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FDRE TECHNICAL & VOCATIONAL TRAINING INSTITUTE

FDRE TECHNICAL AND VOCATIONAL TRAINING INSTITUTE

FACULTY OF AGRICULTURE AND AGRO PROCESSING TECHNOLOGY

DEPARTMENT OF COFFEE, TEA AND SPICE PRODUCTION TECHNOLOGY

EFFECTS OF INTER- ROW SPACING AND VARIETIES ON YIELD AND YIELD COMPONENTS OF FENUGREEK (*TRIGONELLA FOENUM-GRAECUM* L.) IN NEDJO DISTRICT, WEST WOLLEGA, ETHIOPIA

MSC THESIS

By

MIZENU EFREM SHONE

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FDRE TECHNICAL AND VOCATIONAL TRAINING INSTITUTE FACULTY OF AGRICULTURE AND AGRO PROCESSING TECHNOLOGY DEPARTMENT OF COFFEE, TEA AND SPICE PRODUCTION TECHNOLOGY

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MSc Thesis submitted to Federal Technical and Vocational Training Institute Faculty of Agriculture and Agro Processing Technology, Department of Coffee, Tea and Spice Production Technology, in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Coffee, Tea and Spice Production Technology

MIZENU EFEREM SHONE

ADVISOR: Dr. ABERA DABA (PhD)

June, 2026

Addis Abeba, Ethiopia

FDRE TVET INSTITUTE

SCHOOL OF POSTGRADUATE STUDIES

THESIS APPROVAL SHEET

Submitted by:

Mizenu Efrem Shone  08/06/2026

1. PG Candidate Signature Date

Approved by:

2. Advisor

Abera Daba (Ph.D)  08/06/2026

Signature Date

3. Head Department

Mulualem Azene (Ph.D.) _____ _____

Signature Date

4. Director/ Dean Campus/Institute/School

Name _____ _____ _____

Signature Date

5. Campus/ College/Institute/School, SGS Coordinator

Name _____ _____ _____

6. Director/Coordinator of SGS Signature Date

_____ _____ _____

Name Signature Date

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CERTIFICATION SHEET

As thesis research advisor, I hereby certify that I have read and evaluated the thesis prepared by Mizenu Efrem Shone under my guidance, which is entitled 'Effects of Inter-Row Spacing and Varieties on Yield and Yield Components of Fenugreek (*Trigonella foenum-graecum* L.) Production in Nedjo, West Wollega, Ethiopia".

We recommend that the thesis submitted, as it fulfills the requirements for the Degree of Master of Science in Coffee, Tea and Spice production Technology.

Abera Daba (PhD)	_____	08 / 06 / 2026
Advisor	Signature	Date

As members of the Board of Examiners of the Master of Science (MSc) Thesis open defence examination, we certify that, we have read and evaluated the Thesis prepared by Mizenu Efrem Shone and examined the candidate. We recommend that the thesis be accepted as it fulfills the Thesis requirements for the degree of Master of Science in Coffee, Tea and Spice production Technology.

1._____	_____	_____
Chairperson	Signature	Date
2. Elfinesh Firdissa (PhD)	_____	06/30/2026
Internal Examiner	Signature	Date
3. Ambecha Olika (PhD)	_____	07/01/2026
External Examiner	Signature	Date

DEDICATION

This thesis is dedicated to my beloved family for their patience, encouragement, prayers, and unwavering support throughout my journey.

STATEMENT OF THE AUTHOR

I, hereby declare that this thesis is a result of my genuine work and that I have duly acknowledged all sources of materials used for writing it. I solemnly declare that this thesis is not submitted to any other institution anywhere for the award of any academic degree, diploma, or certificate. Short excerpts from this thesis may be reproduced without explicit authorization, provided that full and accurate bibliographic acknowledgment is given to the source. Requests for the extended quotation or partial reproduction of this manuscript may be authorized by either the Head of the Department or the Dean of the Graduate School or the Dean of Graduate Studies, provided that the intended application serves a legitimate scholarly purpose. In all remaining instances, explicit written permission must be secured directly from the author.

Name: Mizenu Efrem Shone

Signature: 

Date: 08/06/2026

Place: Federal Technical and Vocational Training Institution

BIOGRAPHICAL SKETCH

The author, Mizenu Efrem Shone, was born on October 16, 1994, in the Nedjo district, West Wollega Zone, Oromia Regional State of Ethiopia. He attended elementary school at Yako Aleltu School from 2001 to 2008, high school at Nedjo Senior Secondary School from 2009 to 2011, and preparatory education at Nedjo Senior Secondary School from 2012 to 2013. Then, he joined Mettu University, Gambella branch, in 2014 and graduated with a BSc degree in plant science in 2016. After Graduation, he employed by Nedjo Agricultural Poly technic College. At the position of assistant instructor where he served from 2017 to date. In September 2024, he joined the Federal Technical and Vocational Training Institution to pursue his graduate studies leading to an MSc in coffee, tea, and spice production technology.

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ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
DZARC	Debre Zeit Agricultural Research Center
RCBD	Randomized Complete Block Design
SARC	Sinana Agricultural Research Center
m a.s.l	Meters above sea level
Ph	Potential of Hydrogen
SNNPR	Southern Nations, Nationalities, and Peoples' Region
LSD	Least significant difference
CV	Coefficient of Variation
G.C	Gregorian calendar
E.C	Ethiopian calendar
TNSRC	Tepi National Spices Research Center

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ABSTRACT

Fenugreek is an important spice and food crop in Ethiopia; however, its productivity is constrained by suboptimal agronomic practices and the use of low-yielding varieties. This study aimed to evaluate the effects of inter-row spacing and variety on the growth, nodulation, yield, and economic return of fenugreek in Nedjo District, western Ethiopia. The experiment was conducted using a factorial arrangement in a randomized complete block design with three replications. Four inter-row spacings (10, 20, 30, and 40 cm) and four varieties (Burka, Chala, Chafe, and local landrace) were evaluated. The results revealed that both inter-row spacing and variety, as well as their interaction, significantly affected growth, nodulation, and yield components. The highest grain yield (1528 kg ha^{-1}), biomass yield (3673.96 kg ha^{-1}), thousand seed weight (20.26 g), and harvest index (41.58%) were obtained from the Burka variety at 40 cm inter-row spacing, while the lowest performance was recorded from the local variety at 10 cm spacing. Economic analysis further confirmed that Burka at 40 cm spacing provided the highest net benefit (401,000 Birr ha^{-1}) with a marginal rate of return of 15,975%.In conclusion, the Burka variety planted at 40 cm inter-row spacing produced the highest grain yield and economic return under the study conditions, indicating that optimum productivity depends on the specific combination of variety and spacing rather than spacing alone.

Keywords: Fenugreek, inter-row spacing, phenology, nodulation, yield components, variety.

CHAPTER ONE

INTRODUCTION

1.1 Back ground

Fenugreek (*Trigonella foenum-graecum* L.) is an ancient, self-fertile, annual herbaceous legume in the Fabaceae family (Yaldiz and Camlica, 2022). It has trifoliate leaves and fragrant seeds. Known worldwide as a versatile plant, fenugreek mainly grows in semi-arid regions for its uses in human nutrition. It can be grown as a green leafy vegetable or a spice. In addition to its dietary uses, fenugreek holds significant therapeutic value in traditional medicine, a property largely attributed to prominent phytochemicals such as diosgenin. It is also used as quality feed for farm animals (Bal *et al*., 2025). Additionally, fenugreek helps fix atmospheric nitrogen by working with Rhizobium bacteria. This plant promotes sustainable farming and offers both nutritional and economic benefits. As a result, subsequent crops in rotation receive benefits in soil fertility (Toor *et al*., 2025).

The taxonomy of the genus Trigonella has received considerable attention over time. Basu (2006) indicated that older taxonomists like Linnaeus have suggested that as many as 260 species of fenugreek exist. In contrast, about 128 species of fenugreek were reported by (Mehrafarin *et al*., 2011), the seeds of fenugreek have a high composition of protein (25.5%), fats (5–10%), and carbohydrates (45-60%)(Sharma, 2021; Roba and Mohammed, 2024).

The crop has been grown under different agro-ecological conditions around the world, but it is widely cultivated in the arid areas of Asia, Europe, and North Africa (Seal *et al*., 2025). India ranks first in production, consumption, and exportation and contributes to 70–80% of the total production of this crop (Nidhi *et al*., 2020). Other important countries contributing to production are Afghanistan, Pakistan, Iran, Nepal, and Bangladesh in Asia; Egypt, Morocco, Tunisia, and Ethiopia in Africa; and Turkey, France, and Spain in Europe and the Mediterranean region (Basu *et al*., 2019). In addition, other countries such as Argentina, Canada, and the USA have incorporated the cultivation of this herb as an agricultural plant in their farms (Batello *et al*., 2008).

According to Bekele *et al*. (2020), fenugreek subspecies ranging from Eritrea to Somalia are believed to have originated in Ethiopia. Ethiopia cultivates this crop similarly to other cool-season food legumes (Roba and Simion, 2022).

The total area under cultivation was 30,145.56 hectares, with a production volume of 35,328.29 tons and a national productivity of 1.17 tons per hectare, according to Kena and Latera (2025). Fertile Nitisols and Vertisols promote the production of high-quality seeds for domestic use and local markets. Production is concentrated in the high- and mid-altitude zones of the Central, Eastern, and Western highlands (Roba and Tana, 2018).

Fenugreek (*Trigonella foenum-graecum* L.) is both a food crop and an important cash crop grown in the Oromia area. The cultivation area of the crop was 14,374.46 hectares with 13,061.39 tons production and productivity of 0.9 tons/ha (Kena and Latera, 2025). But management practices such as spacing and variety affect the crop's performance significantly (Meena *et al*., 2016). Row spacing has a significant effect on the performance of agronomic practice as reported by Minjaro *et al*. (2023). The organization of rows influences the partitioning of dry matter, photosynthetic activities of leaves, and plant morphology in the spice crop (Seyedi *et al*., 2024). Variety and inter-row spacing affect phenology, growth, and yield performance. Even though the varieties of fenugreek are selected based on their early maturity, high productivity, and tolerance to stresses (Hassan *et al*., 2018), their performances differ depending on the density of plants in the field (Tiwari *et al*., 2016).

Production of fenugreek (*Trigonella foenum-graecum* L.) in Ethiopia is associated with several constraints. One of the major challenges is the limited availability and adoption of improved varieties, along with inadequate agronomic practices such as improper inter-row spacing. Studies conducted in different parts of Ethiopia indicate that smallholder farmers predominantly cultivate low-yielding local varieties under traditional management systems (CSA, 2021: Getu & Hirko, 2022).

In western Ethiopia, particularly in West Wollega, fenugreek productivity remains low compared to its potential. Reports indicate that yields in some areas are around 0.65 t ha^{-1}, which is lower than the national average yield of approximately 1.17 t ha^{-1} and the regional average of about 0.9 t ha^{-1} (Kena and Latera, 2025).These low yields are mainly attributed to the use of unimproved varieties, lack of appropriate spacing, and limited access to improved agronomic recommendations (Gutema *et al*., 2021; Minjaro *et al*., 2023).

1.2. Statements of the problem

Fenugreek (*Trigonella foenum-graecum* L.) is an important annual legume crop belonging to the Fabaceae family. It is widely cultivated across the world, including Ethiopia, due to its economic, nutritional, and medicinal importance. Both its seeds and leaves are highly valued for use as spices and traditional medicine.

