

M.Sc. THESIS

On

**IMPACT OF PLANTING PATTERNS AND WEED CONTROL TREATMENTS ON
THE GROWTH AND DEVELOPMENT OF DILL (*Anethum graveolens*)**

Submitted by

Felix Kodjo Mawuto Equagoo

12400128

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MASTER OF SCIENCE

IN

AGRONOMY

Under the Supervision of

Dr. Prasann Kumar

Associate Professor



LOVELY PROFESSIONAL UNIVERSITY

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DECLARATION

I hereby declare that the dissertation entitled "IMPACT OF PLANTING PATTERNS AND WEED CONTROL TREATMENTS ON THE GROWTH AND DEVELOPMENT OF DILL (*Anethum graveolens* L.)" submitted to Lovely Professional University, Phagwara, Punjab, India, for the award of the degree of Master of Science in Agronomy is a record of original research work done by me under the supervision of **Dr. Prasann Kumar**, Associate Professor, Department of Agronomy and Dr. U.S. Walia, Professor, Department of Agronomy.

The information and data presented in this dissertation are true and original to the best of my knowledge and belief. No part of this dissertation has been submitted to any other university or institution for the award of any degree or diploma.

Felix Kodjo Mawuto Equagoo

Reg. No. 12400128

M.Sc. (Agronomy)

Department of Agronomy

Lovely Professional University

CERTIFICATE I

This is to certify that the dissertation entitled "IMPACT OF PLANTING PATTERNS AND WEED CONTROL TREATMENTS ON THE GROWTH AND DEVELOPMENT OF DILL (*Anethum graveolens* L.)" has been submitted by Mr. Felix Kodjo Mawuto Equagoo (Reg. No. 12400128) in partial fulfilment of the requirements for the degree of Master of Science in Agronomy from Lovely Professional University, Phagwara, Punjab, India.

This work is original and has been carried out under my supervision and guidance. The matter presented in this dissertation has not been submitted for the award of any other degree or diploma.

Dr. Prasann Kumar,
Associate Professor,
Department of Agronomy
Lovely Professional University
Phagwara, Punjab, India

CERTIFICATE II

This is to certify that the dissertation report entitled "IMPACT OF PLANTING PATTERNS AND WEED CONTROL TREATMENTS ON THE GROWTH AND DEVELOPMENT OF DILL (*Anethum graveolens* L.)" submitted by Mr. Felix Kodjo Mawuto Equagoo (Reg. No. 12400128)) to the School of Agriculture, Lovely Professional University, Punjab in partial fulfilment of the requirements for the degree of Master of Science, in the subject of Agronomy has been approved by the Advisory Committee after an oral examination of the student in collaboration with an External Examiner.

(Major Advisor)

Dr. Prasann Kumar,
Associate Professor, Department of Agronomy,
LPU,
Phagwara, Punjab, India

Dr. Sandeep Menon

Professor, Head of the Department,
Department of Agronomy, School of
Agriculture, LPU,
Phagwara, Punjab

External Examiner

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ABSTRACT

Keywords: *Anethum graveolens*, planting pattern, weed management, plastic mulch, seed yield, Split Plot Design.

The present investigation entitled "Impact of Planting Patterns and Weed Control Treatments on the Growth and Development of Dill (*Anethum graveolens* L.)" was carried out at the Research Farm, Department of Agronomy, Lovely Professional University, Phagwara, Punjab, India, during the Rabi (winter) season of 2024–2025. The experiment was conducted in a Split Plot Design with four replications. Four planting patterns constituted the main-plot treatments: Bed sowing (M₁), Flat sowing (M₂), Ridge sowing (M₃), and Alternate ridge sowing (M₄). Four weed management practices constituted the sub-plot treatments: Black plastic mulch (T₁), White plastic mulch (T₂), Hand weeding followed by straw mulch at 5 t ha⁻¹ (T₃), and Unweeded control (T₄). The dill variety used was Ajmer Sowa-1, sown at a seed rate of 10 kg ha⁻¹ with a spacing of 45 × 20 cm. Nitrogen was applied at 87.5 kg ha⁻¹.

Results revealed that planting pattern significantly influenced virtually all measured parameters. Bed sowing (M₁) was consistently superior across all growth, yield, and seed quality parameters at all stages of observation. At 90 DAS, M₁ recorded the highest plant height (70.28 cm) and at harvest 202.75 cm, significantly surpassing Flat sowing (M₂, 196.66 cm). This superiority was attributed to improved drainage, reduced root-zone compaction, and enhanced soil temperature in raised-bed geometry.

Weed management was the dominant production factor. Black plastic mulch (T₁) was significantly superior for all parameters, recording maximum plant height (216.78 cm), dry weight per plant (33.68 g at harvest), seed yield (858.75 kg ha⁻¹), biological yield (3,416.25 kg ha⁻¹), thousand seed weight (3.84 g), and seed mineral quality (K: 29.56 g/100g DW, P: 0.119%, N: 2.97%). The unweeded control (T₄) recorded a seed yield of only 210.00 kg ha⁻¹, confirming the critical importance of weed management in dill production.

The interaction between planting pattern and weed management was significant for seed yield ($F = 2.42^*$). The combination M_1T_1 (Bed sowing + Black plastic mulch) achieved the maximum seed yield of $930.00 \text{ kg ha}^{-1}$, demonstrating the synergistic benefit of combining optimal spatial arrangement with effective weed suppression. Seed mineral quality parameters (K, P, N) followed the consistent ranking $T_1 > T_2 > T_3 > T_4$, explained by the thermal and moisture microclimate advantages of plastic mulching.

Based on the findings of the present study, the combination of Bed sowing with Black plastic mulch (M_1T_1) is recommended for maximizing dill productivity, seed quality, and economic returns under the agro-climatic conditions of Punjab, India.

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LIST OF ABBREVIATIONS

Abbreviation	Full Form
ANOVA	Analysis of Variance
AOAC	Association of Official Analytical Chemists
cm	centimetre(s)
CPWC	Critical Period of Weed Control
DASD	Directorate of Arecanut and Spices Development
DAS	Days After Sowing
DW	Dry Weight
EC	Electrical Conductivity
EO	Essential Oil
FAO	Food and Agriculture Organization
F-value	Variance ratio in Analysis of Variance
g	gram(s)
ha	hectare
H₂SO₄	Sulphuric acid
INM	Integrated Nutrient Management
ISTA	International Seed Testing Association

IWM	Integrated Weed Management
K	Potassium
kg	kilogram(s)
LPU	Lovely Professional University
LSD	Least Significant Difference
M₁	Bed sowing
M₂	Flat sowing
M₃	Ridge sowing
M₄	Alternate ridge sowing
mm	millimetre(s)
m⁻²	per square metre
N	Nitrogen
NS	Non-significant
OC	Organic Carbon
P	Phosphorus
pH	Potential of Hydrogen
q/ha	quintal per hectare
SPD	Split Plot Design
S.Em±	Standard Error of Mean
t	metric tonne(s)

T₁	Black plastic mulch
T₂	White plastic mulch
T₃	Hand weeding followed by straw mulch
T₄	Unweeded control
TSW	Thousand Seed Weight
USDA	United States Department of Agriculture
USD	United States Dollar
WCE	Weed Control Efficiency
%	Percentage
**	Significant at 1% level of probability ($P \leq 0.01$)
*	Significant at 5% level of probability ($P \leq 0.05$)

CHAPTER 1

INTRODUCTION

Spices have been integral to human civilization for millennia, and India's relationship with them is ancient, commercially vital, and deeply woven into its agricultural identity. India is globally recognized as the largest producer, consumer, and exporter of spices, accounting for nearly half of world spice trade by volume (Spices Board of India, 2022). Within this broad portfolio, seed spices — comprising coriander, fennel, fenugreek, ajwain, and dill — command particular attention for their economic weight and the agronomic complexity they present. Grown primarily across the semi-arid and sub-humid belts of Rajasthan, Gujarat, Punjab, Madhya Pradesh, and Uttar Pradesh, these crops collectively occupy approximately 1.8 million hectares and generate substantial foreign exchange earnings while providing farm income to millions of smallholder producers (DASD, 2020; FAO, 2022).

Among the seed spices of the subcontinent, dill (*Anethum graveolens* L.) stands apart for the breadth of its utility and the depth of its historical roots. Botanically an annual or occasionally biennial herb of the Apiaceae family, dill is one of humanity's oldest cultivated plants: seeds recovered from Egyptian archaeological contexts date to approximately 1400 BCE, and the crop's carminative properties are cited in the Ebers Papyrus (Zohary et al., 2012). In India, it is cultivated under the names sowa (Indian dill, *Anethum sowa* Roxb.) and suwa across multiple states, yielding both leafy biomass for the fresh vegetable market and aromatic seeds destined for the spice, pharmaceutical, and essential-oil industries (Malhotra and Vashishtha, 2007).

The commercial appeal of dill rests on a combination of properties that few other seed spices can match. As a spice, the seeds impart a warm, aromatic flavour prized in the pickling industry, bread-making, and pharmaceutical formulations, with essential oil content reaching 2.5–4.0% fresh weight and d-carvone as the principal bioactive constituent (Bailer et al., 2001; Jirovetz et al., 2003). Medicinally, dill is prescribed in Ayurvedic practice for digestive disorders, lactation support, and infantile colic, and experimental pharmacology has confirmed antimicrobial, antioxidant, and anti-inflammatory activities of seed extracts (Iacobellis et al., 2005; Bahramikia and Yazdanparast, 2009). These combined attributes — culinary versatility,

pharmaceutical interest, and attractive market prices — have sustained dill cultivation's economic viability even as production costs have risen across North India.

Agronomically, dill is a temperate crop adapted to subtropical conditions when sown during the cool season. The crop demands a thermal calendar that provides cool conditions (optimal 15–25°C) during vegetative establishment and moderate warmth during reproduction, making mid-October to mid-November sowing optimal for North Indian environments (Gour et al., 2022). A persistent practical challenge in these systems is the crop's irregular and sometimes prolonged field emergence. Dill seeds are small, lack substantial endosperm reserves, and germinate slowly in clay-heavy or compacted seedbeds, creating uneven plant establishment that complicates population management and weed-control timing. Germination percentages under field conditions seldom exceed 60–70%, and the resulting sparse, uneven stand amplifies the competitive advantage of simultaneously germinating weed species (Walia and Singh, 2016; Zehtab-Salmasi et al., 2006).

Of the various constraints that depress dill yields below their biological potential, weed competition is the most consistently damaging in most production environments. The reasons are rooted in the crop's slow, uneven establishment: weeds germinating alongside dill seedlings experience essentially no competitive suppression during the first three weeks, and the resulting infestation can reduce seed yield by 40–60% when left uncontrolled (Patel et al., 2019; Choudhary et al., 2022). Research across diverse dill-growing environments has identified the first 30–40 days after sowing as the critical period of weed competition — the interval within which weeds must be controlled to preserve maximum yield potential (Kumar et al., 2016; Meena et al., 2020). The mechanisms through which weeds inflict this damage are multiple: direct competition for light, water, and mineral nutrients during the critical establishment phase, allelopathic interference with seedling development, and physical obstruction of canopy development (Singh et al., 2021).

Several weed management tools are available to the dill farmer, each carrying distinct trade-offs in cost, efficacy, and environmental impact. Pre-emergence herbicides such as pendimethalin offer scalable chemical control across large cultivated areas, while mulching — whether with black or white polyethylene film — simultaneously suppresses weeds, conserves

soil moisture, modifies the thermal environment at the soil surface, and can significantly advance crop maturity under heat-limited conditions (Kasirajan and Ngouajio, 2012; Lamont, 2005). Hand-weeding and inter-cultivation remain the default on smallholder farms where labour is accessible. Integrated approaches combining mechanical and chemical methods have consistently outperformed any single strategy in cost-effectiveness and sustained weed suppression (Nagar et al., 2022; Bhardwaj and Singh, 2023).

Alongside weed management, the spatial configuration in which dill plants are established — their planting pattern — represents a second major lever through which the agronomist can manipulate crop productivity. Sowing method, row spacing, and resultant plant density jointly determine canopy architecture, light interception, inter-plant competition for resources, and the physical microenvironment available to weeds. Bed sowing, flat sowing, and ridge sowing create structurally distinct canopies with differing consequences for crop-weed competitive dynamics (Mahmood, 2013; Surve et al., 2024). Critically, planting pattern and weed management are unlikely to exert simple, independent, additive effects on dill productivity. A canopy that closes rapidly under an optimal geometry can itself suppress late-emerging weeds, potentially reducing the threshold at which chemical or mechanical control becomes cost-effective and economically justified. This interaction between spatial arrangement and weed management strategy represents one of the central scientific questions motivating the present investigation.

It is against this backdrop — a commercially important crop constrained by weed pressure and suboptimal spatial management, yet with considerable untapped yield potential — that the present study was designed. There is a notable gap in location-specific, quantitative agronomic research for dill under the agroclimatic conditions of Punjab, India, particularly studies that evaluate planting pattern and weed management conjointly in a formal factorial design capable of revealing their interaction. The experiment deployed a Split-Plot Design with four planting patterns as main plots and four weed management treatments as sub-plots, replicated four times, with the explicit aim of characterizing both main effects and their interaction on the growth, yield, and seed quality of dill under Punjab conditions.

Objectives of the Investigation

1. To evaluate the effects of various planting geometries on the growth parameters of Dill and weeds.
2. To assess the effectiveness of different weed control methods on the growth and development of Dill.
3. To find out the interaction effects between planting patterns and weed control treatments on the overall productivity and quality of Dill.

CHAPTER 2

REVIEW OF LITERATURE

The literature about the present investigation, "Impact of Planting Patterns and Weed Control Treatments on the Growth and Development of Dill (*Anethum graveolens*)," has been reviewed and organized under the following subheadings:

1. Losses due to Weeds

The economic toll of weed competition on dill and related spice seed crops has been documented extensively. Yet, it remains among the most poorly managed constraints in smallholder spice farming across the Indian subcontinent. Globally, weeds are estimated to reduce attainable crop yields by approximately 34% annually in developing country agriculture, with individual crops under severe infestation suffering losses that can exceed 80% of potential output (Bhardwaj and Singh, 2023). For dill specifically, this threat is compounded by the crop's biological characteristics: slow and irregular germination, a sparse, slow-closing early canopy, and a shallow root system that is easily outcompeted for water and nutrients by the faster-establishing annuals typical of Rabi-season weed communities in northern India.

Choudhary et al. (2022), working in the semi-arid conditions of Rajasthan, provided direct quantitative evidence of weed-induced losses in dill, recording seed yields 45–50% lower in unmanaged plots than in weed-free controls. The dominant weed species in these fields, *Chenopodium album*, *Fumaria parviflora*, *Phalaris minor*, and *Convolvulus arvensis*, share a set of competitive traits that place dill at a particular disadvantage: rapid germination, aggressive lateral spread, and the capacity to produce large quantities of leaf area before the dill crop has had time to establish a competitive canopy. The concept of a critical period of weed competition proved central to the agronomic interpretation of these findings.

Patel et al. (2019) established that this critical window in dill extends from crop emergence to approximately 40 days after sowing, within which weeds must be controlled to prevent yield losses from becoming economically irreversible. Importantly, their work showed that delaying the first weeding operation by even 10 days beyond this threshold significantly compounded losses, confirming the value of early, preemptive intervention. Meena et al. (2020) similarly documented that weed interference during the first six weeks of crop growth reduced

plant height, branch number, and umbel production in dill by 30–40% relative to weed-free plots, demonstrating that the damage is not confined to yield depression alone but extends to the morphological determinants of yield.

The mechanisms through which weeds inflict this damage are multiple and reinforcing. Kumar et al. (2016), studying fenugreek and related Apiaceae crops, showed that early weed establishment in the first two weeks after sowing dramatically elevated total weed biomass at the time of peak competition, with direct consequences for crop nitrogen, phosphorus, and potassium uptake. In dill, where these three macronutrients drive both vegetative growth and the biosynthesis of terpenoid essential oil compounds, nutrient deprivation carries a double penalty: reduced seed mass and diminished oil content in the harvested product. Choudhary et al. (2023) confirmed this dual effect, recording significantly lower N, P, and K concentrations in the seeds of dill plants grown under weedy conditions, with associated reductions in essential oil content that directly compromised market value.

Yadav et al. (2016) documented a 75% yield reduction in coriander, a closely related Apiaceae species with similar competitive dynamics under uncontrolled weed conditions, providing a useful benchmark for the potential scale of losses when weed management is entirely neglected in this crop family.

From a management perspective, the research literature consistently points to integrated approaches as the most effective response to the weed challenge in dill and related spice crops. Kaur et al. (2020), reviewing weed management research in dill across multiple agro climatic zones, concluded that pre-emergence pendimethalin application at 1.0 kg a.i./ha followed by one hand weeding at 40 DAS delivered the most consistent combination of weed suppression (75–85% control efficiency) and yield improvement (40–60% over the unweeded control) across diverse production environments.

Singh et al. (2021) further established that the economic threshold level for weed competition in Apiaceae seed spice crops is reached relatively early in the season, underscoring the urgency of intervention during the first month after sowing.

Nagar et al. (2022), reviewing a broader body of fennel and dill weed management literature, found that integrated strategies consistently reduced weed dry matter accumulation by 65-80% and improved crop yield by 35-55% over unweeded controls, with no single method, chemical, mechanical, or cultural, achieving equivalent results in isolation.

Gnanavel and Natarajan (2020) arrived at a similar conclusion in their comprehensive review of weed management in seed spice crops, noting that the unpredictability of weed flora composition across seasons and locations makes reliance on any single tool a strategically vulnerable approach.

Bhardwaj and Singh (2023) reinforced this position, arguing that integrating optimized plant spacing with pre-emergence chemical control and timely mechanical weeding offers the best available framework for sustainable, high-productivity dill management under Indian conditions.

2. Role of Planting Patterns on Growth and Yield of Dill

Planting pattern, the combination of sowing method, inter row and intra row spacing, and the consequent plant population density, is one of the most tractable agronomic variables available to the dill farmer, in the sense that it can be modified at no additional input cost simply by adjusting the configuration of the seeder. Yet despite its accessibility, this variable has received comparatively little systematic attention in dill research relative to fertilizer management or variety selection. The available evidence, drawn largely from parallel work on related Apiaceae crops, consistently points to planting geometry as a major determinant of canopy development, resource use efficiency, and ultimately yield and quality.

Bralewski et al. (2005) provided early evidence from dill itself, showing that wider row spacing significantly reduced intraspecific competition during the critical mid-season growth phase, allowing individual plants to develop more vigorous branching and accumulate higher essential oil concentrations in their seeds compared to denser plantings in which mutual shading and root competition progressively limited individual performance.

The general principle they documented that intraspecific competition above the optimal density simultaneously depresses both individual plant performance and area level productivity

was given quantitative treatment by Mehta et al. (2012), who showed in cumin that the optimal population density represents an equilibrium point at which the per plant losses from competition are exactly offset by the gains from more complete field coverage. Understanding where this equilibrium lies in Dill under Punjab's Rabi conditions is precisely the kind of location-specific knowledge that experimental research must provide.

Mahmood (2013) offered the most detailed comparative assessment of sowing methods in a closely related the crop, reporting that ridge sowing at 45 cm row spacing in fennel outperformed both bed sowing and drill sowing in seed yield (1780 kg/ha versus 1549 kg/ha for line sowing at the closest spacing tested), with the advantage attributable to a greater number of reproductive branches per plant (7.90), more umbels per plant (39.67), more seeds per umbel (200.30), and heavier individual seeds (7.77 g per 1000 seeds). The proposed mechanism was straightforward: raised ridges improve root-zone aeration and drainage, create a more friable soil environment for root penetration, and enhance the uniformity of seedling emergence, all of which translate into more vigorous vegetative growth and, ultimately, more productive reproductive branches.

Ayub et al. (2008) reached similar conclusions in fennel, showing that controlled row spacing in line sowing (571.54 kg/ha seed yield) significantly outperformed broadcast sowing by improving per-plant umbel production and seed set, confirming that spatial precision in planting pays measurable dividends in this crop family.

More recent work has extended and refined these findings in detail. Surve et al. (2024) reported that optimized planting geometry in the Rabi season dill significantly enhanced canopy light interception and photosynthetic efficiency, resulting in improved dry matter accumulation, more vigorous branching, and higher seed yield; their results identified ridge sowing as the most productive method under northern Indian plains conditions.

Pandya et al. (2020) confirmed the importance of spacing optimization in dill during the Rabi season, finding that a 45 × 20 cm configuration delivered significantly higher plant height, branch number, umbel count, and seed yield per hectare compared to both narrower and wider alternatives a result consistent with the theoretical expectation that yield is maximized at the

population density where canopy closure is achieved at the earliest possible date without triggering excessive intraspecific competition.

Verma and Choudhary (2021) added an important resilience dimension to these findings, demonstrating that dill plants grown at optimal spacing exhibited greater tolerance to transient water stress and suboptimal fertilizer supply, suggesting that the benefits of appropriate planting geometry extend beyond productivity to include reduced sensitivity to environmental variability.

The interaction between planting geometry and pest and disease management is a further consideration often overlooked in single-factor analyses. Verma et al. (2022) observed that wider row spacing in dill reduced canopy humidity and improved air circulation, thereby lowering the incidence of foliar fungal diseases, including powdery mildew and alternaria blight, with direct benefits for canopy longevity and seed quality late in the season.

