowering also tends to increase. This could be attributed to changes in plant density, where higher seed rates lead to more competition among plants for resources like light, water, and nutrients. Such competition might delay flowering, as plants under higher densities typically invest more in vegetative growth before transitioning to reproductive stages (Huang et al., 2020). The delay in flowering at higher seed rates observed here is consistent with findings by several researchers who suggest that higher planting densities can reduce the growth rate and delay flowering in various crops (Ahmed et al., 2022).

The result of the analysis of variance (ANOVA) revealed that the effect of different seed rates on days to 50% flowering under broadcast sowing did not show a significant difference at the 5% significance level (Appendix Table 2). The treatments, labeled Bsr1 (broadcasting with 12.5 $kgha^{-1}$) to Bsr5 (broadcasting with 22.5 $kgha^{-1}$) seeding rates, showed no significant differences in days to 50% flowering. Specifically, the treatments, ranging from Bsr1 (12.5 $kgha^{-1}$) to Bsr5 (22.5 $kgha^{-1}$) resulted in similar flowering times, with means 76.00 to 77.67 days. This suggests that seed rate within this range does not significantly influence the timing of flowering. All treatments produced flowers within a narrow range, between 76.00

and 77.67 days, which supports the treatments, within the tested range, does not significantly influence the timing of flowering. This finding is consistent with similar studies that suggest that seed rate may not substantially affect flowering time under certain conditions. Khan et al. (2019) observed that varying seed rates in black cumin cultivation had minimal impact on phenological stages, including flowering time, under uniform growing conditions. Similarly, Rahman and Hossain (2020) reported consistent flowering periods in Nigella sativa across different planting densities, suggesting that intrinsic physiological mechanisms may override seeding rate effects. These studies reinforce that, like in the present findings, factors such as genotype, soil fertility, and climatic conditions may play a more critical role in determining flowering time in black cumin than seed rate adjustments.

Days to 90% Physiological Maturity

The result of the analysis of variance revealed that, across all the seed rates with row sowing method had no statistically significant differences on days to 90% physiological maturity (Appendix Table 1). This suggests that seed rate does not significantly affect the mean days to 90% physiological maturity under the experimental conditions. The highest mean 90% physiological maturity of 127.00 days was observed in row sowing with 12.5 kg ha^{-1} seed rate (Rsr4), while the lowest mean of 125.00 days was recorded in in row sowing with 5 kg ha^{-1} seed rate (Rsr1). These values indicate that the variation in days to 90% maturity across the seed rates with row sowing was minimal (Table 2).

The absence of significant differences in maturity date across seed rates implies that seed density had little to no impact on the rate of maturation in this study. This finding aligns with previous research, such as Rahman et al. (2021), who also reported no substantial effect of seed rate on days to maturity under similar conditions. This lack of impact could be attributed to the fact that factors like temperature, soil fertility, and water availability play a more significant role in determining maturity than the seed rate itself.

Similarly, the result of the Analysis of Variance for 90% physiological maturity indicated that the effect of different seed rates under broadcast sowing method was not statistically significant at the 5% level. The analysis showed that while there were some variations between the treatment means, they were not significant (Appendix Table 2). The 90% physiological maturity across all seed rates were very similar, with mean values ranging from 121.67 to 122.33 days. These findings suggest that seed rate does not have a significant effect on the maturity date, as the plants required approximately the same time to reach maturity, regardless of the applied seed rate. This is consistent with previous studies, such as those by Kumar et al. (2019) and Singh et al. (2017), who also found no significant differences in maturity dates due to varying seed rates under different sowing methods. In both studies, despite changes in seed rates, the maturation period of the crops remained nearly identical, reinforcing the idea that maturity date is largely unaffected by seed rate variation.

4.1.3. Plant Height (PH)

The results of the present study demonstrated that plant height was significantly influenced by the different seed rates, under row sowing showed notable differences between treatments (Appendix Table 1). These findings suggest that seed rate had a substantial impact on plant height, and the variations observed across the treatments were statistically meaningful.

Among the treatments, the highest seed rate Rsr4 (12.5 $kgha^{-1}$) with row sowing resulted in the tallest plants, with a mean height of 74.27 cm, followed by Rsr3 (10 $kgha^{-1}$) at 70.87 cm. In contrast, the lowest seed rate (5 $kgha^{-1}$) with row sowing produced the shortest plants, with a mean height of 61.93 cm (Table 2). These results confirm the significant effect of seed rate on plant height, indicating that higher seed rates tend to produce taller plants. The observed relationship between seed rate and plant height is likely due to the increased availability of resources (e.g., nutrients, water) at higher seed rates, which supports more robust vegetative growth. However, it is also important to note that some studies have suggested that excessively high seed rates may lead to competition for resources, which could limit individual plant growth (Smith et al., 2020).

Sharma et al. (2022) also corroborates these findings, noting that row sowing methods, when combined with higher seed rates, enhanced plant height in black cumin, particularly in regions with favorable soil moisture and irrigation. They emphasized that row planting methods provide better management of plant density, nutrient, and water use, which contributes to the superior growth observed in this study. These studies collectively underscore the advantage of row sowing with higher seed rates for achieving optimal plant height and yield in black cumin.

The effects of seed rate on plant height under broadcast sowing were statistically significant at the 5% level. Plants grown at higher seed rates 22.5 $kgha^{-1}$ (Bsr5) and 20 $kgha^{-1}$ (Bsr4) were significantly taller than those grown at lower seed rates 12.5 $kgha^{-1}$ (Bsr1) and 15 $kgha^{-1}$(Bsr2). Specifically, Broadcasting with higher seed rate Bsr5 (22.5 $kgha^{-1}$) produced the tallest plants, with an average height of 69.37 cm, followed by Bsr4 (20.0 $kgha^{-1}$), which had an average height of 66.80 cm. In contrast, plants grown at Bsr1 (12.5 $kgha^{-1}$) were the shortest, with a mean height of 57.03 cm (Table 2).

Similar studies have reported a positive correlation between higher seed rates and increased plant height. For example, a study by Smith et al. (2018) found that higher seed rates led to taller plants, attributed to heightened competition for light and space. However, the differences in plant height between Bsr4 (20.0 $kgha^{-1}$), (17.5 $kgha^{-1}$) Bsr3, and Bsr2 (15 $kgha^{-1}$) were relatively small; suggesting that plant height may plateau at certain higher seed rates. This observation aligns with the work of Johnson et al. (2020), which also found diminishing returns in plant height at higher seed rates beyond a certain threshold.

The observed increase in plant height with higher seed rates can be attributed to competition for light, space, and nutrients, particularly during the early stages of growth. At higher seed rates, plants tend to grow taller to outcompete their neighbors for light, which is a critical resource for photosynthesis. This competitive growth response is consistent with the findings of previous studies, such as those by Brown et al. (2019), where plants in denser stands exhibited taller growth due to light competition.

