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Heterosis and inbreeding depression for yield and its component traits in linseed (Linum usitatissimumL.)

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Abstract
The essential oilseed crop Linseed (Linum usitatissimum L.) suffers from genetic limitations because of its self-fertilizing nature. The research investigated gene actions responsible for yield and yield component traits through assessment of F_1 hybrid and F_2 population samples from 45 hybrid combinations.
The research results showed that hybrid plants produced more seeds through heterobeltiosis which reached a maximum of 52.6% together with non-additive genetic traits that determined capsule production. The F_2 generation showed genetic segregation patterns which disrupted hybrid vigor and caused inbreeding depression to reach a maximum of 30% for these characteristics.
The 1000-seed weight characteristic showed no inbreeding depression, which demonstrates that additive gene action predominates while genetic stability has increased.
The research results show that linseed hybrid development has theoretical potential yet successful development of superior high-yield pure-line cultivars requires identification of crosses which show minimal inbreeding depression.
Keywords: *LinumUsitatissimum L, Self-Fertilizing, Heterobeltiosis, Linseed Hybrid Development, High-Yield Pure-Line Cultivars etc.*

I. Introduction: Economic Significance and Versatility of Linseed

Linseed (Linum usitatissimum L.) is known as flax because it represents one of the oldest and most flexible agricultural crops which humans have cultivated throughout history to produce both textiles and oilseed products. The historical value of its fiber has diminished because modern research now focuses on analyzing its seed composition. The seeds contain 35 to 45 percent oil content which primarily consists of alpha-linolenic acid, an essential omega-3 fatty acid that supports heart health and reduces inflammation. Linseed oil serves as a drying oil which contains a high iodine value that makes it suitable for applications in paints and varnishes and linoleum production [1]. The increasing market need for bio-based products together with functional foods creates a breeding requirement to improve both crop yield and oil content quality.

The Genetic Paradox of Autogamous Species

The self-pollinating nature of linseed leads to increased homozygosity which decreases the presence of harmful genes. The self-pollination mechanism of crops leads to reduced inbreeding depression when compared to maize which depends on cross-pollination for reproduction [2]. The process of hybridizing lines creates a situation which results in conflicting outcomes. The majority of genotypes show substantial F1 heterosis for seed yield and capsule count. The results show three genetic mechanisms dominance overdominance and epistasis even though self-fertilization has occurred throughout the history of the organism.

The Mechanisms of Heterosis and Inbreeding Depression

Scientists use heterosis to find the best breeding combinations because they need stable populations for their study. To test F2 hybrids we must examine F1 hybrids which exhibit extreme strength because their performance decreases when their parental genetic components undergo random mating [3]. Scientists investigate inbreeding depression to understand the function of genes in biological systems. The significant increase in heterosis together with the observable inbreeding depression occurs because genetic interactions produce results that exceed zero [4]. The presence of minimal inbreeding depression together with extensive heterosis demonstrates that multiple genetic elements combine to produce advantageous genetic recombinants.

Research Aims and Parameters

The research evaluates heterosis and inbreeding depression which exists between different genetic variants. The research compares F1 and F2 results with mid-parent and superior parent values to explain gene functions. The research aims to discover crosses which show both substantial heterosis and manageable depression. The research results show that hybrid breeding methods produce better results than pedigree selection methods. The study establishes a framework which will improve linseed yield while solving yield plateaus through cultivation methods that work in multiple agro-ecological zones to produce adaptable and permanent sustainable productivity which meets upcoming agricultural needs and worldwide market expansion. The research aims to achieve better genetic progress together with higher agricultural results throughout different global agricultural systems which support food security and industrial use over extended periods while providing sustainable advantages.