Jat et al. (2021), evaluating the combined effects of planting geometry and fertilizer level, reported that ridge sowing at 45 cm row spacing combined with recommended NPK rates produced the highest seed yield (1642 kg/ha) and essential oil content (3.4%) among all treatment combinations tested, suggesting that planting method and nutrition management interact in ways that reward integrated optimization.

Ahmad et al. (2022), in a parallel study conducted in Pakistan, confirmed the superiority of ridge sowing over flat and broadcast methods in dill, attributing the advantage specifically to improved water infiltration and reduced surface compaction in the ridge system, which benefited both root development and soil water availability during the critical grain filling stage of seed development.

3. Role of Weed Management for Dill Productivity

Translating knowledge of weed-induced losses into effective field practice requires a nuanced understanding of how different weed management tools perform under variable

conditions, how they interact when combined, and what their broader implications are for soil health, input costs, and the long-term sustainability of the production system. The research literature on weed management in dill and related Apiaceae crops is now substantial enough to identify several consistent patterns, even as important context-specific questions, including those specific to Punjab's Rabi conditions, remain unanswered.

The case for integrated weed management in dill was made clearly by Choudhary et al. (2023), who showed that the sequential application of pre emergence pendimethalin at 1.0 kg a.i./ha followed by a single hand weeding at 40 DAS achieved weed control efficiencies exceeding 80% and seed yield improvements of 45–55% over the unweeded check results that neither the herbicide treatment alone nor the hand weeding alone consistently replicated. This finding establishes an important principle: the two approaches complement rather than substitute for each other, with the herbicide addressing the first flush of weed emergence and hand weeding cleaning up escapes and late-germinating species that the chemical treatment misses.

Gupta et al. (2021) corroborated this conclusion, reporting that the herbicide-plus-weeding combination delivered a benefit-to-cost ratio substantially higher than either practice alone, thereby confirming its economic as well as biological superiority.

Kumari et al. (2022) pushed this analysis further, demonstrating a benefit-to-cost ratio of 4.2:1 for the best integrated treatment, and noting that the economic advantages were particularly pronounced in fields with heavy initial weed seed banks, precisely the conditions that characterize many established dill growing areas in Punjab.

Mulching has attracted increasing research attention as a component of dill weed management systems, partly because it suppresses weeds through a physical rather than chemical mechanism, thereby avoiding the residue and resistance concerns associated with repeated herbicide use, and partly because it simultaneously provides several agronomically beneficial side effects. Fracchiolla et al. (2021), working with organic mulch materials (almond hulls and olive leaf residues) in fennel, documented weed biomass reductions of 65–75% relative to unmulched plots, along with measurable improvements in soil moisture retention, temperature buffering, and crop growth parameters.

Farag and Abul Soud (2020) reported that mulched sweet fennel plots showed significantly greater fresh weight accumulation (329.3 g vs. controls), improved leaf number and plant height, and higher N, P, and K concentrations in plant tissues, improvements attributable to reduced weed competition, better soil moisture availability, and the enhanced mineralization of nutrients under the mulch layer.

Meena et al. (2014) extended these findings to dill growing conditions in India, showing that straw mulch at 5 t/ha increased dill seed yield by 37.5% over the control, 10.4% over dust mulch, and 5.6% over plastic mulch, with particularly pronounced effects on plant height, branch number, and umbels per plant.

Hatami et al. (2012) demonstrated in fennel that a full-ridge plus half-furrow polyethylene mulch application provided the best overall combination of weed suppression, water conservation, and yield enhancement among the plastic mulch configurations tested.

Recent work has further refined the understanding of mulching's role in dill production systems. Hassan et al. (2023), reviewing mulching research across vegetable and spice crops, concluded that black plastic mulch provides the most reliable weed suppression across diverse agroclimatic conditions because its complete exclusion of photosynthetically active radiation from the soil surface effectively prevents germination of virtually all light-requiring weed seeds, while organic mulches offer a superior long-term return through soil health improvement.

Rashid and Parrish (2021) highlighted the multifunctionality of mulching in spice crop systems, noting that it simultaneously addresses weed suppression, moisture conservation, thermal moderation, and erosion control, with cumulative benefits to the soil's physical and biological environment that compound over successive seasons.

Tiwari and Singh (2023) evaluated paddy straw mulch in dill production under Indo Gangetic plain conditions agro climatically relevant to the Punjab context of the present study and reported that straw mulch at 5 t/ha reduced weed dry matter at all observation dates, improved soil moisture retention by 18–25% over unweeded plots, and increased both seed yield and harvest index while contributing positively to soil organic carbon trends in the topsoil.

Choudhary et al. (2022) added the important caveat that the economic viability of any mulching strategy depends critically on the planting method employed, since the application and anchorage of mulch materials is substantially more practicable in ridge-sown and bed-sown crops than in conventionally flat-sown stands.

4. Effect of Planting Patterns and Weed Control Treatments on Quality Parameters of Dill

Quality in dill is a composite concept, encompassing seed weight, germination vigor, essential oil content and composition, protein concentration, and overall marketability. These parameters are not independent of yield: the same conditions, optimal spacing, effective weed management, and adequate nutrition that maximize seed production per unit area also tend to maximize seed quality. Yet the relationships are not linear, and some quality parameters respond to management interventions in ways that diverge from simple yield trends, making their independent measurement essential for a complete agronomic evaluation.

Choudhary et al. (2022) provided some of the most direct evidence linking weed management to dill seed quality, recording nitrogen concentrations of 2.8% in seeds from well managed plots versus 1.9% in seeds from unweeded controls a difference of nearly 50% that translated into measurable improvements in seed protein content, germination percentage (86% vs. 61%), and essential oil concentration (3.2% vs. 2.1%). These findings are agronomically interpretable: weeds that compete for soil nitrogen effectively deny the developing seed the precursor material needed for protein synthesis and for the biosynthesis of the nitrogen-containing regulatory molecules that govern terpene accumulation in the essential oil glands.

Bralewski et al. (2005) added a pathological dimension to this quality picture, noting that unweeded dill plots suffered higher rates of seed infection by *Alternaria* and *Fusarium* species pathogens that colonize damaged or weakened seeds preferentially, resulting in seeds with lower germination vigor and higher proportions of physically defective grains, both of which reduce commercial value and constrain the seed's suitability for further propagation.

The effects of planting geometry on quality parameters operate through distinct mechanisms but lead to comparable conclusions about the importance of management optimization. Joshi and Nayak (2022) investigated essential oil composition as a function of agronomic conditions in *Anethum graveolens*. They found that plants grown at optimal spacing with effective weed control accumulated significantly higher concentrations of carvone and limonene, the most commercially valuable oil constituents, compared with plants grown under competitive stress. The proposed mechanism is physiological: plants free from resource competition maintain higher photosynthetic carbon assimilation rates, thereby supporting the energetically costly secondary metabolic pathways that synthesize and store terpenoid compounds in the pericarp oil ducts.

Darzi et al. (2021), who examined density effects on dill essential oil specifically, confirmed that increasing plant population above the optimum reduced oil content per plant and, beyond a threshold, reduced total oil yield per hectare, as well as demonstrating that quality and yield optimization converge at the same optimal population density, rather than trading off against each other.

The interaction between planting pattern and weed management in determining quality outcomes has been examined in several studies whose collective message is consistent. Singh et al. (2014), combining cultural and chemical weed management strategies in dill and cumin, found that the integrated approach produced essential oil contents and seed weights significantly superior to either strategy applied alone, and attributed the advantage to the more complete and sustained relief from competitive stress achieved by the combined treatment.

Kumar et al. (2023), focusing specifically on the quality dimension of planting geometry and weed management interactions, reported that the highest test weight, harvest index, and oil yield per hectare were achieved in the treatment combining optimal row spacing with integrated weed management, and that these quality benefits persisted even when seasonal weather conditions were suboptimal for oil accumulation.

El Ghadban et al. (2020) confirmed in an Egyptian production context that the 45×20 cm spacing yielded the highest essential oil content and oil yield per hectare among all tested geometries. That biofertilization further amplified these quality benefits, suggesting that

optimizing planting geometry unlocks the crop's full responsiveness to inputs that improve nutrient supply.

Patel et al. (2023) reported the most directly relevant recent findings for the present study: in dill grown under Rabi conditions, the combination of ridge sowing with integrated weed management (pre emergence pendimethalin followed by hand weeding at 40 DAS) produced the highest seed test weight, germination percentage, oil content, and oil yield among all treatment combinations confirming that the interaction between these two management variables has quantifiable and commercially significant quality consequences.

Yaldız et al. (2018) placed these findings in an international context, noting that the quality parameters of dill seed marketed internationally are governed primarily by carvone content and germination percentage, both of which respond positively and measurably to integrated, geometry-optimized management approaches that the present investigation seeks to evaluate.

Singh and Meena (2021) drew the general conclusion most relevant to the design of the present study: the interaction between planting pattern and weed management in dill produces synergistic improvements in nutrient uptake, seed quality, and oil yield that justify and indeed necessitate their simultaneous optimization through factorial field experimentation.

CHAPTER 3

MATERIAL AND METHODS

The present investigation entitled "Impact of Planting Patterns and Weed Control Treatments on the Growth and Development of Dill (*Anethum graveolens*)" was carried out at the Agricultural Research Farm, School of Agriculture, Lovely Professional University, Phagwara, Punjab, India, during the Rabi season of 2024–2025. The various details of the treatments, cultural practices, and procedures followed in the investigation are described below.

3.1 Experimental Site and Location

The experiment was conducted at the Agricultural Research Farm of the School of Agriculture, Lovely Professional University (LPU), Phagwara, Punjab, India. The farm is situated in the Trans-Gangetic Plains at coordinates 31°14'37" N latitude and 75°42'04" E longitude, at an altitude of approximately 233 m above mean sea level. Phagwara is located in Kapurthala district of Punjab, situated between the Beas and Sutlej rivers, within the heavily irrigated and agriculturally productive Central Alluvial Plain of the state. The region is characterized by alluvial soils of high fertility and well-developed irrigation infrastructure, making it one of the most productive agricultural zones of northern India.

3.2 Climatic Conditions

The climate of Phagwara (Punjab) is classified as semi-arid and subtropical, with four distinctly marked seasons: hot dry summer, warm humid monsoon, post-monsoon transition, and cool dry winter. The region receives rainfall primarily from the South-West monsoon between June and September, with an annual average of approximately 816 mm. During the Rabi crop period (October to April), conditions are predominantly dry and dependent on irrigation. Summer temperatures reach a maximum of approximately 38.9°C, while winter minima descend to approximately 6.2°C. The months of December and January represent the coolest period of the year, coinciding with the vegetative establishment phase of the dill crop. The warming period of February onward provides the thermal conditions favorable for inflorescence development and seed maturation.

3.3 Soil Characteristics

The experimental soil at the LPU Research Farm predominantly belongs to the Central Alluvial Plain region and is sandy loam in texture, well-drained and moderately fertile. Before sowing, composite soil samples were collected from random locations within the experimental plots at two depths: 0–15 cm and 15–30 cm. The samples were air-dried in shade, crushed, sieved through a 0.2 mm filter, and then analysed for physico-chemical properties. The methods used for each determination and the physico-chemical properties of the experimental soil are presented in Table 3.2.

Table 3.2: Physico-chemical properties of the experimental soil before sowing

Property	Value	Method of Analysis
Soil pH	7.2	Glass electrode pH meter (Jackson, 1973)
Electrical Conductivity (dSm ⁻¹)	0.18	Conductivity Bridge ELICO EM 88 (Jackson, 1973)
Organic Carbon (%)	0.52	Walkley & Black method (1934)
Available N (kg/ha)	218.4	Alkaline permanganate method (Subbiah & Asija, 1956)
Available P ₂ O ₅ (kg/ha)	22.8	Olsen's method (Olsen et al., 1954)
Available K ₂ O (kg/ha)	192.6	Neutral NH ₄ -Acetate + Flame Photometer (Muhr et al., 1965)

Note: Values to be replaced with actual pre-sowing laboratory analysis data.

3.4 Experiment Details

The details of the experimental setup are summarized in Table 3.3.

Table 3.3: Details of the experiment

S. No.	Item	Details
1.	Location	Agricultural Research Farm, LPU, Phagwara
2.	Crop	Dill (<i>Anethum graveolens</i> L.)
3.	Variety	Ajmer Sowa-1
4.	Season	Rabi 2024–25
5.	Design of experiment	Split Plot Design
6.	Number of replications	4
7.	Main plots	4 (Planting patterns)
8.	Sub-plots	4 (Weed control treatments)
9.	Total number of treatments	16
10.	Total number of plots	64
11.	Plot size (sub-plot)	6 m × 3.25 m
12.	Spacing (row to row)	45 cm
13.	Spacing (plant to plant)	20 cm
14.	Seed rate	10 kg/ha
15.	Date of sowing	25 October 2024
16.	Date of harvesting	26 April 2025
16.	Fertilizer (N)	87.5 kg N/ha (Urea — split doses)

3.5 Treatments Details

The experiment was laid out in a Split Plot Design with planting patterns assigned to main plots and weed control treatments assigned to sub-plots, with four replications.

Main Plots — Planting Patterns:

Treatment	Description	Spacing
P ₁	Flat sowing	45 cm × 20 cm
P ₂	Bed sowing (two rows per 90 cm bed)	45 cm × 20 cm
P ₃	Ridge sowing	45 cm × 20 cm
P ₄	Ridge sowing (two rows on slope)	45 cm × 40 cm

Note: The plant population was maintained uniformly across all planting patterns.

Sub-plots — Weed Control Treatments:

Treatment	Description
T ₁	Black plastic mulch
T ₂	White plastic mulch
T ₃	Hand weeding followed by straw mulch (5 t/ha)
T ₄	Unweeded (control)

3.6 Layout of the Experiment

The experiment was set up in a Split Plot Design with four main plots (planting patterns: P₁, P₂, P₃, P₄) and four sub-plots (weed control treatments: T₁, T₂, T₃, T₄), replicated four times.

Each main plot was divided into four sub-plots of 6 m × 3.25 m. A buffer strip of 1 m was maintained between replications to avoid border effects and contamination between treatments. The individual sub-plot net area was 19.5 m², and the total experimental area was approximately 1,248 m² including paths and borders.

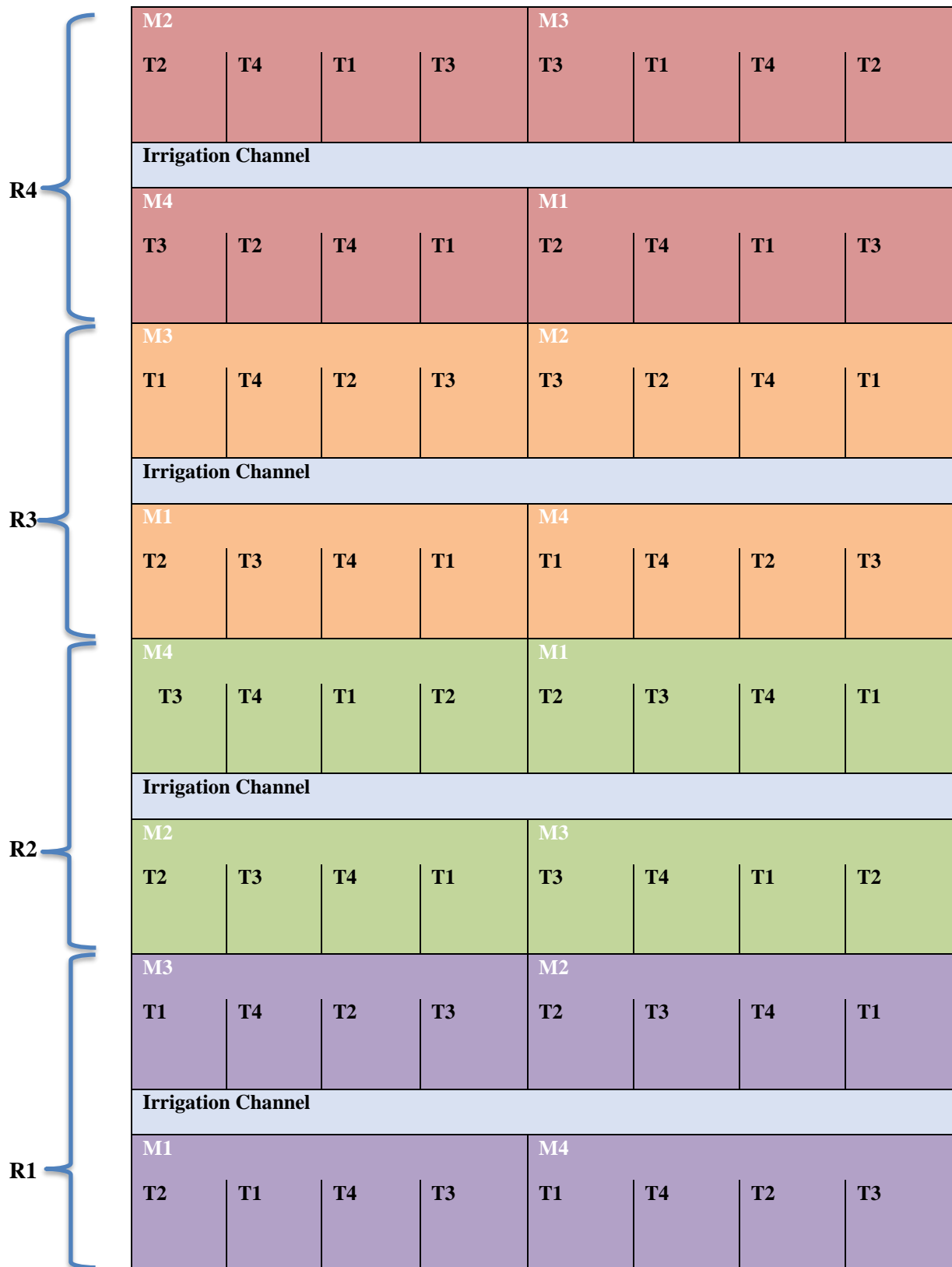


Figure 1. Schematic field layout of the experiment (Split Plot Design, 4 replications, 64 subplots).

3.7 Agronomical Operations

3.7.1 Field Preparation

The experimental field was prepared thoroughly prior to sowing. On 18 October 2024, the field was ploughed and harrowed using a rotovator, which simultaneously broke the soil clods, incorporated crop residues, and brought the soil to a fine, uniform tilth suitable for direct seeding of the small-seeded dill crop. Agricultural residues and weeds from the preceding crop were completely removed from the experimental area. On 21 October 2024, layout and leveling operations were carried out using a plank to achieve a smooth, uniform soil surface, facilitating uniform water distribution during irrigation. On 23 October 2024, individual plots were demarcated using pegs and string according to the experimental design, and the boundaries of all 64 sub-plots were clearly marked with channels and raised borders.



*Figure 3: Rotovating the Experimental Field
— 18 October 2024*



*Figure 4: Rotovated Field Showing Fine
Tilth — 18 October 2024*



Figure 5: Layout and Leveling of Experimental Field — 21 October 2024



Figure 6: Workers Carrying Out Field Preparation and Layout — October 2024



Figure 7: Demarcated and Staked Experimental Plots — 23 October 2024

On 23 October 2024, seeds of *Phalaris minor* (little seed canary grass) were broadcast uniformly over the experimental area at a standard rate to ensure uniform and reproducible weed pressure across all plots (Kaur et al., 2020).

3.7.2 Mulching

On 24 October 2024, one day before sowing, plastic mulches (black and white polyethylene film) were laid over the soil surface in the corresponding treatment plots (T_1 and T_2) and secured at the edges with soil. Sowing holes were then punched at the designated spacing ($45\text{ cm} \times 20\text{ cm}$) through the mulch sheet using a template before seeds were placed. Black plastic mulch (T_1) works by absorbing solar radiation and raising soil temperature while completely blocking light transmission to prevent weed germination. White plastic mulch (T_2) reflects incoming solar radiation, maintaining a cooler root zone, while also preventing light from reaching weed seeds in the soil. Both mulch types eliminate the need for subsequent mechanical weeding in treated plots (Hatami et al., 2012; Fracchiolla et al., 2021).



Figure 8: Plastic Mulch Material Being Carried for Application — 24 October 2024



Figure 9: Black Plastic Mulch (T_1) Applied on Experimental Plots — 24 October 2024

3.7.3 Seeds and Sowing

Seeds of dill variety Ajmer Sowa-1 were procured from a reliable source and tested for germination before sowing. Ajmer Sowa-1 is a high-yielding, improved variety of Indian dill (*Anethum sowa*) developed by the National Research Centre on Seed Spices, Ajmer, Rajasthan, known for its good essential oil content and adaptation to Rabi conditions in the northern plains of India.

On 25 October 2024, seeds were sown manually at a seed rate of 10 kg/ha, placing 2–3 seeds per hill at a depth of 1.5–2 cm, at the designated spacing of 45 cm (row to row) × 20 cm (plant to plant). In mulched plots (T₁ and T₂), seeds were sown through pre-punched holes in the plastic mulch. In flat-sown plots (P₁), seed lines were drawn directly in the well-prepared seedbed. In bed-sown plots (P₂), two rows were established per 90 cm bed. In ridge-sown plots (P₃ and P₄), seeds were placed on the crest or slope of ridges as per the assigned spacing. After sowing, a thin layer of fine soil was applied over the seeds to ensure good seed-to-soil contact.



