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Thermal time (growing degree days) effects on phenology, yield and quality attributes of fennel (*Foeniculum vulgare* L.)

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Abstract

Temperature-driven crop development is a major determinant of phenology, yield and quality in seed spices such as fennel (*Foeniculum vulgare* L.). The present study evaluated the influence of accumulated Growing Degree Days (GDD) on phenological development, seed yield and quality attributes of fennel under semi-arid field conditions. Field experiments were conducted at the ICAR-National Research Centre on Seed Spices, Ajmer, India, over three consecutive seasons (2019, 2020 and 2021). Umbels were harvested at different maturity stages ranging from 25 to 95 days after anthesis (DAA), corresponding to cumulative thermal accumulation of 1317.25 to 2894.25 GDD.

Phenological progression showed a stronger association with cumulative GDD than with calendar days. Panicle emergence, king umbel emergence and anthesis occurred at approximately 853.75, 956.25 and 1034.25 GDD, respectively. Stage-wise thermal requirements (Δ GDD) indicated that early vegetative growth was the most thermally demanding phase (853.8 GDD), whereas reproductive transitions occurred over comparatively shorter thermal intervals, followed by progressively higher Δ GDD during later harvest stages.

The harvest stage and associated GDD significantly influenced seed moisture, biochemical composition, essential oil content, and yield. Seed moisture declined from 75.15% at 25 DAA to 14.18% at 95 DAA. Total oil and essential oil contents were highest at early harvest stages (4.41% and 2.61%, respectively) and decreased steadily with increasing GDD, while crude fibre content increased from 12.31% to 38.36%. Seed yield increased with cumulative GDD and peaked at 24.15 q/ha at 75 DAA (2349.25 GDD), followed by a slight decline at later stages. Correlation analysis revealed strong negative relationships between cumulative GDD and oil, essential oil and protein content, and positive associations with crude fibre, seed index and yield.

Overall, the study demonstrates that GDD is a robust agrometeorological index for predicting fennel phenology and optimizing harvest timing, enabling a balance between yield maximization and quality preservation under variable climatic conditions.

Keywords: Fennel, Growing degree days, Yield, Essential oil, seed quality, maturity

Introduction

Fennel (*Foeniculum vulgare* L.), belonging to the family Apiaceae, is an important aromatic and seed spice crop cultivated worldwide for its culinary, medicinal and industrial value. The seeds are rich in essential oils and phenolic compounds that contribute to their characteristic aroma, flavour and health-promoting properties (Noreen *et al.*, 2023; Lal *et al.*, 2025). Fennel seeds are widely used as flavouring agents in food products and are traditionally consumed as a mouth freshener and digestive aid due to their carminative, antimicrobial and antioxidant activities (Swathi *et al.*, 2016; Manohar *et al.*, 2020). Because of its increasing demand of chewing and culinary types in domestic and international markets, maintaining high seed yield along with superior quality attributes has become a major focus of fennel research. Temperature is one of the most critical environmental factors influencing plant growth and development, as it regulates physiological and biochemical processes such as enzyme activity, photosynthesis, assimilate translocation and secondary metabolite synthesis. In aromatic crops like fennel, temperature not only determines crop phenology and productivity but also significantly affects essential oil accumulation and composition, which are key determinants of seed quality (Saharkhiz and Tarakemeh, 2013; Shojaiefar *et al.*, 2015). Therefore, understanding crop responses to thermal regimes is essential for optimizing agronomic practices such as harvest scheduling.

Growing Degree Days (GDD), also known as thermal time or heat units, provide a quantitative measure of accumulated temperature above a crop-specific base temperature and are widely used to predict crop phenology more accurately than calendar days (McMaster and Wilhelm, 1997; Akyuz *et al.*, 2017; Climate Central, 2022). Phenological stages such as

emergence, flowering, umbel initiation and physiological maturity occur after the accumulation of specific GDD thresholds, as temperature largely governs the rate of developmental processes (Zude-Sasse and Makouate, 2025). The use of GDD allows better synchronization of crop developmental stages with favourable environmental conditions, thereby improving crop management decisions related to sowing, irrigation and harvest timing. Numerous studies across different crops have demonstrated that optimal accumulation of GDD enhances yield attributes by ensuring adequate duration of vegetative and reproductive phases, whereas thermal deficits or excessive heat accumulation may shorten growth duration, impair reproductive development and reduce yield potential (Jeffery *et al.*, 2025; Akyuz *et al.*, 2017; Bondade and Deshpande, 2021; Pathak and Stoddard, 2018). In fennel, non-synchronous flowering and differential seed maturation among umbels further complicate harvest decisions, making the crop particularly sensitive to temperature variations during the flowering and seed-filling stages (Brahmi *et al.*, 2021; El-Gamal *et al.*, 2017). Excessive heat accumulation may accelerate phenological development, reduce seed-filling duration and adversely affect seed weight and essential oil biosynthesis, while insufficient heat may delay maturity and reduce yield.