In Ethiopia, fenugreek is primarily cultivated by smallholder farmers and contributes to household income and soil fertility improvement through biological nitrogen fixation (Roba and Simion, 2022). Despite its importance, the productivity of fenugreek in the country remains low compared to its potential. The low productivity is mainly associated with poor agronomic practices, particularly improper plant population management, and the use of low-yielding local varieties. Appropriate inter-row spacing is essential for efficient utilization of sunlight, soil moisture, and nutrients, while improper spacing leads to either excessive competition or underutilization of resources, resulting in reduced yield. Previous studies have indicated that spacing significantly influences growth and yield components of fenugreek, including plant height, branching, and pod formation (Habib, 2015). Similarly, the use of improved varieties plays a crucial role in enhancing crop productivity (Abebe and Mitiku, 2025). Fenugreek varieties differ in their genetic potential, resulting in variations in yield and yield components under different environmental conditions (Kena and Latera, 2025). Studies conducted in Ethiopia have demonstrated significant differences among varieties in terms of growth performance and productivity, suggesting the need for location-specific evaluation of varieties (Minjaro *et al*. . 2023).

Furthermore, the interaction between inter-row spacing and variety is an important factor influencing fenugreek production. Although several studies in Ethiopia have shown that both spacing and variety independently affect yield, their combined effects vary across agro-ecological conditions (Abebe and Mitiku, 2025). However, such findings are not universally applicable due to differences in soil type, climate, and management practices.

Nedjo District, located in West Wollega Zone of western Ethiopia, is one of the areas where fenugreek is widely cultivated under a mixed farming system, indicating its production potential. The district has favorable agro-ecological conditions, including suitable altitude, rainfall, and soil characteristics for fenugreek production. Nevertheless, productivity in the area remains low.

Currently, farmers in Nedjo District rely mainly on local varieties and traditional planting practices, particularly non-optimal inter-row spacing, with limited access to improved technologies and extension services. These practices lead to poor plant stand establishment, inefficient use of resources, and low yield. Major constraints in the area include lack of improved varieties, absence of location-specific agronomic recommendations, and inadequate crop management practices.

Although previous studies have investigated the effects of inter-row spacing and varieties on fenugreek production in different parts of Ethiopia, these studies are highly location-specific and cannot be directly applied to all agro-ecological zones. In particular, there is a lack of empirical evidence on the combined effect of inter-row spacing and fenugreek varieties under the specific agro-ecological conditions of Nedjo District.

This absence of location-specific information creates a clear research gap and limits the development of appropriate agronomic recommendations for improving fenugreek productivity in the area. Therefore, this study was initiated to evaluate the effects of inter-row spacing and varieties on the growth, yield, and yield components of fenugreek, with the aim of identifying optimal management practices for the study area.

1.3. Objectives of the Study

1.3.1 General Objective

To evaluate the effects of inter-row spacing, fenugreek varieties, and their interaction on the growth, yield, and yield components of fenugreek.

1.3.2 Specific Objectives

- To evaluate the effects of fenugreek varieties on growth, yield, and yield components.
- To determine the effects of different inter-row spacing levels on growth, yield, and yield components.
- To assess the interaction effects of fenugreek varieties and inter-row spacing on growth, yield, and yield components.

CHAPTER TWO

LITERATURE REVIEW

2.1. General Description of the Fenugreek Crop

Fenugreek (*Trigonella foenum-graecum* L.) is an upright, soft hair herb which grows up to a maximum height of 45 to 60 cm (Nidhi *et al*., 2020). Has a long narrow stem with a trifoliate leaf (Kumar *et al*., 2013). The leaves are egg-shaped, may be blunt, and may look like projections like those of a saw and can be 20–25 mm long. The color of these leaves is grayish green. The leaves are occasionally stalked, elongated and up to 5cm in length (Singh, 2023). There are several finger-like structures branching off from the taproot in the roots of the plant (Mustafa, 2025).

The flowers do not take their origin at the very end of the stem, but rise straight out of the tissue of the stem; they might be white or light yellow. Fenugreek produces two types of flowers, namely, cleistogamous (closed) and chasmogamous (open) and most of the flowers are cleistogamous (Kumar, 2017). The keel of the flower is closed throughout the whole flowering period and the plant can therefore self-pollinate. Fruit is 10-15 cm. long, sword-shaped and finally becomes beak-like (Lunagariya *et al*., 2018). Each of the pods may contain 10-20 seeds (Rana, 2022). It blooms in mid-summer and attains physiological maturity in four months (Kumar *et al*., 2023). Fenugreek produces small, flattened, rhomboid-shaped seeds that measure approximately 5 mm in length and exhibit distinct brownish-yellow coloration. Seed is composed of an embryo, a well-developed endosperm (which serves as food storage) and a hard testa (Rai 2021).

2.2. Origins, Distribution and Economic importance of Fenugreek production

The crop has been suggested as originating in the Eastern Mediterranean area and Indian subcontinent (Seal *et al*., 2025). Other geographical regions in Asia, Europe, Africa and Australia have been identified with their respective indigenous varieties (Sharma and Maloo, 2022).This plant is now commonly grown in warm or tropical climates. Significant production zones are the Indian subcontinent, the Mediterranean regions of Europe and northern Africa, western and southern Asia, north and South America, and Australia (Hilles and Mahmood, 2021).

Among these areas, India, Ethiopia, Egypt and Turkey are known as the leading producers of fenugreek seeds (Montgomery, 2009). Certain agronomic traits make Mediterranean

cultivars exceptionally well-suited for production in Western Canada (Lee, 2009). The adaptation of Western Canada to the Mediterranean regions is in part due to the similarities in day length (Narayana *et al*., 2022). Further, fenugreek is highly adaptable to dry land agriculture and has a high capacity to produce seeds even in relatively short growing seasons, which is more favourable for the Western Canadian environment (Mehrafarin *et al*., 2011).

The primary centers of fenugreek diversity are widely acknowledged to be the Eastern Mediterranean region and the Indian subcontinent (Basu *et al*., 2019). After cumin and coriander, fenugreek is the third most popular seed spice in India (Maqbool *et al*., 2024). It is one of the earliest domesticated crop species. Even 3,000 years ago, it was a staple of Indian cuisine. Through trade networks, migration, and agricultural exchange, the crop gradually expanded from these early domestication sites to other regions of Asia, Europe, and North Africa (Narayana *et al*., 2022). Its long history of use as a medicinal plant, pasture crop, and spice greatly aided its expansion beyond its natural habitat. As cultivation spread, fenugreek's geographic distribution and genetic variability increased across various agro-ecological zones, and it became naturalized in several areas with suitable environmental conditions (Roba and Tana, 2018).

Currently, fenugreek is cultivated in warm, temperate, and semi-arid environments across the world (Shahrajabian *et al*., 2021). The key fenugreek production zones include the Mediterranean region, the Middle East countries, East and North Africa, and South Asia, specifically India (Basu *et al*., 2019). The crop is also found in areas of Australia, North and South America, and Europe, particularly in environments with regular rainfalls and temperate climates (Narayana *et al*., 2022).

Its success in both traditional and non-traditional production regions can be attributed to its ability to thrive under diverse agro-climatic conditions, including in areas that use dryland farming techniques and experience short cropping periods (Roba and Tana, 2018). Despite being classified as a minor crop on a global scale, the extensive geographical distribution of fenugreek shows its versatile nature as well as increasing importance economically (Kumar *et al*., 2020)

Fenugreek is of great economic significance in Ethiopia particularly in smallholder-based agricultural systems (Roba and Simion, 2022).

Most of the crop is cultivated in agro-ecological areas of highlands/mid altitudes where the climate is favorable for its cultivation. Domestic consumption and market-oriented production are promoted (Yao *et al*., 2020). The fenugreek seeds are commonly used as a spice in the traditional Ethiopian cuisine, especially in spice mixes, condiments, and sauces (Terefe, 2017). The continuing demand at home ensures a stable local market for producers. The socio-economic importance of fenugreek at the family and community level is significant as it is used for therapeutic purposes and has high nutritional and medicinal values (Singh *et al*., 2023). This is because the crop is a source of nutrition, food security and income generation for the farmers and in the rural areas (Arvadiya *et al*., 2025).

The use of fenugreek in the market is associated with the use of it in the farming system in addition to its use as a family food, which has a positive impact on the agricultural economy (Lal *et al*., 2024). For smallholder farmers, it is an important income source particularly at competitive market prices (Kumawat *et al*., 2017). It is considered to be commercially viable by resource-poor farmers because it is a cold climate crop that requires relatively few inputs. Further, fenugreek being a leguminous plant, improves soil fertility by the process of biological nitrogen fixation, reduces the requirement for artificial nitrogen fertilizer and improves the yield of the succeeding crop in rotation (Narayana *et al*., 2022). While it is not an important export crop of Ethiopia, fenugreek has emerged as a promising regionally and globally important spice (Shimelis, 2021). In general, its versatility adds to Ethiopia's agricultural economy, livelihoods for rural communities, and sustainable farming practices.

2.3. Ecological Requirements of Fenugreek production

2.3.1. Climate requirements

As a cool season crop, fenugreek is sensitive to temperature, precipitation and solar radiation, which affects its development and productivity (Saqib *et al*., 2021). Crop growth is best in moderate climate zones of Ethiopia from 1800 to 2300 masl (Taressa, 2020). The growth stage of vegetative development and reproductive growth are ideal for temperatures around 18°C to 25°C in this elevation range (Bhutia *et al*., 2020). Temperature plays an important part during the entire crop life cycle (Dubey *et al*., 2018). Fenugreek is very sensitive at flowering and pod formation stage, but can tolerate light frost in its early vegetative stages (Yaldiz and Camlica, 2021). High temperatures can

accelerate physiological maturity, particularly during flowering and filling, which can result in wrinkled seeds and decrease in yield.

Another important input that affects crop performance is rainfall (Basu *et al*., 2014). Fenugreek is a plant that grows with 500-1400 mm of annual rainfall (Bagri, 2010). But seasonal rainfall pattern is more significant than annual rainfall (Pavlista and Santra, 2016). The adequate moisture required for germination and early growth occurs during the main rainy season (Meher), whereas the dry, cool and sunny period of the flowering and maturation period is ideal for seed development and harvesting in Ethiopia (Nahar, 2021). During these later stages, overwatering or high humidity can lead to lodging, fungal diseases like powdery mildew and rust, and difficulties in harvesting and drying (Yaldiz and Camlica, 2021).

2.3.2. Soil requirements

Soil type is also very important in the productivity and growth of fenugreek (Hassan *et al*., 2025). The best pH range for crop growth is 6.0 to 7.5 (Tania *et al*., 2024). It can be found growing on loamy or clay-loam soils with a neutral to slightly alkaline soil reaction and good drainage. Adequate drainage is critical to mitigating the spread of pathogens and preventing root stress. The crop is mainly grown in the Ethiopian highlands on two types of soil, namely, heavy black clay soils (Vertisols) and reddish-brown soils (Nitosols) (Narayana *et al*., 2022). Vertisols are poorly drained, and may lead to waterlogging.

To improve soil aeration and surface drainage, management practices like the broad-bed and furrow system are recommended. Fenugreek is a leguminous crop and associated with Rhizobium meliloti to be responsible for biological nitrogen fixation (El Idrissi and Abdelmoumen, 2021). This symbiosis helps the crop to rely less on external nutrient sources, thus enhancing soil fertility. Fenugreek is therefore considered as a nitrogen poor crop and suitable for sustainable and resource poor agriculture.

2.4. Fenugreek Production in Ethiopia

A significant annual cool-season legume, fenugreek is grown extensively in Ethiopia's highlands, especially in the Oromia and Amhara regions, which together produce more than 98% of the nation's total (Getu and Hirko, 2022). There are smaller farming areas in Tigray, Benishangul-Gumuz, and SNNPR (Getnet *et al*., 2025). Like other cool-season legumes, fenugreek thrives in cool, high-altitude conditions (Gotame *et al*., 2018).