Figure 10: Sowing of Dill (*Anethum graveolens* L.) Through Mulch Holes — 25 October 2024

3.7.4 Irrigation

The first irrigation was applied immediately after sowing on the evening of 25 October 2024 and continued until the early hours of 26 October 2024, providing sufficient soil moisture for uniform seed germination. Subsequent irrigations were scheduled based on soil moisture status and crop growth stage as presented in Table 3.4. Irrigation was applied through flood irrigation using field channels.

The irrigation interval was generally maintained at 10–15 days during active vegetative growth, with slight adjustments depending on rainfall, temperature, and soil moisture availability. Proper care was taken to avoid both moisture stress and water stagnation, as excessive moisture may adversely affect root growth and nutrient uptake. Critical growth stages such as vegetative growth, flowering, and seed formation were given special attention to maintain optimum soil moisture for better plant development and yield performance.

Table 3.4: Schedule of irrigation during the crop period

Irrigation No.	Date	Crop Stage / Purpose
1st	25–26 October 2024	At sowing — for germination and seedbed moisture
2nd	17–18 December 2024	After first urea application — early vegetative growth
3rd	27 December 2024	Vegetative growth support — canopy establishment
4th	11–12 January 2025	After second urea application — branching stage
5th	26–27 January 2025	Active vegetative growth — pre-flowering support
6th	10 February 2025	Flowering stage — pollination and early seed set
7th	18–20 March 2025	Seed filling stage — grain development support



Figure 11: First Irrigation Through Field Channels — 25–26 October 2024

3.7.5 Germination Count

The first germination count was recorded on 6 November 2024 (12 days after sowing, DAS). The number of germinated seedlings was counted in each plot from pre-marked 1 m² quadrats placed in representative areas, excluding border rows. Germination percentage was calculated as:

$$\text{Germination (\%)} = (\text{Number of seedlings germinated} / \text{Total number of seeds sown}) \times 100$$

Subsequent germination counts were recorded at 15 and 30 DAS to obtain final establishment percentages.



Figure 12: Germination of Dill Seedlings Through Mulch — 6 November 2024 (12 DAS)

3.7.6 Thinning (Uprooting)

Thinning operations were carried out from 15 to 30 November 2024 (20–35 DAS). Since 2–3 seeds were sown per hill, excess seedlings were removed manually, retaining one healthy, vigorous seedling per hill and maintaining the designated plant-to-plant spacing of 20 cm. Gap filling was also performed during the same period to ensure a uniform plant stand across all plots. All thinning residues were removed from the experimental area.



Figure 13: Thinning of Dill Seedlings — November 2024 (20–35 DAS)

3.7.7 Weed Control Operations

Hand Weeding (T₃):

Manual weeding was carried out in T₃ plots on 29–30 November 2024 (approximately 35 DAS), covering the critical weed competition period. Weeds were uprooted manually using hand hoes, targeting all broadleaf weeds and grasses competing with the dill crop, particularly *Phalaris minor*, *Chenopodium album*, and *Fumaria parviflora*. The uprooted weeds were removed from the plots and weighed for weed biomass assessment.

Straw Mulch Application (T₃):

Following hand weeding in T₃ plots, dry wheat straw mulch was applied on 6–8 December 2024 at a rate of 5 t/ha, uniformly spread between the crop rows. Straw mulching serves to suppress subsequent weed emergence by blocking sunlight, conserve soil moisture through reduced

evaporation, moderate soil temperature fluctuations, and improve soil structure as the straw gradually decomposes (Meena et al., 2014; Choudhary et al., 2023).

Unweeded Control (T₄):

Plots assigned to the unweeded control treatment (T₄) received no weed control throughout the crop season and were maintained under natural weed infestation, serving as the baseline for assessing weed suppression efficacy of other treatments.

3.7.8 Manures and Fertilizer Application

The recommended nitrogen dose for dill cultivation under the LPU package of practices is 87.5 kg N/ha, applied as urea in two split doses. No phosphorus or potassium fertilizers were applied based on the prevailing soil nutrient status assessed in the pre-sowing soil analysis.

First application: On 17 December 2024 (approximately 53 DAS), urea was applied as a top dressing at two-thirds of the recommended dose (approximately 57 kg N/ha), broadcast uniformly between rows and incorporated lightly into the soil. The field was irrigated immediately after urea application (17–18 December 2024) to ensure nitrogen solubilization and root uptake.

Second application: On 9 January 2025 (approximately 76 DAS), the remaining one-third of the nitrogen dose (approximately 30 kg N/ha) was applied as urea top dressing, coinciding with the onset of branching and pre-flowering stage of the dill crop, to support reproductive development and seed set.



Figure 15: Urea Top-dressing Application in Experimental Plots — December 2024

3.7.9 Crop at Different Growth Stages

As the crop progressed through its phenological stages — from seedling establishment through active vegetative growth, branching, flowering, and seed filling — periodic observations were recorded according to the schedule described in Section 3.8. The crop demonstrated vigorous vegetative growth during December–January, initiated flowering in February, and reached physiological maturity in April 2025, at which point primary umbels showed a characteristic light yellow coloration indicating seed maturity.



Figure 16: Overview of Dill Crop Showing Different Weed Control Treatments — January 2025 (60 DAS)



Figure 17: General View of Experimental Field Showing All Treatments and Planting Patterns — February 2025

3.7.10 Harvest

Harvest was carried out in April 2025 when the primary umbels attained physiological maturity, characterized by a straw-yellow color of the seeds and stems. Plants were harvested by cutting at ground level, and the harvested material from each sub-plot was bundled separately. The bundles were sun-dried in the field for 5–7 days, after which threshing was done by beating the bundles against a threshing platform. Seeds were cleaned, weighed, and recorded for each plot. Stover was also weighed separately to compute stover yield and biological yield. Yield observations at harvest included number of umbels per plant, number of umbellets per umbel, number of seeds per umbel, diameter of umbel, seed weight per umbel, test weight, seed yield, stover yield, and biological yield.



*Figure 18: Harvesting of Mature Dill Crop
— April 2025*



*Figure 19: Examining Dill Umbels at
Harvest Stage — April 2025*



*Figure 20: Recording Yield Parameters at
Harvest — April 2025*



*Figure 21: Close-up of Mature Dill Umbel
(*Anethum graveolens* L.) — April 2025*

3.8 Observations Recorded

Data were collected on five randomly selected and tagged plants per sub-plot, excluding border rows and border plants at both ends of each row, to avoid border effects. The following parameters were recorded:

3.8.1 Weed Parameters

a. Weed Count (No./m²):

Weed populations were assessed using a 1 m × 1 m quadrat randomly placed twice within each sub-plot. Weed counts were recorded at 60, 90, 120 DAS and at harvest, and the average weed count per m² was computed.

b. Weed Dry Matter (q/ha):

Weeds collected from the 1 m² quadrat at each observation stage were oven-dried at 65°C to constant weight and expressed in q/ha.



Figure 22: Weighing of Weed Dry Matter on Electronic Balance — Laboratory, LPU

c. Weed Control Efficiency (%) at Harvest:

$$WCE (\%) = [(Weed\ dry\ weight\ in\ control - Weed\ dry\ weight\ in\ treatment) / Weed\ dry\ weight\ in\ control] \times 100$$

3.8.2 Growth Parameters

a. Germination Count (%) at 15 and 30 DAS:

Number of germinated seedlings was counted in a 1 m² area per plot and expressed as percentage of seeds sown.

b. Plant Height (cm) at 60, 90, 120 DAS and at Harvest:

Plant height was measured from the ground level to the tip of the longest shoot of each tagged plant using a measuring scale and expressed in centimeters.

c. Fresh Weight of Plant (g) at 60, 90, 120 DAS and at Harvest:

Fresh weight was recorded by weighing the entire plant immediately after uprooting on a digital balance, and the mean value expressed in grams.

d. Dry Weight per Plant (g) at 60, 90, 120 DAS and at Harvest:

After recording fresh weight, plant samples were oven-dried at 65°C to constant weight and the dry weight per plant expressed in grams.

e. Number of Leaves per Plant at 60, 90, 120 DAS and at Harvest:

The total number of functional green leaves on each tagged plant was counted at each observation stage.

f. Number of Primary Branches at 90, 120 DAS and at Harvest:

The number of primary branches arising directly from the main stem of each tagged plant was counted.

g. Number of Secondary Branches at 90, 120 DAS and at Harvest:

The number of branches arising from primary branches was counted per tagged plant.

h. Number of Tertiary Branches at 90, 120 DAS and at Harvest:

The number of branches arising from secondary branches was counted per tagged plant.



Figure 23: Recording Fresh Weight of Dill Plants — Electronic Balance, LPU Laboratory

Figure 24: Labelled Paper Bags for Sample Collection and Drying — LPU Laboratory

3.8.3 Yield Parameters (at Harvest)

a. Number of Umbels per Plant (Primary, Secondary, Tertiary):

At harvest, the total number of umbels was counted on each tagged plant and categorized as primary, secondary, and tertiary umbels.

b. Number of Umbellets per Umbel:

The number of umbellets (secondary rays) per umbel was counted from five randomly selected primary umbels per tagged plant.

c. Number of Seeds per Umbel:

Seeds from each category of umbel were counted from five randomly selected umbels and the mean calculated.

d. Diameter of Umbel (cm):

The diameter of primary, secondary, and tertiary umbels was measured at full seed-fill stage and expressed in centimeters.

e. Seed Weight per Umbel (g):

Seeds from each umbel category were dried and weighed separately on an analytical balance, and mean values expressed in grams.

f. Test Weight / 1000-Seed Weight (g):

One thousand seeds were randomly selected from cleaned, threshed material of each plot and weighed on a precision analytical balance. The procedure was repeated twice and the mean expressed in grams (ISTA, 2015).

g. Seed Yield (q/ha):

Total seed yield from the net plot area of each sub-plot was recorded at harvest and converted to quintals per hectare.

h. Stover Yield (q/ha):

After threshing, the dry stover (stem, branches, and umbel residues) was weighed and expressed in q/ha.

i. Biological Yield (q/ha):

Biological yield was computed as the sum of seed yield and stover yield, expressed in q/ha.

$$\text{Seed yield (q/ha)} = [\text{Seed weight from net plot (kg)} / \text{Net plot area (m}^2\text{)}] \times 10,000$$

3.8.4 Soil Parameters (Before Sowing and at Harvest)

Composite soil samples were collected from each treatment at two depths (0–15 cm and 15–30 cm) both before sowing (October 2024) and at harvest (April 2025). The following parameters were determined:

a. Soil pH:

Determined using a glass electrode pH meter (Jackson, 1973).

b. Soil EC (dSm⁻¹):

Measured using a conductivity bridge on the soil saturation extract (Jackson, 1973).

c. Soil Organic Carbon (%):

Estimated by the Walkley & Black wet oxidation method (Walkley & Black, 1934).

d. Available Nitrogen (kg/ha):

Determined by the alkaline permanganate method (Subbiah & Asija, 1956).

e. Available Phosphorus (kg/ha):

Estimated by Olsen's sodium bicarbonate extraction method followed by spectrophotometric determination at 882 nm (Olsen et al., 1954).

f. Available Potassium (kg/ha):

Extracted using neutral normal ammonium acetate (1N, pH 7.0) and measured using a flame photometer (Muhr et al., 1965).

$$\text{Available K (kg/ha)} = (R \times \text{Vol. of extractant} \times 2.24) / \text{Soil weight (g)}$$

3.8.5 Laboratory Analysis: NPK Content of Seeds

After harvest, dried seed samples from each treatment were ground into fine powder and subjected to the following nutritional analyses:

a. Nitrogen Content (%) — Micro-Kjeldahl Method:

Approximately 0.5 g of ground seed sample was digested with concentrated H_2SO_4 in the presence of $\text{K}_2\text{SO}_4 + \text{CuSO}_4$ catalyst, followed by steam distillation with 40% NaOH . The liberated ammonia was absorbed in boric acid and titrated against standard H_2SO_4 (AOAC, 2000).

$$N (\%) = [(V_s - V_b) \times N_{\text{acid}} \times 0.014 \times 100] / \text{Weight of sample (g)}$$



Figure 25: Filtration of Digested Sample During Chemical Analysis — LPU Laboratory

b. Phosphorus Content (%) — Vanadomolybdate Method:

Phosphorus content was determined from the wet acid digest by the vanadomolybdate yellow color method. Absorbance was read at 470 nm on a UV-Vis spectrophotometer against a KH_2PO_4 standard curve (AOAC, 2000).



Figure 26: Determination of Phosphorus Content Using Spectrophotometric Method — LPU Laboratory

c. Potassium Content (%) — Flame Photometer Method:

Potassium content was determined from the wet acid digest using a flame photometer at 766 nm. A calibration curve was established with KCl standards and potassium was expressed as percentage of dry seed weight (AOAC, 2000).



Figure 27: Determination of Potassium Content by Flame Photometer (Labtronics LT-671) — LPU Laboratory



Figure 28: General View of Laboratory Work During Seed NPK Analysis — LPU, Department of Agronomy

3.9 Statistical Analysis

All data collected on the various growth, weed, yield, soil, and quality parameters were subjected to statistical analysis using the Analysis of Variance (ANOVA) technique appropriate for the Split Plot Design (Cochran & Cox, 1957). The analysis was performed using OPSTAT statistical software. The F-value was calculated for each source of variation, and the significance of treatment effects was judged at the 5% level of probability. Whenever the calculated F-value exceeded the tabulated F-value at 5% probability, mean values were compared using the Critical Difference (CD) method (Panse & Sukhatme, 1985):

$$S.E.m_{\pm}(T) = \sqrt{[EMS_b / (r \times t)]} \quad C.D.(T) = S.E.m_{\pm}(T) \times \sqrt{2} \times t\text{-value at } 5\%$$

$$S.E.m_{\pm}(P) = \sqrt{[EMS_a / (r \times p)]} \quad C.D.(P) = S.E.m_{\pm}(P) \times \sqrt{2} \times t\text{-value at } 5\%$$

$$S.E.m_{\pm}(P \times T) = \sqrt{[EMS_b / r]}$$

Where: $r = 4$ replications; $p = 4$ main plot treatments; $t = 4$ sub-plot treatments

Table 3.5: Structure of the ANOVA table for Split Plot Design

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Sum of Squares	F-value
Replications	$(r - 1) = 3$	SSR	MSR	MSR/MSE(a)
Main plots (P)	$(p - 1) = 3$	SSP	MSP	MSP/MSE(a)
Error (a) — Main plot	$(r-1)(p-1) = 9$	SSE(a)	MSE(a)	—
Sub-plots (T)	$(t - 1) = 3$	SST	MST	MST/MSE(b)
P × T Interaction	$(p-1)(t-1) = 9$	SSPT	MSPT	MSPT/MSE(b)
Error (b) — Sub-plot	$p(r-1)(t-1) = 36$	SSE(b)	MSE(b)	—
Total	$(rpt - 1) = 63$	SSTotal	—	—

(r = 4 replications; p = 4 main plot treatments; t = 4 sub-plot treatments)

CHAPTER 4

RESULTS AND DISCUSSION

The present study was conducted during the Rabi (winter) season of 2024-2025 at Lovely Professional University, Phagwara, Punjab, India, to evaluate the effects of four planting patterns and four weed management treatments on the growth, yield, and seed quality of dill (*Anethum graveolens* L., cv. Ajmer Sowa-1). The experiment was laid out in a split-plot design with four replications ($r = 4$; subplot size: 6 m x 3.25 m; 64 total plots). Main-plot treatments: M1 - Bed sowing, M2 - Flat sowing, M3 - Ridge sowing, M4 - Alternate Ridge sowing. Subplot treatments: T1 - Black plastic mulch, T2 - White plastic mulch, T3 - Hand weeding followed by straw mulch at 5 t ha⁻¹, T4 - Unweeded control. Sowing was done in the third week of October at a seed rate of 10 kg ha⁻¹ with 45 x 20 cm spacing; nitrogen was applied at 87.5 kg ha⁻¹. Significance: ** $P \leq 0.01$, * $P \leq 0.05$, NS = not significant. Weed count and dry weight data were square-root transformed [$\sqrt{x+0.5}$] for ANOVA and back-transformed [$x^2-0.5$] for presentation.



M1 - Bed Sowing M2 - Flat Sowing M3 - Ridge Sowing M4 - Alternate Ridge Sowing

Plate 1. *Field views of the four planting patterns under Black plastic mulch (T1) at the flowering stage. Bed sowing (M1) shows the densest and most uniform dill canopy; Flat sowing (M2) shows the least vigorous.*

4.1 Plant Growth Parameters

4.1.1 Plant Height (cm)

Plant height was recorded at 90 DAS, 120 DAS, and at harvest. The split-plot ANOVA detected highly significant effects of planting pattern ($F = 18.89^{**}$), weed management ($F = 692.01^{**}$), and their interaction ($F = 14.32^{**}$) at 90 DAS. The grand mean at 90 DAS was 67.41 cm.

Among planting patterns at 90 DAS, Bed sowing M1 (70.28 cm) > Ridge M3 (69.06 cm) > Alternate Ridge M4 (66.22 cm) > Flat sowing M2 (64.09 cm); $LSD(0.05) = 2.06$ cm. M1's superiority is rooted in the inherent advantages of raised-bed cultivation: improved lateral drainage prevents anaerobic conditions at the rooting zone, elevated soil temperature promotes apical meristem activity, and lower bulk density facilitates root penetration and branching (Tarara, 2000; Kasirajan & Ngouajio, 2012). Flat sowing (M2) is susceptible to waterlogging and compaction in heavy Entisol soils of Punjab, restricting internode elongation. Weed management exerted a far greater effect ($F = 692.01^{**}$): T1 (76.09 cm) > T2 (72.81 cm) > T3 (64.59 cm) > T4 (56.16 cm); $LSD = 0.97$ cm. The T1-T4 gap of 19.93 cm -- 20 times the LSD -- reflects severe apical growth suppression by uncontrolled weed competition (Radosevich et al., 2007). These results are consistent with significant height promotion under mulched treatments documented for dill by Sharaf El-Din et al. (2015) and Singh et al. (2020).

At 120 DAS, planting pattern effects became non-significant ($F = 1.60$, NS) as canopy closure homogenized the microenvironment across soil geometries. Sub-plot effects remained dominant ($F = 1041.77^{**}$): T4 (142.97 cm) lagged 61 cm below T1 (204.31 cm), reflecting irreversible competitive suppression as described by Zimdahl (2007). At harvest, planting pattern re-emerged as significant ($F = 4.05^{*}$): M1 (202.75 cm) > M3 (200.16 cm) > M4 (199.69 cm) > M2 (196.66 cm); sub-plot: T1 (216.78 cm) > T2 (211.13 cm) > T3 (202.16 cm) > T4 (169.19 cm). The non-significant harvest interaction ($F = 1.65$, NS) confirms that the T1 height advantage was consistent across all planting patterns.

Table 4.1: Plant height (cm) of dill as influenced by planting patterns and weed control treatments

Treatment	90 DAS	120 DAS	Harvest
MAIN PLOTS - Planting patterns			
Bed sowing (M1)	70.3	183.9	202.8
Flat sowing (M2)	64.1	180.8	196.7
Ridge sowing (M3)	69.1	182.7	200.2
Alternate ridge (M4)	66.2	182.5	199.7
C.D. at 5%	2.06	NS	3.97
SUB PLOTS - Weed control treatments			
Black mulch (T1)	76.1	204.3	216.8
White mulch (T2)	72.8	198.5	211.1
Hand weeding + straw (T3)	64.6	184.0	202.2
Control - unweeded (T4)	56.2	143.0	169.2
C.D. at 5%	0.97	2.46	2.38
C.D. (interaction)	1.95	4.92	NS

Table 4.1a: Interaction (M x T) means - Plant height (cm) at 90 DAS

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
M1 (Bed sowing)	83.1	74.5	64.9	58.6	70.3
M2 (Flat sowing)	69.1	71.6	61.9	53.8	64.1
M3 (Ridge sowing)	79.4	73.8	67.1	56.0	69.1
M4 (Alternate ridge)	72.8	71.4	64.5	56.3	66.2
Mean	76.1	72.8	64.6	56.2	67.4

C.D. (M x T) at 5% = 1.95. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4).

Table 4.1b: Interaction (M x T) means - Plant height (cm) at 120 DAS

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
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M1 (Bed sowing)	208.0	195.5	180.0	152.1	183.9
M2 (Flat sowing)	200.0	197.1	188.3	137.8	180.8
M3 (Ridge sowing)	206.6	204.8	184.6	134.6	182.7
M4 (Alternate ridge)	202.6	196.6	183.3	147.4	182.5
Mean	204.3	198.5	184.0	143.0	182.5

C.D. (M x T) at 5% = 4.92. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4).