Quality attributes such as seed size, sweetness, essential oil content and composition are strongly influenced by the duration and conditions of seed development, which are governed by thermal time accumulation (Msaada *et al.*, 2009; Canavar and Kaynak, 2010).

Appropriate GDD during seed filling promotes assimilate partitioning and synthesis of secondary metabolites, whereas imbalanced thermal regimes can lead to inferior sensory quality and reduced market value. Despite the recognized importance of temperature in fennel production, limited information is available on the direct relationship between accumulated GDD and phenological development, seed yield and quality attributes of fennel under field conditions. In this context, the present study was undertaken to evaluate the influence of Growing Degree Days (GDD) on phenology, seed yield and

quality attributes of fennel, with the aim of improving prediction of crop stages and optimizing harvest timing for enhanced productivity and quality.

Material and Methods

The field experiment was conducted at the Indian Council of Agricultural Research - National Research Centre on Seed Spices (ICAR-NRCSS), Ajmer, Rajasthan, India, located in the north-western region of the country (26.3661° N, 74.5933° E). The fennel variety AF-1, released by ICAR-NRCSS, Ajmer, was used as the experimental material. Fennel seeds were sown on 16 October during three consecutive cropping seasons (2019-20, 2020-21 and 2021-22). Each experimental plot measured 10 × 6 m², and the crop was planted at a spacing of 50 cm between rows and 30 cm between plants.

Fertilizer was applied as per recommended practices, with 25 kg N/ha and 25 kg P₂O₅/ha applied as basal dose at sowing, while the remaining 25 kg N/ha was top-dressed in two equal splits at one-month intervals. To estimate yield and quality, twenty-five umbels each from main, primary and secondary orders were tagged at anthesis. Umbels were harvested at eight maturity stages at 10-day intervals, namely 25, 35, 45, 55, 65, 75, 85 and 95 days after anthesis (DAA).

Anthesis occurred over an average duration of 101 days. Harvested umbels were shade-dried, and seeds were manually separated. Seeds from all umbel orders were pooled to estimate seed yield (kg/ha) and quality parameters. Standard agronomic practices were followed throughout the crop growth period to ensure healthy crop establishment. Dried seeds were packed in paper bags and stored at room temperature until further quality analysis.

Growing Degree Days (GDD)

GDD was used to quantify the accumulation of thermal time required for the phenological development of fennel during the crop-growing season. GDD was calculated using daily maximum and minimum air temperatures following the standard method described by McMaster and Wilhelm (1997):

$$GDD = \sum \left(\frac{T_{max} + T_{min}}{2} - T_{base} \right)$$

Where:

T_{max} = daily maximum air temperature (°C),

T_{min} = daily minimum air temperature (°C), and

T_{base} = base temperature (°C) below which crop growth is assumed to cease.

For fennel, a base temperature (T_{base} 5 °C) was adopted, as commonly used for cool-season crops and aromatic plants. Daily GDD values were calculated from the date of sowing until final harvest and subsequently summed to obtain cumulative GDD for each phenological stage and harvest event.

When the calculated daily mean temperature was below the base temperature, the corresponding GDD value was set to zero to avoid negative heat accumulation. No upper temperature threshold was imposed, as the prevailing temperature range during the growing season did not exceed critical limits for fennel development.

Daily weather data were obtained from the agrometeorological observatory located at the experimental site of ICAR-NRCSS, Ajmer. Cumulative GDD values were used to characterize stage-wise phenological development and to determine incremental GDD (ΔGDD) requirements between successive growth and harvest stages.

Seed quality

The moisture content of freshly harvested fennel seeds was determined using the oven-drying method. Total Soluble Solids (TSS) were calculated using a portable refractometer (Atago PAL-1) (AOAC, 1994). A standard micro-Kjeldahl method was used to determine the total nitrogen concentration and crude protein content ($N \times 6.25$). Crude fiber content was estimated as per AOAC (1994).

Oil content was extracted using an Accelerated Solvent Extraction System (Dionex India Pvt. Ltd.). Oil was obtained after evaporating the solvent in a rotary evaporator. Thirty-gram seed powder was utilized for oil estimation. Essential oil content was determined by hydro-distillation using a Clevenger-type apparatus (Clevenger, 1928). Accurately weighed ground seed samples (50 g) were placed in a round-bottom flask with distilled water (ratio 1:10 w/v) and distilled for 3 h until no further increase in oil volume was observed. The collected oil was separated, dried over anhydrous

sodium sulfate to remove residual moisture, and the volume was recorded. All analyses were carried out in triplicate and stored at -20°C until gas chromatography-head space (GC-HS) analysis. The oil content was expressed as percentage (%) with respect to the initial material.