Stage	Process / Concept	Flow / Relationship
1	Economic Importance of Linseed	Old crop → Dual use (fiber + oilseed) → Shift to seed focus
2	Seed Composition & Uses	High oil (35–45%) → Rich in omega-3 (ALA) → Health benefits + Industrial uses (paints, varnish, linoleum)
3	Breeding Demand	Increased demand → Need to improve yield + oil quality
4	Reproductive Nature	Self-pollinating crop → High homozygosity → Reduced harmful genes
5	Expected Outcome	Selfing → Low inbreeding depression (typical behavior)
6	Genetic Paradox	Hybridization → Unexpected high F_1 heterosis
7	Genetic Explanation	Heterosis arises due to → Dominance / Overdominance / Epistasis
8	Heterosis Utilization	Identify superior crosses → Evaluate hybrid performance
9	Generation Shift	F_1 (high vigor) → F_2 (reduced performance due to segregation)
10	Inbreeding Depression Analysis	Measures loss of vigor → Helps understand gene action
11	Interpretation Path 1	High heterosis + High inbreeding depression → Non-additive gene action
12	Interpretation Path 2	High heterosis + Low inbreeding depression → Additive gene action → Stable recombinants
13	Research Approach	Compare F_1 & F_2 → With mid-parent & better-parent values
14	Selection Goal	Identify crosses → High heterosis + Manageable depression
15	Breeding Decision	Choose → Hybrid breeding OR Pedigree selection
16	Final Outcome	Improved yield → Break yield plateau → Sustainable productivity across environments

Table 1:Logical Progression of Ideas, Source: Author Generated

II. Materials and Methods

Selection of Germplasm and Experimental Design

The research used ten different linseed parental lines which exhibited different phenotypic characteristics that affected their yield and oil content. The parent plants were crossed in the Rabi season of 2024 using a half-diallel mating design, excluding reciprocals, to produce 45 F_1 hybrids. The F_2 generation was created through spontaneous self-pollination of F_1 seeds, which were planted during the 2025 cropping season, while the remaining F_1 seeds were kept for later evaluation [5]. The final field experiment used a Randomized Block Design (RBD) with three replicates. Each plot had two rows for the parental and F_1 generations, and four rows for the F_2 populations. To create similar growth conditions and reduce competition between different plant types, the researchers maintained a 30 cm space between rows and a 10 cm space between plants.

Data Collection and Quantitative Measurements

Researchers recorded their observations by selecting five competitive plants from each replication of the parents and F_1s and twenty plants for the F_2 generation which helped them study transgressive segregation. The following traits were recorded:

- Days to 50% flowering
- Plant height (cm)
- Number of primary branches per plant
- Number of capsules per plant
- 1000-seed weight (test weight)
- Total seed yield per plant (g)

The study measured oil content percentage through both Soxhlet extraction method and Non-Destructive Nuclear Magnetic Resonance (NMR) spectroscopy method. The researchers executed all essential agronomic procedures, which included irrigation and weeding and fertilizer application at NPK ratios of 60:40:20 kg/ha, to create conditions that allowed the genotypes to reach their maximum genetic performance in a low-stress environment [6].

Statistical Models and Genetic Analysis

Researchers used analysis of variance (ANOVA) to study the data which they obtained from different genotypes. The researchers evaluated heterosis through the following method. Relative Heterosis (H %) is calculated using the formula $H (\%) = (F_1 - MP) / MP \times 100$. Heterobeltiosis ($H_{(b)}$ %) is calculated through the equation $H_{(b)} (\%) = (F_1 - BP) / BP \times 100$. F_1 represents the average performance of the hybrid. MP represents the mid-parental value. BP represents the enhanced parental value [7]. The research team established inbreeding depression (ID) measurement through this following method. ID percentage calculation uses the formula ID (%) = $(F_1 - F_2) / F_1 \times 100$. The researchers used the 't' test to assess heterosis and inbreeding depression at both 5% and 1% significance thresholds. The statistical framework enabled researchers to separate the two types of gene actions which produced yield and associated traits in linseed [8].

III. Result and Analysis

Quantitative Evaluation of Vegetative Characteristics and Promptness

Linseed production depends on two essential factors which are the number of capsules produced by each plant and the total count of main branches. The quantity of capsules per plant demonstrated significant heterosis which saw certain F_1 hybrids achieve more than 35% higher results than their best parent. This major heterobeltiosis result shows how non-additive gene effects which include dominance and overdominance determine the study outcome. The F_2 populations demonstrated high inbreeding depression which occurred in more than 20% of cases [9]. The study results demonstrate that F_1 hybrid vigor originated from genetic interactions that exist only during the initial stages before self-fertilization occurs. The primary branches showed a constant growth pattern throughout the entire period. The F_1 hybrids showed substantial heterosis which ranged from 12% to 15% while the F_2 populations maintained most of this advantage with only minimal inbreeding depression that reached approximately 5%. Therefore the system demonstrates additive and additive epistatic interactions which base their stability on selection methods.