However, the relatively small differences in height between Bsr4, Bsr3, and Bsr2 suggest that the effect of seed rate on plant height may plateau at certain higher seed rates, similar to findings in another research by Lee et al. (2017). This indicates that once a certain density is reached, the competitive advantage of taller plants may be reduced, and additional increases in seed rate do not result in a proportional increase in height. These results emphasize that while higher seed rates may initially enhance plant height, there is an optimal range beyond which further increases yield diminishing returns.

Similar research by Davis et al. (2021) has highlighted the diminishing effect of seed rate on plant height after a certain threshold is exceeded. In the current study, this threshold appears to occur at or near Bsr4 (20.0 $kgha^{-1}$), beyond which increasing seed rate does not significantly affect plant height. These findings suggest the need to optimize seed rate for effective resource utilization and plant growth.

Thus, while higher seed rates may enhance plant height in the early growth stages, it is crucial to find a balanced seed rate to avoid unnecessary competition that could limit overall crop productivity. This is supported by similar findings in previous literature, such as by Patel et al. (2015), which advocate for optimal seed rates that maximize plant growth without exceeding the threshold where additional seed rate increase does not provide further benefits.

4.1.4. Number of branches per plant:

The analysis of variance (ANOVA) for the number of branches per plant showed significant differences between seed rates under row sowing. This indicated that the seed rate had a statistically significant impact on number of branches per plant, with the variation observed across treatments being meaningful. Among the treatments, the lowest seed rate, Rsr1 (5 kgha^{-1}), resulted in the highest mean number of branches per plant, with an average mean of 31.33 branches followed by Rsr2 (7.5 kg ha^{-1}), which had 29.00 branches under row sowing. In contrast, the highest seed rate, Rsr4 (12.5 kg ha^{-1}), produced the lowest mean number of branches per plant, with 16.33 branches. Overall, the number of branches per plant decreased as the seed rate increased, ranging from 31.33 at the lowest seed rate to 16.33 at the highest seed rate (Table 2).

The observed decrease in the number of branches per plant with increasing seed rate suggests that competition for resources, such as light, space, and nutrients, plays a crucial role in branch development. At lower seed rates, plants experience less competition for these resources, allowing them to allocate more energy toward branch development, which leads to a higher number of branches per plant. In contrast, at higher seed rates, increased competition among plants likely limits the resources available for each individual plant, resulting in fewer branches.

This finding is consistent with previous research, such as that by Smith et al. (2020), which suggested that lower plant densities promote better branching due to reduced competition for light and nutrients. As plant density increases, competition becomes more intense, and plants may prioritize vertical growth over branching to compete for light and resources, leading to a reduction in the number of branches.

The results of this study highlight the importance of optimizing seed rate to balance plant density and resource allocation. Lower seed rates (5 kg ha^{-1}) seem to favor branching, while higher seed rates (12.5 kg ha^{-1}) may inhibit it due to increased competition. Therefore, managing seed rate carefully could enhance the branching potential of plants.

The results the analysis of variance in the broadcast sowing method showed a highly significant difference on the number of branches per plant across the various seed rate. The lowest seed rate, Bsr1 (12.5 kg ha^{-1}), produced the highest number of branches, with an average of 21.00 branches per plant while, the highest seed rate, Bsr5 (22.5 kg ha^{-1}), resulted in the fewest branches, with an average of 12.67 branches per plant under broadcast sowing (Table 2).

These results suggest that broadcasting, especially at higher seed rates, reduces the number of branches, as the seed rate increased, plants faced greater competition for resources, such as light, water, and nutrients. This is consistent with the observed trend that higher seed rates, such as Bsr5, resulted in fewer branches per plant. Conversely, lower seed rates, like Bsr1, allowed for more space and resources per plant, facilitating better individual development, which promoted greater branching potential.

The significant reduction in the number of branches at higher seed rates (22.5 kg ha^{-1}) in broadcast sowing supports findings from recent studies (e.g., Singh et al., 2023; Kaur et al., 2022), which suggest that increased seed rates can reduce plant branching due to overcrowding. This overcrowding limit access to essential growth factors, such as sunlight and nutrients. In high-density systems, plants may also exhibit more vertical growth, prioritizing height over lateral branching as they compete for sunlight. These findings align with those of Kumar et al. (2023), who reported that lower seed rates resulted in better branching, likely due to reduced resource competition. This less competitive environment promotes favorable conditions for branching. In contrast, higher seed rates tend to prioritize plant survival and vertical growth, leading to reduced lateral development and fewer branches.

Table 2. Mean value of Main effect of different seed rates under row and broadcast sowing on growth and phenology of black cumin

Treatments	Seed rate (kg ha^{-1})	DE	DF	DM	PH	NBPP
Row sowing	**5**	12.00 b	80.00b	125.0a	61.93b	31.33a
	7.5	12.33 b	80.00b	125.7a	64.23b	29.00ab
	10	13.33 a	81.00ab	125.7a	70.87a	23.67b
	12.5	14.00 a	81.67a	127.0a	74.27a	16.33c
LSD		0.881	1.290	2.184	3.548	6.283
CV (%)		3.4	0.8	0.9	2.6	12.5
Broadcast sowing	**12.5**	10.67a	77.67a	121.7a	57.03 c	21.00 a
	15	11.67a	76.00a	122.0a	63.60b	17.67ab
	17.5	11.33a	76.33a	122.3a	66.40ab	18.00ab
	20	11.67 a	76.67a	122.3a	66.80ab	16.67b
	22.5	10.67a	76.33a	122.3a	69.37a	12.67c
LSD		0.972	2.048	1.417	4.477	3.859
CV (%)		4.6	1.4	0.6	3.7	11.9

Means within a column having the same letters are not significantly different. * - Significant at 5% level, ** - Significant at 1% level DE=Days to Emergence, DF= Days to 50% flowering, DM=Days to maturity, PH=Plant height, NBPP= Number of branches per plant

4.2. Effect of Sowing Methods and Seed Rates on Yield and Yield Components of Black Cumin

4.2.1. Number of Capsules per Plant (NCPP):

The result of the analysis of variance (ANOVA) for the number of capsules per plant in row sowing at different seed rates showed statistically significant differences at ($p < 0.05$). Among the treatments; 5 kg ha^{-1} (Rsr1) seed rate under row sowing resulted in the highest mean number of capsules per plant with an average of 26.67 capsules and the lowest (14.00 capsules) mean value of number of capsules per plant were obtained from 12.5 kg ha^{-1} (Rsr4) seeding rate under row sowing. (Table 3).

The results highlighted a clear trend in which lower seed rates resulted in a higher number of capsules per plant, with 5 kg ha^{-1} seed rate showing significantly more capsules than 12.5 kg ha^{-1} seed rate which exhibiting lower values under row sowing methods. The highest seed rate (12.5 kg ha^{-1}) resulted in the lowest number of capsules, likely due to increased competition for resources such as nutrients, water, and space at the same sowing methods. At lower seed rates, plants have more access to these resources, which likely improves their ability to allocate more towards capsule development. This reduced competition at lower plant densities may contribute to better reproductive success, as individual plants are able to thrive more effectively. These findings are consistent with previous studies, such as those by (Hassan et al., 2019), which indicate that lower plant densities can enhance reproductive success by minimizing intraspecific competition. Thus, optimizing seed rate is crucial for maximizing capsule production, as higher seed rates lead to reduced individual plant performance due to the intensified competition for available resources.