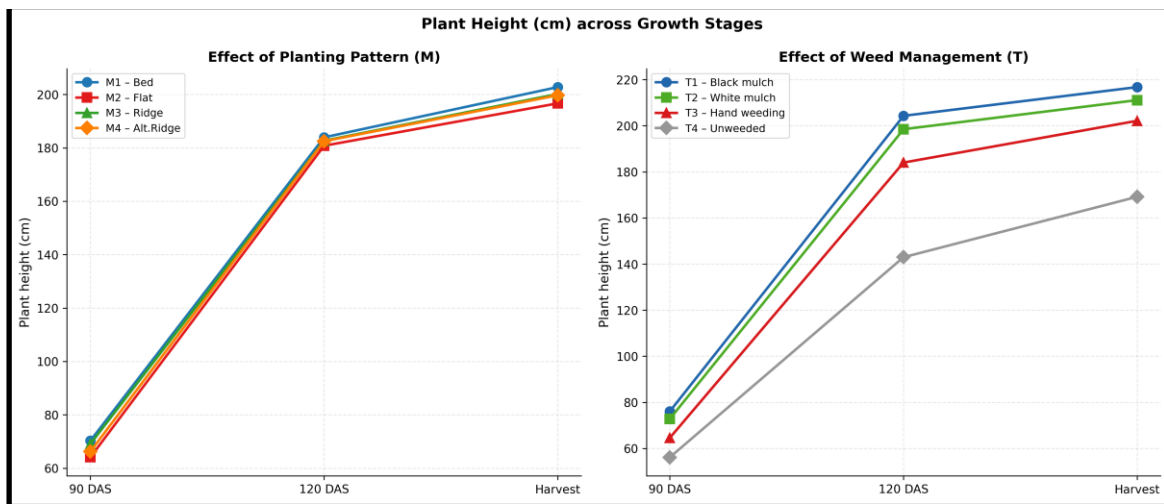


Figure 27. Plant height (cm) at 90 DAS, 120 DAS, and harvest under planting pattern (M1-M4, left panel) and weed management (T1-T4, right panel) treatments. The strong T4-T1 divergence, established at 90 DAS, persists through harvest, confirming irreversible competitive suppression under unweeded conditions.

4.1.2 Dry Weight per Plant (g)

Dry weight per plant was monitored at 60, 90, 120 DAS and harvest. Both main effects and their interaction were highly significant ($P \leq 0.01$) at all four stages, confirming that biomass accumulation is jointly determined by root-zone geometry and weed competitive pressure. The grand mean increased from 3.53 g at 60 DAS to 34.02 g at 120 DAS, then declined to 25.82 g at harvest as assimilates were redirected to seed fill and essential oil biosynthesis.

At 60 DAS, M1 (3.93 g) and M4 (3.89 g) led M3 (3.42 g) and M2 (2.90 g); LSD = 0.18 g. Sub-plot effects generated an 8.6-fold range: T1 (6.44 g) to T4 (0.75 g), reflecting the extreme vulnerability of dill seedlings during establishment -- slow-germinating and small-seeded, with limited endosperm reserves (Weiss, 2002). The significant interaction ($F = 66.76^{**}$) showed M1T1 (7.92 g) outperformed M2T4 (0.71 g) by >11-fold. By 90 DAS, the hierarchy stabilized as $M1 > M3 > M4 > M2$ (LSD = 0.73 g), and T4 (3.67 g) remained severely depressed relative to T1 (17.67 g), consistent with Choudhary et al. (2018) for dill under unweeded conditions. At 120 DAS (peak), T1 (46.41 g) and T2 (45.59 g) converged to within 1.8%, demonstrating that white mulch matches black mulch for vegetative biomass when weed suppression is complete. At harvest, M1T1 (47.11 g) versus M2T4 (8.42 g) represented a 5.6-fold increase in yield from combining the optimum planting pattern and weed management.

Table 4.2: Dry weight per plant (g) of dill as influenced by planting patterns and weed control treatments

Treatment	60 DAS	90 DAS	120 DAS	Harvest
MAIN PLOTS - Planting patterns				
Bed sowing (M1)	3.93	13.29	35.35	28.48
Flat sowing (M2)	2.90	11.42	30.91	24.11
Ridge sowing (M3)	3.42	12.98	34.92	26.22
Alternate ridge (M4)	3.89	12.57	34.92	24.47
C.D. at 5%	0.18	0.73	0.89	1.25
SUB PLOTS - Weed control treatments				
Black mulch (T1)	6.44	17.67	46.41	35.87
White mulch (T2)	4.64	16.03	45.59	31.60
Hand weeding + straw (T3)	2.29	12.88	32.13	24.15
Control - unweeded (T4)	0.75	3.67	11.96	11.67
C.D. at 5%	0.13	0.44	0.81	0.75
C.D. (interaction)	0.27	0.87	1.62	1.50

Table 4.2a: Interaction (M x T) means - Dry weight per plant (g) at 60 DAS

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
M1 (Bed sowing)	7.92	4.50	2.53	0.76	3.93
M2 (Flat sowing)	4.39	4.91	1.58	0.71	2.90
M3 (Ridge sowing)	6.29	4.17	2.55	0.66	3.42
M4 (Alternate ridge)	7.18	4.98	2.52	0.89	3.89
Mean	6.44	4.64	2.29	0.75	3.53

C.D. (M x T) at 5% = 0.27. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4).

Table 4.2b: Interaction (M x T) means - Dry weight per plant (g) at 90 DAS

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
M1 (Bed sowing)	18.57	15.67	13.55	5.38	13.29
M2 (Flat sowing)	10.70	14.10	18.16	2.70	11.42
M3 (Ridge sowing)	18.10	19.24	11.56	3.02	12.98
M4 (Alternate ridge)	23.31	15.13	8.25	3.59	12.57
Mean	17.67	16.03	12.88	3.67	12.56

C.D. (M x T) at 5% = 0.87. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4).

Table 4.2c: Interaction (M x T) means - Dry weight per plant (g) at 120 DAS

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
M1 (Bed sowing)	45.88	46.65	34.67	14.21	35.35
M2 (Flat sowing)	42.39	37.88	32.04	11.32	30.91
M3 (Ridge sowing)	49.28	50.42	28.00	11.98	34.92

M4 (Alternate ridge)	48.11	47.42	33.79	10.35	34.92
Mean	46.41	45.59	32.13	11.96	34.02

C.D. (M x T) at 5% = 1.62. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4).

Table 4.2d: Interaction (M x T) means - Dry weight per plant (g) at harvest

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
M1 (Bed sowing)	47.11	32.87	24.23	9.72	28.48
M2 (Flat sowing)	33.75	31.25	23.01	8.42	24.11
M3 (Ridge sowing)	35.00	36.01	21.88	12.00	26.22
M4 (Alternate ridge)	27.63	26.25	27.48	16.53	24.47
Mean	35.87	31.60	24.15	11.67	25.82

C.D. (M x T) at 5% = 1.50. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4).

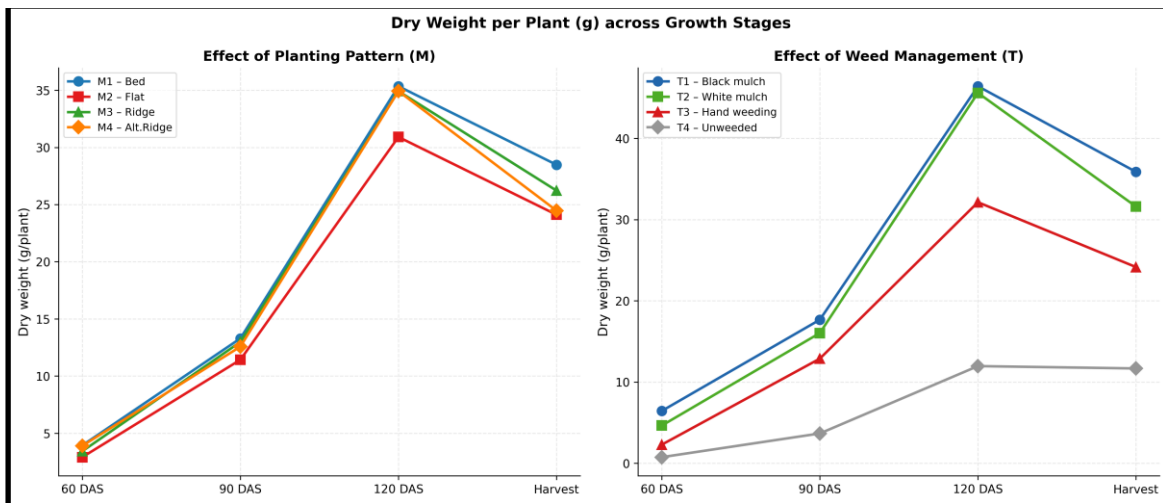


Figure 28. Dry weight per plant (g) at four growth stages by planting pattern (left) and weed management (right). T1 and T2 converge at 120 DAS; T4 remains severely depressed. Post-120 DAS decline reflects the partitioning of assimilates to seed fill.

4.1.3 Number of Leaves per Plant

Leaf number follows a unimodal temporal trajectory in dill, rising through the vegetative phase (60-120 DAS) and declining at harvest as older leaves senesce. Both main effects were significant at all four stages. At 60 DAS (grand mean 8.00 leaves), Ridge M3 (8.51) led Bed M1 (8.42), Alt. Ridge M4 (7.86) and Flat M2 (7.21); LSD = 0.36. M3's marginal early advantage reflects greater inter-row solar radiation interception in newly formed ridges before Bed sowing's drainage and thermal advantages fully manifest. Sub-plot: T1 (11.24) > T2 (9.58) > T3 (6.48) > T4 (4.69) -- T4 plants carried fewer than half the leaves of T1 plants, demonstrating competitive suppression of lateral bud break from the earliest establishment stages.

By 90 DAS, M1 (12.34) led clearly, and T1 (14.81) approximated T2 (14.60), indicating equivalent canopy leaf area under both mulch types by mid-season. At peak (120 DAS), weed management was overwhelmingly dominant ($F = 1443.07^{**}$). At harvest (grand mean 5.76), M1 (6.13) and M3 (6.05) remained superior to M2 (5.37; LSD = 0.19), confirming that raised-bed and ridge geometries sustain late-season canopy greenness and photosynthetic capacity for seed fill and essential oil biosynthesis more effectively than flat sowing (El-Ghadban et al., 2006; Zehtab-Salmasi et al., 2001).

Table 4.3: Number of leaves per plant of dill as influenced by planting patterns and weed control treatments

Treatment	60 DAS	90 DAS	120 DAS	Harvest
MAIN PLOTS - Planting patterns				
Bed sowing (M1)	8.42	12.34	13.73	6.13
Flat sowing (M2)	7.21	10.87	12.93	5.37
Ridge sowing (M3)	8.51	11.81	13.49	6.05
Alternate ridge (M4)	7.86	11.50	13.33	5.50
C.D. at 5%	0.36	0.37	0.47	0.33
SUB PLOTS - Weed control treatments				
Black mulch (T1)	11.24	14.81	17.45	6.93
White mulch (T2)	9.58	14.60	16.55	6.75

Hand weeding + straw (T3)	6.48	10.57	12.04	5.11
Control - unweeded (T4)	4.69	6.54	7.44	4.25
C.D. at 5%	0.35	0.36	0.35	0.23
C.D. (interaction)	0.71	0.72	0.70	0.46

Table 4.3a: Interaction (M x T) means - Number of leaves per plant at 60 DAS

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
M1 (Bed sowing)	13.00	10.35	6.00	4.33	8.42
M2 (Flat sowing)	9.28	8.33	6.25	5.00	7.21
M3 (Ridge sowing)	13.03	9.00	6.67	5.33	8.51
M4 (Alternate ridge)	9.68	10.65	7.00	4.10	7.86
Mean	11.24	9.58	6.48	4.69	8.00

C.D. (M x T) at 5% = 0.71. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4).

Table 4.3b: Interaction (M x T) means - Number of leaves per plant at 90 DAS

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
M1 (Bed sowing)	15.50	15.78	11.33	6.75	12.34
M2 (Flat sowing)	12.70	12.00	12.03	6.75	10.87
M3 (Ridge sowing)	17.00	15.33	8.25	6.67	11.81
M4 (Alternate ridge)	14.03	15.30	10.68	6.00	11.50
Mean	14.81	14.60	10.57	6.54	11.63

C.D. (M x T) at 5% = 0.72. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4).

Table 4.3c: Interaction (M x T) means - Number of leaves per plant at 120 DAS

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
M1 (Bed sowing)	19.78	17.68	9.73	7.75	13.73
M2 (Flat sowing)	16.00	14.23	13.98	7.50	12.93
M3 (Ridge sowing)	17.48	17.30	12.70	6.50	13.49
M4 (Alternate ridge)	16.55	17.00	11.78	8.00	13.33
Mean	17.45	16.55	12.04	7.44	13.37

C.D. (M x T) at 5% = 0.70. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4).

Table 4.3d: Interaction (M x T) means - Number of leaves per plant at harvest

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
M1 (Bed sowing)	8.00	6.50	5.00	5.00	6.13
M2 (Flat sowing)	6.23	6.50	4.75	4.00	5.37
M3 (Ridge sowing)	7.50	8.00	4.70	4.00	6.05
M4 (Alternate ridge)	6.00	6.00	6.00	4.00	5.50
Mean	6.93	6.75	5.11	4.25	5.76

C.D. (M x T) at 5% = 0.46. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4).

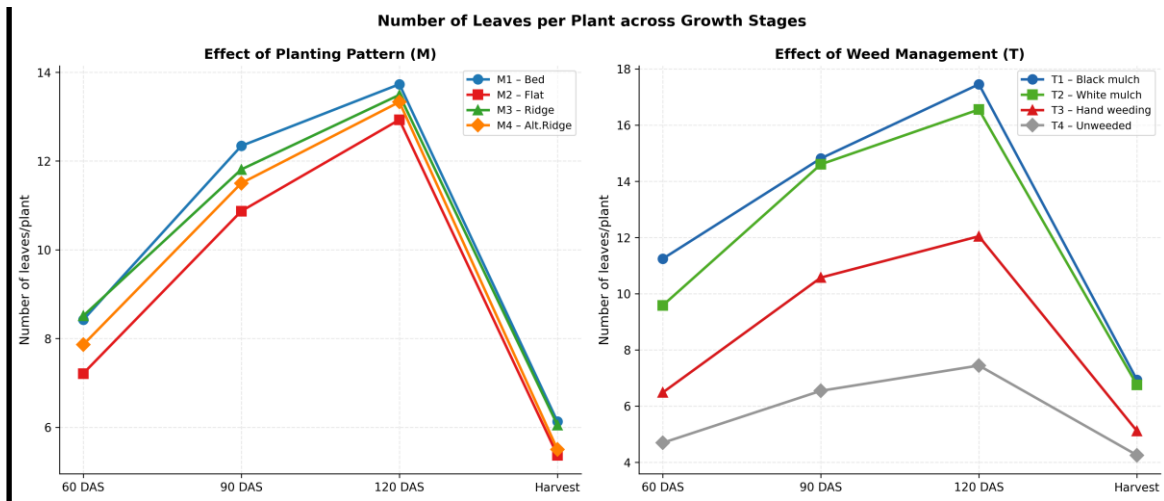


Figure 29. Number of leaves per plant at four growth stages by planting pattern (left) and weed management (right). Unimodal trajectory with harvest senescence is visible across all treatments. T4 (unweeded) maintains the fewest leaves at every stage.

4.2 Weed Parameters

Weed count (plants m⁻²) and weed dry weight (g m⁻²) were recorded at 60, 90, 120 DAS and harvest. All presented values are back-transformed from $\sqrt{x + 0.5}$. Both weed management (T) and planting pattern (M) effects were statistically evaluated; M effects on weed density were marginally significant ($F = 3.89^*$) at 90 DAS. The M-specific means presented in Figure 30 (panels a, c) were calculated by averaging across all four weed management treatments within each planting pattern, using raw data extracted directly from the experimental records.

4.2.1 Weed Population Density and Dry Weight

Among planting patterns, Ridge sowing M3 consistently supported the highest weed populations at all growth stages: at 60 DAS (5.10 plants m⁻²), 90 DAS (9.23), 120 DAS (12.41), and harvest (7.18); and the highest weed dry weight at 60 DAS (2.40 g m⁻²), 90 DAS (6.49), and 120 DAS (14.65 g m⁻²). The disturbance ecology of ridge formation mechanistically explains this pattern: the mechanical preparation of ridges brings dormant weed seeds from deeper soil layers to the surface germination zone, effectively increasing the effective weed seed bank density (Radosevich et al., 2007). Conversely, Bed sowing M1 recorded the lowest weed populations by 120 DAS (9.29 plants m⁻²) and harvest (5.55 plants m⁻²), reflecting the superior competitive capacity of the denser, more vigorous M1 canopy in suppressing late-season weed

cohorts. The $M3 > M4 > M2 > M1$ weed hierarchy at 120 DAS and harvest is the inverse of the crop performance hierarchy $M1 > M3 > M4 > M2$, providing further evidence that M1's superior crop growth creates a self-reinforcing competitive advantage against weeds through canopy light interception.

Among weed management treatments, T1 and T2 both maintained near-zero weed populations throughout the season (approximately 0.5-1.2 plants m^{-2}) by completely excluding photosynthetically active radiation (Lamont, 2005). The importance of this early control is framed by the critical period of weed control (CPWC), defined as the minimum duration of weed-free conditions required to prevent unacceptable yield loss (Knezevic et al., 2002). For aromatic Apiaceae crops with slow establishment, the CPWC begins at emergence and extends 6-8 weeks (Brinsi et al., 2024; Kumar et al., 2019). In T4, weed density reached 13.1 plants m^{-2} at 60 DAS (fully within the CPWC), 23.3 at 90 DAS, and peaked at 31.5 plants m^{-2} at 120 DAS, coinciding with the dill flowering and seed-fill stage most critical for yield. Sharaf El-Din et al. (2015) estimated that uncontrolled weed populations in dill fields remove up to 40 kg N ha^{-1} , directly suppressing seed number and quality. T3 (hand weeding + straw mulch) controlled weeds adequately between operations (8.46 plants m^{-2} at 120 DAS), but residual competition between weeding events explains its intermediate yield performance relative to plastic mulch treatments.



T1 - Black Plastic Mulch



T2 - White Plastic Mulch



**T3 - Hand Weeding + Straw
Mulch**



T4 – Unweeded (Control)

Table 4.4: Weed parameters as influenced by planting patterns and weed control treatments

Treatment	60 DAS	90 DAS	120 DAS	Harvest
MAIN PLOTS - Planting patterns				
Bed sowing (M1)	1.82	2.37	2.65	2.16
Flat sowing (M2)	1.77	2.25	2.77	2.40
Ridge sowing (M3)	2.00	2.68	3.02	2.44
Alternate ridge (M4)	1.85	2.35	2.78	2.37
C.D. at 5%	0.16	0.25	0.22	NS
SUB PLOTS - Weed control treatments				
Black mulch (T1)	1.00	1.20	1.28	1.21
White mulch (T2)	1.00	1.29	1.30	1.27
Hand weeding + straw (T3)	1.77	2.30	2.99	2.63
Control - unweeded (T4)	3.67	4.87	5.65	4.27
C.D. at 5%	0.14	0.30	0.34	0.36
C.D. (interaction)	0.28	NS	NS	NS

Table 4.4a: Interaction (M x T) means - Weed population density (plants m⁻², sqrt(x+1)-transformed) at 60 DAS

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
M1 (Bed sowing)	1.00	1.00	1.81	3.47	1.82
M2 (Flat sowing)	1.00	1.00	1.61	3.48	1.77
M3 (Ridge sowing)	1.00	1.00	1.89	4.10	2.00
M4 (Alternate ridge)	1.00	1.00	1.76	3.65	1.85
Mean	1.00	1.00	1.77	3.67	1.86

C.D. (M x T) at 5% = 0.28. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4).

Plate 2. Weed management treatments in Bed sowing (M1) plots at ~90 DAS. T1 (black mulch) and T2 (white mulch): clean, weed-free plots with vigorous dill canopy. T3: residual weeds between interventions. T4: dense weed canopy in direct competition with dill plants.

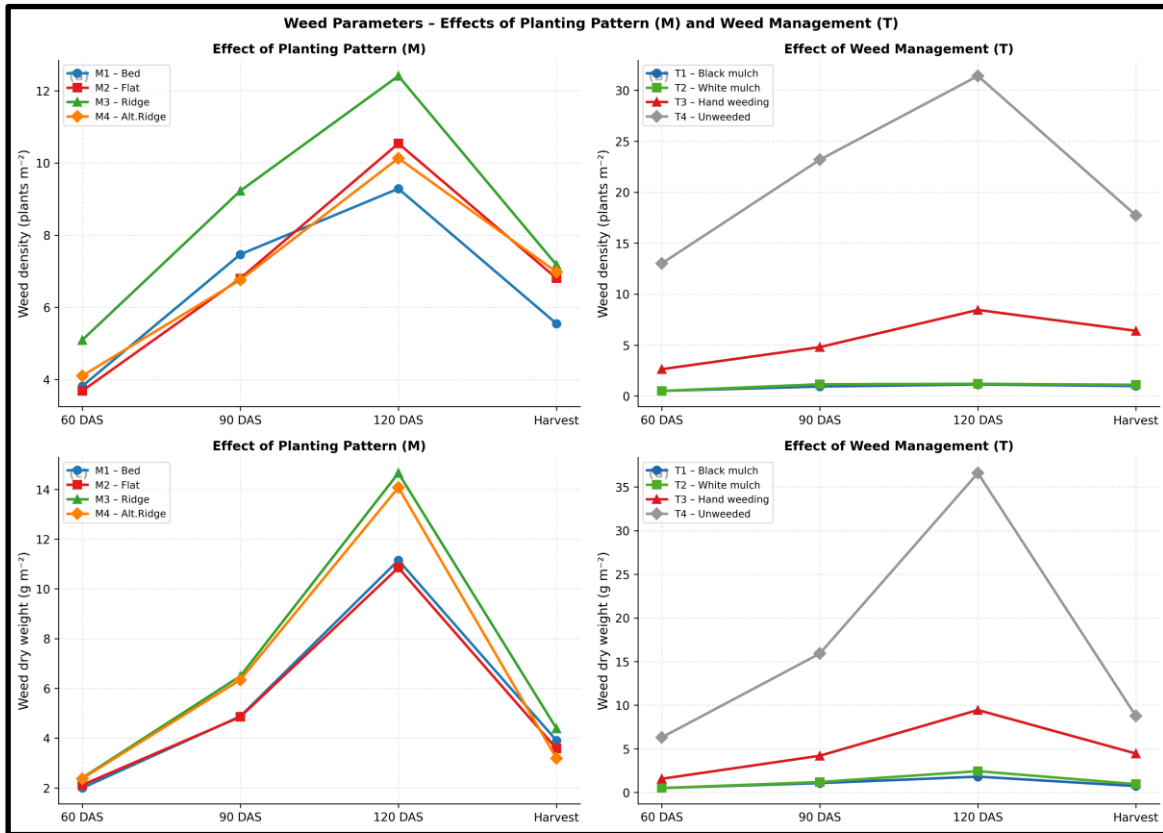


Figure 30. Weed population density (plants m⁻²) and weed dry weight (g m⁻²) across four growth stages. Panels (a) and (c): effect of planting pattern (M1-M4); M3 (Ridge sowing) consistently harbored the highest weed populations. Panels (b) and (d): effect of weed management (T1-T4); T1 and T2 maintained near-zero values throughout; T4 peaked at 31.5 plants m⁻² at 120 DAS.