Gas chromatography-headspace (GC-HS) was used to identify and determinate the essential oil components of fennel seeds. Twenty-mL headspace vials sealed with silicone septa coated in aluminum were filled with a one-gram sample of dried coriander seeds. To volatilize the essential oils, these vials were heated to 100°C for ten minutes in an HS autosampler. Following that, the volatiles were moved to a gas chromatograph (GC) fitted with an HP5 column. With an oven temperature program that began at 60°C for one minute, increased to 100°C at $4^{\circ}\text{C}/\text{min}$, and finally reached 260°C at $50^{\circ}\text{C}/\text{min}$, the GC inlet temperature was adjusted to 250°C . With the loop and transfer line temperatures kept at 105°C and 110°C , respectively, a split injection ratio of 1:50 was employed. The components of essential oils were identified by comparing their retention times to established benchmarks, and their quantification was based on the peak areas observed by a flame ionisation detector (FID).

Statistical analysis

The experiment was laid out on a Randomized Complete Block Design with three replications. The obtained data were subjected to analysis of variances, and the significant differences among treatment means were compared using the LSD test according to Gomez and Gomez (1984).

Results and Discussion

Phenological development and cumulative growing degree days (GDD)

The phenological development and harvesting sequence of fennel umbels exhibited a strong and progressive association with cumulative growing degree days (GDD) accumulated from sowing (Fig. 1). Panicle emergence occurred at 853.75 GDD, marking the thermal threshold for transition from vegetative to reproductive growth. This was followed by king umbel emergence at 956.25 GDD, indicating a relatively short thermal interval between these early reproductive

stages. Flowering (anthesis) commenced at 1034.25 GDD, suggesting that approximately 180 GDD beyond panicle emergence were required for floral differentiation and development, underscoring the sensitivity of fennel reproductive initiation to thermal accumulation.

The first harvest was initiated at 1317.25 GDD, corresponding to the attainment of physiological maturity in the earliest formed umbels. Subsequent harvests occurred at cumulative thermal sums of 1456.75, 1633.25, 1830.75, 2131.75, 2349.25, 2619.00 and 2894.25 GDD for the second through eighth harvests, respectively. Thus, the harvesting period extended across a wide thermal window of approximately 1577 GDD from the first to the final harvest. The progressively increasing GDD requirements for successive harvests reflect staggered flowering and asynchronous seed maturation among primary, secondary and tertiary umbels, a characteristic feature of fennel and other indeterminate or semi-indeterminate seed spice crops.

All phenological events and harvest stages followed a consistent sequence when expressed in terms of cumulative thermal time rather than calendar days, highlighting the superiority of GDD as a predictor of crop development. Growing degree days integrate temperature effects on physiological processes such as cell division, organ differentiation and biomass accumulation, thereby providing a more reliable measure of developmental progress than elapsed time alone (Parent & Tardieu, 2014; Baskaran *et al.*, 2020). The dual-axis representation further illustrates that advanced maturity stages were achieved only at higher GDD levels, which likely promoted prolonged seed filling and metabolic activity necessary for seed weight accumulation and essential oil biosynthesis (Msaada *et al.*, 2009; (Brahmi *et al.*, 2021 and El-Gamal *et al.*, 2017). However, excessive thermal accumulation during later stages may predispose seeds to over-maturity, shattering and quality deterioration. Overall, the results demonstrate that GDD-based phenological assessment offers a robust framework for optimizing harvest timing, improving yield stability and maintaining quality attributes of fennel under variable thermal environments.