The result of the analysis of variance (ANOVA) for broadcast sowing showed high significant effects on the number of capsules per plant. The seed rates ranged from 12.5 to 22.5 kg ha^{-1}, and a distinct trend was observed where lower seed rates resulted in higher capsule production. The result showed highest number of capsules per plant with the broadcast sowing with lowest seed rate, 12.5 kg ha^{-1} (Bsr1) produced an average of (17.33 capsules), while, the highest seed rate with broadcasting, 22.5 kg ha^{-1} (Bsr5), resulted in the lowest number of capsules, with an average of (9.67 capsules) (Table 3).

The findings clearly showed that seed rate has a significant impact on the number of capsules produced per plant in broadcast sowing. A clear inverse relationship was observed between seed rate and capsule production: as the seed rate increased, the number of capsules per plant decreased. Specifically, Bsr1 (12.5 kg ha^{-1}) produced the highest number of capsules, while Bsr5 (22.5 kg ha^{-1}) produced the fewest number of capsules per plant. This pattern is likely due to the increased competition for essential resources such as water, nutrients, and light at higher seed rates. The higher seed density in treatments like Bsr5 (22.5 kg ha^{-1}) would have led to stronger competition among plants, restricting their access to these vital resources. As a result, the plants were less able to allocate sufficient energy towards reproductive structures, such as capsules, which resulted in fewer capsules produced per plant.

In contrast, the lower seed rate of 12.5 kg ha^{-1} under broadcasting reduced competition among plants, allowing for better resource allocation to reproductive growth, including capsule production. As a result, plants at this lower density had significantly higher capsule production. The intermediate seed rates (Bsr2 (17.5 kg ha^{-1}), Bsr3 (20 kg ha^{-1}), and Bsr4 (22.5 kg ha^{-1})) showed a progressive decline in capsule production, although the decrease was not strictly linear. This suggests that there may be an optimal seed rate for maximizing reproductive success, where seed rate is neither too low (leading to inefficient land use) nor too high (leading to excessive competition).

The results are consistent with previous research, such as studies by Singh et al. (2023) and Kaur et al. (2022), which demonstrate that high-density planting systems often reduce reproductive output due to the increased competition for resources. In such systems, plants often prioritize vertical growth, which may limit lateral development and reduce the formation of reproductive structures such as flowers, pods, or capsules.

Furthermore, the steepest decline in capsule production from the lowest (12.5 kg ha^{-1}) to the highest seed rate (22.5 kg ha^{-1}) in broadcast sowing further emphasizes that overcrowding, resulting from high seed rates, can severely hinder plant reproduction. This suggests that optimizing seed rate is crucial for maximizing reproductive success and crop yield. Managing seed rates carefully can prevent overcrowding, allowing plants to better utilize available resources and, in turn, improve reproductive output.

4.2.2. Number of Seeds per Capsule (NSPC):

The ANOVA result for row sowing with different seed rates for the number of seeds per capsule showed significant differences (at $P < 0.05$) (appendix table 2) between the treatments, indicating that seed rate significantly influenced the number of seeds per capsule. The highest number of seeds per capsule (88.65 seeds) was recorded from 5 kg ha^{-1} followed 7.5 kg ha^{-1} with (86.98 seeds per capsule) whereas the lowest number of seeds per capsule (78.60 seeds) was recorded in 12.5 kg ha^{-1} seed rates under row sowing methods. This confirms that Rsr1 and Rsr2 had significantly more seeds per capsule compared to Rsr4 (Table 3).

This result indicated that a clear relationship between seed rate and the number of seeds per capsule, with lower seed rates consistently producing a higher number of seeds per capsule. In the row planting method, Rsr1 (5 kg ha^{-1}) produced the highest seed count per capsule, followed by Rsr2 (7.5 kg ha^{-1}), and Rsr3 (10 kg ha^{-1}), while Rsr4 (12.5 kg ha^{-1}) had the lowest count. This suggests that reduced competition for resources, such as water, nutrients, and space, at lower seed rates allowed plants to allocate more resources to seed production rather than vegetative growth. At higher seed rates, like Rsr4 (12.5 kg ha^{-1}) plants experienced more competition, leading to fewer seeds per capsule. These findings are aligned with the research results of Smith et al. (2020), who found that, higher plant densities can limit seed production due to resource competition.

Similarly, the result of the analysis of variance for the broadcast sowing method showed high significant differences between seed rate for the number of seeds per capsule. The highest number of seeds per capsule (79.81 seeds) was recorded from the seed rate of 15.0 kg ha^{-1} (Bsr2) which was significantly higher than the other treatments. In other ways, the fewer seeds per capsule (62.12 seeds) was obtained from 22.5 kg ha^{-1} (Bsr5) seed rates (Table 3).

In the broadcasting method, the seed rate of 15.0 kg ha^{-1} resulted in the highest number of seeds per capsule, and it was significantly different from the higher seed rate (22.5 kg ha^{-1}), which showed a marked decline in seed number per capsule. The reduction in seed count at higher seed rates can be attributed to increased competition among plants for vital resources. As the seed rate increases, individual plants struggle to access the necessary nutrients and light for optimal reproductive development, leading to fewer seeds being set per capsule. This pattern is supported by the findings of Zhang et al. (2022) and Singh et al. (2021), who noted that, increased plant density negatively impacts reproductive success due to heightened competition for resources.

Equally, the lower seed rate (12.5 kg ha^{-1}) allowed plants to access more resources, promoting greater seed production per capsule. These results align with studies by Ali et al. (2020) and Kumar et al. (2022), which suggest that optimizing seed rates can improve reproductive success by minimizing competition among plants. Furthermore, the minimal difference in seed count between Bsr1 to Bsr3 (relatively lower seed rates) indicates that small variations in seed rate may not always produce significant differences in seed set. This suggests that an optimal seed rate range of around 12.5 to 17.5 kg ha^{-1}could maximize seed yield while minimizing resource competition. These findings emphasize the importance of managing seed rates to optimize reproductive outcomes. Ensuring that plants are not overcrowded and have sufficient resources can lead to better seed set, improving overall crop yield.

4.2.3. Thousand seed weight:

The ANOVA result for row planting method of thousand seed weight showed significant differences between the seed rates. The highest seed weight (2.983 grams) was obtained at 5 kg ha^{-1} followed by 7.5 kg ha^{-1} (2.917 grams). The seed rate of 10 kg ha^{-1} exhibited a slightly lower mean of 2.673 grams, while 12.5 kg ha^{-1} showed the lowest mean of (2.350 grams) (Table 3).

