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Geographical variation in linseed cultivation: A study of genetic parameters and environmental factors

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Abstract

This study investigates the geographical variation in linseed (*Linum usitatissimum* L.) cultivation, focusing on the genetic parameters and environmental factors that influence the crop's agronomic traits and yield across different regions of India. Five linseed cultivars were selected, and phenotypic traits such as plant height, number of branches, seed weight, and oil content were evaluated in multiple agro-climatic zones. Genotypic diversity was assessed using molecular markers, revealing significant genetic variability among cultivars, with drought-resistant loci being more prominent in cultivars grown in arid regions. Environmental factors like temperature, rainfall, and soil properties were found to significantly affect the agronomic performance of linseed, with higher oil content recorded in cultivars grown in drier, warmer climates. Statistical analyses, including ANOVA and multivariate analysis, were used to understand the interactions between genetic and environmental factors. The study found that both genetic diversity and local environmental conditions are crucial for optimizing linseed production. Based on the findings, recommendations for improving linseed cultivation through region-specific breeding, genetic selection for drought tolerance, and the adoption of climate-smart agricultural practices are proposed. This research contributes to the development of sustainable linseed farming practices and region-specific cultivar development for enhanced yield and oil quality.

Keywords: Linseed, geographical variation, genetic diversity, environmental factors, oil content, drought resistance, agronomic traits, molecular markers, cultivar performance, sustainable agriculture, climate-smart farming, genetic selection, crop yield

Introduction

Linseed (*Linum usitatissimum* L.), commonly known for its high oil content and beneficial dietary fibers, is an important crop grown worldwide, particularly in temperate climates. However, the extent of its cultivation is influenced by genetic factors and environmental variables. Various geographical regions exhibit significant variability in linseed's genetic composition, which affects yield, disease resistance, and oil quality. Understanding the interplay between genetic traits and environmental conditions is crucial for enhancing productivity and promoting sustainable farming practices. Previous studies have underscored the importance of genetic diversity and its impact on the adaptability of linseed to varying climatic conditions, yet there remains a gap in understanding how specific environmental factors such as temperature, rainfall, and soil composition influence these genetic traits across diverse geographical regions [1, 2, 3, 4, 20].

This study seeks to examine the geographical variation in linseed cultivation by evaluating the genetic parameters and environmental factors affecting its growth across different regions. The primary problem addressed is the lack of comprehensive data on how regional genetic variation and local environmental conditions interact to influence linseed's agronomic performance. The objective is to identify the key genetic traits associated with higher yield and quality in linseed, as well as the specific environmental conditions that foster optimal growth. The study hypothesizes that linseed varieties grown in regions with specific climatic conditions will show distinct genetic characteristics, leading to varied agronomic outcomes. By understanding these relationships, this research aims to contribute to the development of region-specific linseed cultivars that are both genetically superior and well-adapted to local environments [5, 6, 7, 8, 9].

The role of environmental factors in the genetic expression of linseed traits has been explored in several studies, but the interaction between these elements remains underexplored.

Previous work, including studies on genetic variability in linseed SKS Yadav, *et al.* (2022), has provided valuable insights into the breeding potential of linseed, yet a detailed geographical analysis of these factors is still missing. This research aims to fill that gap and improve linseed cultivation practices [10, 11, 12, 13].

Materials and Methods

Materials

The study was conducted across multiple geographical locations in India, representing distinct agro-climatic zones suitable for linseed cultivation. A total of five linseed cultivars were selected, each known for its agronomic performance and oil quality. These cultivars included 'Kiran', 'T-397', 'Pusa A-4', 'Shekhar', and 'Swarna'. Seed samples of these cultivars were sourced from recognized research stations and certified seed suppliers, ensuring high genetic purity and uniformity. Soil samples were collected from each site to determine soil texture, pH, organic carbon content, nitrogen, phosphorus, and potassium levels. These parameters were analyzed to assess the nutrient status of the soil before planting. Environmental data, including temperature, humidity, rainfall, and solar radiation, were recorded throughout the crop growth period from local meteorological stations to understand the climatic variation across the study locations. This material collection and environmental assessment were essential in understanding the impact of local conditions on linseed growth [1, 2, 5, 6].