It prefers loamy or sandy loam soils with good drainage, a slightly alkaline pH, a temperature range of 8 to 27°C, and an annual rainfall of 400 to 1500 mm (Nega *et al*., 2025). Sowing usually takes place after the main rainy season to utilize residual soil moisture and prevent waterlogging (Mamatha and Panyam, 2021). Farmers grow fenugreek as a sole crop and in intercropping systems with sorghum, particularly in areas like Eastern Hararghe. They often rotate it with other crops, using both native and improved varieties, to maintain soil fertility (Hassan *et al*., 2025).

Most of the fenugreek cultivation in Ethiopia is done through smallholder farmers, and the benefits of the crops include their economic and nutritional value (Kebede, 2020). Because of its compatibility with highland agriculture, there are many possibilities of boosting the cultivation levels, increasing the areas used, and enhancing the lives of people residing in such regions. Such possibilities are even better due to the research being done.

2.5. Challenges in Fenugreek Production

There are several biophysical and environmental conditions that inhibit fenugreek productivity in Ethiopia (Tilahun *et al*., 2025). Uncertain rainfall, drought, and excess waterlogging are some of the conditions that hinder germination, growth, and development of the seeds (Nega *et al*., 2025; Roba and Simion, 2022). Fenugreek crop is very vulnerable to climatic conditions like temperature at flowering and podding stages (Panjabrao, 2019). Excess temperature causes early maturation of the seeds and produces dry seeds in the end, leading to reduced production (Maity *et al*., 2016). Other growth inhibitors include soil-related constraints such as poor fertility, drainage problems with heavy clay soils, and poor soil management practices (Meena *et al*., 2018). Moreover, there is a great danger of pests and diseases such as rust, powdery mildew, and aphids among others that affect seed production significantly (Ghule *et al*., 2021).Cultivation of fenugreek is also challenged by socio-economic and management-associated issues (Rana *et al*., 2026).

The productivity of fenugreek is limited by extensive utilization of low-yield local landraces, and improved high-yielding cultivars have not been adopted extensively due to their unavailability and poor extension service (Getu and Hirko, 2022). Availability of high-quality seeds, fertilizers, and agrochemicals is restricted among small-scale farmers (Melese *et al*., 2025). Moreover, traditional agricultural methods, inadequate crop rotation, and improper spacing during intercropping are some factors contributing to low yield of

fenugreek (Roba and Simion, 2022). The aforementioned issues associated with biophysical, environmental, and socio-economic determinants emphasize the need for holistic measures like encouraging improved cultivars, agronomic practices, and effective management of pests and diseases to enhance productivity (Roba and Tana, 2018).

2.6. Effects of Fenugreek varieties on Yield and yield Components

Because of differences in genetic makeup among varieties and their interaction with the environment, fenugreek is characterized by a high level of variability in terms of yield and yield attributes (Gowda *et al*., 2006; Tilahun *et al*., 2025). Therefore, variety selection plays a critical role in enhancing productivity. Superiority of improved varieties compared to local varieties in seed yield, biomass production, pods/plant, and seed size reveals the role of genetic improvement in enhancing crop production (Meena *et al*., 2025).Evidence from Ethiopia shows that improved cultivars outperform local landraces in growth performance, agro-ecological adaptability and nutrient use efficiency (Fikreselassie *et al*., 2012; Sharanya *et al*., 2018). Significant varietal differences in key yield parameters have also been confirmed by experimental results, indicating a high degree of genetic diversity and selection potential (Serbessa *et al*., 2019).

Cultivar variability has an impact on growth period, adaptation, and tolerance to different pests and diseases, thus impacting productivity stability in different agro-ecological zones (Kena and Latera, 2025; Nega *et al*., 2025). On average, better varieties tend to improve the quantity of growth elements, specifically pod and seed per plant numbers, thus improving economic value of crops. Better tolerance levels allow for their better adaptation under different environmental conditions (e.g., soil fertility or drought levels) (Hassan *et al*., 2025).

Phenology-related traits like days to 50% flowering, physiological maturity also exhibit variability. Late maturing types tend to perform well under irrigated/favorable conditions, whereas early maturing ones are preferred in short-duration seasons/areas where water is limiting (Sharma, 2021). Even though such traits are genetically regulated, environment variables including temperature, day length, soil moisture, and nutrients exert considerable impact on trait expression (Karmakar *et al*., 2014; Yaldiz and Camlica, 2021).

Variations in the yield component traits that contribute to the end seed yield also exist among various varieties. Variations in vegetative and reproductive traits arise because of

the differences in plant height, plant branching habit, root nodules, and accumulation of dry matter (Provorov & Tikhonovich, 2003; Alam, 2018). Seed yield per hectare is primarily determined by its key components: pod number per plant, pod length, the number of seeds per pod, and 1,000-seed weight (Tesso & Alemu, 2020; Gupta *et al*., 2026). All factors considered, the diversity of the traits related to phenology, growth characteristics, yield components, and adaptability highlights the need for thorough comparison in selecting the best fenugreek varieties (Meena *et al*., 2025; Tilahun *et al*., 2025).

2.7. Effects of Inter- row spacing on Fenugreek Yield and Yield Components

Among the several causes responsible for low production of *Trigonella foenum-graecum* L. is insufficient density of plants. High and low plant densities, both exceeding certain critical limits, result in decreased production. The plant density in terms of area has an effect on the size of the plant, the yield attributes, and the ultimate seed yield (Agajie, 2018; Reza, 2021). Effective spacing allows the plant systems to grow optimally by making use of sunlight, soil minerals, water, and even the space on the soil (Rezaei *et al*., 2015; Ouji *et al*., 2022).

Inter-row spacing has a major influence on plant population, canopy structure, light capture, uptake of nutrients, and efficient use of resources (Waskle, 2017; Abdurahman, 2022). Wider spacing minimizes competition for resources, leading to an increase in root development and availability of energy required to sustain symbiotic relation between the host plant and bacteria (Wafula *et al*., 2021; Khairnar *et al*., 2025). Optimal inter-row spacing ensures efficient use of photosynthetic capability of leaves and distribution of dry matter to facilitate vegetative growth and reproduction (Habib, 2015).

Optimal spacing optimizes efficient use of solar radiation, promotes greater branching capacity, and efficient light, water, soil, and aerial resources' utilization that enhances development both in roots and above ground, increasing productivity and yield components of fenugreek (Gezahegn and Tesfaye, 2017; Amiriyan *et al*., 2023). Insufficient inter-row spacing leads to increased competition among plants or inefficiency in land use that negatively affects crop productivity (Atlaw and Sharma, 2017; Motuma and Hunduma, 2020). Although wider spacing is expected to ensure better vegetative development, greater branching capacity, and healthy leaves due to less competition for

sunlight, water, soil, and air, close spacing might not allow intercultural activities efficiently (Habib, 2015; Umer, 2024).

According to empirical research conducted in 2022 at Wolaita Sodo, Ethiopia, plant density and environmental factors are closely related to yield responses to inter-row spacing (Lishan *et al*., 2022). Plant population per unit area declines with increasing spacing, giving individual plants more access to growth resources. Sarkar (2021) revealed that increased inter-row spacing greatly increased seed yield per hectare, while Tunçtürk (2011) found that broader spacing configurations produced the maximum seed yield (777.0–785.0 kg ha^{-1}).

Similarly, Meena *et al*. (2016) discovered that seed yield was significantly improved when row spacing was increased from 20 to 40 cm, while crops planted at 60 cm spacing generated significantly greater test weight than those at narrow spacing. Nevertheless, a higher total vegetative dry matter accumulation might also result from increased plant density (Bekele and Beshir, 2005), even though closer spacing could increase the risk of lodging (Tamrat *et al*., 2019; Tarekegn *et al*., 2024). Higher plant density has been shown to increase plant height (Moniruzzaman *et al*., 2009). However, as the population increases, the number of leaves per plant diminishes (Gebremedhin. 2015). Spacing has a significant impact on branching, with larger inter- and intra-row spacing showing the greatest lateral growth (Alemayehu *et al*., 2015; Gezahegn and Tesfaye, 2017). Together, these results show that while wider spacing enhances individual plant performance and some yield components, soil moisture, nutrient availability, and relative humidity levels determine the ideal plant population (Deora, 2022).

2.10. Interaction Effects of Inter Row Spacing and Varieties of Fenugreek Productivity.

Crop phenology, growth, yield, and yield components are all greatly impacted by the interaction between fenugreek variety and inter-row spacing (Mohammed *et al*., 2023). Higher production potential, early maturity and resistance to unfavorable climatic conditions are the main reasons why varieties are chosen (Hassan *et al*., 2018). However, since each variety's genetic composition influences characteristics such as branching capacity, canopy design, pod development, and seed filling, not all varieties respond to plant spacing in the same way (Tiwari *et al*., 2016; Meena *et al*., 2025).

While varietal selection determines the crop's genetic potential, optimal row spacing ensures effective use of light, nutrients, water, and air, thereby improving growth performance. Since their combined effect strongly influences overall productivity, recent research emphasizes that these two factors should be evaluated interactively rather than separately (Abebe and Mitiku, 2025).

Burka variety grown using an inter-row spacing of 40 cm recorded the highest level of seed production (1586 kg ha^{-1}), based on a study carried out in Woliso Woreda, Central Ethiopia. Such a high output was mainly associated with increased levels of biomass production, increased numbers of branches, and greater pod numbers per plant. Likewise, Minjaro *et al*. (2023) observed that most of the yield components such as pod length, number of seeds per pod, and harvest index were improved under medium inter-row spacing of 25 cm in the Abay Chomen District.

Spacing has been found to help in improving structure and growth, and decreasing leaf diseases as a result of improved aeration in the canopy especially for wide-canopied varieties (Sharanya *et al*., 2018; Gezahegn, 2019). These findings suggest that plant morphology and environmental adaptability influence varietal reaction to spacing. Whereas compact varieties can produce better results at moderate spacing, vigorous branching varieties usually thrive under wide spacing where their full canopies develop (Demssie. 2016). Genotype by spacing interaction studies carried out in specific environments provide scientific grounds for formulating accurate agronomic practices in fenugreek cultivation to enhance productivity, profitability, and sustainability (Feleke *et al*., 2021). In summary, the choice of appropriate fenugreek varieties and optimal inter-row spacing is critical in enhancing yield and yield attributes and guaranteeing consistency in production.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1. Description of Experiment area

This experiment was conducted at Nedjo Agricultural Polytechnic College (NAPTC). It is located in the west Wollega Zone of the Oromia national Regional State in Ethiopia. Nedjo town l86 kilometers from Nekemte City which is about 515 kilometers west of Addis Ababa. Geographically, the experimental site is located at 9°30′ N latitude and 35°30′ E longitude, with an altitude of 1,830 meters above sea level. The area is characterized by a humid tropical climate with a unimodal rainfall pattern, where the main rainy season extends from April to October. The long-term mean annual rainfall of the area is about 1,200 mm, while the mean minimum and maximum temperatures 12°C and 26°C, respectively (Asefa and Kebede, 2024). The soil of the experimental site is classified as Nitisol, characterized by deep, well-drained, reddish-brown soil. The soil has a moderately acidic reaction with a pH of around 5.5 (Takele *et al*., 2023). It is generally fertile with good physical structure, suitable for crop production, although soil acidity may limit nutrient availability. The farming system in the area is predominantly mixed crop-livestock production, where crops such as maize, sorghum, and pulses, including fenugreek, are commonly grown.