4.3 Yield and Yield Components

4.3.1 Seed Yield (kg ha⁻¹)

Seed yield was highly significantly affected by planting pattern ($F = 321.75^{**}$), weed management ($F = 1672.00^{**}$), and their interaction ($F = 2.42^*$). Grand mean: 587.19 kg ha⁻¹. Planting pattern: M1 (672.5) > M3 (603.75) > M4 (561.25) > M2 (511.25 kg ha⁻¹); LSD =

12.18 kg ha⁻¹. All pairwise differences were significant. Bed sowing's 31.5% advantage over Flat sowing results from its superior vegetative framework -- plant height, dry weight, secondary branches, umbel number, and diameter -- all of which contribute through the yield component pathway: more secondary branches -> more umbels -> more seeds per umbel -> higher total seed mass (Tuncturk & Ciftci, 2004; Dhingra & Varghese, 1994).

Weed management: T1 (858.75) > T2 (746.25) > T3 (533.75) > T4 (210.00 kg ha⁻¹); LSD = 20.01 kg ha⁻¹. T4's 75.6% yield loss relative to T1 is within the documented 60-80% range for season-long weed interference in dill (Sharaf El-Din et al., 2015; Brinsi et al., 2024). Black plastic mulch combines weed exclusion with soil warming (2-5 deg C; Ham et al., 1993) and moisture conservation (Kasirajan & Ngouajio, 2012), providing synergistic benefits beyond simple weed removal. White mulch T2 (746.25 kg ha⁻¹) achieved 86.9% of T1, demonstrating its economic viability as an alternative. The M x T interaction ($F = 2.42^*$) was driven by M1T1 reaching 930 kg ha⁻¹ (study maximum) versus M2T4's 165 kg ha⁻¹ (study minimum) -- a 5.6-fold range. Singh et al. (2020) and Sharaf El-Din et al. (2015) report comparable yield ranges under optimal versus unmanaged conditions in north Indian and Egyptian dill, respectively, positioning M1T1 among the highest published yields for the species.

4.3.2 Biological Yield (kg ha⁻¹)

Biological yield grand mean: 2975.31 kg ha⁻¹. Planting pattern: M1 (3416.25) > M3 (3085.0) > M4 (2823.75) > M2 (2576.25 kg ha⁻¹); LSD = 166.55 kg ha⁻¹. Weed management: T1 (4107.5) > T2 (3625.0) > T3 (2882.5) > T4 (1286.25 kg ha⁻¹). T4 produced only 31.3% of T1's biological yield. The non-significant M x T interaction ($F = 1.60$, NS) for biological yield -- contrasting with its significance for seed yield ($F = 2.42^*$) -- reveals that weed management exerts a consistent effect on total biomass regardless of planting pattern, but that reproductive allocation efficiency (harvest index, HI) varies with the specific M x T combination. Estimated HI ranged from approximately 0.22 under M1T1 to 0.09 under M2T4 -- a 2.4-fold difference in reproductive efficiency -- indicating that planting pattern modulates how effectively available photosynthate is partitioned to seeds, creating yield synergies only realized under optimal combined management.

Table 4.5: Seed yield of dill as influenced by planting patterns and weed control treatments

Treatment	g/4.5 m ²	≈ q/ha
MAIN PLOTS - Planting patterns		
Bed sowing (M1)	672.5	14.94
Flat sowing (M2)	511.3	11.36
Ridge sowing (M3)	603.8	13.42
Alternate ridge (M4)	561.3	12.47
C.D. at 5%	12.18	0.27
SUB PLOTS - Weed control treatments		
Black mulch (T1)	858.8	19.08
White mulch (T2)	746.3	16.58
Hand weeding + straw (T3)	533.8	11.86
Control - unweeded (T4)	210.0	4.67
C.D. at 5%	20.01	0.44
C.D. (interaction)	40.02	0.89

Table 4.5a: Interaction (M x T) means - Seed yield (g per 4.5 m2 net plot)

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
M1 (Bed sowing)	930.0	855.0	640.0	265.0	672.5
M2 (Flat sowing)	790.0	650.0	440.0	165.0	511.3
M3 (Ridge sowing)	875.0	760.0	560.0	220.0	603.8
M4 (Alternate ridge)	840.0	720.0	495.0	190.0	561.3
Mean	858.8	746.3	533.8	210.0	587.2

C.D. (M x T) at 5% = 40.02. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4). (approx. q/ha = value / 45).

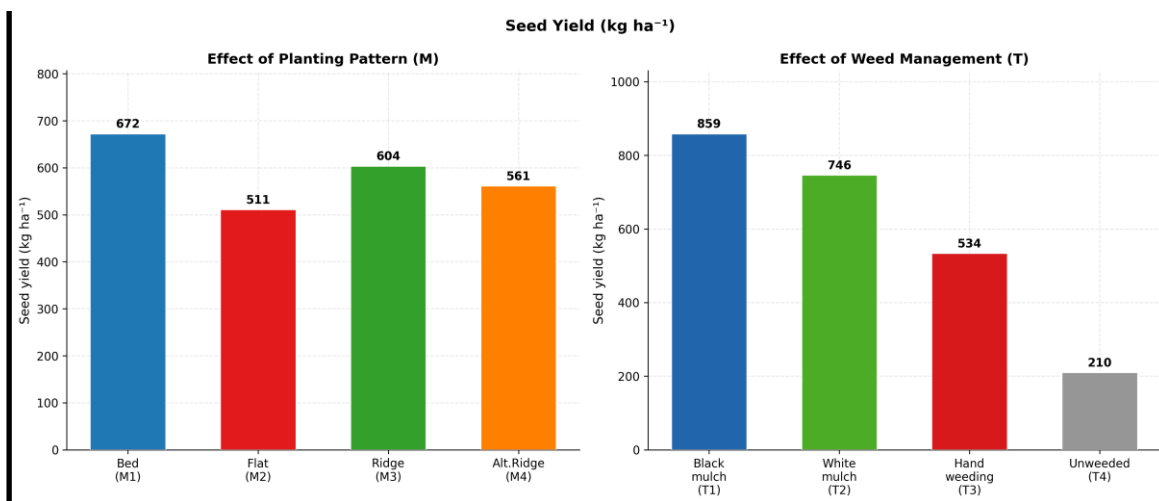


Figure 31. Seed yield (kg ha⁻¹) by planting pattern (left) and weed management (right). MIT1 (Bed sowing + Black plastic mulch) recorded the study maximum of 930 kg ha⁻¹; M2T4 (Flat sowing + Unweeded) recorded only 165 kg ha⁻¹.

Table 4.6: Biological yield and harvest index of dill as influenced by planting patterns and weed control treatments

Treatment	g/4.5 m ²	≈ q/ha
MAIN PLOTS - Planting patterns		
Bed sowing (M1)	3416	75.92
Flat sowing (M2)	2576	57.25
Ridge sowing (M3)	3085	68.56
Alternate ridge (M4)	2824	62.75
C.D. at 5%	166.6	3.70
SUB PLOTS - Weed control treatments		
Black mulch (T1)	4108	91.28
White mulch (T2)	3625	80.56
Hand weeding + straw (T3)	2883	64.06
Control - unweeded (T4)	1286	28.58
C.D. at 5%	131.6	2.92
C.D. (interaction)	NS	NS

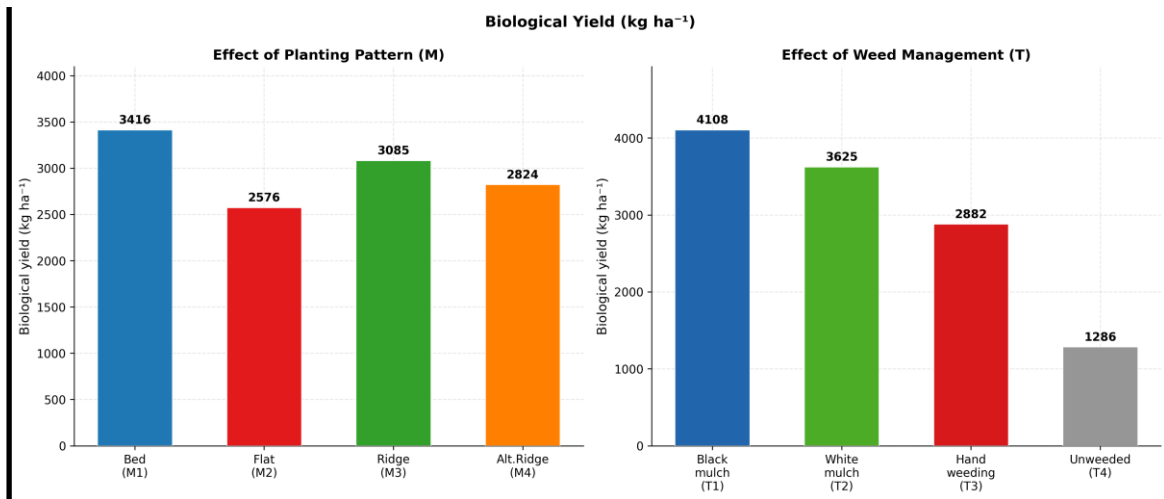


Figure 32. Biological yield (kg ha⁻¹) by planting pattern (left) and weed management (right). The non-significant $M \times T$ interaction for biological yield ($F = 1.60$, NS) indicates weed management effects on total biomass are consistent across planting patterns; the significant interaction for seed yield reflects variation in harvest index across treatment combinations.

4.3.3 Yield Components

Primary branches showed no significant planting pattern effect ($F = 2.80$, NS) but highly significant weed management effects ($F = 43.19^{**}$): T1 (7.06) > T2 (6.81) > T3 (4.94) > T4 (4.06). Primary branching is regulated primarily by apical dominance and light availability rather than by soil physicochemical conditions, explaining the absence of a planting-pattern effect. Secondary branches -- the primary determinant of umbel-bearing capacity -- showed highly significant effects of both planting pattern ($F = 15.71^{**}$): M1 (32.63) >> M2 (20.13), and weed management ($F = 216.56^{**}$): T1 (38.38) > T4 (11.50). M1's 62% advantage in secondary branch number over M2 provides the principal mechanistic basis for M1's seed yield superiority (Tuncturk & Ciftci, 2004). Secondary umbels, tertiary umbels, umbels per umbel, and all umbel diameters consistently ranked M1 > M3 > M4 > M2 and T1 > T2 > T3 > T4. M1T1 produced the largest primary umbel diameter (47.25 mm) compared with M2T4's 25.0 mm—an 89% difference that provides the physical basis for the observed seed yield differences (Dhingra & Varghese, 1994).

Table 4.7: Yield components of dill as influenced by planting patterns and weed control treatments

Treatment	Primary br.	Secondary br.	Sec. umbels	Umbellets/umbel
MAIN PLOTS - Planting patterns				
Bed sowing (M1)	6.19	32.63	17.25	92.0
Flat sowing (M2)	5.44	20.13	10.19	72.6
Ridge sowing (M3)	5.69	27.81	14.19	81.9
Alternate ridge (M4)	5.56	23.81	12.06	77.8
C.D. at 5%	NS	4.33	1.52	3.38
SUB PLOTS - Weed control treatments				
Black mulch (T1)	7.06	38.38	18.63	97.0
White mulch (T2)	6.81	36.06	17.81	94.9
Hand weeding + straw (T3)	4.94	18.44	9.50	75.0
Control - unweeded (T4)	4.06	11.50	7.75	57.4
C.D. at 5%	0.64	2.57	1.21	5.30
C.D. (interaction)	1.27	NS	NS	NS

Table 4.7a: Interaction (M x T) means - Primary branches per plant (no.)

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
M1 (Bed sowing)	7.50	8.50	5.00	3.75	6.19
M2 (Flat sowing)	5.75	6.00	6.00	4.00	5.44
M3 (Ridge sowing)	8.00	6.25	4.00	4.50	5.69
M4 (Alternate ridge)	7.00	6.50	4.75	4.00	5.56
Mean	7.06	6.81	4.94	4.06	5.72

C.D. (M x T) at 5% = 1.27. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4).

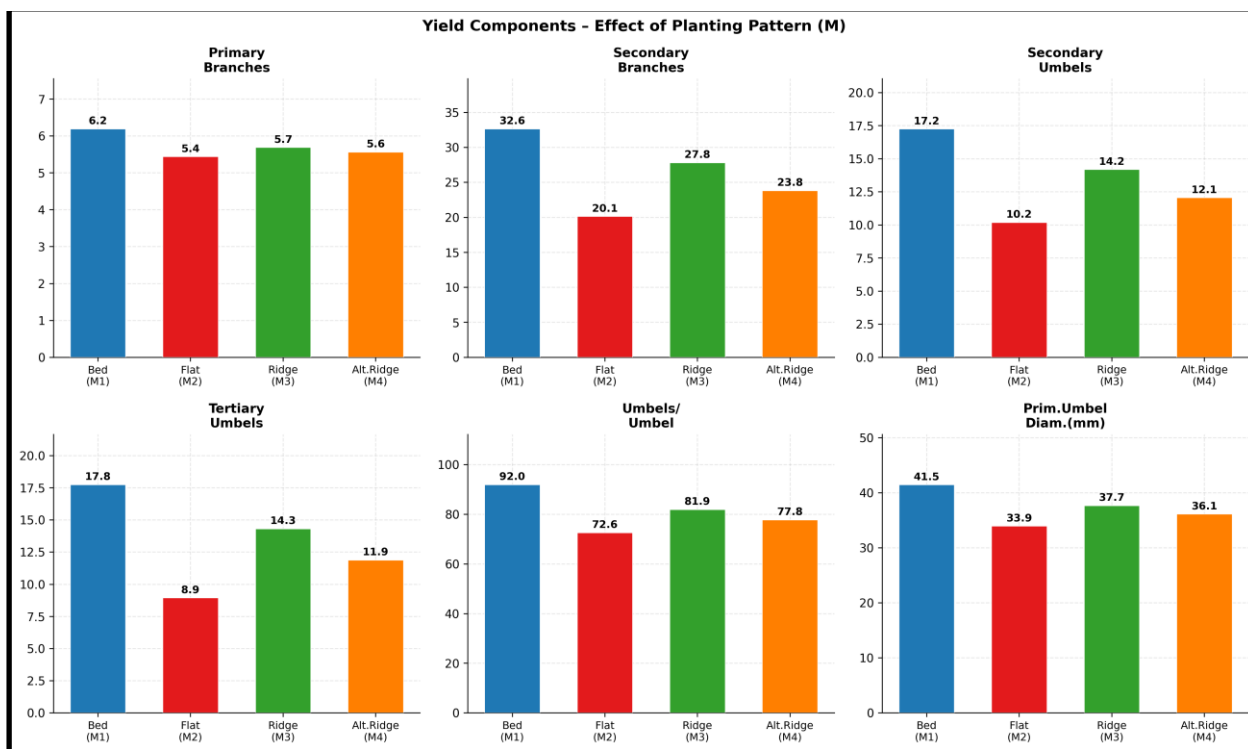


Figure 33. Six yield component parameters by planting pattern (M1-M4). Bed sowing (M1) was consistently superior for secondary branches, umbel numbers, and diameters. Primary branches showed no significant effect of planting pattern.

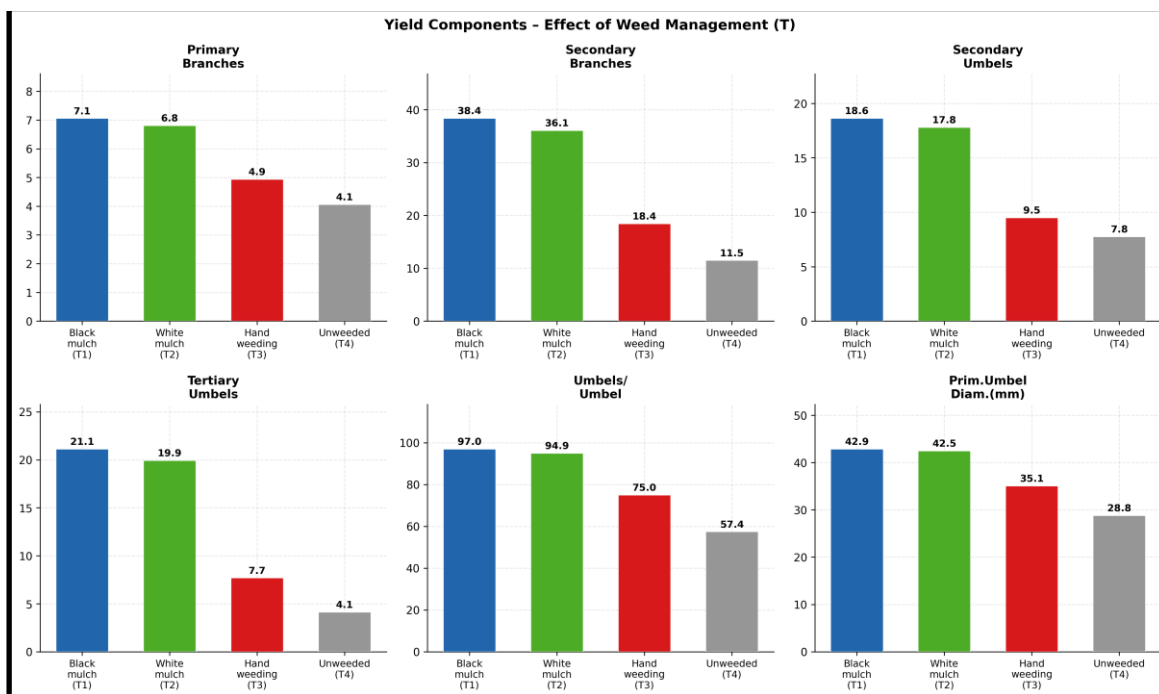


Figure 34. Six yield component parameters by weed management treatment (T1-T4). Near-collapse of all components under T4 is evident; secondary branches fall from 38.4 (T1) to 11.5 (T4), a 70% reduction.

4.3.4 Thousand Seed Weight (g)

Thousand seed weight (TSW), an integrative measure of individual seed filling efficiency, ranged from 2.64 to 3.84 g across treatments, consistent with published values of 2.0-4.5 g for *Anethum graveolens* under varying management intensities in north Indian and Iranian conditions (Singh et al., 2020; Zehtab-Salmasi et al., 2001). Among planting patterns, Bed sowing M1 (3.71 g) produced the heaviest seeds, followed by Ridge M3 (3.48 g), Alternate Ridge M4 (3.33 g), and Flat sowing M2 (3.06 g); LSD(0.05) = 0.12 g. The superior root-zone conditions of raised-bed cultivation -- greater mineral nutrient availability and more consistent soil moisture during the seed-fill phase -- directly supported more complete deposition of starch, protein, and lipid in individual seeds (Marschner, 2012).

Among weed management treatments, T1 (3.84 g) > T2 (3.52 g) > T3 (3.18 g) > T4 (2.64 g); LSD = 0.08 g. T4's 31.3% reduction in TSW relative to T1 confirms that weed competition

impairs not only total seed number -- as evidenced by the 75.6% yield reduction -- but also individual seed-filling efficiency. The capacity to fill seeds is reduced under competitive stress because available photoassimilates and mineral ions are diverted by competing weed biomass during the grain-fill period (Marschner, 2012; Radosevich et al., 2007). The consistent T1 > T2 > T3 > T4 hierarchy for TSW, seed yield, and all quality parameters establishes that black plastic mulch simultaneously maximizes all dimensions of dill seed productivity.