The row sowing method consistently resulted in higher thousand seed weight. As the seed rate increased in row sowing, the thousand seed weight showed a slight decrease.

Similarly, the ANOVA result from broadcast sowing method on thousand seed weight also indicated highly significant differences (at $P < 0.01$) between the treatments, suggesting that the seed rate applied to the field significantly affected the seed weight of thousand seeds. The highest value (2.660 grams) was obtained at the rate of 12.5 kg ha^{-1} while the lowest value (2.103 grams) was recorded from the highest rate (22.5 kg ha^{-1}). The means for thousand seed weight showed that the treatments Bsr1 (12.5 kg/ha), Bsr2 (15.0 kg/ha), and Bsr3 (17.5 kg/ha) had similar seed weights per 1000 seeds, while Bsr4 (20.0 kg/ha) and Bsr5 (22.5 kg/ha) exhibited significantly lower seed weights. Broadcasting sowing resulted in lower thousand seed weight, particularly at higher seed rates (Table 3).

The results indicated that lower seed rates in row sowing Rsr1 (5 kg ha^{-1}) and Rsr2(7.5 kg ha^{-1}) led to higher thousand seed weights. This could be due to reduced competition among plants, allowing each seed to develop more fully. As seed rate increased in row sowing Rsr3 (10 kg ha^{-1}) and Rsr4 (12.5 kg ha^{-1}), competition for resources like water, nutrients, and light intensified, leading to smaller seeds. This is similar with findings of Jiang et al., (2017); Singh et al., (2020), who also reported that lower seed rates can reduce plant competition, thereby allowing for better seed development.

In contrast, the broadcasting method resulted in a decrease in thousand seed weight as seed rates increased, particularly in treatments Bsr4 (20 kg ha^{-1}) and Bsr5 (22.5 kg ha^{-1}). These findings suggest that the broadcasting method might not provide enough space and resources for the plants to grow optimally, leading to lower seed weights at higher seed rates. Similar results were reported by Maqbool et al. (2018), where higher seed rates in broadcasting sowing led to increased plant competition and lower seed quality.

4.2.4. Seed yield per plant:

The result of the analysis of variance (ANOVA) under row sowing on seed yield $plant^{-1}$) showed significant differences (at $P < 0.05$) between the treatments, indicates that seed rate significantly influenced yield per plant. The highest seed yield of (6.27 g $plant^{-1}$) was attained from the seed rate of 5 kg ha^{-1}), followed by 10 kg ha^{-1} with (5.07 g $plant^{-1}$), while the lowest yield of (3.23 g $plant^{-1}$) was exhibited in 12.5 kg ha^{-1} under row sowing systems (Table 3).

On the other hand, for the broadcasting sowing method the result of analysis of variance for seed yield per plant revealed no significant differences (at $P > 0.05$) between the treatments. Even if non-significant difference was recorded; the highest seed yield (4.23 g $plant^{-1}$) was obtained from 12.5 kg ha^{-1} and the lowest seed yield (2.93 g $plant^{-1}$) was recorded in 22.5 kg ha^{-1} seed rates with broadcast sowing methods (Table 3).

The results for row sowing suggest that lower seed rates 5 $kgha^{-1}$ (Rsr1) led to higher yield per plant, likely due to reduced competition among plants for resources such as water, nutrients, and space. This finding is consistent with previous research indicates that excessive plant density can hinder individual plant growth and yield potential due to increased competition Smith et al., (2020). Rsr1 (5 $kgha^{-1}$), resulted in the highest yield of (6.27 grams) per plant, which shows the potential of lower seed rates for optimizing plant growth and yield. Conversely, Rsr4, which had the highest seed rate (12.5 kgha^{-1}), exhibited the lowest yield of (3.23 g plant^{-1}), further supporting the notion that higher seed rates lead to greater competition and reduced yield per plant.

In contrast, the analysis of broadcast sowing did not show significant differences in yield per plant across the treatments. However, a trend towards higher yields at lower seed rates Bsr1 (12.5 kgha^{-1}) and Bsr3 (17.5 kgha^{-1}) was still evident. The highest yield per plant was observed in Bsr1 (12.5 kgha^{-1} seed rate), with an average of (4.23 g plant^{-1}), suggests that this seed rate may be more optimal for plant growth under broadcasting conditions. The lack of statistical significance in broadcasting may indicate that other factors, such as environmental conditions or agronomic practices, played a role in influencing plant growth and yield.

Interestingly, the highest seed rate in broadcast Bsr5 (22.5 kgha^{-1}) resulted in the lowest yield per plant, (2.93 grams), which is consistent with the findings of Ali et al. (2020) and Zhang et al. (2022), who reported that, excessive planting density can reduce growth and yield due to increased competition. Although this trend was not statistically significant, it suggests that higher seed rates in broadcasting could lead to decreased yield per plant.

4.2.5. Effects on Seed yield per hectare:

The result of the analysis of variance (ANOVA) for row sowing on seed yield per hectare (kg ha^{-1}) showed highly significant differences (at $P < 0.01$) between the treatments, this indicated that the different seed rates had a substantial effect on yield per hectare. The highest yield (2137 kg ha^{-1}) was recorded with seed rate of 10 kg ha^{-1} followed by the seed rate of 7.5 kg ha^{-1} with (2122 kg ha^{-1}) yield under row sowing. The lowest yield (1383 kg ha^{-1}) was obtained at a rate of 5 kg ha$^{-1.}$ The test was confirmed that the seed rate of 10 kg

ha^{-1} and 7.5 kg ha^{-1} had significantly higher yields compared to 12.5 kg ha^{-1} and 5 kg ha^{-1} under row sowing methods (Table 3).

Similarly, in the broadcast sowing method, highly significant differences (at $P < 0.01$) were observed across the treatments on seed yield. The treatment with the highest yield (1714 kg ha^{-1}) was attained at the seed rate of 20.0 kg ha^{-1}, followed closely by 17.5 kg ha^{-1} and 15.0 kg ha^{-1} which had recorded a yield of 1709 and 1653 kg ha^{-1} respectively at broadcast sowing. While the lowest yield (1232 kg ha^{-1}) was recorded at seed rate of 12.5 kg ha^{-1} (Table 3).

In the row sowing method, the highest yields were observed with intermediate seed rates 10 $kgha^{-1}$ and 7.5 $kgha^{-1}$ (Rsr3 and Rsr2), which is consistent with the theory that an optimal plant density allows for better use of space and resources, leading to higher overall yields. Rsr3 (10 $kgha^{-1}$) and Rsr2 (7.5 $kgha^{-1}$) both yielded significantly higher than Rsr1 (5 $kgha^{-1}$) and Rsr4 (12.5 $kgha^{-1}$), suggests that too low or too high a seed rate may not be ideal for maximizing yield. Lower seed rates like Rsr1 may have resulted in fewer plants per hectare, which, although allowing for larger individual plants, led to a lower overall yield. Conversely, Rsr4 (higher seed rate 12.5 $kgha^{-1}$) showed a decrease in yield, likely due to excessive plant competition for space and resources, which is in line with findings from previous studies of Smith et al., (2020).