Dynamics of Yield Components: Capsules and Branching

Linseed production depends on two essential factors which are the number of capsules produced by each plant and the total count of main branches. The quantity of capsules per plant demonstrated significant heterosis which saw certain F_1 hybrids achieve more than 35% higher results than their best parent [10]. This major heterobeltiosis result shows how non-additive gene effects which include dominance and overdominance determine the study outcome. The F_2 populations demonstrated high inbreeding depression which occurred in more than 20% of cases [11]. The study results demonstrate that F_1 hybrid vigor originated from genetic interactions that exist only during the initial stages before self-fertilization occurs. The primary branches showed a constant growth pattern throughout the entire period. The F_1 hybrids showed substantial heterosis which ranged from 12% to 15% while the F_2 populations maintained most of this advantage with only minimal inbreeding depression that reached approximately 5%. Therefore, the system demonstrates additive and additive epistatic interactions which base their stability on selection methods.

Observations on Seed Yield and 1000-Seed Weight

The seed output per plant had the greatest heterosis among all parameters because it displayed complex polygenic traits. Relative heterosis showed variation between 8.4% and 52.6% across the 45 different crossbreeding experiments [12].

The top-performing hybrids which developed from parental stock showing high oil production and branch development potential showed strong heterobeltiosis which indicated their high hybrid breeding capacity [13].

The F_2 generation showed high inbreeding depression which caused yield losses up to 30% when compared to F_1. The advantageous heterozygous gene combinations have lost their value because of this situation.

The test weight for 1000-seed weight showed moderate heterosis between 4% and 10% while inbreeding depression showed a slight effect between 2% and 6%. The stability of seed weight shows that its genetic control operates through simple genetic pathways which exhibit high heritability thus making it suitable for selection during early generation breeding.

Relationship Between Heterosis and Inbreeding Depression

The study found F_1 heterosis to F_2 inbreeding depression as its main discovery. The self-pollinated linseed crop showed hybrid vigor trade-off through its crosses which produced high seed output and experienced inbreeding depression [14]. The most beneficial crossings for pedigree breeding showed moderate heterosis with 15% to 20% range and they showed minimal inbreeding depression which was below 5% [15]. The crossings will produce transgressive segregants who will exceed the performance of their parent lines while maintaining a homozygous genetic state. The oil content percentage showed stable results from the F_1 generation to the F_2 generation because it showed low heterosis and the inbreeding depression effect remained unimportant. The regulation of oil content results from additive gene activity which enables first generation selection without major decline in performance [16].

Trait	Range of	Type of Heterosis	Inbreeding Depression	Genetic Interpretation

	Heterosis (%)		(%)	
Days to 50% flowering	−5.4 to −12.8	Negative (Desirable for earliness)	1.2 to 3.5	Additive gene action (stable inheritance)
Plant height	Up to +18.5	Positive	Moderate reduction in F_2	Partial additive gene action

Table 2: Heterosis and Inbreeding Depression for Vegetative Traits, Source: Author Generated

Trait	F_1 Heterosis (%)	F_2 Inbreeding Depression (%)	Genetic Control	Breeding Implication
Capsules per plant	>35	>20	Non-additive (dominance/overdominance)	Not stable, hybrid advantage temporary
Primary branches per plant	12 to 15	~5	Additive × additive epistasis	Suitable for selection in later generations

Table 3: Heterosis and Inbreeding Depression for Yield Components, Source: Author Generated

Trait	Relative Heterosis (%)	Inbreeding Depression (%)	Stability	Genetic Interpretation
Seed yield per plant	8.4 to 52.6	Up to 30	Low stability	Strong non-additive gene action
1000-seed weight	4 to 10	2 to 6	High stability	High heritability, additive gene action

Table 4: Heterosis and Inbreeding Depression for Yield and Seed Traits, Source: Author Generated

Category of Crosses	Heterosis Level (%)	Inbreeding Depression (%)	Interpretation	Breeding Value
High heterosis crosses	>35 (Yield traits)	High (>20–30)	Non-additive gene action	Suitable for hybrid breeding only
Moderate heterosis crosses	15 to 20	Low (<5)	Additive gene action	Best for pedigree selection
Low heterosis crosses	<10	Negligible	Limited genetic gain	Less useful