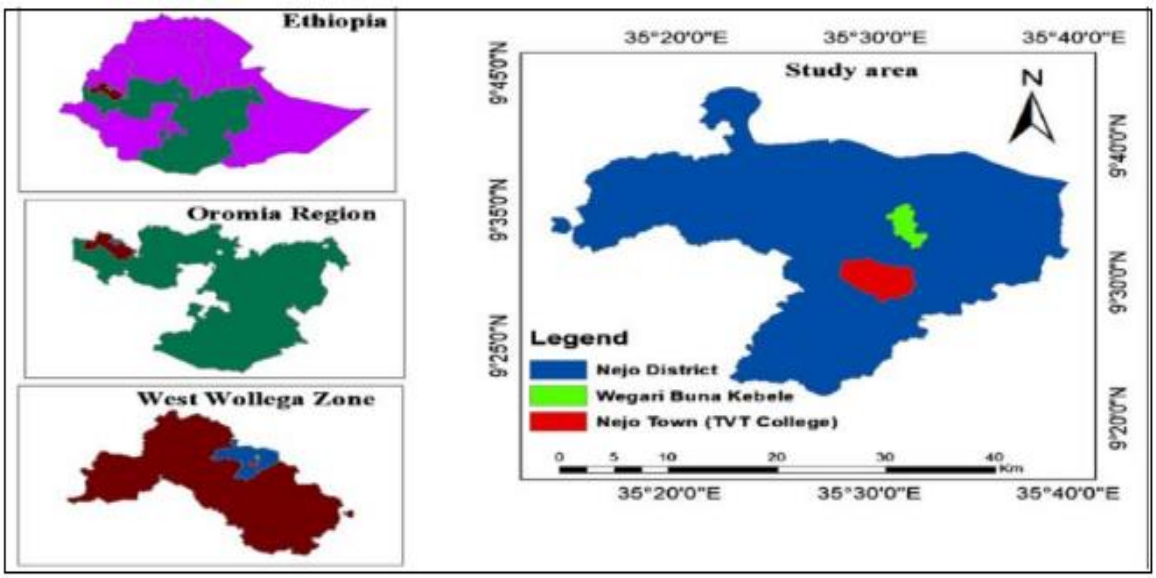


Figure 1: Map of the study area

3.2. Experimental Materials

The four varieties of fenugreek used for experimentation include: "Chafe," "Burka," "Chala," and "Local" varieties. Burka and Chala fenugreek varieties were obtained from Kulumsa Agricultural Research Center; Chafe variety was obtained from Ambo Agricultural Research Center and the Local land race variety was bought from the local market. Manual sowing of fenugreek was conducted on prepared seedbeds on 04 September 2025. Agronomic practices were applied as per crop recommendation package .

Table 1: Fenugreek varieties description

NO	Varieties	Breeder	Released year	Yield ton/ha	Altitude (masl)	Rainfall (mm)
1	Burka	SARC	2016	2.2	1650–2400	120–500
2	Chala	DZARC	2005	1.8	1650-2400	900–1000
3	Chafe	TNSRC & DZARC	2021	1.2	1900–2450	800–1100
4	Local land race					

Source: Ministry of Agriculture (2005–2021).

3.3. Treatments and Experimental Design

This experiment was conducted by employing RCBD factorial with three replications in order to examine the effect of plant density and genetic variation on the fenugreek performance. In this regard, there were two main factors involved in the experimental work: Four different inter-row space (10 cm, 20 cm, 30 cm, and 40 cm) and four types of fenugreek varieties including Burka, Chala, Chafe, and Local land race check, hence constituting a total of 16 treatments combinations. A constant intra-row spacing of 10 cm was maintained for all treatments to ensure uniform plant distribution within rows. Plant population varied across treatments due to differences in inter-row spacing. The corresponding plant population densities were 1,000,000, 500,000, 333,333 and 250,000 plants ha^{-1} for 10 cm, 20 cm, 30 cm, and 40 cm inter-row spacing, respectively. Each plot measured 3 m × 2 m (6 m^2). The net plot size was 2 m × 2.4 m, excluding border rows and 0.3 m from both ends of each row to avoid border effects. Spacing between plots and blocks was maintained at 0.5 m and 1 m, respectively. Fertilizer was applied uniformly to all plots based on local recommendations. NPS fertilizer was applied at a rate of 100 kg ha^{-1} at planting using the band placement method along the rows. No additional nitrogen fertilizer was applied, considering the nitrogen-fixing ability of fenugreek. All other

agronomic practices, including land preparation, sowing date, weeding, and crop management, were applied uniformly to all treatments as per local recommendations.

3.4. Experimental Procedures and Field Management

Land Preparation: This site for conducting the experiment was made ready according to the practices recommended for seeds that are of pulses of smaller size. The site was ploughed three times using an oxen drawn plow in order to get fine tilth, which is necessary for uniform sprouting of fenugreek. Then, leveling of the site was done manually.

Sowing: Sowing took place during the main rainy season (04 September 2025). Seeds were hand-drilled into rows at a consistent depth of 2–3 cm to avoid poor emergence. Accordingly, the seed rate per plot varied with spacing, with 12 g, 6 g, 4 g, and 3 g used for 10 cm, 20 cm, 30 cm, and 40 cm inter-row spacing, respectively.

Fertilizer Application: NPS fertilizer was applied uniformly to all plots at a rate of 100 kg ha^{-1} at the time of planting. The fertilizer was applied using the band placement method along the planting rows and covered with soil immediately after application to minimize nutrient loss.

Moisture Management: The experiment was conducted under rain-fed conditions. No supplementary irrigation was applied, and crop growth depended entirely on the natural rainfall distribution during the growing season.

Weed Management: Weeds were controlled manually twice: first at three weeks after sowing and second at the early flowering stage to minimize competition for nutrients, moisture, and light.

Harvesting: Fenugreek was harvested manually at physiological maturity when pods turned yellowish-brown. Plants were cut using a sickle, bundled, and sun-dried before threshing. Threshing was carried out by beating, followed by cleaning through winnowing.

Post-Harvest Handling: Harvested plants were bundled and sun-dried for several days until reaching a constant weight. Threshing was done manually by beating the dried plants, followed by cleaning through winnowing to remove chaff and other impurities. The cleaned seeds were further dried to a safe moisture level before weighing and recording yield data.

3.5 Field Data Collection

3.5.1 Phenological variables

Days to establishment: Days to 50 % emergence were measured by counting the days from sowing up to the point where 50% of the plants had sprouted.

Days to 50% flowering: Dates of first and 50% flowering of the selected plants were recorded, and days taken for 50% flowering from sowing were calculated.

Days to 90% physiological maturity: Days to 90% physiological maturity were counted from the date of emergence till 90% maturity in the plants on the plot. Determination of physiological maturity in fenugreek is visual, and the plant is considered mature when its leaves and pods turn yellowish-green.

3.5.2. Growth parameters

Plant Height: Plant height was determined randomly for ten plants within each plot, and the average height of each plot was calculated in centimeters from the base to the tip of the plants at physiological maturity.

Branches number per plant: Ten randomly selected plants from each plot were used to determine the branch number of each plant; an average value was taken as branch number per plant at physiological maturity.

Lodging percent: Visual observation for lodging percentage in all plots was done before harvesting using a standardized 1–5 rating scale. The scale was based on the angle of inclination of the plants from the vertical position, where a score of 1 (0–15°) indicated no lodging, 2 (15–30°) indicated 25% lodging, 3 (30–45°) indicated 50% lodging, 4 (45–60°) indicated 75% lodging, and 5 (60–90°) indicated 100% lodging. The assessment was conducted following the method described by Tsehaye *et al*. (2020).

3.5.3. Nodule parameter

Nodule fresh weight: Fresh weight of nodules was estimated by weighing together nodules obtained from 10 randomly chosen plants at the flowering stage per plot, including those for evaluating the effectiveness, using a very sensitive analytical balance to get the fresh weight per plant.

Nodule dry weight: was determined by oven-drying nodules collected from the roots of 10 randomly sampled plants at 70 °C for 48 hours. These were then weighed with a very sensitive analytical balance, and mean dry weight per plant was estimated.

Effective and non-effective nodules per plant: Effective and non-effective nodules were identified through dissecting each nodule by a sharp blade. Nodules having green or white inside were identified as non-effective while those pink or red inside were effective, suggesting their involvement in nitrogen fixation process.

3.5.4. Yield and yields components

The number of pods per plant: Number of pods per plant was obtained by counting pods from ten randomly chosen plants.

Pod length: Length of the pod was obtained by measuring from the base to the tip of the pod for 10 randomly selected pods per plant.

Number of seeds per pod: Total number of pods harvested from ten randomly selected plants was counted; they were threshed, seeds were counted, and total seeds were divided by total pods to calculate the average number of seeds per pod.

Above-ground dry biomass: It was calculated from the net plot area by harvesting the plants just above the soil surface; net plot area was measured after sun drying for one week and converted to kg per hectare.

Thousand grain weight: Thousand-seed weight was determined based on the weight of 1000 seeds from seed yields of each plot through manual counting and electronic weighing.

Grain Yield: Clean seed yield was determined by weighing threshed seeds from the net plot area.

Harvest index: It was calculated as the ratio between dry grain yield and total above ground biomass yield per plot and calculated using equation (Yang *et al*., 2022).

$$\text{Harvesting Index} = \frac{\text{Grain yield}}{\text{Above ground biomass yield}} \text{ X } 100$$

3.6. Data Analysis

All data were subjected to analysis of variance (ANOVA) using statistical procedures conducted by R studio Version 9.2 statistical software analysis program. It was checked using the scatter plot technique. Mean comparison was done using LSD at the 5% probability level when treatment effect were significant.

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1. Days to 50% Emergence

The analysis of variance showed that there was no statistically significant ($P > 0.05$) effect of inter-row spacing, varieties, and their interaction on the days taken for 50% emergence (Appendix Table 1).This could be attributed to the fact that during the emergence stage, the seedlings have not grown to a certain level where they would need to compete for important resources, such as sunlight, soil nutrition, or water. Therefore, the spatial arrangement, due to the inter-row spacing, as well as the genetic differences between the varieties studied, does not affect emergence. This finding is consistent with Abebe and Mitiku (2025), who reported that there was no statistically significant difference due to inter-row spacing, variety, or their interactions on the days to 50% emergence.

Table 2: Main effect of days of 50% emergence, days of 50% flowering, and days of 90% physiological maturity as affected by spacing and variety

Factor	Treatment	Parameters		
		50% DE	50% DF	90% DM
Inter-row spacing (cm)	40	5^{a}	46.41^{a}	126.92^{a}
	30	5^{a}	45.5^{a}	125.92^{a}
	20	5^{a}	44.0^{b}	123.16^{b}
	10	5^{a}	43.0^{b}	121.33^{c}
	LSD (5%)	Ns	1.15	1.287
Varieties	Burka	5^{a}	44.50^{b}	119.83^{c}
	Chala	5^{a}	44.00^{b}	126.92^{b}
	Chafe	5^{a}	48.33^{a}	135.6^{a}
	Local	5^{a}	42.08^{c}	114.91^{d}
	LSD (5%)	NS	1.15	1.287
	CV (%)	7.10	2.34	0.933

Means in a column with the same letter are not significantly different at the 5% probability level; CV = Coefficient of variation, LSD = Least Significant Difference, 50%DE = 50%Days of emergence, 50%DF = Days of 50% flowering, 90%DM = Days to 90% physiological maturity.