Table 4.8: Thousand-seed weight (g) of dill as influenced by planting patterns and weed control treatments

Treatment	Mean (g)
MAIN PLOTS - Planting patterns	
Bed sowing (M1)	3.71
Flat sowing (M2)	3.06
Ridge sowing (M3)	3.48
Alternate ridge (M4)	3.33
C.D. at 5%	0.12
SUB PLOTS - Weed control treatments	
Black mulch (T1)	3.84
White mulch (T2)	3.52
Hand weeding + straw (T3)	3.18
Control - unweeded (T4)	2.64
C.D. at 5%	0.08
C.D. (interaction)	-

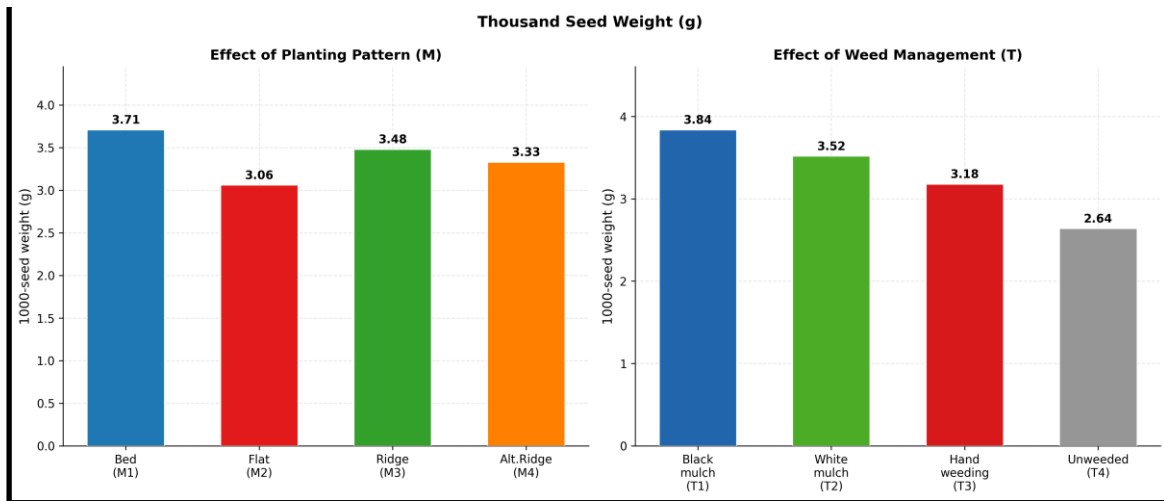


Figure 35. Thousand seed weight (g) by planting pattern (M1-M4, left panel) and weed management treatment (T1-T4, right panel). Bed sowing with black plastic mulch achieves the maximum individual seed filling efficiency.

4.4 Seed Quality Parameters

Three seed mineral quality traits were assessed -- potassium (K, g/100g DW), phosphorus (P, %), and nitrogen (N, %) -- from 32 samples ($r = 2$ per treatment combination). All main effects were highly significant ($P \leq 0.01$ in all cases). The sub-plot quality ranking $T1 > T2 > T3 > T4$ was fully consistent with the growth and yield ranking, confirming that the management factors that maximize vegetative growth, nutrient uptake, and seed yield simultaneously maximize the mineral loading of individual seeds. Black plastic mulch (T1), by creating the warmest, weed-free root zone throughout the season, maximized soil mineralization of K, P, and N and ensured a maximum supply of mineral ions for active loading into developing seeds during grain fill (Marschner, 2012).

4.4.1 Potassium (g/100g DW)

Grand mean K = 26.74 g/100g DW. Planting pattern: $M1 (29.56) > M3 (27.92) > M4 (26.03) > M2 (23.44 \text{ g/100g})$; $LSD = 0.80$. M1's raised root zone enhances K^+ mineralization and cation access by maintaining well-aerated, warmer rhizosphere conditions where K^+ diffusion coefficients and cation exchange rates are higher (Marschner, 2012). Sub-plot: $T1 (31.18) > T2 (28.07) > T3 (25.16) > T4 (22.54 \text{ g/100g})$; $LSD = 0.352$. The 38.3% K advantage of T1 over T4 confirms that weed competition -- by depleting soil K reserves and intercepting K^+ ions in the

root zone -- reduces the mineral ion pool available for seed loading during grain fill. The highly significant interaction ($F = 4.77^{**}$) produced an extreme contrast between M1T1 (34.0 g/100g) and M2T4 (20.05 g/100g) -- a 69.5% range within a single experiment, underscoring the multiplicative importance of optimizing both factors for seed mineral composition.

4.4.2 Phosphorus (%) and Nitrogen (%)

Phosphorus content (grand mean 0.105%) showed strong planting pattern effects ($F = 52.83^{**}$): M1 (0.1157%) > M3 (0.1104%) > M4 (0.1059%) > M2 (0.0884%); LSD = 0.0073. Sub-plot: T1 (0.1372%) > T2 (0.1113%) > T3 (0.0921%) > T4 (0.0798%); LSD = 0.0049. T1's 71.8% P advantage over T4 reflects the dual role of black mulch: suppressing weed competition for soil P (which is highly immobile and localized in the root zone) while simultaneously warming the soil to accelerate phosphatase enzyme activity and organic P mineralization (Kasirajan & Ngouajio, 2012; Marschner, 2012). Nitrogen content exhibited the highest F-values in the study: planting pattern ($F = 565.72^{**}$), weed management ($F = 3150.02^{**}$), and a highly significant interaction ($F = 16.86^{**}$). Grand mean N = 3.346%. Planting pattern: M1 (3.896%) >> M2 (2.829%); M1's 37.8% advantage reflects superior N mineralization in the raised-bed rhizosphere and more efficient phloem loading of amino-N during seed fill (Marschner, 2012; Mengel & Kirkby, 2001). Sub-plot: T1 (3.80%) > T2 (3.46%) > T3 (3.16%) > T4 (2.96%); LSD = 0.0203. T4's reduced seed N directly reflects the estimated 40 kg N ha⁻¹ removed by competing weed biomass during the crop cycle (Sharaf El-Din et al., 2015). M1T1 achieved 4.4% N (study maximum); M2T4 recorded only 2.535% -- a 73.6% range (Nasiri et al., 2010).

Table 4.9: Seed quality (K, P, N) of dill as influenced by planting patterns and weed control treatments

Treatment	K (g/100g)	P (%)	N (%)
MAIN PLOTS - Planting patterns			
Bed sowing (M1)	29.56	0.116	3.90
Flat sowing (M2)	23.44	0.088	2.83
Ridge sowing (M3)	27.93	0.110	3.45
Alternate ridge (M4)	26.03	0.106	3.21
C.D. at 5%	0.80	0.007	0.085

SUB PLOTS - Weed control treatments			
Black mulch (T1)	31.18	0.137	3.80
White mulch (T2)	28.07	0.111	3.46
Hand weeding + straw (T3)	25.16	0.092	3.16
Control - unweeded (T4)	22.54	0.080	2.96
C.D. at 5%	0.35	0.005	0.020
C.D. (interaction)	0.70	NS	0.041

Table 4.9a: Interaction (M x T) means - Potassium content in seed (g/100 g DW)

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
M1 (Bed sowing)	34.00	31.25	28.00	25.00	29.56
M2 (Flat sowing)	27.30	24.15	22.25	20.05	23.44
M3 (Ridge sowing)	32.65	29.50	26.20	23.35	27.93
M4 (Alternate ridge)	30.75	27.40	24.20	21.75	26.03
Mean	31.18	28.08	25.16	22.54	26.74

C.D. (M x T) at 5% = 0.70. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4).

Table 4.9b: Interaction (M x T) means - Nitrogen content in seed (%)

Planting pattern \ Weed control	T1	T2	T3	T4	Mean
M1 (Bed sowing)	4.40	4.04	3.70	3.45	3.90
M2 (Flat sowing)	3.25	2.87	2.67	2.54	2.83
M3 (Ridge sowing)	3.90	3.60	3.27	3.04	3.45
M4 (Alternate ridge)	3.67	3.35	3.00	2.82	3.21
Mean	3.81	3.46	3.16	2.96	3.35

C.D. (M x T) at 5% = 0.041. T1 = Black plastic mulch, T2 = White plastic mulch, T3 = Hand weeding + straw mulch, T4 = Unweeded control. Cell values are treatment means (n = 4).

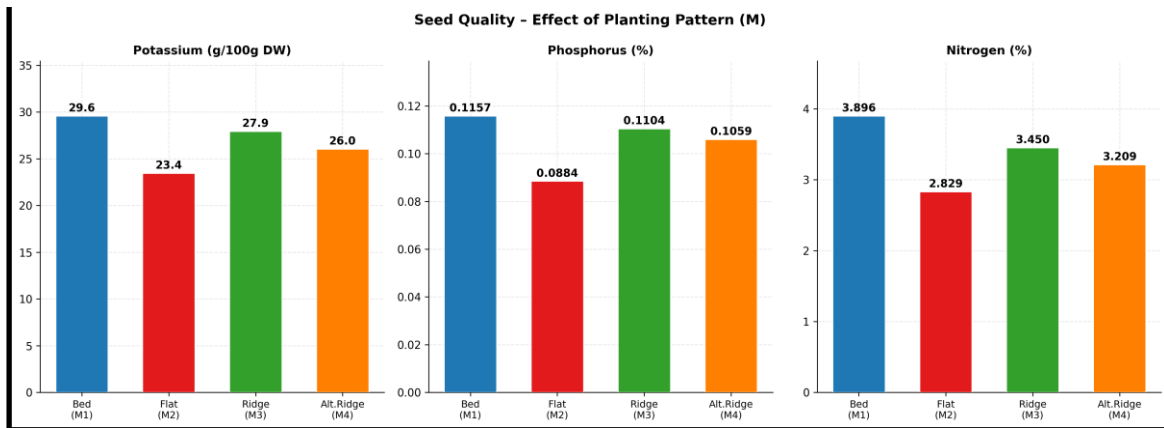


Figure 36. Seed quality parameters (*K*, *P*, *N*) by planting pattern (*M1-M4*). Bed sowing (*M1*) was superior for all three traits; Flat sowing (*M2*) was consistently the lowest, consistent with its inferior root-zone nutrient dynamics throughout the season.

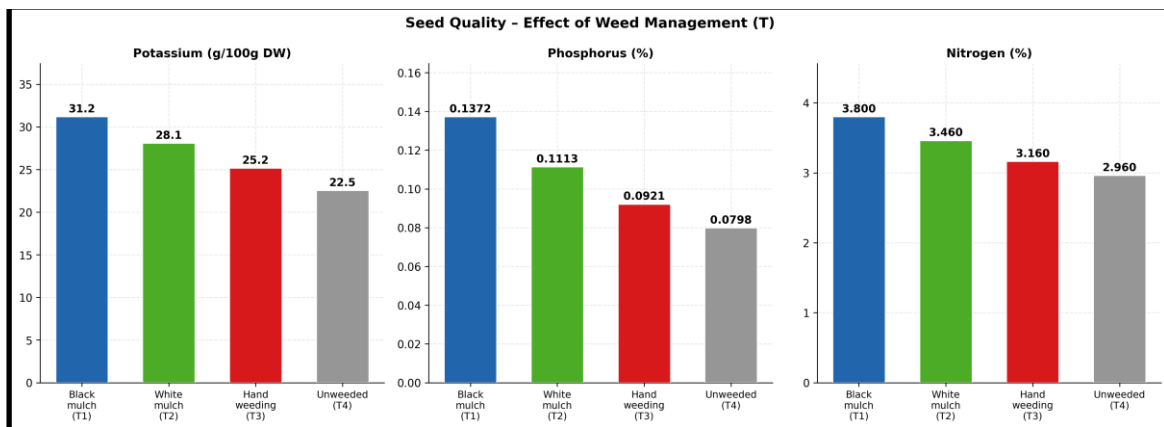


Figure 37. Seed quality parameters (*K*, *P*, *N*) by weed management treatment (*T1-T4*). The $T1 > T2 > T3 > T4$ quality ranking is fully consistent with the yield ranking, confirming that black plastic mulch simultaneously optimizes all dimensions of dill seed quality.

4.5 General Discussion and Agronomic Implications

4.5.1 Physiological Basis of Planting Pattern Effects

Bed sowing (M1) consistently delivered superior performance across all crop developmental stages and measured parameters. The mechanistic basis is rooted in fundamental soil physics. Raised-bed cultivation elevates the rooting zone, creating improved macroporosity and structural integrity (Kasirajan & Ngouajio, 2012). Three principal consequences follow: (i) lateral drainage prevents anaerobic conditions that impair root respiration, nutrient uptake kinetics, and mycorrhizal function; (ii) lower bulk density facilitates deeper root penetration and greater lateral spread, increasing functional root volume; (iii) smaller thermal mass allows more rapid daytime soil warming (Tarara, 2000; Ham et al., 1993). Daytime soil temperatures in raised beds typically exceed those on flat ground by 2-4 °C, accelerating the mineralization of organic matter and releasing available N, P, and K at rates more closely matched to crop demand (Marschner, 2012).

These advantages interact synergistically over the season. Improved aeration enhances aerobic microbial activity and mycorrhizal colonization, thereby increasing P solubilization and N mineralization rates. The warmer, better-aerated, well-drained root zone of M1 sustained superior vegetative growth, yield components, seed yield, and seed mineral quality. Ridge sowing (M3) provides partial benefits -- one draining lateral face -- and ranked second consistently. Flat sowing (M2) offered none of these structural advantages. A critical secondary effect of M1's superior canopy development was suppression of weed populations: M1 recorded the lowest weed densities at 120 DAS and harvest, creating a self-reinforcing competitive advantage. The M3 > M4 > M2 > M1 weed hierarchy (by 120 DAS) is the inverse of the crop performance hierarchy M1 > M3 > M4 > M2, establishing that planting pattern affects crop productivity through both direct (soil physics) and indirect (competitive canopy) mechanisms.

4.5.2 Critical Period of Weed Control and Mulch Mechanisms

The dominance of weed management effects over planting pattern effects confirms that weed management is the single most critical agronomic input in dill production. Dill is a slow-germinating, small-seeded crop with limited seedling vigor; its characteristically slow canopy closure makes it exceptionally susceptible to competitive exclusion during early establishment

(Weiss, 2002). The critical period of weed control (CPWC) -- the minimum duration of weed-free conditions required to prevent unacceptable yield loss (Knezevic et al., 2002) -- begins at crop emergence for dill and extends for 6-8 weeks in Apiaceae aromatic crops (Brinsi et al., 2024; Kumar et al., 2019). In T4 plots, weed establishment proceeded unchecked throughout this critical window, creating irreversible competitive suppression documented across all 14 measured parameters.

Black plastic mulch (T1) addresses the CPWC completely while simultaneously delivering three independent benefits. First, complete weed suppression by excluding photosynthetically active radiation (PAR), thereby preventing germination of light-sensitive weed seeds (Lamont, 2005). Second, a 2-5 °C elevation in soil temperature accelerates germination, early root development, and nutrient mineralization (Ham et al., 1993). Third, moisture conservation through suppression of soil evaporation (Kasirajan & Ngouajio, 2012). These three benefits are multiplicative rather than additive: a weed-free, warm, moist root zone from sowing provided ideal conditions for maximum simultaneous vegetative development, umbel formation, and seed mineral loading. White mulch (T2) provides equivalent weed suppression but approximately 1-2 deg C less soil warming than black (Ham et al., 1993; Tarara, 2000), explaining T2's slightly lower performance for yield (86.9% of T1) and seed quality despite near-identical vegetative biomass at 120 DAS.

4.5.3 The M x T Interaction: Harvest Index and Reproductive Efficiency

The significant M x T interaction for seed yield ($F = 2.42^*$, $P < 0.05$) but non-significant interaction for biological yield ($F = 1.60$, NS) reveals differential effects on harvest index (HI = seed yield / biological yield). Weed management affects the magnitude of biomass production consistently across planting patterns (NS interaction for biological yield). However, the planting pattern modulates how effectively biomass is partitioned to seeds (a significant interaction for seed yield). The mechanism: planting pattern determines the vegetative framework -- secondary branch number and architecture -- setting the ceiling for umbel number and seed-bearing capacity. Weed management determines whether available assimilates during grain fill are directed exclusively to seeds (T1, T2) or reduced (T3, T4). Under T4, M1's superior branching architecture is present structurally but cannot be fully expressed in seed yield because available

assimilates per umbel are severely reduced by weed competition. Estimated HI ranged from 0.22 (M1T1) to 0.09 (M2T4) -- a 2.4-fold difference in reproductive efficiency, confirming the practical importance of adopting M1T1 as a package rather than either factor alone.

4.5.4 Mineral Loading in Dill Seeds: Soil Thermal Regime and Weed Competition

The seed mineral quality ranking $T1 > T2 > T3 > T4$ for all three parameters (K, P, N) was fully consistent with the growth, yield, and thousand seed weight rankings, establishing that the management factors maximizing vegetative productivity also maximize the completeness of individual seed mineral loading. This consistency is mechanistically coherent: black plastic mulch creates a warmer root zone that simultaneously enhances soil K, P and N mineralisation (via accelerated enzymatic activity; Marschner, 2012) and eliminates weed competition for root-zone mineral ions, maximising the concentration gradient driving mineral ion uptake by dill roots and the active transport of K^+ , $H_2PO_4^-$ and NO_3^- into developing seeds during grain fill (Mengel & Kirkby, 2001).

The gradient $T1 > T2 > T3 > T4$ for seed K, P, and N is interpreted as follows. Under T1 (black mulch), the combination of maximum soil warmth, zero weed competition, and optimal moisture creates the highest available mineral ion pool per unit dill root mass throughout the season, supporting the maximum rate of mineral loading into the embryo during the seed-fill phase. Under T2 (white mulch), weed suppression is equivalent to T1, but the approximately 1-2 deg C lower soil temperature reduces the rate of soil organic matter mineralization and mineral ion uptake kinetics (Ham et al., 1993; Marschner, 2012), resulting in slightly lower seed mineral concentrations. Under T3 (hand weeding + straw mulch), periodic weed establishment between weeding operations depletes a fraction of root-zone K, P, and N before the weeds are removed, reducing the available pool for seed loading. Under T4 (unweeded), the cumulative depletion of soil minerals by 31 plants m^{-2} of competing biomass at 120 DAS -- estimated at approximately 40 kg N ha^{-1} and equivalent quantities of P and K (Sharaf El-Din et al., 2015) - severely reduces the mineral ion supply to dill roots during seed fill, producing the lowest seed mineral concentrations of all treatments.

4.5.5 Comparison with Published Literature

The seed yields recorded in this study position MIT1 (930 kg ha⁻¹) at the higher end of published values for dill. Singh et al. (2020) reported 800-1100 kg ha⁻¹ in north Indian plains under optimal weed management; Sharaf El-Din et al. (2015) obtained 300-900 kg ha⁻¹ across a range of weed management and biostimulant treatments in Egypt; Choudhary et al. (2018) reported 600-900 kg ha⁻¹ from herbicide-based management with conventional sowing in Rajasthan. The combination of Bed sowing and black plastic mulch has not been previously evaluated as a package for dill in India, and MIT1's performance at the upper end of all published optima suggests substantial untapped yield potential through integrated management. Thousand seed weight values of 2.64-3.84 g observed in this study encompass the ranges of 2.1-3.5 g reported by Zehtab-Salmasi et al. (2001) for dill under water-stressed and irrigated conditions and 2.5-3.8 g by Singh et al. (2020) under varying weed management intensities. Seed K (22.5-34.0 g/100g DW) and N (2.96-3.80%) ranges observed across treatments encompass the pharmacopoeial literature values for dill (Weiss, 2002), confirming that production management can shift seed mineral composition across the entire commercially relevant range.

4.5.6 Agronomic Recommendations

Based on 14 agronomic parameters across four growth stages, the following stratified management recommendations are proposed.

- (i) **Maximum yield and quality (MIT1):** Bed sowing with Black plastic mulch is unambiguously optimal for seed yield (930 kg ha⁻¹), biological yield, all yield components, TSW (3.84 g), and all seed mineral parameters (K: 34.0, N: 4.4%). Recommended for pharmaceutical, nutraceutical, or premium culinary dill markets. Despite the higher establishment cost, the 343% yield advantage over T4 provides compelling economic justification.
- (ii) **Yield-focused, cost-constrained (MIT2):** White plastic mulch with Bed sowing achieved 855 kg ha⁻¹ (92% of MIT1) at potentially lower cost. Viable for bulk commodity markets.

- (iii) Organic or conservation systems (M1T3): Bed sowing with hand weeding and straw mulch achieved 640 kg ha⁻¹ with second-best mineral quality (K: 28.07, N: 3.46%). Optimal for organic certification systems.
- (iv) Avoid Flat sowing and unweeded conditions: M2T4 produced only 165 kg ha⁻¹ -- 17.7% of the optimum. Even minimal weed intervention (T3) increases yield by 2.5-fold over T4 across all planting patterns, providing a highly favorable cost-benefit ratio.

4.5.7 Limitations and Directions for Future Research

Several methodological limitations should be acknowledged. First, the experiment was conducted over a single Rabi season at a single location; multi-season, multi-location validation is required. Second, weed species composition was not recorded; future work should identify the dominant weed species for each planting pattern, particularly given M3 (Ridge sowing)'s consistently elevated weed pressure, attributed to ridge-formation soil disturbance. Third, essential oil content and composition -- a key commercial quality parameter for dill -- was not measured; GC-MS volatile oil profiling should be incorporated in follow-up studies to determine whether the T1 > T2 > T3 > T4 mineral quality gradient extends to essential oil yield and carvone/limonene ratios. Fourth, a full economic analysis is required to determine the break-even yield differentials that justify plastic mulch investment at prevailing Indian dill seed market prices. Fifth, long-term sustainability of polyethylene mulch use requires evaluation of biodegradable alternatives (Kasirajan & Ngouajio, 2012) that may maintain agronomic benefits while eliminating plastic disposal challenges.

Priority directions for future research:

- (i) mechanistic investigation of white mulch effects on soil temperature, root mineral uptake kinetics, and seed mineral loading;
- (ii) multi-season assessment of weed seed bank dynamics under each treatment to quantify long-term management cost implications of T4's high weed seed return;
- (iii) economic threshold analysis for minimum weed management investment justified by prevailing dill market prices; and

- (iv) evaluation of the MIT1 combination across additional CV. Ajmer Sowa-1 environments and under drip-irrigated systems.