In contrast, the broadcasting method showed that higher seed rates 20.0 $kgha^{-1}$, 17.5 $kgha^{-1}$ and 15.0 $kgha^{-1}$ resulted in significantly higher yields compared to lower seed rates 12.5 $kgha^{-1}$. The highest yield was recorded for Bsr4 (20.0 $kgha^{-1}$), followed by Bsr3 (17.5 $kgha^{-1}$) and Bsr2 (15.0 $kgha^{-1}$), with Bsr1 (12.5 $kgha^{-1}$) showing the lowest yield. These results suggest that in broadcast sowing, a moderate to high seed rate (17.5 to 20.0 $kgha^{-1}$) might be optimal for achieving higher yields. However, Bsr5 (22.5 $kgha^{-1}$) did not outperform the 17.5 $kgha^{-1}$or 20.0 $kgha^{-1}$treatments, indicating that beyond a certain seed rate, the yield may decrease. This is likely due to the increased competition for resources, such as water, nutrients, and light, when plant density becomes too high Ali et al., (2020); Zhang et al., (2022).

These findings suggest that while higher seed rates can be beneficial in some cases, there is a threshold beyond which the competition between plants reduces the potential for increased yield. Therefore, a balanced seed rate approach should be considered for optimizing yield, particularly in broadcasting sowing systems.

The analysis for yield per hectare revealed that row sowing resulted in significantly higher yield per hectare compared to broadcast sowing.

The higher yield per hectare in row sowing is a direct result of better plant spacing and optimized resource allocation. While the broadcast sowing method may initially seem advantageous due to its simplicity, the overcrowding of plants leads to lower overall yields.

Table 3. Mean value of Main effect of different seed rates under row and broadcast sowing on yield and yield components of black cumin

Treatments	Seed rate (kg ha^{-1})	NCPP	NSPC	YPP	YPH	1000 seed WT
Row sowing	**5**	26.67 a	88.65a	6.267 a	1383c	2.983a
	7.5	24.00 a	86.98a	4.933ab	2122a	2.917a
	10	21.33a	85.65a	5.067a	2137a	2.673ab
	12.5	14.00b	78.60b	3.233b	1647b	2.350 b
LSD		5.338	6.124	1.897	195.6	0.3706
CV (%)		12.4	3.6	19.5	5.4	6.8
Broadcast sowing	**12.5**	17.33a	75.72a	4.233 a	1232c	2.660a
	15	14.67ab	79.81a	4.000ab	1653a	2.553a
	17.5	14.00ab	75.05a	3.733ab	1709a	2.570a
	20	13.33 b	67.22b	3.633ab	1714a	2.283b
	22.5	9.67c	62.12b	2.933b	1549b	2.103b
LSD		3.539	7.280	1.083	87.6	0.2574
CV (%)		13.6	5.4	15.5	3.0	5.6

Means within a column having the same letters are not significantly different. * - Significant at 5% level, ** - Significant at 1% level, NCPP= Number of capsules per plant, NSPC= Number of seed per capsule, YPP= Seed yield per pant, 1000 SWT = thousand seed weight and YHA= Seed yield per hectare.

4.3. Interaction effect of seed rate and sowing method on growth and phenological parameters of black cumin

4.3.1. Days of 50% emergence

The analysis of variance (ANOVA) for days of emergence revealed significant effects of seed rate and sowing method on the response variable. However, the interaction between seed rate and sowing method was not statistically significant (*at* $p > 0.05$), result indicating that the effect of seed rate did not differ substantially between sowing methods.

Although the interaction term was just above the significance threshold, the test revealed clear differences between treatment combinations. For instance, the lowest days to 50% emergence was recorded in sr1 broadcast (10.67 days) and the highest in sr4 row (14.00 days) (table 4), indicating that the combination of higher seed rates and row sowing optimizes days to emergence.

Both seed rate and sowing method significantly influence days to emergence, with the highest days to emergence achieved by the highest seed rate under row sowing. These findings suggest that optimizing seed density in conjunction with precise sowing methods can enhance grain yield or dry grain weight, potentially improving crop productivity (Smith et al., 2020).

4.3.2. Days of 50% flowering

The analysis of variance (ANOVA) for days to 50% flowering indicated that only sowing method had a significant effect (at $p < 0.001$), while seed rate and the interaction between seed rate and sowing method were not significant (at $p > 0.05$) (Appendix table 3).

Although the seed rate × sowing method interaction was not statistically significant, the Bonferroni test suggests some practical differences worth noting. The earliest flowering was recorded at sr2 broadcast (76.00 days), while the latest occurred at sr1 row (80.67 days) (Table 4). However, these differences are more relevant agronomically than statistically, given the non-significance of the interaction term.

Sowing method significantly affects the timing of flowering, with row planting delaying flowering by approximately 3.5 days on average compared to broadcasting. Seed rate, in contrast, showed no measurable effect. These findings imply that for earlier flowering (possibly beneficial in short-season environments), broadcast sowing may be preferable, while row sowing may extend the vegetative phase for potentially greater biomass accumulation.

4.3.3. Days of 90% physiological maturity

The ANOVA results indicate that there was a significant interaction effect between seed rate and sowing method on maturity days ($p < 0.05$). This significant interaction suggests that the impact of seed rate on crop maturity was not consistent across sowing methods, highlighting the importance of considering both agronomic practices jointly when assessing crop development timing.

From the mean comparisons, the earliest maturity was observed in sr1 (12.5 $kgha^{-1}$) under broadcast sowing (121.7 days), while the latest maturity occurred in sr1 (5 $kgha^{-1}$) under row sowing (128.3 days) (Table 4). The Treatments under broadcast sowing consistently led to earlier maturity compared to those under row sowing across all seed rates.

These findings imply that broadcast sowing tends to accelerate crop maturity, possibly due to increased plant competition for light and nutrients, which may trigger earlier reproductive development. In contrast, this finding is similar with (Zhao et al., 2007) who reported row sowing likely provides better spacing, reducing stress and extending vegetative growth phases, thereby delaying maturity

Interestingly, the influence of seed rate on maturity appears to be moderated by sowing method. Under row sowing, higher seed rates led to relatively delayed maturity (e.g. sr1 row = 128.3 days vs sr4 row = 124.7 days), whereas under broadcast sowing, seed rate had a minimal effect. This could be due to the uniformity of plant growth in row sowing being more sensitive to population density than the relatively disorganized structure of broadcast stands.

Overall, this interaction has practical implications for synchronizing crop maturity with local climate conditions or harvesting schedules. For example, in areas with a narrow harvesting window or risk of late-season drought, broadcast sowing with a lower seed rate might be preferable to ensure timely maturity.

4.3.4. Plant height (PH)

The analysis of variance for plant height (PH) revealed that both seed rate and sowing method had highly significant effects on plant height. However, the interaction effect between seed rate and sowing method was not statistically significant (at $p > 0.05$), suggesting that the effect of seed rate on plant height was relatively consistent across the two sowing methods.