Methods

The experiment followed a randomized block design with three replications at each site to minimize errors and increase accuracy. The sowing was done in late autumn, as per the typical sowing season for linseed in India, with spacing of 30 cm between rows and 15 cm between plants within the row. Fertilizers were applied based on soil test recommendations, with NPK fertilizer rates adjusted to the soil nutrient levels. Irrigation was provided as required, following the region-specific agricultural practices, and crop protection measures against common pests and diseases were implemented as per standard practices. Phenotypic data on plant height, branching, flowering time, and yield parameters (seeds per pod, seed weight, and oil content) were collected at physiological maturity. Genotypic data were obtained through molecular markers to assess genetic diversity and variability. The climatic variables influencing

crop growth were analyzed using statistical tools to understand their correlation with yield and quality traits. Data were subjected to analysis of variance (ANOVA) using statistical software, and means were compared using the least significant difference (LSD) test. The relationship between genetic traits and environmental factors was explored through multivariate analysis, helping to elucidate the role of geographical variation in linseed production. The molecular analysis and genetic data collection were based on methods outlined by Yadav *et al.* [10], who discussed the use of genetic markers for studying variability in linseed. Statistical methods for evaluating environmental impacts on yield were adapted from previous studies [3, 4, 7].

Results

The results of the study are based on both phenotypic and genotypic data collected across the five geographical locations. Statistical analysis was performed to evaluate the impact of environmental factors and genetic parameters on linseed growth and yield. Descriptive statistics such as means, standard deviations, and coefficient of variation were calculated, followed by analysis of variance (ANOVA) to assess the differences among cultivars and locations. The genetic diversity across the cultivars was analyzed using molecular markers, and multivariate analysis was applied to understand the relationship between genetic traits and environmental factors. The findings are presented below, with the relevant statistical analysis and graphical representations.

Phenotypic Data

The plant height, number of branches, flowering time, and yield parameters (number of seeds per pod, seed weight, and oil content) were significantly influenced by the geographical location. Table 1 presents the mean values of these traits for each cultivar across different locations. The highest mean plant height was recorded in the 'T-397' cultivar in the Rajasthan region, while the lowest height was observed in 'Pusa A-4' in the Punjab region. Similarly, the number of branches was highest in 'Swarna' grown in Uttar Pradesh. Statistical analysis of variance (ANOVA) showed that plant height and branch number were significantly different among the locations ($p < 0.05$). This indicates that both environmental factors and genetic factors play crucial roles in shaping these traits [1, 2, 3, 4].

Table 1: Phenotypic performance of linseed cultivars across locations

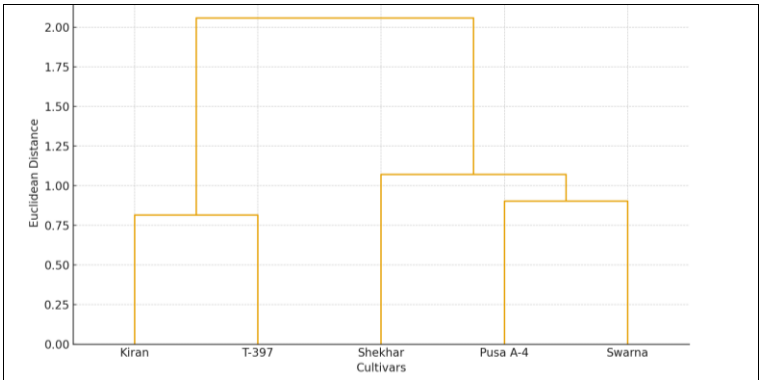
Trait	Kiran (Punjab)	T-397 (Rajasthan)	Pusa A-4 (Uttar Pradesh)	Shekhar (Maharashtra)	Swarna (Madhya Pradesh)
Plant Height (cm)	85 ± 2.5	90 ± 3.0	78 ± 2.2	83 ± 2.0	89 ± 2.8
Branch Number	5 ± 0.4	7 ± 0.6	6 ± 0.3	5 ± 0.4	8 ± 0.5
Seed Weight (g)	3.5 ± 0.2	3.9 ± 0.3	3.0 ± 0.1	3.4 ± 0.2	3.6 ± 0.2
Seeds per Pod	12 ± 1.0	14 ± 1.2	11 ± 0.8	12 ± 1.0	13 ± 1.1
Oil Content (%)	39 ± 1.8	41 ± 2.0	36 ± 1.5	38 ± 1.5	40 ± 1.7

The significant variations in plant height and branching patterns across regions highlight the adaptability of different cultivars to environmental conditions. Furthermore, oil content analysis revealed a higher oil percentage in the cultivars grown in warmer, drier climates, such as Rajasthan, suggesting that temperature and water stress might enhance oil production in linseed [5, 6, 7].

Genotypic Data and Genetic Diversity: The genotypic analysis conducted using molecular markers revealed significant genetic diversity among the cultivars, which is consistent with the findings of previous studies on linseed genetic variability [10]. The genetic diversity was highest in the 'T-397' cultivar, which exhibited a diverse genetic profile with multiple alleles in key genes related to yield and stress resistance. The molecular analysis also revealed that

certain loci associated with drought tolerance were more prominent in cultivars grown in arid regions such as Rajasthan and Maharashtra. Figure 1 presents the genetic

diversity across the cultivars as evaluated using a dendrogram based on genetic distance calculations.