Table 5: Relationship Between Heterosis and Inbreeding Depression, Source: Author Generated

Trait	Heterosis (%)	Inbreeding Depression (%)	Genetic Control	Breeding Implication
Oil content (%)	Very low	Near zero	Additive gene action	Effective early-generation selection

Table 6: Stability of Oil Content Across Generations, Source: Author Generated

IV. Discussion

Genetic Framework of Heterosis in Linseed

The study revealed considerable heterosis in Linum usitatissimum, thereby contesting the prevailing notion that autogamous species are incapable of exhibiting hybrid vigor via genetic manipulation. The observed heterobeltiosis, particularly in seed yield and capsule number, suggests that, notwithstanding a species' inclination towards homozygosity, the combination of dissimilar alleles from separate parental lines fosters an enhanced physiological state.

The dominance hypothesis explains this phenomenon because F_1 hybrid plants achieve benefits from their harmful recessive genes which are hidden by their beneficial dominant alleles. Overdominance effects in linseed remain relevant because F_1 plants achieved better results than their best parent in specific crosses. F_2 generation showed substantial inbreeding depression across these traits which indicates that these effects will eventually fade away. The research findings match previous studies on oilseed crops which demonstrate that hybrid seeds boost production output while the genetic makeup of linseed maintains performance stability through additive gene effects in multiple generations.

Assessing the Extent of Inbreeding Depression

The performance drop between F_1 and F_2 demonstrates the specific type of gene activity that becomes active during this period. The current study indicates that the significant reduction in yield and capsule count proves that non-additive gene activity which includes dominance and epistasis effects F_1 hybrid performance. The process of developing stable pure-line varieties from breeding programs faces major challenges because inbreeding depression creates serious problems for this task. A hybrid which shows high heterosis and strong inbreeding depression indicates that its beneficial gene combinations become lost through the process of recombination and segregation.

Plant height and 1000-seed weight showed moderate to low inbreeding depression which resulted in improved genetic stability. The characteristics of this system are controlled by additive genetic factors which selection procedures can use to stabilize their expression. The F_2 and F_3 generations will experience major improvements because their genetic progress will exceed the decline in vigor which happens during this period.

Physiological Foundation and Competitive Edge

The physiological basis of linseed heterosis results from increased source-sink relationships. Hybrid plants show more primary and secondary branches which create better support systems for their capsule growth. The higher branch development in F_1 populations results in increased capsule production which boosts the plant's total sink capacity. The oil content remained stable across generations because inbreeding depression didn't affect it. The metabolic processes that control how fatty acids are made are highly conserved. This is because they work separately from the genetic factors that control plant growth and weight. This independence allows breeders to improve both oil quality and yield, since increasing homozygosity doesn't limit their ability to develop these traits.

Consequences for Future Breeding Approaches

The findings of this study are significant because they help researchers choose the best breeding methods for developing linseed varieties. The strong hybrid vigor seen in the results suggests that commercial hybrid linseed production will be successful, once effective systems for cytoplasmic male sterility and natural cross-pollination are available, similar to the practices used for hybrid sunflowers and rapeseed.

The current limitations in hybrid linseed seed production technology require practitioners to concentrate their efforts on creating better breeding methods. The hybrids display minor heterosis during F_1 and they show slight inbreeding depression throughout F_2. The additive × additive epistatic interactions create transgressive segregants through these combinations which emerge in later generations. These segregants prove highly valuable because they represent new pure lines that exceed both parent lines through their combination of excellent traits which do not require ongoing hybrid seed production.

V. Conclusion

The research establishes that linseed displays hybrid vigor due to self-fertilization while showing different trait-specific advantages. The F_2 generation presented significant heterobeltiosis results for multiple variables which included seed yield and capsule count but showed high inbreeding depression because non-additive gene patterns-controlled inheritance.

The measurement of 1000-seed weight and principal branch count showed reduced inbreeding depression which resulted from stable genetic regulation that depended mainly on additive gene effects. The breeding process aims to find parent combinations which will produce moderate F_1 generation heterosis combined with reduced F_2 generation inbreeding depression. The combination will produce superior transgressive segregants which will become fixed in subsequent generations.

The research shows that pedigree selection remains the primary method for linseed hybrid seed production even though male sterility systems need further development to allow commercial production. The method will create beneficial alleles which will help linseed farming overcome its existing productivity challenges.

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