4.2. Days of 50% Flowering

The analysis of variance showed that both variety and inter row space had a highly significant effect ($p < 0.01$) on days of 50% flowering. But their interaction had not significant ($p > 0.05$) (Appendix Table 2). The highest duration of 50% flowering (46.41 days) was observed in 40 cm inter row space, followed by (45.5 days) in 30cm inter row space, while the lowest duration was obtained in 10 cm inter row space (43 days) (Table 2). In 40 cm spacing, the availability of adequate soil moisture, nutrients, and solar radiation facilitated the prolongation of the vegetative phase in plants. They focused on the production of more biomass, branching, and then moved to the reproductive phase, while 10 cm spacing, there was a high intensity of intra-specific competition and physiological stress among the plants. Resource scarcity might have led to physiological stress and the initiation of "escape flowering," where they hastened their flower development process to produce seeds before the shortage of resources. Therefore, days to 50% flowering decreased with increasing plant population density. This result is consistent with Agajie (2018), who reported an increase in days to 50% flowering in chickpeas as inter-row spacing increased from 20 to 50 cm. Similarly; Habib (2015) reported the longest period to attain 50% flowering in wide inter-row spacing and the shortest period in narrow spacing in fenugreek.

Significant phenological variation was observed among the varieties. The local variety reached 50% flowering the earliest (42.08 days), whereas the Chafe variety exhibited the longest duration (48.33 days) (Table 2). These variations are primarily driven by the genetic makeup of the cultivars and their interaction with the environment. Different varieties are programmed with distinct biological clocks; for instance, the local variety might be adapted for early flowering to escape terminal drought, while the Chafe variety is likely a late-flowering type that requires a longer period of nutrient accumulation and heat units to reach reproductive maturity. These results are in agreement with (Tesso and Alemu, 2020; Kena and Latera, 2025), who all reported highly significant differences in days to 50% flowering across various genotypes of chickpea and fenugreek.

4.3. Days to 90% Physiological Maturity

Analysis of variance showed that both factors inter-row spacing and varieties had highly significant ($P < 0.01$) effects on the of days to 90% physiologic maturity. Their interaction had not significant effect ($P > 0.05$) (Appendix Table 2). The earliest maturity period of 90% physiological maturity was achieved at 10 cm spacing with duration of 121.33 days. In contrary, the latest maturity period was obtained at 40 cm inter-row spacing (126.91 days) followed by 30 cm inter row spacing (125.92 days) (Table 2). The reason behind such pattern lies in the fact that intraspecific competition for light, water, and other nutrients intensifies as distance between plants reduces. This competition triggers physiological stress resulting in accelerated plant maturity.

Conversely, wider plant spacing reduced competitive stress, allowing individual plants to maximize resource acquisition and sustain physiological activity over an extended duration. It is worth mentioning that the interaction between variety and spacing did not prove statistically significant which means all varieties have responded similarly to distance with narrow spacing triggering early maturity and large distance leading to later maturity. These findings align with (Umer, 2024), who found that increasing inter-row spacing from 30 cm to 45 cm delayed the maturity stage of common beans. Similarly, Mebrat *et al*. (2016) noted that the higher inter-row spacing increased from 20 cm to 40 cm delayed the maturity of chickpeas.

The local variety showed the shortest time in reaching maturity (114.91 days), whereas the Chafe variety showed the longest maturity period to reach 90% physiological maturity (135.66 days) (Table 2).The major differences in maturity between varieties can be due to genetic factors that control the phenological life cycle of crops. Different genotypes have distinct biological clocks, leading to either fast or slow development stages. This findings are aligned with (Serbessa *et al*., 2019), who highlighted notable differences in the timing of maturation among fenugreek genotypes. In addition, Sharanya *et al*. (2018) observed that the days to maturity differed among various varieties.

Table 3: The interaction effects of inter row space and varieties on, plant height and number of branches on fenugreek varieties

Treatment		Parameters	
Varieties	Inter Row spacing (cm)	PH (cm)	NB
Chala	10	46.0^{bc}	3.65^{def}
	20	42.3^{fg}	3.65^{def}
	30	39.3^{h}	6.60^{a}
	40	36.0^{i}	5.87^{ab}
Chafe	10	48.5^{a}	2.70^{def}
	20	46.6^{ab}	3.40^{def}
	30	45.5^{bcd}	6.40a
	40	44.4^{cde}	6.70a
Burka	10	35.6^{i}	3.40^{def}
	20	43.5^{def}	3.80^{def}
	30	39.2^{h}	5.64^{abc}
	40	35.6^{i}	6.48^{a}
Local	10	42.8^{ef}	2.13^{f}
	20	40.7^{gh}	2.30^{ef}
	30	37.1^{i}	4.25^{bcd}
	40	30.9^{j}	4.00^{cde}
Mean		41.475	4.435
LSD (5%)		2.0	1.8
CV (%)		1.63	13.70

Means in a column with the same letter are not significantly different at the 5% probability level; CV = Coefficient of variation, LSD = Least Significant Difference, PH = plant height, NB = Number of branches.

4.4. Plant Height

From the results of analysis of variance, both the main and interaction effect of inter-row spacing and varieties had highly significant effects on plant height ($P < 0.01$) (Appendix Table 3). The highest plant height 48.5 cm was recorded from Chafe variety with the narrow inter-row spacing of 10 cm, whereas the lowest plant height 30.9 cm was obtained from the local variety with 40 cm inter-row spacing (Table 3). The results showed that increase in population density was correlated to an increase in plant height of fenugreek.

Nevertheless, the intensity of this interaction varied between the different varieties. It was observed that the Chafe variety had the tallest plants when planted in narrow spaces at 10 cm; this can be as a result of its genetic ability to perform elongation growth as well as its high level of light sensitivity. This therefore implies that Chafe is more reactive to

crowding pressure through elongation growth. In contrast the local variety had relatively smaller plant height irrespective of spacing used. This could be because of its limited genetic vigor as well as lack of sensitivity to changes in the environment. With wide spacing, where light competition is minimal, plants will not elongate as much as when spacing is narrow.

The findings agree with Atlaw & Sharma (2017) according to whom higher densities cause more plant heights because of competition for sunlight, which causes less sunlight availability per individual plant. This is confirmed by another study carried out by Abdurahman (2022) showing higher plant heights for chickpeas and green beans grown under high plant densities. Furthermore, Minjaro *et al*. (2023) found that Ebbisa variety reached its highest plant height (58.77 cm) under narrow rows (20 cm) than wide rows (30 cm).

4.5. Number of Branches

Analysis of Variance showed that both inter-row spacing and varieties had a highly significant effect ($P \leq 0.01$) on number of branches, whereas their interaction effect had significant ($p \leq 0.05$) effect on this trait (Appendix table 3). The maximum number of branches per plant (6.70) was obtained from the Chafe variety at 40 cm of inter-row spacing, followed by the Burka variety (6.48) branches per plant on the same inter row space while the minimum number was obtained from the local variety (2.13) at 10 cm inter row spacing (Table 3).

The interaction of Chafe and Burka varieties with 40 cm inters row spacing showed high adaptability to these environmental conditions due to their higher genetic makeup and their ability to adjust their growth under different conditions. The varieties were able to make effective use of the available space to promote vegetative growth and branching abilities. In contrast the interaction of local variety with 10 cm inter row spacing conditions led to increased competition among the varieties, forcing the varieties to compete hard for the available nutrients.

In such a situation, the assimilate flow goes more toward vertical growth than horizontal growth, thus causing low branching. The local variety showed the least branching when grown in narrow spacing conditions.

The findings are in agreement with Gezahegn and Tesfaye (2017), who found that increased spacing, which corresponds to low plant density, had the effect of producing more branches, while decreased spacing produced fewer branches due to high plant density. In the same way, Alemayehu *et al*. (2015) observed that wider inter-row spacing would encourage lateral growth rather than apical dominance. Mehmet (2008), where there was an observed increase in branch number as the plant spacing increased. He noted that there was an increase from 4.47 branches at 30cm plant spacing to 5.95 branches at 60cm plant spacing for the soybean variety. In the same manner, Abdurahman (2022) found a decrease in branch number as plant population increased in chickpea.

Table 4: The main effects of inter row spacing and varieties on lodging percent of fenugreek

Factor	Treatment	Parameter
		L%
Inter-row spacing (cm)	40	3.4[d]
	30	3.6[c]
	20	3.7[b]
	10	3.9[a]
	LSD (5%)	0.027
Varieties	Burka	3.65[a]
	Chala	3.65[a]
	Chafe	3.65[a]
	Local	3.65[a]
	LSD (5%)	Ns
	CV (%)	0.679

Means in a column with the same letter are not significantly different at the 5% probability level; CV = Coefficient of variation, LSD = Least Significant Difference, L% = Lodging percent, Ns = Non-significant

4.6. Lodging Percentage

Analysis of Variance revealed that the inter-row space had highly significantly effect on the lodging percent ($P < 0.01$). Conversely, the variety and their interaction effects had non-significant (Appendix Table 3). The least lodging percentage observed was 3.4 percent at the widest inter row space of 40 centimeters, whereas the highest one was 3.9 percent at the smallest distance of 10 centimeters (Table 4).

The influence of inter row spacing on the occurrence of lodging was caused by the difference in the competition process and structure development at different densities. The low inter-row spacing of 10 cm results in dense planting, increasing competition for sunlight. Consequently, the plant is prone to rapid stem elongation. In this case, tall, weak stems are produced with low stem diameter and low mechanical strength, which predisposes the plant to lodging. Conversely, increased inter-row spacing (40 cm) eliminates competition among the plants for sunlight, water, and nutrients. This means that plants develop shorter and stronger stems with high stem diameter and high root anchorage capacity. These characteristics increase resistance to lodging. The lack of significant variation between the varieties as well as the interaction between varieties and inter-row spacing is an indication that the varieties under investigation have similar genetic potential for lodging resistance under these conditions. Therefore, lodging was primarily influenced by plant population density rather than varietal differences.

This result in line with (Gezahegn and Tesfaye, 2017), who showed that the smallest distance between rows (30 cm) contributed to higher rates of lodging when compared to larger distances, where lodging occurred proportionately depending on the density of planting. High-density arrangements promote an increase in lodging mainly because of the increased competition between plants for light and other vital resources. This study is in line with (Tamrat *et al*., 2019), who indicated that high plant densities (≥ 250,000 plants/ha) in faba beans resulted in over crowdedness, leading to fragile stems and shallow roots. Similar results were obtained by (Tarekegn *et al*., 2024), who claimed that narrow rows in legumes led to higher rates of lodging because of weak stems and crowded canopies.

Table 5: The main effects of inter row spacing and varieties on, nodule fresh weight, nodule dry weight, effective nodule and ineffective nodule of fenugreek

Factor	Treatment	Parameters			
		NFW (mg/plant)	NDW (mg/plant)	EN	IEN
Inter-row spacing (cm)	40	72.0[a]	33.0[a]	15.74[a]	5.541[c]
	30	62.0[b]	29.0[b]	15.28[ab]	6.891[c]
	20	53.5[c]	25.0[c]	14.87[b]	8.975[b]
	10	45.0[d]	20.75[d]	14.65[b]	10.741[a]
	LSD (5%)	1.789	0.99	0.824	1.407
Varieties	Burka	69.5[a]	33.0[a]	18.108[a]	6.691[b]
	Chala	62.5[b]	29.0[b]	16.083[b]	7.258[b]
	Chafe	54.5[c]	25.0[c]	13.925[c]	8.70[a]
	Local	46.0[d]	20.75[d]	12.433[d]	9.50[a]
	LSD (5%)	1.789	0.99	0.824	1.407
	CV (%)	2.77	3.32	4.973	15.987

Means in a column with the same letter are not significantly different at 5% probability level; CV = Coefficient of variation, LSD = Least Significant Difference, NFW = Nodule fresh weight, NDW = Nodule dry weight, EN = Effective nodule, IEN = Ineffective Nodule

4.7. Nodule Fresh Weight

Analysis of variance revealed that both inter-row spacing and variety were statistically highly significant ($p < 0.01$), but there was no significant interaction between them ($p > 0.05$) (Appendix Table 4). The highest fresh weight of nodules (72 mg per plant) was observed for the largest inter-row spacing of 40 cm, whereas the lowest nodule fresh weight was found in the treatment with 10 cm inter-row spacing (45 mg per plant) (Table 5) The superiority in terms of fresh weight observed in plants spaced 40 cm apart is mainly due to increased vigor in plants because of the reduction in inter-specific competition. At wide inter-row spacing, plants benefit from more solar energy and moisture, leading to improved photosynthetic efficiency and better nutrient absorption, hence more developed primary and secondary branches, thick stems, and increased fresh nodule biomass per unit area. At the 10 cm inter-row spacing, plants experience physiological stress owing to extremely high intra-specific competition, resulting in smaller plants and thin stems. Though there are many plants planted at this row spacing, the low biomass per plant makes their total biomass low. The findings are supported by

(Tarekegn *et al*., 2024), who reported a maximum fresh weight (46.04 t ha^{-1}) in cowpea seed production when using 40 cm inter-row spacing.