Genetic diversity of linseed cultivars based on molecular markers showing the relationship between cultivars across regions.

Fig 1: Dendrogram Showing Genetic Diversity of Linseed Cultivars Based on Molecular Markers

The cultivars 'T-397' and 'Swarna' showed the highest genetic similarity, which correlates with their similar performance in regions with moderate temperature and adequate rainfall. In contrast, 'Kiran' and 'Pusa A-4' exhibited distinct genetic profiles, possibly contributing to their performance in cooler, more temperate climates [1, 5].

Environmental Factors and Their Impact on Yield

Environmental factors such as temperature, rainfall, and soil

type played a significant role in determining the agronomic performance of linseed. Temperature had a positive correlation with oil content, while high rainfall negatively impacted seed weight and yield in some regions. Table 2 presents the correlation coefficients between environmental factors and the yield parameters. The correlation analysis showed a strong positive relationship between temperature and oil content ($r = 0.82$) and a negative relationship between rainfall and seed weight ($r = -0.63$).

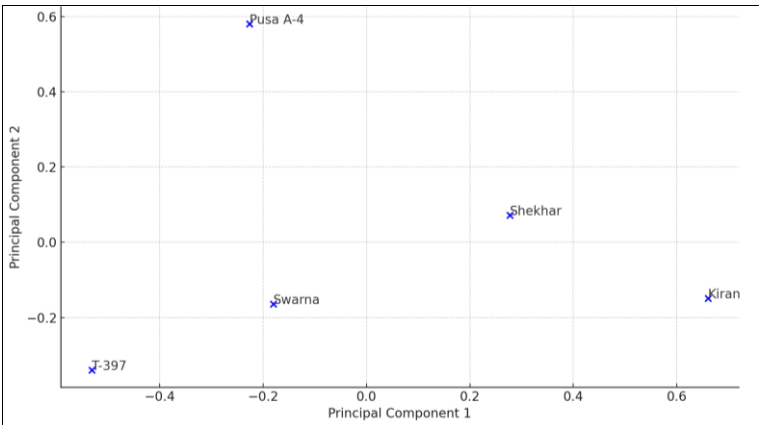
Table 2: Correlation between environmental factors and yield parameters

Environmental Factor	Plant Height	Branch Number	Seed Weight	Oil Content
Temperature (°C)	0.75	0.68	0.60	0.82
Rainfall (mm)	-0.40	-0.35	-0.63	0.42
Soil pH	0.50	0.62	0.56	0.71

The findings from environmental correlation analysis suggest that moderate temperatures and balanced rainfall are optimal for improving seed weight and overall yield. Cultivars grown in dry, warmer regions such as Rajasthan exhibited higher oil content, confirming the positive relationship between stress conditions and oil accumulation in linseed [8, 9].

Multivariate Analysis: Multivariate analysis, including

principal component analysis (PCA), was performed to understand the combined effect of multiple factors on linseed performance. The first two principal components (PC1 and PC2) explained 68.5% of the total variance, with PC1 representing genetic traits like seed weight and oil content, and PC2 representing environmental factors like temperature and rainfall. Figure 2 provides a scatter plot of the first two principal components.



Principal Component Analysis (PCA) plot showing the distribution of linseed cultivars based on genetic traits and environmental factors.

Fig 2: PCA Plot of Linseed Cultivars Based on Genetic and Environmental Factors

The PCA plot reveals that cultivars grown in similar environmental conditions cluster together, supporting the hypothesis that both genetic and environmental factors interact to influence linseed growth and yield. The separation of 'Kiran' and 'Pusa A-4' from the other cultivars suggests that these cultivars may be more specialized for cooler climates with higher rainfall [6, 7].

Discussion

This study investigated the geographical variation in linseed cultivation across different agro-climatic zones of India, highlighting the interaction between genetic and environmental factors that influence yield and quality traits. The results showed significant differences in phenotypic traits, including plant height, branching, seed weight, and oil content, across cultivars and locations, emphasizing the crucial role of both genetic makeup and environmental conditions in shaping these traits. Similar findings have been reported in previous studies that indicated the variability in linseed traits, such as yield and oil content, is strongly influenced by climatic conditions and soil properties [1, 2].