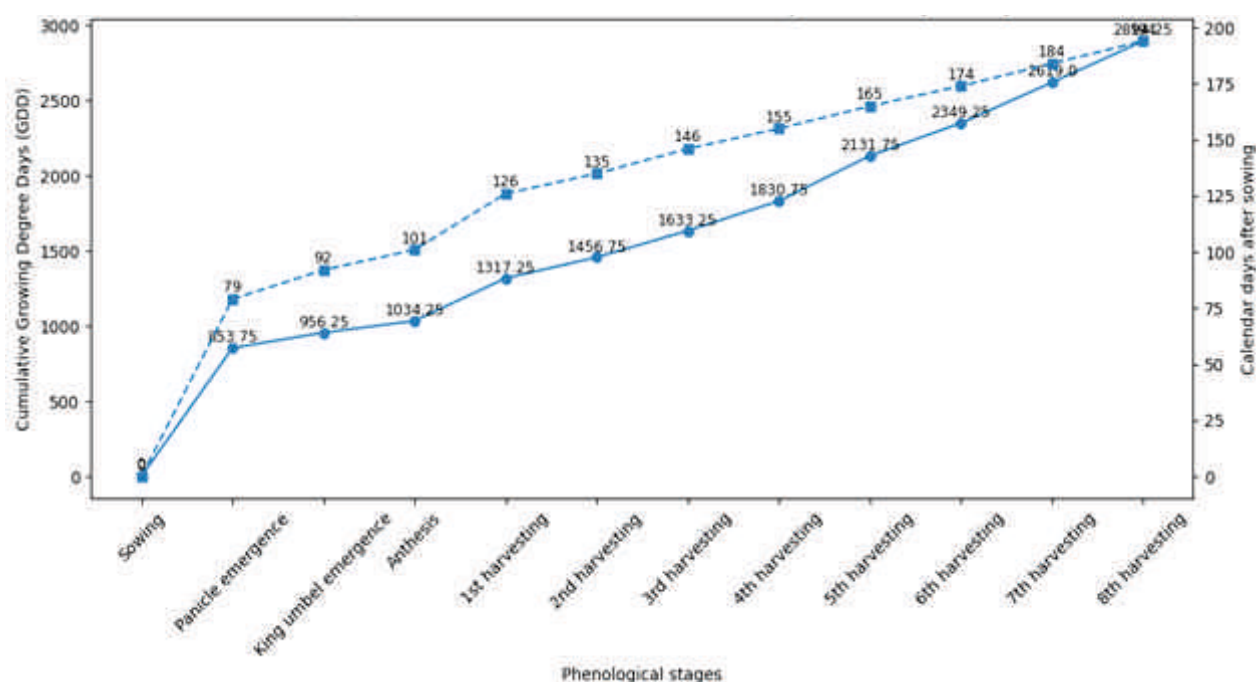


Fig.1: Dual-axis relationship between cumulative Growing Degree Days (GDD) and calendar days after sowing at different phenological stages and harvest intervals of fennel (*Foeniculum vulgare* L.) during the 2019, 2020 and 2021 season

Stage-wise thermal requirements (Δ GDD)

Stage-to-stage thermal requirements, expressed as incremental growing degree days (Δ GDD), varied substantially across phenological and harvesting stages of fennel (Fig. 2). From sowing to panicle emergence, the crop accumulated the highest single thermal input (853.8 GDD), indicating that early vegetative growth constituted the longest and most thermally demanding phase of development. This phase encompasses leaf initiation, canopy expansion and biomass accumulation prior to reproductive transition, processes that require sustained exposure to favourable temperatures (Hatfield and Prueger, 2015).

Following panicle emergence, progression to king umbel emergence required only 102.5 GDD, while a further 78.0 GDD were sufficient to reach anthesis. These comparatively low Δ GDD values indicate rapid advancement through early reproductive stages once floral initiation had occurred. Similar short thermal intervals between successive reproductive stages have been reported in different crops, reflecting the strong regulatory influence of temperature on floral

differentiation and reproductive development (Jagadish *et al.*, 2021).

The interval between anthesis and the first harvest required 283.0 GDD, representing the cumulative thermal demand for pollination, fertilization and early seed filling. This developmental window is particularly sensitive to temperature, as increased thermal accumulation accelerates physiological maturity and shortens the duration of seed development (Asseng *et al.*, 2020). The magnitude of Δ GDD recorded in the present study suggests that prevailing thermal conditions were conducive to relatively uniform seed development prior to the initiation of harvesting.

Subsequent harvest intervals exhibited marked variability in Δ GDD requirements. The transition from the first to second harvest occurred after 139.5 GDD, while 176.5 GDD and 197.5 GDD were required between the second-third and third-fourth harvests, respectively. A notably higher Δ GDD (301.0 GDD) was observed between the fourth and fifth harvests, followed by Δ GDD values of 217.5, 269.8 and 275.3 GDD for the fifth–sixth, sixth–seventh and seventh–eighth harvests, respectively. This

progressive increase in thermal requirement toward later harvests reflects staggered flowering and asynchronous seed maturation among primary, secondary and tertiary umbels.

The elevated Δ GDD requirement between the fourth and fifth harvests indicates delayed maturation of later-formed umbels, a characteristic feature of crops exhibiting indeterminate or semi-indeterminate flowering behaviour. Comparable patterns of extended thermal requirements for later reproductive cohorts have been reported in fennel and other seed spice crops (Carrubba and Lombardo, 2020; Tripathi *et al.*, 2022). The sustained Δ GDD demands (>217 GDD per interval) from the fifth to eighth harvest further demonstrate prolonged reproductive activity under

continued thermal accumulation, resulting in an extended harvest window.