In terms of different varieties used, Burka variety registered the highest fresh nodule weight at 69.5 mg, whereas the local variety had the lowest fresh biomass at 46 mg (Table 5). The increased fresh nodule weight of the Burka variety compared to the local check can be attributed to the higher genetic potential and ability to utilize resources efficiently. The improved varieties are endowed with a greater aggressiveness of the root system and ability to accumulate more biomass through enhanced photosynthesis. Consequently, the improved varieties can utilize environmental factors such as water, light, and nutrients and transform them to vegetative parts better than the local landrace due to its limited genetic potential. These results are consistent with (Fikreselassie *et al*., 2012) who indicated that improved varieties tend to have higher genetic potential compared to local landraces.

4.8. Nodule Dry weight

Analysis of variance revealed that there was a highly significant ($p < 0.01$) effect of inter-row spacing and variety on the dry weight of nodules. However, the interaction between the two factors under consideration was non-significant ($p > 0.05$) (Appendix Table 4). The highest dry weight of nodules (33 mg) was obtained at an inter-row spacing of 40 cm, while the lowest (20.75 mg) was observed at a spacing of 10 cm (Table 5). The marked rise in the nodule dry weight with the increase in inter-row spacing is mainly due to the decline in intra-specific competition for sunlight, water, nutrients, and space. With the 40 cm inter-row spacing, plants develop a good vegetative growth indicated by thick stems and high levels of branching. As opposed to the 10 cm inter-row spacing where competition for resources is very high, plants at this spacing show poor vegetative growth. This finding agrees with (Tarekegn *et al*., 2024), which noted that a greater inter-row spacing of 40 cm enhances biological yield among legume plants. The varieties with the highest nodule dry weight were the Burka varieties (33 mg) while the one with the lowest nodule dry weight was the local variety (20.75 mg).

High productivity of improved fenugreek varieties can be explained by their genes responsible for vigorous growth and effective utilization of resources. Improved fenugreek varieties have better photosynthesis abilities and greater root systems. These factors help them quickly convert solar energy into structural biomass in terms of thick stems and many side branches. Local plants probably lack genetic characteristics needed for vigorous

growth and, therefore, grow slowly and have small sizes. This conclusion agrees with the data obtained in (Gowda *et al*., 2006), where it was shown that some fenugreek genotypes had considerably greater dry masses because of their high growth effectiveness.

4.9. Effective and ineffective Nodules

According to Venkataraman and Kannaiyan (1993), nodules are categorized as effective and ineffective. The presence of leghemoglobin (nodule internal tissue pigmented pink) will allow to identify effective nodules. Effective nodules are formed by effective strains rhizobia, well developed and pink in colour due to leghemoglobin and the bacteroid tissue is well organized with plenty of bacteroides. On the other hand, ineffective strains rhizobia form ineffective nodules which are generally small and contain poorly developed bacteroid tissue showing accumulation of starch in host cells which do not contain Rhizobium and of dextran in host cells infected by rhizobium. The bacteroides of ineffective nodule contain glycogen.

4.9.1. Effective Nodules

An analysis of variance showed that both the spacing between rows and the variety significantly ($p < 0.01$) affected the number of effective nodules per plant. However, the interaction effect of spacing and variety was not significant ($p > 0.05$) (Appendix Table 5). The largest numbers of effective nodules (15.74 and 15.28) were registered at the spacing distances of 40 cm and 30 cm, respectively. On the other hand, the smallest number of effective nodules (14.65) was registered at the 10 cm inter-row space (Table 5). This increase in the number of nodules at wide spacing is explained by the lower level of intraspecific competition for growth factors, including light, water, and nutrient availability.

At 40 cm spacing, the plants show increased photosynthetic activity and produce more carbohydrates, which are transported to the roots and support rhizobacteria. Since the formation and maintenance of active nodules requires significant energy demand, more nodules develop on healthy plants spaced sufficiently far from each other. In contrast, plants at 10 cm inter row spacing exhibit increased physiological stress and low energy levels, produce fewer effective nodules. These results are supported by Waskle (2017), who reported significantly higher effective nodules (11.34 and 17.14) when there was a large distance of 45 cm between plants compared to a smaller distance of 30 cm at 30 and

45 days after planting, respectively. Similarly Khairnar *et al*. (2025) reported that wider spatial distribution mitigates inter-plant competition, which promotes robust root architecture expansion and provides the necessary metabolic resources to support symbiotic relationships.

Genotypic variability was observed in nodulation efficiency. The highest nodulation efficiency was observed for the Burka variety, with an average of 18.10 effective nodules formed, whereas the local variety had the least efficiency at 12.43 (Table 5). The outstanding nodulation efficiency of the Burka variety relative to the local variety is attributed to their greater genetic capacity to fix nitrogen and achieve symbiosis. Improved varieties have been able to establish better root association and biological compatibility with local Rhizobia. In addition, such improved varieties have been able to establish better associations with local rhizobial strains because of their capacity to recruit more bacteria for carbon needed for the formation of active nodules. According to Provorov and Tikhonovich (2003), such genotypic differences contribute to varietal differences in effective nodulation efficiency.

4.9.2. Ineffective Nodules

The analysis of variance showed that a highly significant effect of inter row spacing and variety on the number of ineffective nodules ($p < 0.01$). However, their interaction was not significant effect on the number of ineffective nodules ($p > 0.05$) (Appendix Table 5). The highest number of ineffective nodules (10.74) was recorded at 10 cm row spacing, while the lowest was at 40 cm inter row spacing (5.54) (Table 5). Higher number of ineffective nodule at 10 cm spacing is attributed to intense intra-specific competition and the resulting physiological stress. When plants are densely crowded, limited light and nutrient availability reduce the production of photo-assimilates (carbon). Because the development of functional, nitrogen-fixing nodules is an energy-intensive process, carbon-stressed plants allow rhizobia infection but fail to provide the metabolic energy required to transition those nodules into an "effective" state. Conversely, at the wider 40 cm spacing, plants maintain higher vegetative vigor, ensuring sufficient energy flow to the root system to support fully functional nodules. This result in line with (Wafula *et al*., 2021), who reported higher ineffective nodulation under narrower inter row spacing when compared to wider inter row spacing in chickpea varieties.

Significant variations were observed when comparing the level of nodule inefficiency. The local variety had the highest number of ineffective nodules (9.50). The Burka variety had the lowest number of ineffective nodules (6.69) (Table 5). The high occurrence of ineffective nodules in the Local variety indicates is a low level of specificity between the host and strain, leading to infection by incompatible or parasitic rhizobia, which do not produce leghemoglobin; thus, the ineffective nodules appear white or yellow. Additionally, the higher competition for nutrients increases plant stress due to water scarcity; hence, they limit carbon transfer to the root system. This energy limits nodule development to be stopped prematurely. These findings are consistent with (Gupta *et al*., 2026), who documented that varietal variations in inefficient nodulation in legumes are primarily linked to genetic diversity in nitrogen fixation efficiency.

Table 6: The interaction effects of inter row space and varieties on, number of pod per plant, pod length and number of seed per pod of fenugreek varieties

Treatment		Parameters		
Varieties	Inter Row spacing (cm)	NPPP	PL (cm)	NSPP
Chala	10	11.43^{fgh}	14.5^{fg}	12.46^{gh}
	20	13.16^{def}	15.0^{ef}	14.5^{cdef}
	30	16.13^{abc}	17.5^{bcd}	15.40^{c}
	40	16.53^{ab}	18.3^{abc}	17.36^{b}
Chafe	10	9.30^{hi}	13.2^{ghi}	11.36^{hi}
	20	12.66^{ef}	14.0^{fgh}	13.46^{efg}
	30	14.23^{cde}	16.4^{de}	14.16^{def}
	40	14.40^{bcde}	17.0^{cd}	15.23^{cd}
Burka	10	15.0^{bcd}	12.7^{hi}	13.53^{efg}
	20	15.70^{abc}	14.3^{fg}	15.16^{cd}
	30	17.30^{a}	18.6^{ab}	18.43^{ab}
	40	16.23^{abc}	19.7^{a}	18.70^{a}
Local	10	8.43^{i}	9.6^{k}	10.53^{i}
	20	8.46^{i}	9.8^{k}	11.46^{hi}
	30	10.16^{ghi}	11.0^{jk}	13.4^{fg}
	40	12.26^{efg}	12.0^{ij}	14.56^{cde}
Mean		13.214	14.6	14.36
LSD (5%)		2.24	1.51	1.12
CV (%)		5.69	3.46	2.57

Means in a column with the same letter are not significantly different at 5% probability level; CV= Coefficient of variation, LSD = Least significance deference, NPPP = Number of pod per plant, PL = Pod length, NSPP = Number of seed per pod.

4.10. Number of Pods per Plant

Analysis of variance revealed that the main and interaction effect of inter-row spacing and varieties had highly significant ($p < 0.01$) effect on pod number per plant (Appendix Table 6). The maximum number of pods per plant was obtained with wide spacing of 30 cm in association with the Burka variety (17.30). The minimum pods number per plant (8.43) was recorded at the inter-row spacing of 10 cm with the local variety (Table 6). The interaction between the varieties and inter-row spacing was significant suggesting that varieties reacted differently to changes in inter-row spacing. The fact that Burka variety performed better with 30 cm spacing indicates that this variety can better benefit from lesser competition and efficiently utilize the available resources for vegetative growth and reproductive development. In this situation, increased branching and improved assimilate partitioning to boost pods per plant.

The local variety, on the other hand, showed relatively poor performance under narrow spacing (10 cm) where greater plant density led to more competition for light, nutrients and water. This probably stunted its growth and prevented it from developing reproductive structures, causing a decrease in number of pods per plant. However, lower performance of the local variety across spacing levels might also suggest that it's limited genetic potential.

This finding agree with Gezahegn (2019), who found that pods per plant for common bean increased from 24.2 to 32.1 when inter-row spacing increased from 30 cm to 50 cm. Similarly, Tiwari *et al*. (2016) found that pods/plant increased with an increase in spacing from 25 × 10 cm to 30 × 10 cm for fenugreek. Tunçtürk (2011) found that there was a considerable increase in pods per plant with a significant increase in row spacing for fenugreek.

4.11. Pod Length

Analysis of variance revealed that pod length was highly significantly influenced ($P < 0.01$) by both the main effects and the interaction of inter-row spacing and variety (Appendix Table 6). The longest pod length recorded was 19.7 cm, resulting from the interaction of the Burka variety with 40 cm inter-row spacing, while the shortest pod length of 9.6 cm was observed from the interaction of 10 cm inter-row spacing with the local variety (Table 6). The significant interaction effect indicates that the response of pod length to inter-row spacing varied among the tested varieties. The Burka variety does

better at wider spacing (40 cm), implying a high genetic potential and more effective ability to take advantage of a lower competitors' intensity and resources to reproductive development. These conditions might be led to an increase in assimilate production and partitioning, as evidenced by the increased pod elongation, due to improved light interception, nutrient uptake and moisture availability.