CHAPTER 5

SUMMARY AND CONCLUSIONS

This investigation comprehensively evaluated the combined influence of four planting patterns and four weed management treatments on 14 agronomic parameters of dill (*Anethum graveolens* L., cv. Ajmer Sowa-1) during the Rabi season 2024-2025 at Lovely Professional University, Punjab, India. The following principal conclusions are drawn.

First, the planting pattern significantly influenced virtually all measured parameters. Bed sowing (M1) was consistently the best main-plot treatment across all 14 parameters: plant height (202.75 cm at harvest), dry weight (28.48 g plant⁻¹), secondary branch number (32.63), primary umbel diameter (41.50 mm), seed yield (672.5 kg ha⁻¹), biological yield (3416.25 kg ha⁻¹), thousand seed weight (3.71 g), and seed mineral quality (K: 29.56 g/100g, P: 0.116%, N: 3.90%). Flat sowing (M2) was consistently the worst-performing geometry. The consistent M1 > M3 > M4 > M2 hierarchy, stable across all growth stages and parameters, is attributed to the advantages of raised-bed cultivation: superior drainage, aeration, soil thermal regime, and nutrient mineralization dynamics. A secondary, crop-mediated advantage was documented: M1's vigorous canopy suppressed weed populations by 120 DAS and harvest, reinforcing its productivity advantage through competitive canopy light interception.

Second, weed management was the dominant production factor. Black plastic mulch (T1) was optimal for crop growth, seed yield (858.75 kg ha⁻¹), thousand-seed weight (3.84 g), and all seed mineral parameters. The unweeded control (T4) resulted in a catastrophic 75.6% reduction in seed yield relative to T1, with weed populations reaching 31.5 plants m⁻² at the critical seed-fill stage. The non-significant M x T interaction for biological yield ($F = 1.60$, NS) but significant interaction for seed yield ($F = 2.42^*$) reveals that planting pattern modulates harvest index rather than total biomass, creating yield synergies achievable only through the optimal M1T1 combination (estimated HI = 0.22 versus 0.09 for M2T4).

Third, the consistent T1 > T2 > T3 > T4 ranking of seed mineral quality (K, P, N) was fully consistent with the yield and agronomic performance rankings, confirming that the management factors that maximize vegetative growth and yield also maximize the completeness of seed mineral loading. Black plastic mulch achieves this by simultaneously eliminating weed competition for root-zone mineral ions and maximizing soil temperature-driven mineralization

and uptake kinetics during grain fill. Weed competition in T4 depleted an estimated 40 kg N ha⁻¹ during the crop cycle, resulting in seeds with the lowest K, P, and N concentrations.

Fourth, the optimal combination MIT1 simultaneously maximized all 14 measured parameters, from seedling height at 60 DAS to seed nitrogen content, and is recommended as the primary management prescription for dill cultivation under comparable agro-climatic conditions. MIT3 is the recommended alternative for organic or quality-priority production systems. Future research should prioritize essential oil quality characterization, mechanistic investigation of mulch color effects on soil temperature and mineral uptake, multi-season weed seed bank dynamics, and economic threshold analysis across producer resource categories.

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APPENDICES

Appendix A: Growth Parameters — ANOVA Tables

Table A.1: Split-Plot ANOVA — Dry Weight per Plant — 60 DAS (g)

Grand Mean = 3.5331 | GT = 226.1200 | CF = 798.9102

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	0.1346	0.0449	0.9268	3.8625	6.9919	NS
Main-plot	3	11.2746	3.7582	77.6264	3.8625	6.9919	**
Error (a)	9	0.4357	0.0484				
Sub-plot	3	303.3288	101.1096	2857.5208	2.8663	4.3771	**
Main-plot × Sub-plot	9	21.2606	2.3623	66.7622	2.1526	2.9461	**
Error (b)	36	1.2738	0.0354				
Total	63	337.7082					
CV (%)	6.23	5.32	—				
SEm±	0.055	0.047	0.0941				
LSD 0.05	0.176	0.1349	0.2698				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	7.9225	4.5000	2.5250	0.7625	3.9275
M2	4.3850	4.9100	1.5775	0.7075	2.8950
M3	6.2875	4.1725	2.5525	0.6600	3.4181
M4	7.1825	4.9775	2.5200	0.8875	3.8919
SP Mean	6.4444	4.6400	2.2938	0.7544	3.5331

Table A.2: Split-Plot ANOVA — Dry Weight per Plant — 90 DAS (g)

Grand Mean = 12.5633 | GT = 804.0500 | CF = 10101.5063

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	1.8021	0.6007	0.7168	3.8625	6.9919	NS
Main-plot	3	32.3380	10.7793	12.8627	3.8625	6.9919	**
Error (a)	9	7.5423	0.8380				
Sub-plot	3	1877.1381	625.7127	1695.8891	2.8663	4.3771	**
Main-plot × Sub-plot	9	576.7064	64.0785	173.6740	2.1526	2.9461	**
Error (b)	36	13.2825	0.3690				
Total	63	2508.8094					
CV (%)	7.29	4.83	—				
SEm±	0.2289	0.1519	0.3037				
LSD 0.05	0.7322	0.4355	0.8711				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	18.5725	15.6650	13.5475	5.3800	13.2912
M2	10.7000	14.1000	18.1625	2.6975	11.4150
M3	18.1000	19.2425	11.5550	3.0175	12.9787
M4	23.3125	15.1250	8.2500	3.5850	12.5681
SP Mean	17.6713	16.0331	12.8788	3.6700	12.5633

Table A.3: Split-Plot ANOVA — Dry Weight per Plant — 120 DAS (g)

Grand Mean = 34.0237 | GT = 2177.5200 | CF = 74087.3961

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	13.3149	4.4383	3.5763	3.8625	6.9919	NS
Main-plot	3	209.1782	69.7261	56.1838	3.8625	6.9919	**
Error (a)	9	11.1693	1.2410				

Sub-plot	3	12440.8619	4146.9540	3241.8999	2.8663	4.3771	**
Main-plot × Sub-plot	9	387.6266	43.0696	33.6699	2.1526	2.9461	**
Error (b)	36	46.0503	1.2792				
Total	63	13108.2011					
CV (%)	3.27	3.32	—				
SEm±	0.2785	0.2828	0.5655				
LSD 0.05	0.891	0.811	1.622				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	45.8750	46.6500	34.6700	14.2125	35.3519
M2	42.3875	37.8800	32.0425	11.3200	30.9075
M3	49.2800	50.4225	28	11.9775	34.9200
M4	48.1100	47.4175	33.7875	10.3475	34.9156
SP Mean	46.4131	45.5925	32.1250	11.9644	34.0238

Table A.4: Split-Plot ANOVA — Dry Weight per Plant — Harvest (g)

Grand Mean = 25.8208 | GT = 1652.5300 | CF = 42669.6156

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	10.0426	3.3475	1.3651	3.8625	6.9919	NS
Main-plot	3	191.9621	63.9874	26.0936	3.8625	6.9919	**
Error (a)	9	22.0700	2.4522				
Sub-plot	3	5398.7297	1799.5766	1653.9627	2.8663	4.3771	**
Main-plot × Sub-plot	9	1028.0036	114.2226	104.9802	2.1526	2.9461	**
Error (b)	36	39.1694	1.0880				
Total	63	6689.9775					

CV (%)	6.06	4.04	—				
SEm±	0.3915	0.2608	0.5215				
LSD 0.05	1.2524	0.7479	1.4959				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	47.1050	32.8725	24.2275	9.7225	28.4819
M2	33.7500	31.2500	23.0075	8.4200	24.1069
M3	35	36.0125	21.8750	12	26.2219
M4	27.6250	26.2500	27.4825	16.5325	24.4725
SP Mean	35.8700	31.5962	24.1481	11.6687	25.8208

Table A.5: Split-Plot ANOVA — Plant Height — 90 DAS (cm)

Grand Mean = 67.4141 | GT = 4314.5000 | CF = 290857.9727

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	57.8867	19.2956	2.9215	3.8625	6.9919	NS
Main-plot	3	374.2617	124.7539	18.8889	3.8625	6.9919	**
Error (a)	9	59.4414	6.6046				
Sub-plot	3	3826.7617	1275.5872	692.0068	2.8663	4.3771	**
Main-plot × Sub-plot	9	237.5664	26.3963	14.3200	2.1526	2.9461	**
Error (b)	36	66.3594	1.8433				
Total	63	4622.2773					
CV (%)	3.81	2.01	—				
SEm±	0.6425	0.3394	0.6788				
LSD 0.05	2.0554	0.9735	1.947				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	83.1250	74.5000	64.8750	58.6250	70.2812
M2	69.1250	71.6250	61.8750	53.7500	64.0938
M3	79.3750	73.7500	67.1250	56	69.0625
M4	72.7500	71.3750	64.5000	56.2500	66.2188
SP Mean	76.0938	72.8125	64.5938	56.1562	67.4141

Table A.6: Split-Plot ANOVA — Plant Height — 120 DAS (cm)

Grand Mean = 182.4531 | GT = 11677.0000 | CF = 2130505.1406

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	117.7031	39.2344	2.3781	3.8625	6.9919	NS
Main-plot	3	79.1719	26.3906	1.5996	3.8625	6.9919	NS
Error (a)	9	148.4844	16.4983				
Sub-plot	3	36749.4531	12249.8177	1041.7680	2.8663	4.3771	**
Main-plot × Sub-plot	9	1236.7344	137.4149	11.6863	2.1526	2.9461	**
Error (b)	36	423.3125	11.7587				
Total	63	38754.8594					
CV (%)	2.23	1.88	—				
SEm±	1.0155	0.8573	1.7145				
LSD 0.05	3.2486	2.4588	4.9176				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	208	195.5000	180	152.1250	183.9062
M2	200	197.1250	188.2500	137.7500	180.7812

M3	206.6250	204.7500	184.6250	134.6250	182.6562
M4	202.6250	196.6250	183.2500	147.3750	182.4688
SP Mean	204.3125	198.5000	184.0312	142.9688	182.4531

Table A.7: Split-Plot ANOVA — Plant Height — Harvest (cm)

Grand Mean = 199.8125 | GT = 12788.0000 | CF = 2555202.2500

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	10.9062	3.6354	0.1474	3.8625	6.9919	NS
Main-plot	3	299.5938	99.8646	4.0486	3.8625	6.9919	*
Error (a)	9	222	24.6667				
Sub-plot	3	21748.7188	7249.5729	657.2368	2.8663	4.3771	**
Main-plot × Sub-plot	9	163.9375	18.2153	1.6514	2.1526	2.9461	NS
Error (b)	36	397.0938	11.0304				
Total	63	22842.2500					
CV (%)	2.49	1.66	—				
SEm±	1.2416	0.8303	1.6606				
LSD 0.05	3.9722	2.3814	4.7629				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	220.6250	211	206	173.3750	202.7500
M2	212.1250	208.5000	197.8750	168.1250	196.6562
M3	216.2500	214.5000	203	166.8750	200.1562
M4	218.1250	210.5000	201.7500	168.3750	199.6875
SP Mean	216.7812	211.1250	202.1562	169.1875	199.8125

Table A.8: Split-Plot ANOVA — Number of Leaves per Plant — 60 DAS*Grand Mean = 7.9989 | GT = 511.9300 | CF = 4094.8801*

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	0.1977	0.0659	0.3204	3.8625	6.9919	NS
Main-plot	3	17.1845	5.7282	27.8456	3.8625	6.9919	**
Error (a)	9	1.8514	0.2057				
Sub-plot	3	420.5182	140.1727	579.2989	2.8663	4.3771	**
Main-plot × Sub-plot	9	54.0839	6.0093	24.8350	2.1526	2.9461	**
Error (b)	36	8.7109	0.2420				
Total	63	502.5466					
CV (%)	5.67	6.15	—				
SEm±	0.1134	0.123	0.246				
LSD 0.05	0.3627	0.3527	0.7054				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	13	10.3500	6	4.3325	8.4206
M2	9.2750	8.3250	6.2500	5	7.2125
M3	13.0250	9	6.6675	5.3325	8.5062
M4	9.6750	10.6500	7	4.1000	7.8563
SP Mean	11.2438	9.5813	6.4794	4.6913	7.9989

Table A.9: Split-Plot ANOVA — Number of Leaves per Plant — 90 DAS*Grand Mean = 11.6292 | GT = 744.2700 | CF = 8655.2786*

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	0.3375	0.1125	0.5371	3.8625	6.9919	NS

Main-plot	3	18.0733	6.0244	28.7600	3.8625	6.9919	**
Error (a)	9	1.8853	0.2095				
Sub-plot	3	734.7957	244.9319	973.3595	2.8663	4.3771	**
Main-plot × Sub-plot	9	93.8196	10.4244	41.4266	2.1526	2.9461	**
Error (b)	36	9.0589	0.2516				
Total	63	857.9703					
CV (%)	3.94	4.31	—				
SEm±	0.1144	0.1254	0.2508				
LSD 0.05	0.3661	0.3597	0.7194				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	15.5000	15.7750	11.3250	6.7500	12.3375
M2	12.7000	12	12.0250	6.7500	10.8688
M3	17	15.3250	8.2500	6.6675	11.8106
M4	14.0250	15.3000	10.6750	6	11.5000
SP Mean	14.8063	14.6000	10.5687	6.5419	11.6292

Table A.10: Split-Plot ANOVA — Number of Leaves per Plant — 120 DAS

Grand Mean = 13.3703 | GT = 855.7000 | CF = 11440.9764

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	0.0117	0.0039	0.0115	3.8625	6.9919	NS
Main-plot	3	5.5255	1.8418	5.4458	3.8625	6.9919	*
Error (a)	9	3.0439	0.3382				
Sub-plot	3	1019.3967	339.7989	1443.0743	2.8663	4.3771	**
Main-plot × Sub-plot	9	101.1189	11.2354	47.7152	2.1526	2.9461	**

Error (b)	36	8.4769	0.2355				
Total	63	1137.5736					
CV (%)	4.35	3.63	—				
SEm±	0.1454	0.1213	0.2426				
LSD 0.05	0.4651	0.3479	0.6959				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	19.7750	17.6750	9.7250	7.7500	13.7312
M2	16	14.2250	13.9750	7.5000	12.9250
M3	17.4750	17.3000	12.7000	6.5000	13.4938
M4	16.5500	17	11.7750	8	13.3313
SP Mean	17.4500	16.5500	12.0437	7.4375	13.3703

Table A.11: Split-Plot ANOVA — Number of Leaves per Plant — Harvest

Grand Mean = 5.7609 | GT = 368.7000 | CF = 2124.0577

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	1.1742	0.3914	2.2471	3.8625	6.9919	NS
Main-plot	3	7.0080	2.3360	13.4110	3.8625	6.9919	**
Error (a)	9	1.5677	0.1742				
Sub-plot	3	80.8205	26.9402	262.4307	2.8663	4.3771	**
Main-plot × Sub-plot	9	20.7264	2.3029	22.4335	2.1526	2.9461	**
Error (b)	36	3.6956	0.1027				
Total	63	114.9923					
CV (%)	7.24	5.56	—				
SEm±	0.1043	0.0801	0.1602				

LSD 0.05	0.3338	0.2297	0.4595				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	8	6.5000	5	5	6.1250
M2	6.2250	6.5000	4.7500	4	5.3688
M3	7.5000	8	4.7000	4	6.0500
M4	6	6	6	4	5.5000
SP Mean	6.9313	6.7500	5.1125	4.2500	5.7609

Appendix B: Weed Parameters — ANOVA Tables

Table B.1: Split-Plot ANOVA — Weed Dry Weight — 60 DAS (transformed, $\sqrt{+1}$)

Grand Mean = 1.5106 | GT = 96.6784 | CF = 146.0424

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	0.0709	0.0236	0.6898	3.8625	6.9919	NS
Main-plot	3	0.0772	0.0257	0.7518	3.8625	6.9919	NS
Error (a)	9	0.3082	0.0342				
Sub-plot	3	27.6895	9.2298	268.6028	2.8663	4.3771	**
Main-plot × Sub-plot	9	0.3647	0.0405	1.1791	2.1526	2.9461	NS
Error (b)	36	1.2370	0.0344				
Total	63	29.7476					
CV (%)	12.25	12.27	—				
SEm±	0.0463	0.0463	0.0927				
LSD 0.05	0.148	0.1329	0.2658				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	1	1	1.5288	2.3746	1.4758
M2	1	1	1.2997	2.6042	1.4760
M3	1	1	1.4539	2.7371	1.5477
M4	1	1	1.4567	2.7146	1.5428
SP Mean	1	1	1.4348	2.6076	1.5106

Table B.2: Split-Plot ANOVA — Weed Dry Weight — 90 DAS (transformed, $\sqrt{+1}$)

Grand Mean = 2.1924 | GT = 140.3110 | CF = 307.6121

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	1.3833	0.4611	4.3656	3.8625	6.9919	*
Main-plot	3	1.1587	0.3862	3.6569	3.8625	6.9919	NS
Error (a)	9	0.9506	0.1056				
Sub-plot	3	82.2273	27.4091	214.3719	2.8663	4.3771	**
Main-plot \times Sub-plot	9	2.0263	0.2251	1.7609	2.1526	2.9461	NS
Error (b)	36	4.6029	0.1279				
Total	63	92.3490					
CV (%)	14.82	16.31	—				
SEm \pm	0.0812	0.0894	0.1788				
LSD 0.05	0.2599	0.2564	0.5128				

Interaction Means (M \times T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	1.2587	1	2.3442	3.6633	2.0666
M2	1.1250	1.2405	2.0240	3.8090	2.0496
M3	1.4601	1.2605	2.2348	4.3884	2.3359

M4	1.1604	1.6975	2.0667	4.3444	2.3173
SP Mean	1.2511	1.2996	2.1675	4.0513	2.1924

Table B.3: Split-Plot ANOVA — Weed Dry Weight — 120 DAS (transformed, $\sqrt{+1}$)

Grand Mean = 3.1194 | GT = 199.6392 | CF = 622.7470

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	5.2814	1.7605	4.5292	3.8625	6.9919	*
Main-plot	3	3.5697	1.1899	3.0613	3.8625	6.9919	NS
Error (a)	9	3.4982	0.3887				
Sub-plot	3	213.9287	71.3096	199.5454	2.8663	4.3771	**
Main-plot × Sub-plot	9	3.3585	0.3732	1.0442	2.1526	2.9461	NS
Error (b)	36	12.8650	0.3574				
Total	63	242.5015					
CV (%)	19.99	19.16	—				
SEm±	0.1559	0.1494	0.2989				
LSD 0.05	0.4986	0.4286	0.8573				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	1.4823	1.1429	3.1829	5.7409	2.8872
M2	1.5025	1.3352	3.0392	5.6681	2.8863
M3	1.8136	2.0486	3.2557	6.5211	3.4097
M4	1.2794	2.3265	3.1357	6.4352	3.2942
SP Mean	1.5194	1.7133	3.1534	6.0913	3.1194

Table B.4: Split-Plot ANOVA — Weed Dry Weight — Harvest (transformed, $\sqrt{+1}$)

Grand Mean = 1.8934 | GT = 121.1768 | CF = 229.4346

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	0.9579	0.3193	5.4070	3.8625	6.9919	*
Main-plot	3	0.4785	0.1595	2.7012	3.8625	6.9919	NS
Error (a)	9	0.5315	0.0591				
Sub-plot	3	40.4052	13.4684	167.8053	2.8663	4.3771	**
Main-plot × Sub-plot	9	2.6727	0.2970	3.7000	2.1526	2.9461	**
Error (b)	36	2.8894	0.0803				
Total	63	47.9352					
CV (%)	12.83	14.96	—				
SEm±	0.0608	0.0708	0.1417				
LSD 0.05	0.1944	0.2031	0.4063				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	1	1	2.7143	2.8734	1.8969
M2	1.1721	1.3622	1.7755	3.1496	1.8648
M3	1.0711	1.3746	2.3218	3.3358	2.0258
M4	1.1801	1.0711	2.0869	2.8057	1.7860
SP Mean	1.1058	1.2020	2.2246	3.0411	1.8934

Table B.5: Split-Plot ANOVA — Weed Population Density — 60 DAS (transformed, $\sqrt{+1}$)

Grand Mean = 1.8608 | GT = 119.0916 | CF = 221.6064

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	0.1729	0.0576	1.5064	3.8625	6.9919	NS
Main-plot	3	0.4471	0.1490	3.8946	3.8625	6.9919	*
Error (a)	9	0.3444	0.0383				

Sub-plot	3	76.4901	25.4967	678.2032	2.8663	4.3771	**
Main-plot × Sub-plot	9	0.7568	0.0841	2.2366	2.1526	2.9461	*
Error (b)	36	1.3534	0.0376				
Total	63	79.5647					
CV (%)	10.51	10.42	—				
SEm±	0.0489	0.0485	0.0969				
LSD 0.05	0.1565	0.139	0.2781				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	1	1	1.8059	3.4660	1.8180
M2	1	1	1.6149	3.4845	1.7749
M3	1	1	1.8897	4.0999	1.9974
M4	1	1	1.7637	3.6483	1.8530
SP Mean	1	1	1.7685	3.6747	1.8608

Table B.6: Split-Plot ANOVA — Weed Population Density — 90 DAS (transformed, $\sqrt{+1}$)