Although the interaction term was not significant, the test showed practical differences among combinations. The tallest plants were found in sr4 with row sowing (74.27 cm), while the shortest plants were in sr1 with broadcast sowing (57.03 cm) (Table 4). This reinforces the idea that both higher seed rate and row sowing contribute additively to plant height.

The nonsignificant interaction implies that the benefit of row sowing is consistent across seed rates, and vice versa, meaning these factors can be optimized independently for plant height improvement without concern for their combined interaction effect.

The results highlight that both increasing seed rate and using row sowing are effective agronomic strategies for enhancing plant height in the tested crop. Given the agronomic importance of plant height as it often correlates with biomass and yield potential, these findings provide practical guidance for improving crop architecture.

4.3.5. Number of branches per plant (NBPP)

The ANOVA for number of branches per plant revealed that seed rate, sowing method and their interaction (at $p < 0.001$) were all highly significant, indicating that both main effects and their combination significantly influenced branching.

The significant interaction between seed rate and sowing method indicates that the effect of seed rate on branching depends on the sowing method and vice versa. According to the result, the highest number of branches (31.33) was observed at sr1 with row sowing, while the lowest (16.33) was seen at sr4 with row sowing (Table 4).

Interestingly, while row sowing generally increased branching, the benefit diminished at the highest seed rate (sr4), where even row sowing could not compensate for the dense plant population. This demonstrates a threshold effect, suggesting that row sowing is most beneficial at lower to moderate seed rates for maximizing branching.

4.4. Interaction effect of seed rate and sowing method on yield and yield components of black cumin

4.4.1. Number of capsules per plant (NCPP)

The analysis of variance for the number of capsules per plant (NCPP) revealed highly significant effects of both seed rate and sowing method (at $p < 0.001$), along with a significant interaction between these factors (at $p < 0.05$). These results demonstrate that both planting density and establishment method significantly influence reproductive output in this crop system.

The ANOVA revealed a statistically significant interaction between seed rate and sowing method on the number of capsules per plant (NCPP). This indicates that the effect of seed rate on number of capsules per plant is not consistent across the two sowing methods, suggesting an interaction between the two factors.

The means table illustrates that under the row sowing method, number of capsules per plant generally decreased with increasing seed rate: from 26.67 (sr1) to 14.00 (sr4). However, in the broadcast method, this decline was more gradual, from 17.33 (sr1) to 13.33 (sr4). The highest number of capsules per plant was observed at sr1 with row sowing (26.67), while the lowest was sr4 with broadcast sowing (13.33) (Table 5). The result confirmed significant differences between some of these treatment combinations, supporting the presence of a meaningful interaction.

This interaction implies that optimal seed rate depends on the sowing method used. Row sowing at lower seed rates (sr1 or sr2) appears to enhance capsule production per plant, possibly due to better plant spacing and resource use efficiency (El Naim et al., 2010). Conversely, higher seed rates may have caused overcrowding, increased intra-plant competition and reduced productivity, especially in row sowing where spatial arrangement might exacerbate competition more than in broadcast.

Overall, these findings underscore the importance of considering sowing method when determining optimal seed rate for maximizing yield traits like number of capsules per plant.

4.4.2. Number of seeds per capsule

The ANOVA revealed that while both seed rate and sowing method individually had significant effects on number of seeds per capsule, their interaction effect was not statistically significant (at $p > 0.05$). This indicates that the influence of seed rate on number of seeds per capsule did not significantly differ across the two sowing methods.

Despite the non-significant interaction, the mean values show a consistent trend: row sowing resulted in higher number of seed per capsule across all seed rates compared to broadcast sowing. The highest number of seed per capsule was observed in sr1 with row sowing (88.65), while the lowest was in sr4 with broadcast sowing (67.22) (Table 5). This suggests that although the interaction was statistically insignificant, row sowing tends to enhance seed development per capsule, possibly due to better light penetration and reduced intra-plant competition (Ali et al., 2011).

In summary, although the interaction effect was not statistically significant, the trend in means suggests a favorable impact of lower seed rates and row sowing on number of seed per capsule. This aligns with agronomic principles emphasizing optimal plant population and spatial arrangement for maximizing reproductive efficiency.

4.4.3. Yield per Plant (YPP)

The analysis of variance showed that both seed rate and sowing method had statistically significant main effects on yield per plant (YPP). However, the interaction between seed rate and sowing method was not significant (at $p > 0.05$), indicating that the effect of seed rate on yield per plant did not vary significantly between the two sowing methods.

Despite the non-significant interaction, the pattern of means suggests a consistent biological trend: row sowing resulted in higher yields at every seed rate level compared to broadcast sowing. The highest yield (6.27 g/plant) was achieved with sr1 (lowest seed rate) under row sowing, while the lowest (3.03 g/plant) occurred at sr4 under broadcast (Table 5). These results suggest that while the interaction term was not statistically significant, agronomic implications remain relevant.

The result revealed that sr1 row sowing was significantly superior to most other treatments, forming its own high-performing group. In contrast, sr4 treatments, regardless of sowing method, were statistically among the lowest performers. This suggests a yield penalty at higher seed rates, likely due to increased intra-plant competition for nutrients and light (Natarajan and Willey, 1986).

In summary, although the interaction effect was not significant, agronomic trends indicate that low seed rates combined with row sowing can significantly enhance yield per plant, aligning with existing findings on optimized plant population and layout strategies.

4.4.4. 1000-Seed Weight

The ANOVA results demonstrated that both seed rate and sowing method had statistically significant effects on 1000-seed weight. However, the interaction effect between seed rate and sowing method was not significant (at $p > 0.05$), suggesting that the effect of seed rate on seed weight was consistent across both sowing methods.

From the means table, it is evident that the highest 1000-seed weight (2.983 g) was achieved at the lowest seed rate (sr1) under row sowing, while the lowest weight (2.283 g) occurred at sr4 under broadcast sowing (Table 5).

This trend indicates that lower seed rates are generally favorable for producing heavier seeds, likely due to reduced intra-specific competition for nutrients and space. In practical terms, this suggests that for maximizing 1000-seed weight key quality trait rowers should prefer lower seed rates combined with row sowing, even though statistical interaction was not significant.

4.4.5. Yield per Hectare (YPH)

The analysis of variance revealed that all three effects seed rate, sowing method and their interaction (at $p < 0.001$) were statistically highly significant for yield per hectare (YPH). This significant interaction implies that the effect of seed rate on yield differed depending on the sowing method and vice versa.

The mean yield data supports this conclusion. The highest yield (2137 kg/ha) was obtained from sr3 (third seed rate) under row sowing, closely followed by sr2 under row sowing (2122 kg/ha). In contrast, the lowest yield was recorded under sr1 broadcast sowing (1232 kg/ha) (Table 5). These patterns show a clear trend: moderate seed rates combined with row sowing maximized productivity.