The local variety, showed relatively poor performance at 10 cm inters row space, where greater plant density led to more competition for essential resources. This also probably reduced photosynthetic efficiency and the allocation of assimilate to reproductive structures, resulting in shorter and poor pods. The lower performance of local variety at spacing levels also may be attributed to the lower genetic potential and competition. The interaction effect thus shows that pod length is not a result of spacing or variety per se but rather it is the interaction of the two. Wider spacing was more advantageous for improved varieties like Burka than local varieties which had a restricted ability to convert favorable conditions to increased reproductive growth.

The result in line with the findings of Tunçtürk (2011) and Habib *et al*. (2019), which showed that a higher inter-row distance specifically contributed to greater pod length in different varieties of fenugreek plants. In a related development, Minjaro *et al*. (2023) observed that fenugreek plants grown at a row spacing of 30 cm produced more elongated pods (11.28 cm) than those grown at 22.5 cm spacing (10.24 cm).

4.12. Number of Seeds per Pod

Analysis of Variance showed that both inter-row spacing and varieties had a highly significant effect ($P \leq 0.01$) on number of seeds per pod, whereas their interaction effect had significant ($p \leq 0.05$) effect on this trait (Appendix Table 7). The highest seed numbers per pod (18.70) occurred due to interactions of the Burka variety with 40 cm inter-row spacing, and the lowest values (10.53) occurred in the interaction of the local variety with 10 cm inter-row spacing (Table 6). The interaction between variety and inter-row spacing was significant suggesting that the number of seeds per pod produced in response to inter-row spacing was different for the varieties tested. The superiority of Burka variety at wider spacing (40 cm) indicates the ability of the variety to make better use of the reduced competition and increased resource availability for reproductive development. Better access to light, soil moisture and nutrient was probably responsible for higher

photosynthetic activity and assimilate production, which led to improved seed set and lower seed abortion rates.

The local variety, however, responded less to narrow spacing (10 cm), under which higher plant densities led to greater competition for key resources. This probably decreased assimilate availability for reproductive growth resulting in fewer seeds per pod. Another explanation for its poorer performance might be that this local variety has less genetic potential and is less efficient in its use of resources when it is competing with other varieties. Moreover, the decrease in seed per pod for all varieties at the narrowest spacing implies that too much competition is detrimental to reproductive efficiency, with no genetic differences. This concurs with the findings of Meena *et al*. (2016), who reported that the maximum number of seed per pod could be obtained in wide row spacing, where a spacing of 25 cm led to an increase in the seed number per plant by 11.9%, while the narrow row spacing of 20 cm produced low number of seeds of 3.75.

Moreover, Abebe and Mitiku (2025) reported the need for selection of varieties, since improved varieties have been developed for high seed number per pod.

Table 7: The main effects of inter row spacing and varieties on biomass yield of fenugreek

Factor	Treatment	Parameter
		BY (Kg/h)
Inter-row spacing (cm)	10	1924.12[d]
	20	2744.81[c]
	30	3454.25[b]
	40	3673.96[a]
LSD (5%)		189.7267
Varieties	Burka	2949.66[a]
	Chala	2949.58[a]
	Chafe	2948.97[a]
	Local	2948.93[a]
LSD (5%)		Ns
CV (%)		5.872

Means in a column with the same letter are not significantly different at 5% probability level; CV = Coefficient of variation, LSD = Least significance deference, BY = Biomass yield, Ns = Non-significant.

4.13. Biomass yield

Analysis of variance showed that the inter-row spacing was highly significant ($P < 0.01$), effect on the aboveground dry biomass. However, the variety and their interaction effect was not significantly affected (Appendix Table 7). The highest above-ground dry biomass

recorded was 3673.96 kg ha^{-1} at the widest inter-row spacing of 40 cm; conversely, the lowest dry biomass of 1924.12 kg ha^{-1} was recorded at the narrowest spacing of 10 cm. Moderate ground biomass was recorded from planting of fenugreek at 20cm and 30cm (Table 7). The significant effect of inter-row spacing on above-ground dry biomass might be attributed to different factors relating to the number of plant population and availability of growth resources. With higher spacing (40 cm), each plant encounters low competition for important growth elements such as light, nutrition, and soil moisture. Such growing conditions facilitate growth and development of large foliage and stems and increase the biomass of above-ground dry mass.

At the same time, narrower spacing (10 cm) promotes higher plant population density and hence competition for growth elements, especially sunlight. As a result, plant growth is limited by high competition; therefore, the process of photosynthesis becomes inefficient and results in low production of dry matter, despite having more plants. Although plant population increases with narrowing spacing, their growth rate is reduced; thus, the net productivity becomes low. The non-significant influence of varieties and interaction between varieties and inter-row spacing indicates that the varieties used in this experiment have equal genetic capabilities for producing biomass under the existing environmental conditions. Thus, the biomass produced in this experiment was mainly dependent on plant spacing and not on variety difference. These results in line with (Ouji *et al*., 2022) in the sense that the environment of the crops, especially light intensity and carbon dioxide concentrations, influences the photosynthetic process significantly. Optimal spacing helps ensure growth of aerial and subterranean parts of plants through utilization of solar energy, land area, and nutrients present in the soil and water sources.

Table 8: The interaction effects of inter row space and varieties on, 1000 seed weight, grain yield and harvest index of fenugreek varieties

Treatment		Parameters		
Varieties	Inter Row spacing (cm)	TSW (g)	GY kg/h	HI%
Chala	10	12.46^{fg}	623^{ef}	32.39^{def}
	20	13.23^{ef}	925^{c}	33.67^{cde}
	30	16.40^{bc}	1413^{ab}	40.89^{a}
	40	17.33^{b}	1508a	41.05^{a}
Chafe	10	11.36^{gh}	598^{ef}	31.07^{ef}
	20	12.43^{fg}	878^{cd}	32.0^{ef}
	30	14.26^{de}	1346^{ab}	38.97^{ab}
	40	15.30^{cd}	1498^{a}	40.77^{a}
Burka	10	13.46^{ef}	698de	36.26^{bcd}
	20	15.36^{cd}	998^{c}	36.35^{bc}
	30	17.60^{b}	1400^{ab}	40.53^{a}
	40	20.26^{a}	1528^{a}	41.58^{a}
Local	10	9.36^{i}	487^{f}	25.31^{g}
	20	10.20^{hi}	700de	25.51^{g}
	30	10.40^{hi}	993^{c}	28.74^{fg}
	40	11.53^{gh}	1220^{b}	33.20^{cde}
Mean		13.8	1050.81	34.89
LSD (5%)		1.42	74.33	1.44
CV (%)		3.46	6.45	3.79

Means in a column with the same letter are not significantly different at 5% probability level; CV = Coefficient of variation, LSD = Least significance deference, TSW = Thousand seed weight, GY = Grain yield, HI-harvest index.

4.14. Thousand Seed Weight

The analysis of variance revealed that the main and interaction of inter-row spacing and variety had a highly significant effect on the thousand-grain weight ($p < 0.01$) (Appendix Table 7). The highest thousand-grain weight was recorded in the Burka variety at inter-row spacing of 40 cm producing weights of 20.26g. In contrast, the lowest thousand-grain weight was recorded in the local variety (9.36g), grown at the narrowest inter-row spacing of 10 cm (Table 8). The superiority of the Burka variety at wider spacing (40 cm) indicates that it is more efficient in getting the benefit from the lower level of competition and higher resource availability for grain filling. As a result of these circumstances, higher rates of light interception, nutrient uptake and moisture availability are likely to have led to higher net photosynthesis and assimilate production that would have led to more assimilate translocation to developing grains and higher grain weight. Burka variety, have

a higher genetic potential and more ability to capitalize on good conditions when spaced wide. The local variety, showed a limited response in narrow spacing (10 cm) due to increased competition for essential resources. The latter probably caused a decrease in availability of assimilate during the grain filling period, resulting in lighter grain. The lower performance of the local variety at all spacing levels could also be a reflection of its lower genetic potential and lower efficiency of the use of available resources for its grain mass production. These findings in line with Khan *et al*. (2010), who reported a greater thousand-seed weight (29.87 g) in chickpeas at a 45 cm spacing compared to 30 cm. Additionally, Sarkar, (2021) verified that suitable row spacing significantly improves yield components, such as the 1000-grain weight, by optimizing the growth conditions for legumes crops.

4.15. Grain Yield

Analysis of Variance revealed that inter-row spacing and varieties had a highly significant effect ($P \leq 0.01$) on grain yield, whereas their interaction effect had significant ($p \leq 0.05$) effect on this trait (Appendix Table 8).The maximum value for the grain yield was obtained at 40 cm inter-row spacing with Burka variety 1,528 kg ha^{-1} and the minimum value of grain yield was recorded from the local variety 487 kg ha^{-1} at 10 cm inter-row spacing (Table 8). The higher yield of Burka variety with wider 40 cm inter row spacing could be due to a more efficient use of resources resulting from the improved genetic potential of this variety. Better varieties generally tend to be "phenotypically plastic" in the sense that when they are given more space, they will grow more vigorously in canopy, branching and rooting. At 40 cm, the Burka variety was able to express its genetic superiority to the fullest extent by avoiding intra-specific competition. This spacing enhanced the availability and utilization of key resources such as solar radiation, soil moisture, and essential nutrients. This very favorable microenvironment led to better vegetative growth, thereby providing the sources of carbohydrates produced in photosynthesis and making it possible to transport the carbohydrates to the sinks to the growing pods. This led to greater branching, better pod formation and greater seed per pod. In contrast, the sharp drop in yield seen at the narrow spacing 10 cm inter row space points to a reduced tolerance of high plant density and high resource stress in the local variety. Local landraces frequently have more vegetative and tall growth habit and less efficient leaf pooling, and are very susceptible to mutual shading when crowded. At 10 cm spacing, the highest plant density resulted in high light and soil nutrient competition. The

local cultivar was not as architecturally improved as other cultivars (erect leaf angles for light penetration) and caused early leaf senescence (dying off) and limited net photosynthesis through mutual shading. This resulted in a high level of physiological stress and the plant had to divert its resources from reproduction to vegetative propagation. Consequently the local variety experienced poor grain filling, aborted flowers and reduced pod formation, which reduced its yield potential to minimum recorded level. This in line with the findings of Reza (2021) and Abebe and Mitiku (2025), all of whom noted that sowing fenugreek at wider spacing (30 and 40 cm) resulted in better seed production compared to the narrower 20 cm spacing.

4.16. Harvest Index

Analysis of Variance showed that both inter-row spacing and varieties had a highly significant effect ($P \leq 0.01$) on harvest index, whereas their interaction effect had significant ($p \leq 0.05$) effect on this trait (Appendix Table 8). The highest harvest index (41.58%) was achieved by planting the Burka variety using 40 cm inter-row spacing, followed by Chala variety (41.05%) planted at the same inter-row spacing. The lowest harvest index was recorded for the local variety when it was planted at a 10 cm inter-row spacing (Table 8). The interaction effect suggests that this resulted from differences among varieties in plant spacing pattern responses to changes, which arose from differences among varieties in growth habit, resource use efficiency and assimilate partitioning capacity. It was observed that the harvest index of improved varieties like Burka and Chala increased more under wider spacing at 40 cm indicating that their genetic ability to regulate source–sink relationship is better expressed in the absence of inter-plant competition. The wider spacing in these combinations most likely resulted in improved canopy structure and light distribution which were specific to the structural trait of these varieties, thus boosting photosynthetic production and allocation to reproductive organs. Conversely, the local one had a relatively low harvest index, especially for narrow spacing, implying that the physiological and morphological traits of the latter are less suited for high density.