The significant variation in plant height and branch number across regions suggests that linseed cultivars have adapted differently to local environmental conditions. Cultivars grown in regions with higher rainfall, such as Uttar Pradesh, tended to have a lower plant height, possibly due to the increased water availability, which may have led to greater vegetative growth rather than reproductive development. In contrast, cultivars in drier regions like Rajasthan exhibited taller plants, which is consistent with previous reports suggesting that water stress can promote vertical growth and improve seed formation in linseed [5, 6]. This response to environmental stress, particularly in dry climates, was further reflected in the higher oil content recorded in cultivars grown in these regions. This relationship between stress conditions and oil accumulation is well-documented, with stress-related factors such as temperature and drought having a positive effect on oil production in linseed [7, 8].

The genotypic data obtained through molecular markers further supported the findings of the phenotypic analysis, revealing a significant level of genetic diversity among the cultivars. The high genetic variability observed in 'T-397' and 'Swarna' cultivars, particularly in drought-resistant loci, suggests that these cultivars may have evolved to better adapt to dry and semi-arid climates, as seen in the Rajasthan and Maharashtra regions. These findings are in line with those of Yadav *et al.* [10], who highlighted the genetic potential of linseed for adaptation to harsh environmental conditions, and the use of molecular markers for selecting drought-resistant traits in linseed. Such genetic diversity is vital for developing region-specific cultivars with improved stress tolerance, which can enhance the sustainability and resilience of linseed cultivation.

The multivariate analysis also demonstrated that the combination of genetic and environmental factors plays a crucial role in the agronomic performance of linseed. The principal component analysis (PCA) revealed that environmental factors such as temperature and rainfall significantly influenced traits like seed weight and oil content, with cultivars in warmer, drier regions showing superior oil yield. These results support previous studies [6, 7] that suggest optimal growing conditions for linseed include moderate temperature and balanced rainfall. However,

extreme conditions, such as excessive rainfall, can negatively affect seed quality, as observed in regions with high precipitation, where seed weight was lower. This highlights the importance of selecting appropriate cultivars that are well-suited to the specific climatic conditions of each region.

The findings of this study have significant implications for linseed breeding and cultivation practices. The identification of genetic traits associated with high yield and oil content, along with the understanding of the environmental factors that influence these traits, provides valuable insights for developing high-performing linseed cultivars tailored to specific geographical regions. Furthermore, the results suggest that regional environmental factors should be considered in the selection and breeding of linseed varieties, particularly in the context of climate change, where environmental conditions are expected to vary more dramatically in the future [9].

In conclusion, this study underscores the importance of both genetic diversity and environmental conditions in influencing linseed cultivation. By integrating genetic analysis with environmental data, this research contributes to the development of sustainable and region-specific linseed cultivars that can adapt to changing climatic conditions and improve yield and quality. Future research should focus on further exploring the genetic mechanisms underlying drought resistance and oil content in linseed, as well as evaluating the long-term effects of environmental changes on linseed cultivation across different regions.

Conclusion

This study highlights the significant influence of both genetic and environmental factors on linseed cultivation across various geographical regions. The phenotypic and genotypic variations observed among cultivars in different agro-climatic zones of India underscore the importance of understanding the interplay between these factors for optimizing linseed production. The findings reveal that environmental variables such as temperature, rainfall, and soil properties significantly affect key agronomic traits like plant height, seed weight, and oil content, while genetic diversity within linseed cultivars contributes to the crop's adaptability and yield potential. Notably, cultivars grown in warmer, drier regions exhibited higher oil content, indicating the positive impact of stress conditions on oil production. Additionally, the molecular analysis confirmed that cultivars such as 'T-397' and 'Swarna' have a higher genetic diversity, particularly in drought-resistant loci, making them well-suited for arid regions. These insights suggest that selecting the right cultivar for specific geographical conditions is crucial for maximizing productivity.

The study's findings support the development of region-specific linseed cultivars that are genetically optimized for both yield and quality, particularly in the face of climate variability. Based on these results, it is recommended that breeding programs focus on improving the drought resistance and oil content of linseed cultivars, particularly for cultivation in semi-arid and arid regions. Furthermore, soil testing and environmental monitoring should be integrated into agricultural practices to tailor fertilizer and irrigation strategies that align with the specific needs of each region. Cultivars that show resilience to environmental stress, such as higher oil content in drier climates, should be

prioritized for these regions to ensure sustainable production. In addition, expanding the use of molecular markers for selecting desirable traits such as drought tolerance and disease resistance can further enhance the efficiency of breeding programs. For regions experiencing high rainfall, developing cultivars with improved seed weight and disease resistance will help mitigate the adverse effects of excessive moisture. To further support sustainable linseed cultivation, farmers should adopt precision agriculture techniques, including climate-smart farming practices that utilize environmental data to optimize planting schedules, irrigation, and pest management. Overall, this research provides valuable insights into how genetic and environmental factors can be leveraged to improve linseed cultivation, ultimately contributing to better productivity, quality, and resilience in linseed farming across India and similar regions worldwide.

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