The clear quantification of Δ GDD between successive phenological and harvesting stages underscores the robustness of thermal time as a predictive framework for crop development. Unlike calendar days, Δ GDD provides a physiologically meaningful metric that remains comparatively stable across seasons and environments with variable temperature regimes (Parent and Tardieu, 2014). The stage-specific Δ GDD thresholds identified in this study therefore offer valuable inputs for phenological modelling and can be effectively used to optimize sowing dates, irrigation scheduling and labour planning for sequential harvest operations.

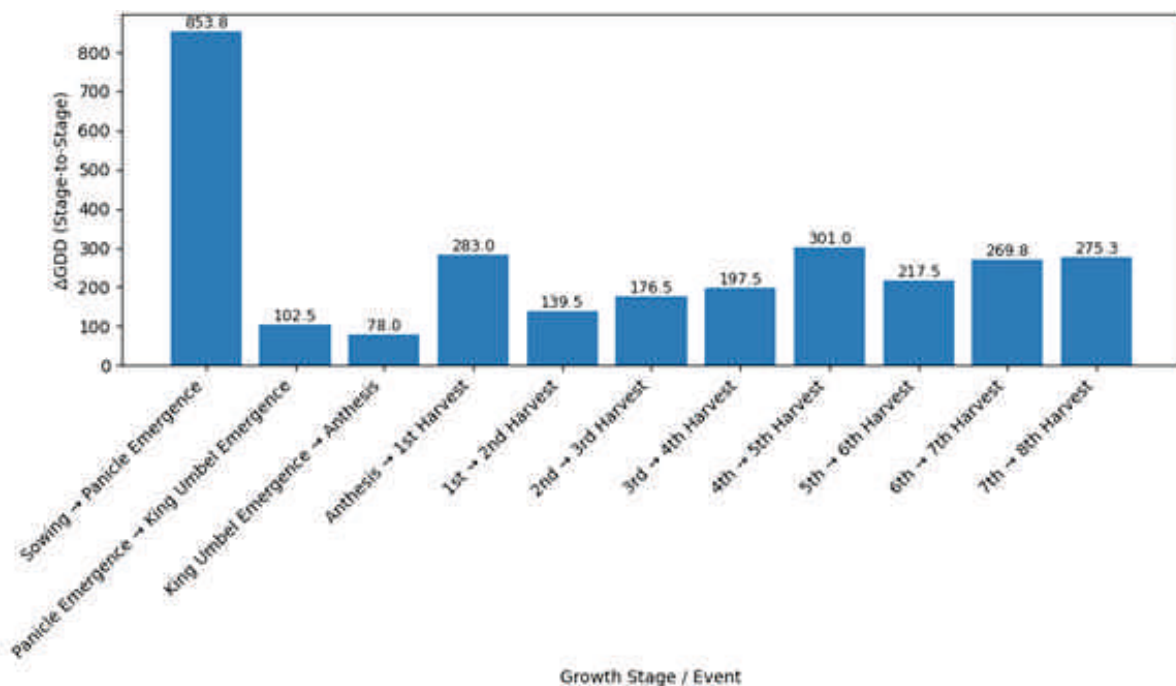


Fig. 2: Stage wise accumulated growing degree days

Effect of harvest stage (DAA) and cumulative GDD on seed quality, biochemical traits, and yield

Harvest stages and corresponding cumulative growing degree days (GDD), exerted a significant influence on seed moisture, biochemical composition, essential oil constituents, and yield of fennel (Table 1). Progressive advancement in harvest timing from 25 to 95 DAA (1317.25 to 2894.25 GDD) resulted in marked and consistent trends across most quality and yield parameters.

Seed moisture content declined sharply with increasing harvest age and thermal accumulation, decreasing from 75.15% at 25 DAA (1317.25 GDD) to 14.18% at 95 DAA (2894.25 GDD). This reduction reflects progressive desiccation associated with seed maturation and physiological dry-down. A similar declining trend was observed for total soluble solids (TSS), which decreased from 24.21 °B at early harvest to 2.55 °B at the final harvest stage, indicating the conversion of soluble carbohydrates into structural and storage compounds during seed maturation.

Total oil and essential oil contents were highest at earlier harvest stages and declined significantly with advancing GDD. Total oil content decreased from 4.41% at 25 DAA to 1.27% at 95 DAA, while essential oil content declined from 2.61% to 1.43% over the same interval. These results suggest that oil biosynthesis peaks during early seed development and subsequently declines due to dilution effects and metabolic conversion during later stages of maturation. Similar declines in essential oil concentration with delayed harvesting have been reported in fennel and other seed spice crops, where oil accumulation is closely linked to early reproductive development and enzymatic activity (Carrubba and Lombardo, 2020; Tripathi *et al.*, 2022; Lal *et al.*, 2025).