In this interaction local variety with 10 cm inter row spacing, the increased competition might have led to a greater reduction in the assimilates available and the efficiency in assimilates partitioning, thus reducing the reproductive output per total biomass. This

result in line with Abdurahman (2022), the harvest index was higher with wider row spacing and lower at narrow inter row spacing.

4.17. Partial Budget Analysis of fenugreek varieties and inter-row spacing

Partial budget analysis was conducted to evaluate the economic feasibility of the treatments following standard procedures. Grain yield obtained from each treatment was adjusted downward by 10% to reflect the difference between experimental and farmers' field conditions. The adjusted yield was then multiplied by the prevailing market price to estimate the gross field benefit.

The total variable costs considered in the analysis included the cost of seed, fertilizer (NPS), and labor costs for land preparation, planting, weeding, and harvesting. The net benefit was determined by deducting the total variable cost from the gross field benefit. The marginal rate of return (MRR) was computed as the ratio of the change in net benefit to the change in total variable cost between successive treatments and expressed as a percentage.

The results indicated that the treatment consisting of Burka variety with 40 cm inter-row spacing produced the highest grain yield (1,528 kg ha^{-1}) and adjusted yield (1,375 kg ha^{-1}). This treatment also resulted in the maximum net benefit of 401,000 Birr ha^{-1} with a marginal rate of return of 15,975%. In contrast, the lowest net benefit (64,100 Birr ha^{-1}) was recorded from the local variety at 10 cm spacing.

The high marginal rate of return obtained from Burka at 40 cm spacing indicates its economic advantage over other treatments. Therefore, this treatment can be considered the most economically feasible option under the study conditions for farmers in Nedjo District and similar agro-ecological areas.

Table 9. Partial budget analysis of the response of fenugreek yields on the varieties and inter row space

Treatment		Fenugreek Yield kg ha^{-1}		Income ET Birr			
Var	Row	GY	10% AGY	TGB (Birr ha^{-1})	TVC (Birr ha^{-1})	NB (Birr ha^{-1})	MRR (%)
LOC	40	1220	1098	219600	10300	209300	D
BUR	40	1528	1375	412500	11500	401000	15,975
CHL	40	1508	1357	407100	11500	395600	D
CHF	40	1498	1348	404400	11500	392900	D
LOC	30	993	893.7	178740	12700	166040	D
CHL	30	1413	1271.7	381510	14700	366810	10,038.5
BUR	30	1400	1260	378000	14700	363300	D
CHF	30	1346	1211	363300	14700	348600	D
LOC	20	700	630	126000	16100	109900	D
BUR	20	998	898	269400	19100	250300	8343
CHL	20	925	823.5	247050	19100	227950	D
CHF	20	878	790	237000	19100	217900	D
LOC	10	487	438	87600	23500	64100	D
BUR	10	698	628	188400	29500	158900	1580
CHL	10	623	560.7	168210	29500	138710	D
CHF	10	598	538	161400	29500	131900	D

Keys: GY = Grain yield kg ha^{-1}, AGY = Adjusted grain yield 10%, TGB = Total gross benefit birr ha^{-1}, TVC = Total variable cost birr ha^{-1}, NB = Net benefit birr ha^{-1}, MRR = Marginal Rate of return %, ETB = Ethiopian birr per hectare, fenugreek local varieties selling price = 200 Birr/kg, fenugreek improved varieties selling price = 300 Birr/kg

5. SUMMARY AND CONCLUSION

Fenugreek is a multifunctional spice crop, where every part is utilized as a condiment, fodder, and leafy vegetable. In Ethiopia, fenugreek is cultivated on high plateaus (1800–2300 m a.s.l) within a subtropical environment characterized by distinct rainy and dry seasons. The yield potential of fenugreek is significantly affected by the choice of variety and inter-row spacing.

The results showed that inter row spacing affects agronomic characteristics such as days to 50 percent flowering, days to 90 percent physiological maturity, number of primary branches, pods, above-ground biological yield, weight of thousand seeds, fresh and dry weights, effective and ineffective nodules, percentage of lodging, plant height, harvest index, and grain yield. It was observed that 10 cm spacing gave the minimum duration for 50 percent flowering (43.0 days) and early physiological maturity (121.33 days), while the maximum value was achieved by widest spacing 40 cm inter row space. On the basis of performance of varieties, it is clear that local variety attained physiological maturity at the earliest time (114.9 days). Regarding performance of Burka variety, it gave better results, including maximum primary branches (6.70), maximum pod length (19.7 cm), highest seed number per pod (18.70), better thousand seed weight (20.26 g) and maximum grain yield (1528 kg ha^{-1}). However, the minimum results were obtained by the local variety at 10 cm spacing.

From this study, it can be concluded that the use of appropriate inter-row spacing plays a vital role in achieving increased production of fenugreek varieties. As per the highest grain yield results from treatment analysis, the Burka variety with 40 cm inter-row spacing provided a yield of 1528 kg ha^{-1} along with an adjusted grain yield of 1375 kg ha^{-1} and net benefit value of 401000 Birr ha^{-1} and MRR of 15,975%, whereas the lowest net benefit value of 64,100 Birr ha^{-1} was reported for the Local varieties with 10cm inter-row space treatment. Thus, it is suggested that the farmers of the study area and similar agro-climatic zones should cultivate Burka variety with 40 cm spacing.

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APPENDIX

Table 1: ANOVA table of, 50% days of emergency

Source of Variation	DF	Parameter	
		50% DE	
		MS	P
Block	2	1.2622e-29	0.3798
Row	3	1.2622e-29	0.4064^{Ns}
Var.	3	1.2622e-29	0.4064^{Ns}
Row*Var.	9	1.2622e-29	0.4612^{Ns}
Error	30	1.2622e-29	
CV (%)		7.10	

Var. = Verities, Ns = Non-significant, DF = Degree of freedom, 50%DE = 50% Days of emergency, CV = Coefficient of variation, MS = Mean square, P = P-value

Table 2: ANOVA Table of 50% days of flowering and 90% days of maturity

Source of Variation	DF	Parameters			
		50% DF		90%DM	
		MS	P	MS	P
Block	2	0.521	0.6541	7.15	0.01061
Row	3	27.854	6.250e-08**	78.17	1.329e-12 **
Var	3	82.299	1.735e-13 **	976.17	< 2.2e-16 **
Row*Var	9	1.521	0.2997Ns	1.44	0.40993^{Ns}
Error	30	1.210		1.35	
CV (%)		2.34		0.969	

Var. = Verities, Ns = Non-significant, **= highly significant at 1% level, DF = Degree of freedom, 50%DF = 50% Days of flowering, 90% DM = 90% Days of maturity, CV = Coefficient of variation, MS = Mean square, P = P-value

Table 3: ANOVA Table of plant height, number of branch and lodging%

Source of Variation	DF	Parameters					
		PH (cm)		NB		L%	
		MS	P	MS	P	MS	P
Block	2	0.00	1	0.000	1.000	0.00000	1
Row	3	529.25	< 2.2e-16 **	70.146	< 2.2e-16**	1.53600	<2e-16**
Var	3	145.80	< 2.2e-16 **	8.588	8.549e-09**	0.00000	1^{Ns}
Row*Var	9	19.02	3.548e-12 **	1.482	0.014*	0.00000	1^{Ns}
Error	30	0.46		0.369		0.00062	
CV (%)		1.636		13.70		0.679	

Var. = Verities, Ns = Non-significant, * = Significant at 5% level, ** = highly significant at 1% level, DF = Degree of freedom, PH = Plant height, NB = Number of branch, L% = Lodging percent CV = Coefficient of variation, MS = Mean square, P = P-value

Table 4: ANOVA Table of nodule fresh weight and nodule dry weight

Source of Variation	DF	Parameters			
		NFW (mg)		NDW (mg)	
		MS	P	MS	P
Block	2	25.00	0.0005933	4.00	0.01336
Row	3	1604.75	< 2.2e-16 **	332.19	< 2e-16**
Var	3	1234.75	< 2.2e-16 **	332.19	< 2e-16**
Row*Var	9	1.42	0.8298703Ns	0.19	0.98648Ns
Error	30	2.60		0.80	
CV (%)		2.77		3.32	

Var. = Verities, Ns = Non-significant, **= highly significant at 1% level, DF = Degree of freedom, NFW = Nodule fresh weight, NDW = Nodule dry weight, CV = Coefficient of variation, MS = Mean square, P = P-value

Table 5: ANOVA Table of effective nodule and ineffective nodule

Source of Variation	DF	Parameters			
		EN		IEF	
		MS	P	MS	P
Block	2	1.488	0.113248	0.405	0.6232
Row	3	6.273	0.001924**	187.620	4.065e-13**
Var	3	74.012	< 2.2e-16**	19.985	9.670e-06**
Row*Var	9	0.843	0.232772Ns	0.112	0.9766Ns
Error	30	0.567		1.651	
CV (%)		4.97		15.98	

Var. = Verities, Ns = Non-significant, **= highly significant at 1% level, DF = Degree of freedom, EN = Effective nodule, IEN = Ineffective nodule, CV = Coefficient of variation, MS = Mean square, P = P-value

Table 6: ANOVA Table of number of pod per plant and pod length

Source of Variation	DF	Parameters			
		NPPP		PL(cm)	
		MS	P	MS	P
Block	2	0.053	0.7617566	0.000	1
Row	3	107.870	< 2.2e-16**	141.373	< 2.2e-16**
Var	3	84.212	< 2.2e-16**	89.015	< 2.2e-16**
Row*Var	9	5.068	0.0001235**	7.591	3.743e-10**
Error	30	0.567		0.256	
CV (%)		5.696		3.46	

Var. = Verities, **= highly significant, DF = Degree of freedom, NPPP = Number of pod per plant, PL = Pod length, CV= Coefficient of variation, MS = Mean square, P = P-value

Table 7: ANOVA Table of number of seed per pod and biomass yield and 1000 seed weight

Source of Variation	DF	Parameters					
		NSPP		BY(kg/h)		TSW	
		MS	P	MS	P	MS	P
Block	2	0.000	1.00000	0	0.9988	0.070	0.5827
Row	3	138.168	< 2e-16**	21305391	<2e-16**	138.320	< 2.2e-16**
Var	3	35.460	< 2e-16**	2	1.0000Ns	85.303	< 2.2e-16**
Row*Var	9	1.132	0.01757*	0	1.0000Ns	6.827	3.449e-10**
Error	30	0.298		29995		0.229	
CV (%)		3.80		5.93		3.46	

Var. = Verities, Ns = Non-significant, *= Significant at 5% level, **= highly significant, DF = Degree of freedom, NSPP = Number of seed per pod, BY=Biomass yield, TSW = Thousand seed weight, CV = Coefficient of variation, MS = Mean square, P = P-value

Table 8: ANOVA Table of grain yield and harvest index

Source of Variation	DF	Parameters			
		GY(kg/h)		HI (%)	
		MS	P	MS	P
Block	2	0	1.00000	0.00	1.00000
Row	3	5128988	< 2.2e-16**	510.52	< 2e-16**
Var	3	226624	2.496e-13**	257.06	< 2e-16**
Row*Var	9	14757	0.03352*	7.55	0.01003 *
Error	30	4604		1.75	
CV (%)		6.45		3.786	

Var. = Verities, *= Significant at 5% level, ** = highly significant, DF = Degree of freedom, GY = Grain yield, HI = Harvest index, CV = Coefficient of variation, MS = Mean square, P = P-value.