Grand Mean = 2.4126 | GT = 154.4034 | CF = 372.5064

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	0.0453	0.0151	0.1581	3.8625	6.9919	NS
Main-plot	3	1.6454	0.5485	5.7425	3.8625	6.9919	*
Error (a)	9	0.8596	0.0955				
Sub-plot	3	140.5436	46.8479	276.4258	2.8663	4.3771	**
Main-plot × Sub-plot	9	1.4566	0.1618	0.9550	2.1526	2.9461	NS
Error (b)	36	6.1012	0.1695				
Total	63	150.6517					

CV (%)	12.81	17.06	—				
SEm±	0.0773	0.1029	0.2058				
LSD 0.05	0.2472	0.2952	0.5904				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	1.1830	1	2.4802	4.8289	2.3730
M2	1.1453	1.1036	1.9796	4.7711	2.2499
M3	1.2488	1.6453	2.4843	5.3357	2.6785
M4	1.2071	1.3941	2.2634	4.5305	2.3488
SP Mean	1.1961	1.2857	2.3019	4.8666	2.4126

Table B.7: Split-Plot ANOVA — Weed Population Density — 120 DAS (transformed, $\sqrt{+1}$)

Grand Mean = 2.8048 | GT = 179.5064 | CF = 503.4773

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	0.2261	0.0754	0.9885	3.8625	6.9919	NS
Main-plot	3	1.1203	0.3734	4.8990	3.8625	6.9919	*
Error (a)	9	0.6860	0.0762				
Sub-plot	3	203.4488	67.8163	294.2583	2.8663	4.3771	**
Main-plot × Sub-plot	9	1.7460	0.1940	0.8418	2.1526	2.9461	NS
Error (b)	36	8.2967	0.2305				
Total	63	215.5240					
CV (%)	9.84	17.12	—				
SEm±	0.069	0.12	0.24				
LSD 0.05	0.2208	0.3442	0.6885				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	1.2500	1.1036	3.0646	5.1934	2.6529
M2	1.2866	1.1036	2.9922	5.6854	2.7669
M3	1.3213	1.4571	3.1253	6.1641	3.0169
M4	1.2488	1.5460	2.7821	5.5526	2.7824
SP Mean	1.2767	1.3025	2.9910	5.6489	2.8048

Table B.8: Split-Plot ANOVA — Weed Population Density — Harvest (transformed, $\sqrt{+1}$)

Grand Mean = 2.3437 | GT = 149.9967 | CF = 351.5470

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	3.2013	1.0671	6.7183	3.8625	6.9919	*
Main-plot	3	0.7754	0.2585	1.6273	3.8625	6.9919	NS
Error (a)	9	1.4295	0.1588				
Sub-plot	3	99.5854	33.1951	129.0645	2.8663	4.3771	**
Main-plot × Sub-plot	9	4.3022	0.4780	1.8586	2.1526	2.9461	NS
Error (b)	36	9.2591	0.2572				
Total	63	118.5529					
CV (%)	17.00	21.64	—				
SEm±	0.0996	0.1268	0.2536				
LSD 0.05	0.3187	0.3636	0.7273				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	1	1	2.9961	3.6362	2.1581
M2	1.3874	1.5460	2.1870	4.4867	2.4018

M3	1.1036	1.4126	2.8608	4.3943	2.4428
M4	1.3675	1.1036	2.4582	4.5593	2.3721
SP Mean	1.2146	1.2655	2.6255	4.2691	2.3437

Appendix C: Yield and Yield Component Parameters — ANOVA Tables

Table C.1: Split-Plot ANOVA — Seed Yield — Harvest (g/plot)

Grand Mean = 587.1875 | GT = 37580.0000 | CF = 22066506.2500

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	2387.6250	795.8750	3.4315	3.8625	6.9919	NS
Main-plot	3	223868.7500	74622.9167	321.7468	3.8625	6.9919	**
Error (a)	9	2087.3750	231.9306				
Sub-plot	3	3906768.7500	1302256.2500	1672.0006	2.8663	4.3771	**
Main-plot × Sub-plot	9	16956.2500	1884.0278	2.4190	2.1526	2.9461	*
Error (b)	36	28039	778.8611				
Total	63	4180107.7500					
CV (%)	2.59	4.75	—				
SEm±	3.8073	6.977	13.954				
LSD 0.05	12.1803	20.0112	40.0224				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	930	855	640	265	672.5000
M2	790	650	440	165	511.2500
M3	875	760	560	220	603.7500
M4	840	720	495	190	561.2500

SP Mean	858.7500	746.2500	533.7500	210	587.1875
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Table C.2: Split-Plot ANOVA — Biological Yield — Harvest (g/plot)

Grand Mean = 2975.3125 | GT = 190420.0000 | CF = 566559006.2500

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	609003.1250	203001.0417	4.6815	3.8625	6.9919	*
Main-plot	3	6218868.7500	2072956.2500	47.8057	3.8625	6.9919	**
Error (a)	9	390259.3750	43362.1528				
Sub-plot	3	73047818.7500	24349272.9167	723.3726	2.8663	4.3771	**
Main-plot × Sub-plot	9	483406.2500	53711.8056	1.5957	2.1526	2.9461	NS
Error (b)	36	1211787.5000	33660.7639				
Total	63	81961143.7500					
CV (%)	7.00	6.17	—				
SEm±	52.059	45.8672	91.7344				
LSD 0.05	166.5456	131.5543	263.1086				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	4430	4100	3520	1615	3416.2500
M2	3700	3180	2380	1045	2576.2500
M3	4300	3750	2950	1340	3085
M4	4000	3470	2680	1145	2823.7500
SP Mean	4107.5000	3625	2882.5000	1286.2500	2975.3125

Table C.3: Split-Plot ANOVA — Primary Branches per Plant (no.)

Grand Mean = 5.7188 | GT = 366.0000 | CF = 2093.0625

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	7.1875	2.3958	3.8764	3.8625	6.9919	*
Main-plot	3	5.1875	1.7292	2.7978	3.8625	6.9919	NS
Error (a)	9	5.5625	0.6181				
Sub-plot	3	101.6875	33.8958	43.1947	2.8663	4.3771	**
Main-plot x Sub-plot	9	31.0625	3.4514	4.3982	2.1526	2.9461	**
Error (b)	36	28.2500	0.7847				
Total	63	178.9375					
CV (%)	13.75	15.49	-				
SEm+/-	0.1965	0.2215	0.4429				
LSD 0.05	0.6288	0.6352	1.2704				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	7.5000	8.5000	5	3.7500	6.1875
M2	5.7500	6	6	4	5.4375
M3	8	6.2500	4	4.5000	5.6875
M4	7	6.5000	4.7500	4	5.5625
SP Mean	7.0625	6.8125	4.9375	4.0625	5.7188

Table C.4: Split-Plot ANOVA — Secondary Branches per Plant (no.)

Grand Mean = 26.0938 | GT = 1670.0000 | CF = 43576.5625

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	236.1875	78.7292	2.6820	3.8625	6.9919	NS
Main-plot	3	1383.0625	461.0208	15.7055	3.8625	6.9919	**
Error (a)	9	264.1875	29.3542				

Sub-plot	3	8348.8125	2782.9375	216.5593	2.8663	4.3771	**
Main-plot x Sub-plot	9	84.5625	9.3958	0.7312	2.1526	2.9461	NS
Error (b)	36	462.6250	12.8507				
Total	63	10779.4375					
CV (%)	20.76	13.74	-				
SEm+/-	1.3545	0.8962	1.7924				
LSD 0.05	4.3332	2.5704	5.1409				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	44.7500	45.2500	24.2500	16.2500	32.6250
M2	32.7500	27.7500	12.7500	7.2500	20.1250
M3	40	38.2500	19.7500	13.2500	27.8125
M4	36	33	17	9.2500	23.8125
SP Mean	38.3750	36.0625	18.4375	11.5000	26.0938

Table C.5: Split-Plot ANOVA — Secondary Umbels per Plant (no.)

Grand Mean = 13.4219 | GT = 859.0000 | CF = 11529.3906

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	52.0469	17.3490	4.8020	3.8625	6.9919	*
Main-plot	3	440.7969	146.9323	40.6694	3.8625	6.9919	**
Error (a)	9	32.5156	3.6128				
Sub-plot	3	1502.4219	500.8073	176.4312	2.8663	4.3771	**
Main-plot x Sub-plot	9	49.6406	5.5156	1.9431	2.1526	2.9461	NS
Error (b)	36	102.1875	2.8385				
Total	63	2179.6094					

CV (%)	14.16	12.55	-				
SEm+/-	0.4752	0.4212	0.8424				
LSD 0.05	1.5202	1.2081	2.4161				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	22.2500	23.7500	11.7500	11.2500	17.2500
M2	14.7500	14	6.5000	5.5000	10.1875
M3	20	18.2500	10.5000	8	14.1875
M4	17.5000	15.2500	9.2500	6.2500	12.0625
SP Mean	18.6250	17.8125	9.5000	7.7500	13.4219

Table C.6: Split-Plot ANOVA — Tertiary Umbels per Plant (no.)

Grand Mean = 13.2188 | GT = 846.0000 | CF = 11183.0625

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	303.1875	101.0625	8.8792	3.8625	6.9919	**
Main-plot	3	669.8125	223.2708	19.6162	3.8625	6.9919	**
Error (a)	9	102.4375	11.3819				
Sub-plot	3	3535.0625	1178.3542	182.1610	2.8663	4.3771	**
Main-plot x Sub-plot	9	151.5625	16.8403	2.6033	2.1526	2.9461	*
Error (b)	36	232.8750	6.4688				
Total	63	4994.9375					
CV (%)	25.52	19.24	-				
SEm+/-	0.8434	0.6358	1.2717				
LSD 0.05	2.6983	1.8237	3.6474				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	27.7500	25.5000	11.2500	6.5000	17.7500
M2	16.7500	12.5000	4.2500	2.2500	8.9375
M3	20.2500	23.5000	8.7500	4.7500	14.3125
M4	19.7500	18.2500	6.5000	3	11.8750
SP Mean	21.1250	19.9375	7.6875	4.1250	13.2188

Table C.7: Split-Plot ANOVA — Umbellets per Umbel (no.)

Grand Mean = 81.0938 / GT = 5190.0000 / CF = 420876.5625

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	42.3125	14.1042	0.7918	3.8625	6.9919	NS
Main-plot	3	3234.3125	1078.1042	60.5251	3.8625	6.9919	**
Error (a)	9	160.3125	17.8125				
Sub-plot	3	16662.5625	5554.1875	101.7367	2.8663	4.3771	**
Main-plot x Sub-plot	9	368.5625	40.9514	0.7501	2.1526	2.9461	NS
Error (b)	36	1965.3750	54.5938				
Total	63	22433.4375					
CV (%)	5.20	9.11	-				
SEm+/-	1.0551	1.8472	3.6944				
LSD 0.05	3.3755	5.298	10.5961				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	106.5000	101.5000	86.7500	73.2500	92
M2	85.2500	89.2500	67.5000	48.5000	72.6250

M3	100.5000	95.5000	75.5000	56.2500	81.9375
M4	95.7500	93.5000	70.2500	51.7500	77.8125
SP Mean	97	94.9375	75	57.4375	81.0938

Table C.8: Split-Plot ANOVA — Primary Umbellets per Plant (no.)

Grand Mean = 37.3125 | GT = 2388.0000 | CF = 89102.2500

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	5.6250	1.8750	0.3750	3.8625	6.9919	NS
Main-plot	3	487.6250	162.5417	32.5083	3.8625	6.9919	**
Error (a)	9	45	5				
Sub-plot	3	2162.6250	720.8750	83.8836	2.8663	4.3771	**
Main-plot x Sub-plot	9	33.5000	3.7222	0.4331	2.1526	2.9461	NS
Error (b)	36	309.3750	8.5938				
Total	63	3043.7500					
CV (%)	5.99	7.86	-				
SEm+/-	0.559	0.7329	1.4658				
LSD 0.05	1.7884	2.102	4.204				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	47.2500	45	39.5000	34.2500	41.5000
M2	38.5000	40.5000	31.7500	25	33.9375
M3	43.7500	43	35.2500	28.7500	37.6875
M4	42	41.5000	33.7500	27.2500	36.1250
SP Mean	42.8750	42.5000	35.0625	28.8125	37.3125

Table C.9: Split-Plot ANOVA — Secondary Umbellets per Plant (no.)

Grand Mean = 27.7969 | GT = 1779.0000 | CF = 49450.6406

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	27.4219	9.1406	2.4364	3.8625	6.9919	NS
Main-plot	3	443.9219	147.9740	39.4415	3.8625	6.9919	**
Error (a)	9	33.7656	3.7517				
Sub-plot	3	2800.2969	933.4323	133.0505	2.8663	4.3771	**
Main-plot x Sub-plot	9	70.3906	7.8212	1.1148	2.1526	2.9461	NS
Error (b)	36	252.5625	7.0156				
Total	63	3628.3594					
CV (%)	6.97	9.53	-				
SEm+/-	0.4842	0.6622	1.3244				
LSD 0.05	1.5492	1.8992	3.7984				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	36.5000	36.5000	29.2500	24.7500	31.7500
M2	30.5000	31	22.2500	14.2500	24.5000
M3	35.2500	34	25.2500	18.2500	28.1875
M4	34.5000	33.2500	23.7500	15.5000	26.7500
SP Mean	34.1875	33.6875	25.1250	18.1875	27.7969

Table C.10: Split-Plot ANOVA — Tertiary Umbellets per Plant (no.)

Grand Mean = 15.7969 | GT = 1011.0000 | CF = 15970.6406

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	0.2969	0.0990	0.0253	3.8625	6.9919	NS

Main-plot	3	377.5469	125.8490	32.1174	3.8625	6.9919	**
Error (a)	9	35.2656	3.9184				
Sub-plot	3	817.2969	272.4323	51.0312	2.8663	4.3771	**
Main-plot x Sub-plot	9	25.7656	2.8628	0.5363	2.1526	2.9461	NS
Error (b)	36	192.1875	5.3385				
Total	63	1448.3594					
CV (%)	12.53	14.63	-				
SEm+/-	0.4949	0.5776	1.1553				
LSD 0.05	1.5832	1.6567	3.3135				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	23.2500	21.2500	17.7500	15.5000	19.4375
M2	15.7500	17	11.7500	6.7500	12.8125
M3	20	19.2500	15.2500	10.5000	16.2500
M4	18.2500	18	13	9.5000	14.6875
SP Mean	19.3125	18.8750	14.4375	10.5625	15.7969

Table C.11: Split-Plot ANOVA — Primary Umbel Diameter (cm)

Grand Mean = 15.6923 | GT = 1004.3100 | CF = 15759.9778

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	8.6626	2.8875	3.6224	3.8625	6.9919	NS
Main-plot	3	94	31.3333	39.3073	3.8625	6.9919	**
Error (a)	9	7.1742	0.7971				
Sub-plot	3	383.4377	127.8126	202.3173	2.8663	4.3771	**
Main-plot x Sub-plot	9	14.6145	1.6238	2.5704	2.1526	2.9461	*

Error (b)	36	22.7428	0.6317				
Total	63	530.6317					
CV (%)	5.69	5.07	-				
SEm+/-	0.2232	0.1987	0.3974				
LSD 0.05	0.7141	0.5699	1.1398				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	19.6225	18.5925	16.7725	13.8525	17.2100
M2	16.4100	16.8900	11.8925	10.3475	13.8850
M3	19.1325	17.5175	15.6225	12.5275	16.2000
M4	18.2750	17.0775	14.7150	11.8300	15.4744
SP Mean	18.3600	17.5194	14.7506	12.1394	15.6923

Table C.12: Split-Plot ANOVA — Secondary Umbel Diameter (cm)

Grand Mean = 11.5586 | GT = 739.7500 | CF = 8550.4697

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	17.9404	5.9801	5.8078	3.8625	6.9919	*
Main-plot	3	57.2657	19.0886	18.5384	3.8625	6.9919	**
Error (a)	9	9.2671	1.0297				
Sub-plot	3	418.2988	139.4329	122.6338	2.8663	4.3771	**
Main-plot x Sub-plot	9	2.4104	0.2678	0.2356	2.1526	2.9461	NS
Error (b)	36	40.9315	1.1370				
Total	63	546.1140					
CV (%)	8.78	9.23	-				
SEm+/-	0.2537	0.2666	0.5331				

LSD 0.05	0.8116	0.7646	1.5292				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	15.0100	14.7225	12.3050	9.0725	12.7775
M2	12.6100	12.6350	9.4775	6.0900	10.2031
M3	14.3000	13.8275	11.5900	8.1950	11.9781
M4	13.9475	13.3375	10.8375	6.9800	11.2756
SP Mean	13.9669	13.6306	11.0525	7.5844	11.5586

Table C.13: Split-Plot ANOVA — Tertiary Umbel Diameter (cm)

Grand Mean = 6.7822 / GT = 434.0600 / CF = 2943.8763

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	3	1.8567	0.6189	0.5499	3.8625	6.9919	NS
Main-plot	3	52.6084	17.5361	15.5820	3.8625	6.9919	**
Error (a)	9	10.1287	1.1254				
Sub-plot	3	245.7216	81.9072	86.0956	2.8663	4.3771	**
Main-plot x Sub-plot	9	5.5400	0.6156	0.6470	2.1526	2.9461	NS
Error (b)	36	34.2487	0.9514				
Total	63	350.1041					
CV (%)	15.64	14.38	-				
SEm+/-	0.2652	0.2438	0.4877				
LSD 0.05	0.8485	0.6994	1.3988				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean

M1	9.4600	9.4450	7.6575	5.5950	8.0394
M2	7.7600	7.4750	5.2800	1.7850	5.5750
M3	8.7875	8.7125	6.8725	4.0675	7.1100
M4	8.2875	7.9700	5.9500	3.4100	6.4044
SP Mean	8.5738	8.4006	6.4400	3.7144	6.7822

Appendix D: Seed Quality Parameters — ANOVA Tables

Table D.1: Split-Plot ANOVA — Potassium Content in Seeds (g/kg DM)

Grand Mean = 26.7375 | GT = 855.6000 | CF = 22876.6050

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	1	0.2450	0.2450	0.9639	10.1280	34.1162	NS
Main-plot	3	166.3075	55.4358	218.1082	9.2766	29.4567	**
Error (a)	3	0.7625	0.2542				
Sub-plot	3	332.8075	110.9358	1062.8583	3.4903	5.9525	**
Main-plot x Sub-plot	9	4.4800	0.4978	4.7691	2.7964	4.3875	**
Error (b)	12	1.2525	0.1044				
Total	31	505.8550					
CV (%)	1.89	1.21	-				
SEm+/-	0.1782	0.1142	0.2284				
LSD 0.05	0.8022	0.352	0.7039				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	34	25	31.2500	28	29.5625
M2	27.3000	20.0500	24.1500	22.2500	23.4375
M3	32.6500	23.3500	29.5000	26.2000	27.9250

M4	30.7500	21.7500	27.4000	24.2000	26.0250
SP Mean	31.1750	22.5375	28.0750	25.1625	26.7375

Table D.2: Split-Plot ANOVA — Phosphorus Content in Seeds (% DM)

Grand Mean = 0.1051 | GT = 3.3630 | CF = 0.3534

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	1	0	0	0.4244	10.1280	34.1162	NS
Main-plot	3	0.0034	0.0011	52.8257	9.2766	29.4567	**
Error (a)	3	0.0001	0				
Sub-plot	3	0.0151	0.0050	252.4353	3.4903	5.9525	**
Main-plot x Sub-plot	9	0	0	0.2418	2.7964	4.3875	NS
Error (b)	12	0.0002	0				
Total	31	0.0188					
CV (%)	4.39	4.24	-				
SEm+/-	0.0016	0.0016	0.0032				
LSD 0.05	0.0073	0.0049	0.0097				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	0.1470	0.0915	0.1205	0.1040	0.1157
M2	0.1200	0.0650	0.0935	0.0750	0.0884
M3	0.1430	0.0835	0.1185	0.0965	0.1104
M4	0.1390	0.0790	0.1125	0.0930	0.1059
SP Mean	0.1372	0.0798	0.1113	0.0921	0.1051

Table D.3: Split-Plot ANOVA — Nitrogen Content in Seeds (% DM)

Grand Mean = 3.3459 | GT = 107.0700 | CF = 358.2495

Source of Variation	DF	SS	MSS	F Calculated	F Tab (5%)	F Tab (1%)	Significance
Replication	1	0.0069	0.0069	2.4409	10.1280	34.1162	NS
Main-plot	3	4.7998	1.5999	565.7234	9.2766	29.4567	**
Error (a)	3	0.0085	0.0028				
Sub-plot	3	3.2780	1.0927	3150.0150	3.4903	5.9525	**
Main-plot x Sub-plot	9	0.0526	0.0058	16.8579	2.7964	4.3875	**
Error (b)	12	0.0042	0.0003				
Total	31	8.1500					
CV (%)	1.59	0.56	-				
SEm+/-	0.0188	0.0066	0.0132				
LSD 0.05	0.0846	0.0203	0.0406				

Interaction Means (M × T)

Main Plot \ Sub-plot	T1	T2	T3	T4	MP Mean
M1	4.4000	3.4500	4.0350	3.7000	3.8962
M2	3.2500	2.5350	2.8650	2.6650	2.8287
M3	3.9000	3.0350	3.6000	3.2650	3.4500
M4	3.6700	2.8150	3.3500	3	3.2088
SP Mean	3.8050	2.9587	3.4625	3.1575	3.3459