The composition of essential oil constituents exhibited distinct and stage-specific responses to thermal time. Estragole content increased initially, reaching a maximum at 35 DAA (32.56%), followed by a gradual decline to 19.65% at 95 DAA. In contrast, trans-anethole content increased steadily with harvest delay, peaking at 55 DAA (35.56%), before declining at later stages. Fenchone content showed relatively smaller variation but remained comparatively higher

during mid-harvest stages (55-75 DAA). These shifts indicate dynamic biochemical transformations in essential oil composition during seed maturation, influenced by cumulative heat units and enzymatic regulation of secondary metabolite pathways (Brahmi *et al.*, 2021 and El-Gamal *et al.*, 2017).

Crude protein content declined with increasing harvest age, from 21.44% at 25 DAA to 13.13% at 95 DAA. This reduction may be attributed to the dilution of nitrogenous compounds as structural carbohydrates and fibre accumulate during late seed maturation. Conversely, crude fibre content increased progressively with delayed harvesting, reaching a maximum of 38.36% at 95 DAA, reflecting enhanced deposition of cell wall components and lignification as maturity advanced.

Seed index increased steadily up to 75 DAA (7.79), followed by a slight decline at later stages, indicating that maximum seed weight was attained at mid-to-late harvest stages before the onset of over-maturity. Yield exhibited a distinct response pattern, increasing significantly with delayed harvesting and peaking at 75 DAA (24.15 q/ha), then declining marginally at 85 and 95 DAA. This suggests that optimal yield was achieved at intermediate harvest stages, where sufficient seed filling had occurred without excessive losses due to shattering or over-drying. Similar results were also reported by Rao (2022) in snap bean under short-temperate-season climates and by Sümer (2023) in pea. GDD can be more effective than season length for recognizing physiological responses to temperature and has been used to calculate yield potential in chickpea, wheat, cowpea, grape, tomato and fennel (Jeffery *et al.*, 2025; Akyuz *et al.*, 2017; Bondade and Deshpande, 2021; Pathak and Stoddard, 2018; Lal *et al.*, 2025).

The results demonstrated that cumulative GDD strongly regulates both qualitative and quantitative traits of fennel seeds. Early harvests favored higher oil content and protein concentration, whereas later harvests enhanced fibre content and yield up to an optimum stage. The integration of harvest timing with thermal time thus provides a robust framework for balancing yield and quality attributes. These findings reinforce the utility of GDD-based harvest scheduling

for optimizing fennel production under variable climatic conditions, consistent with previous reports emphasizing thermal indices as reliable predictors of harvest maturity in spice and oilseed crops (Hatfield and Prueger, 2015; Asseng *et al.*, 2020; Kailas *et al.*, 2025).

Correlation analysis among cumulative GDD, seed quality attributes, and yield

Correlation study revealed strong and systematic relationships among cumulative growing degree days (GDD), seed quality parameters, essential oil constituents, and yield (Fig. 3 and Table 2). Cumulative GDD exhibited a highly significant negative correlation with moisture content ($r = -0.911$), total soluble solids ($r = -0.918$), total oil ($r = -0.976$), essential oil ($r = -0.992$), and crude protein ($r = -0.902$). These strong inverse relationships indicate that as thermal time increased and seeds progressed toward advanced maturity, moisture and metabolically active constituents declined due to desiccation, dilution, and structural accumulation. Similar association for yield and associated traits were also reported by Vanitha *et al.* (2025) in rice.

In contrast, cumulative GDD showed a strong positive correlation with crude fibre ($r = 0.993$), seed index ($r = 0.803$), and yield ($r = 0.718$). This suggests that increasing thermal accumulation promotes seed filling, fibre deposition, and biomass accumulation, ultimately enhancing yield up to an optimum maturity stage. The strong association between GDD and crude fibre reflects increased cell wall development and lignification during later stages of seed maturation.

Moisture content was positively correlated with TSS ($r = 0.963$), total oil ($r = 0.938$), and essential oil ($r = 0.859$), indicating that higher seed moisture at earlier harvest stages coincided with elevated concentrations of soluble carbohydrates and oil fractions. Conversely, moisture content exhibited strong negative correlations with seed index ($r = -0.947$), crude fibre ($r = -0.886$), and yield ($r = -0.911$), demonstrating that immature, high-moisture seeds were associated with lower physical maturity and reduced yield potential.

Total soluble solids were positively correlated with total oil ($r = 0.894$) and essential oil ($r = 0.878$), reflecting coordinated metabolic activity during early seed

development. However, TSS showed strong negative correlations with seed index ($r = -0.941$), crude fibre ($r = -0.909$), and yield ($r = -0.822$), suggesting that soluble carbohydrate content decreases as assimilates are converted into structural and storage components during seed maturation.