The result confirmed this differentiation by assigning sr3 row and sr2 row to the highest statistical group ("a"), clearly separating them from treatments involving lower seed rates and broadcast sowing. This demonstrates a synergistic interaction: not only are moderate seed rates beneficial, but their effect is significantly enhanced when used with row sowing.

The interaction effect may be attributed to improved plant spacing, light interception, and nutrient uptake under row sowing, especially when plant population density is optimal. Waliullah et al. (2021) conducted a study in Bangladesh to determine the optimal sowing date and method for black cumin. They found that line sowing on December 1st resulted in higher plant growth and seed yield compared to broadcast sowing. This supports the idea that sowing method significantly affects yield outcomes.

Table 4. Interaction effect of seed rate and sowing method on growth & phenology of black cumin

Treatment										
Seed rates	Sowing methods									
	DE		DF		DM		NBPP		PH	
	Row	Broadcast	Row	Broadcast	Row	Broadcast	Row	Broadcast	Row	Broadcast
Sr1	12.00abc	10.67a	80.67d	77.67abcd	128.3e	121.7a	31.33a	21.00bc	61.93cd	57.03d
Sr2	12.33bc	11.67ab	80.33cd	76.00a	126.7de	122.0ab	29.00ab	17.67c	64.23bcd	63.60bcd
Sr3	13.33cd	11.33ab	80.00bcd	76.33ab	125.0cd	122.3abc	23.67abc	18.00c	70.87ab	66.40bc
Sr4	14.00d	11.67ab	79.67abcd	76.67abc	124.7bcd	122.3abc	16.33 c	16.67c	74.27a	66.80bc
LSD (5%)	0.906		2.179		1.535		4.592		4.152	
CV	4.3		1.6		0.7		12.1		3.6	

Means within a column having the same letters are not significantly different. * - Significant at 5% level, ** - Significant at 1% level, Sr = Seed rate, DE=Days to Emergence, DF= Days to 50% flowering, DM=Days to maturity, PH=Plant height, NBPP= Number of branches per plant

Table 5. Interaction effect of seed rate and sowing method for yield & yield components of black cumin

Treatment										
Seed rates	Sowing methods									
	NCPP		NSPC		YPP		YPH		1000 SWT	
	Row	Broadcast	Row	Broadcast	Row	Broadcast	Row	Broadcast	Row	Broadcast
sr1	26.67a	17.33bcd	88.65a	75.72abc	6.267a	4.233ab	1383bc	1232c	2.983a	2.660ab
Sr2	24.00ab	14.67cd	86.98ab	79.81abc	4.933ab	3.400b	2122a	1594b	2.917a	2.553ab
Sr3	21.33abc	14.00d	85.65ab	75.05bc	5.067ab	3.567b	2137a	1643b	2.673ab	2.570ab
Sr4	14.00d	13.33d	78.60abc	67.22c	3.233b	3.033b	1647b	1659b	2.350b	2.283b
LSD (5%)	3.951		7.555		1.476		165.4		0.3044	
CV	12.4		5.4		20.0		5.6		6.6	

Means within a column having the same letters are not significantly different. * - Significant at 5% level, ** - Significant at 1% level, Sr = Seed rate, NCPP= Number of capsules per plant, NSPC= Number of seed per capsule, YPP= Seed yield per pant, 1000 SWT = thousand seed weight and YHA= Seed yield per hectare.

5. CONCLUSION AND RECOMMENDATIONS

5.3. Conclusion

This study was conducted to evaluate the effects of different sowing methods and seed rates on the growth, yield and yield components of black cumin (*Nigella sativa L.*) at the Endamekony district of Southern Tigray, Ethiopia. Black cumin, a highly valued spice and medicinal crop, faces productivity challenges due to inappropriate agronomic practices. The research aimed to address these gaps by evaluating row and broadcast sowing methods with different seed rates, ranging from 5– 12.5 kgha^{-1} for row and 12.5 to 22.5 kgha^{-1} for broadcast sowing.

The result of this study showed that the effects of the individual factors on both sowing methods (row sowing and broadcasting) and seed rates were significant different on most of the parameters studied. Statistically, significant variations were obtained on growth, yield, and yield components of black cumin with both sowing methods and seed rates. Increasing the seed rates from 5 kg ha^{-1} to 10 kg ha^{-1} on row sowing resulted in increased in the average black cumin seed yield in the range of 1383 to 2137 kg ha^{-1}. Similarly, seed yield increased from 1232 to 1714 kgha^{-1} as seed rate increases from 12.5 to 20 kgha^{-1} and slightly drops yield into 1549 kgha^{-1} as seed rate rises to 22.5 kgha^{-1} in broadcast method sowing. The interaction effect was statistically highly significant for yield per hectare. The highest yield (2137 kg/ha) was obtained from sr3 and followed by sr2 under row sowing (2122 kg/ha). In contrast, the lowest yield was recorded under sr1 broadcast sowing (1232 kg/ha).

Overall, row sowing with a seed rate of 10 kgha^{-1} resulted in superior performance, achieving the highest seed yield (2137 kgha^{-1}) and better growth parameters such as plant height, number of branches per plant, and number of capsules per plant. Regarding broadcasting, although it has been performed lower than row sowing in all measured parameters, within the broadcasting method itself, the broadcasting method showed improved yield performance at a higher seed rate of 20 $kgha^{-1}$ with seed yield of 1714 $kgha^{-1}$, though it was less efficient compared to row sowing.

5.4. Recommendations

These findings offer valuable insights for farmers, researchers, and policymakers aiming to improve black cumin production. On the basis of the study, the following recommendations are made for the cultivation of black cumin in the study area and similar agro ecology.

For optimal black cumin production, row sowing with a seed rate of 10 $kgha^{-1}$ as a main effect and interaction effect and broadcast sowing with 20 kg ha^{-1} as a main effect is highly recommended, as it maximizes yield and improves plant growth by reducing competition and optimizing resource use.

- However, if broadcasting is preferred due to resource limitations or local practices, farmers are advised to use a seed rate of 20 $kgha^{-1}$. Increasing seed rates beyond this in broadcasting led to reduced performance across all parameters due to overcrowding and competition.
- Extension services should focus on promoting row sowing techniques and ideal seed rates while providing guidance on the drawbacks of high seed rates, particularly in broadcasting.
- It is also recommended that further research is important to explore more improved agronomic practices focus on: varietal improvements, plant biomass, spacing, quality of the crop, fertilization and irrigation strategies, pest and diseases across diverse environments to further optimize black cumin production.