Total oil content was strongly and positively associated with essential oil ($r = 0.951$) and estragole concentration ($r = 0.877$), indicating synchronized biosynthesis of oil fractions and specific volatile compounds during early to mid-developmental stages. In contrast, total oil exhibited strong negative correlations with crude fibre ($r = -0.949$) and yield ($r = -0.793$), reflecting a trade-off between oil concentration and structural biomass accumulation at advanced maturity.

Among essential oil constituents, estragole showed a strong positive correlation with crude protein ($r = 0.874$) and a negative association with crude fibre ($r = -0.896$), suggesting preferential accumulation of estragole in metabolically active, protein-rich seeds at earlier harvest stages. Trans-anethole displayed comparatively weaker correlations with most parameters, indicating greater compositional stability across harvest stages. Fenchone showed a modest positive correlation with yield ($r = 0.393$), suggesting its relative persistence during the later stages of seed maturation (Lal *et al.*, 2025).

Overall, the correlation matrix clearly demonstrates that cumulative thermal time is a dominant driver of both quantitative and qualitative changes in fennel seeds. Increasing GDD favors yield and physical maturity traits, whereas biochemical quality attributes such as oil, essential oil, protein, and soluble solids are higher at lower thermal accumulations. These relationships highlight a physiological trade-off between yield maximization and quality preservation and reinforce the importance of GDD-based harvest scheduling to achieve targeted production goals. The results in line with Vanitha *et al.* (2025) in rice, Kailas *et al.* (2025) in long bean and Jeffrey *et al.* (2025) in chickpea.

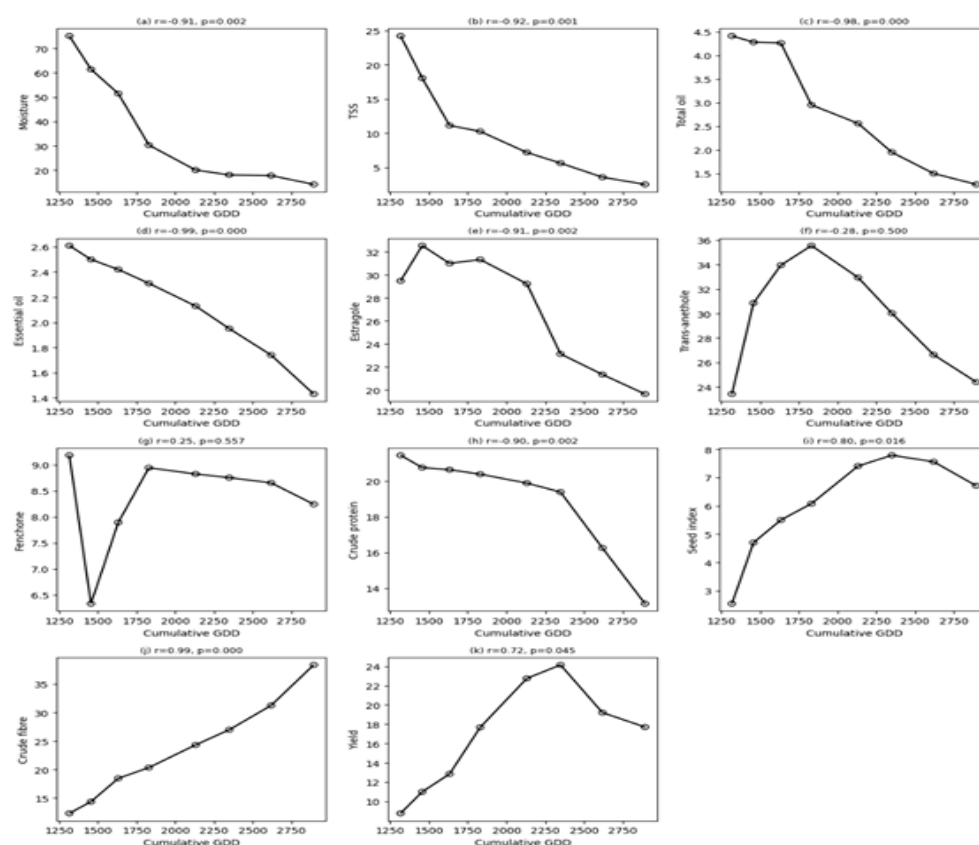
Conclusion

The study confirmed that phenology, yield and quality attributes of fennel were strongly regulated by

Table 1: Growing degree days, yield and quality attributes of fennel seed harvested at different stages