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7. APPENDICS

APPENDIX TABLES:

Table 1. Analysis of variance of the effect of different seed rates under row sowing on growth, yield and yield component of black cumin

Source of variation	d.f.	Mean square									
		DE	**DF**	**DM**	**PH**	**NBPP**	**NCPP**	**NSPC**	**YPP**	**YPH**	**1000 SWt**
Rep	**2**	0.0833	2.083	4.083	24.033	20.333	12.250	33.415	1.777	12566	0.0298
Trt	**3**	2.5278*	2.00*	2.111^{ns}	98.359**	132.972*	89.222*	58.608*	4.671*	412679**	0.246*
error	**6**	0.1944	0.416	1.194	3.154	9.889	7.139	9.396	0.901	9582.	0.034
Significance level		*	*	**ns**	**	*	*	*	*	**	*

Where, * - Significant at 5% level, ** - Significant at 1% level and ns – non significant. D.f = degree of freedom, DE=Days to Emergence, DF= Days to 50% flowering, DM=Days to maturity, PH=Plant height, NBPP= Number of branches per plant, NCPP= Number of capsules per plant, NSPC= Number of seed per capsule, YPP= Seed yield per pant, 1000 SWt = thousand seed weight and YHA= Seed yield per hectare

Table 2. Analysis of variance of the effect of different seed rates under broadcast sowing on growth, yield and yield component of black cumin

Source of variation	d.f.	Mean square									
		DE	**DF**	**DM**	**PH**	**NBPP**	**NCPP**	**NSPC**	**YPP**	**YPH**	**1000 SWt**
Rep	**2**	0.600	2.600	1.0667	4.878	12.200	15.200	161.82	0.1007	28178	0.0671
Trt	**4**	0.7667^{ns}	1.233^{ns}	0.2667^{ns}	66.786**	27.100**	22.933**	153.38**	0.725^{ns}	121153**	0.1618**
error	**8**	0.2667	1.183	0.5667	5.655	4.200	3.533	14.95	0.330	2163	0.0186
Significance level		**ns**	**ns**	**ns**	**	**	**	**	**ns**	**	**

Where, * - Significant at 5% level, ** - Significant at 1% level and ns – non significant. d.f = degree of freedom, DE=Days to Emergence, DF= Days to 50% flowering, DM=Days to maturity, PH=Plant height, NBPP= Number of branches per plant, NCPP= Number of capsules per plant, NSPC= Number of seed per capsule, YPP= Seed yield per pant, 1000 SWt = thousand seed weight and YHA= Seed yield per hectare

Table 3. Analysis of variance of the interaction effect of different seed rates and sowing methods on growth, yield and yield component of black cumin

Source of variation	d.f.	Mean square									
		DE	**DF**	**DM**	**PH**	**NBPP**	**NCPP**	**NSPC**	**YPP**	**YPH**	**1000 SWt**
Rep	**2**	0.1250	1.167	2.6250	18.212	24.542	22.042	77.58	2.4004	43716.	0.05701
seed_ratevs sowing_method	**3**	0.8194^{ns}	0.611^{ns}	6.0417*	11.921^{ns}	42.597**	25.333*	8.89^{ns}	0.9206^{ns}	104442.	0.03410^{ns}
error	**6**	0.2679	1.548	0.7679	5.622	6.875	5.089	18.61	0.7104	8920.**	0.03021
Significance level		**ns**	**ns**	**	**ns**	**	*	**ns**	**ns**	**	**ns**

Where, * - Significant at 5% level, ** - Significant at 1% level and ns – non significant. d.f = degree of freedom, DE=Days to Emergence, DF= Days to 50% flowering, DM=Days to maturity, PH=Plant height, NBPP= Number of branches per plant, NCPP= Number of capsules per plant, NSPC= Number of seed per capsule, YPP= Seed yield per pant, 1000 SWt = thousand seed weight and YHA= Seed yield per hectare

APPENDIX FIGURES:

1. Lay outing and Land preparation

2. Row making, Seed preparing and Sowing





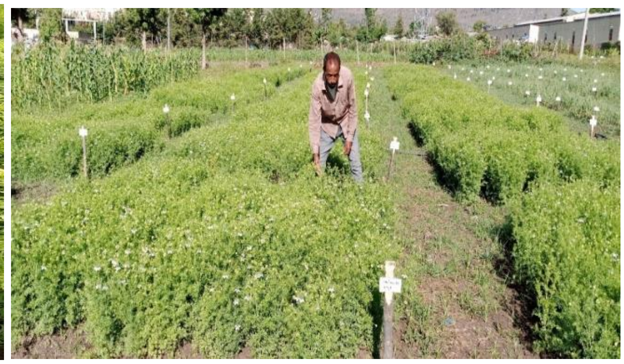

3. At initial growth stage

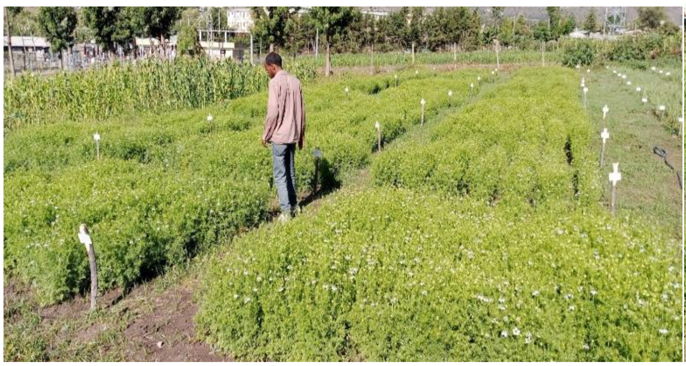
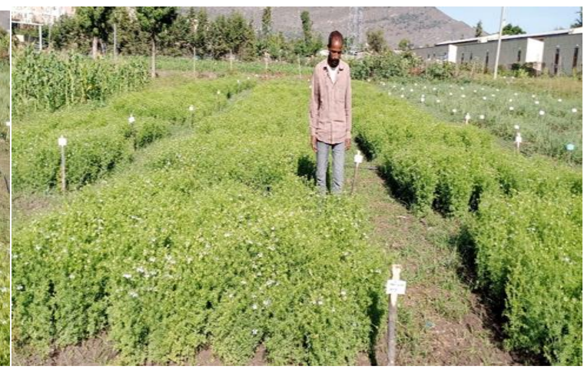


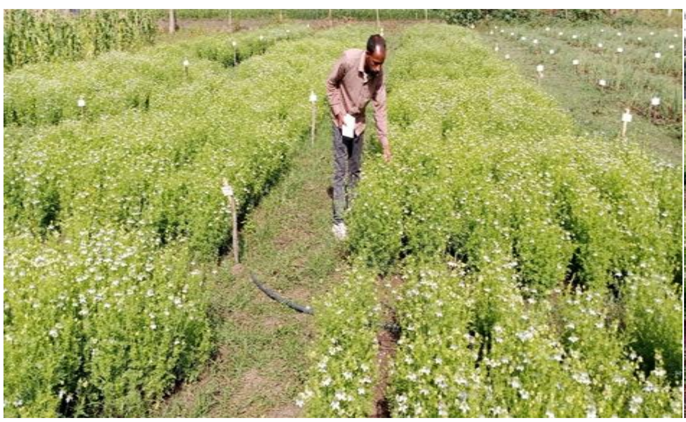



4. Developmental stage, Crop management and Data collection

5. Flower initiation and flowering stage





6. Maturation, Harvesting and drying