Treatments	Cumulative GDD	Moisture content (%)	TSS (°B)	Total oil (%)	Essential oil (%)	Estragole	Trans anethole	Fenchone	Crude protein (%)	Seed index	Crude fibre	Yield (q/ha)
25 DAA	1317.25 ^g	75.15 ^a	24.21 ^a	4.41 ^a	2.61 ^a	29.49 ^c	23.42 ^f	9.18 ^a	21.44 ^a	2.54 ^g	12.31 ^h	8.77 ^e
35 DAA	1456.75 ^f	61.46 ^b	18.05 ^b	4.28 ^a	2.50 ^{ba}	32.56 ^a	30.86 ^d	6.33 ^f	20.75 ^{ba}	4.70 ^f	14.35 ^g	11.00 ^e
45 DAA	1633.25 ^e	51.49 ^c	11.15 ^c	4.26 ^a	2.42 ^{ba}	31.01 ^b	33.96 ^c	7.89 ^d	20.63 ^{ba}	5.50 ^d	18.45 ^f	12.85 ^d
55 DAA	1830.75 ^d	30.33 ^d	10.28 ^{dc}	2.95 ^b	2.31 ^{bac}	31.35 ^b	35.56 ^a	8.94 ^b	20.38 ^b	6.08 ^c	20.34 ^e	17.68 ^c
65 DAA	2131.75 ^c	20.07 ^e	7.21 ^{de}	2.56 ^{cb}	2.13 ^{bdc}	29.24 ^c	32.95 ^c	8.82 ^b	19.88 ^{bc}	7.41 ^b	24.31 ^d	22.75 ^a
75 DAA	2349.25 ^b	18.08 ^g	5.65 ^{fe}	1.95 ^{cd}	1.95 ^{dc}	23.14 ^d	30.03 ^d	8.75 ^{bc}	19.38 ^c	7.79 ^a	26.98 ^c	24.15 ^a
85 DAA	2619.25 ^a	17.80 ^g	3.60 ^{fe}	1.5 ^d	1.74 ^{ed}	21.35 ^e	26.63 ^e	8.65 ^c	16.25 ^d	7.56 ^d	31.24 ^b	19.21 ^{cb}
95 DAA	2894.25 ^a	14.18 ^g	2.55 ^f	1.27 ^d	1.43 ^e	19.65 ^f	24.40 ^f	8.24 ^d	13.13 ^e	6.71 ^e	38.36 ^a	17.71 ^c

Means with different letters are significantly different within columns ($p \leq 0.05$)



Points represent treatment means. Pearson's correlation coefficient (r) and significance level (p) are shown in each panel.

Fig. 3: Relationship between cumulative growing degree days (GDD) and (a) moisture content, (b) total soluble solids, (c) total oil, (d) essential oil, (e) estragole, (f) trans-anethole, (g) fenchone, (h) crude protein, (i) seed index, (j) crude fibre and (k) seed yield of fennel

Table 2: Correlation between cumulative growing degree days (GDD) and different attributes

Parameters	Growing degree days	Moisture Content	TSS	Total Oil	Essential oil	Eseragole	Transanethole	Fenchone	Crude Protein	Seed index	Crude fiber	Seed yield
Growing degree days	1.000	-0.911**	-0.918**	-0.976**	-0.992**	-0.908**	-0.281	0.246	-0.902**	0.803*	0.993**	0.718*
Moisture content		1.000	0.963**	0.938**	0.859*	0.694	-0.095	-0.316	0.676	-0.947**	-0.886**	-0.911**
TSS			1.000	0.894*	0.878*	0.710*	-0.106	-0.189	0.729*	-0.941**	-0.909**	-0.822*
Total oil				1.000	0.951**	0.877*	0.239	-0.353	0.823*	-0.824*	-0.949**	-0.793*
Essential oil					1.000	0.946**	0.495	-0.058	0.946**	-0.733*	-0.995**	-0.633
Estragole						1.000	0.241	0.217	0.874*	-0.565	-0.896**	-0.515
Trans-anethole							1.000	0.159	0.495	0.272	-0.287	0.241
Fenchone								1.000	-0.058	0.159	0.217	0.393

Correlation coefficients marked with * and ** are significant at $p \leq 0.05$ and $p \leq 0.01$, respectively.

accumulated Growing Degree Days (GDD). Key phenological stages occurred at consistent GDD thresholds, making thermal time a reliable predictor of crop development. Early harvests at lower GDD favored higher oil, essential oil and protein contents, whereas intermediate GDD levels (2349 GDD) optimized seed yield. Delayed harvesting increased fibre content but reduced quality. The application of GDD-based harvest scheduling can improve yield stability, quality management, and climate-resilient fennel production through precise phenological prediction.

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Conflict of Interest

The authors declare that the research was conducted beyond any commercial or financial affairs that could be taken as a potential conflict of interest

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