

Article

Thermal-Time-Based Analysis of Garlic Growth and Yield Formation Under Contrasting Field Management

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Abstract

Garlic bulb yield formation depends on thermal-time availability, source–sink coordination, and field management, but their integrated effects under field-scale conditions remain unclear. This study evaluated garlic growth and final bulb weight (BW) during the 2024–2025 season across 26 field plots in Uiseong, Korea, using cumulative growing degree days (GDD), longitudinal canopy and bulb measurements, correlation analysis, PCA, and exploratory Random Forest (RF)-based variable importance. Delayed sowing reduced cumulative GDD at harvest by approximately 45 °C·d and was associated with lower final BW. Total plant weight (TPW) peaked around 692.2 °C·d, whereas BW continued to increase toward harvest, indicating temporal separation between whole-plant biomass accumulation and bulb filling. At harvest, BW was most strongly associated with bulb diameter (BD), while canopy traits showed weaker or stage-dependent relationships. RF analysis using the harvest-stage BW subset ($n = 78$) suggested that early canopy and structural traits, particularly LN, PH, SL, and SD, were associated with BW variance partitioning; however, importance values were interpreted as exploratory rankings rather than causal evidence. Overall, garlic bulb yield formation under the present field conditions appeared to be associated with thermal-time availability, sink morphology, early structural status, and localized management conditions; however, plot-level treatment comparisons did not detect significant independent treatment effects, indicating that these patterns should be interpreted as descriptive field-based trends.

Keywords: *Allium sativum* L.; growing degree days; sowing date; source–sink relationship; principal component analysis



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1. Introduction

Garlic (*Allium sativum* L.) is a globally important horticultural crop valued for its culinary uses, nutritional benefits, and pharmacological properties [1,2]. As a sterile diploid species propagated vegetatively through cloves, its productivity depends on genetic potential and is strongly influenced by environmental conditions [3,4]. Among these environmental factors, temperature and photoperiod are major determinants of garlic development and the timing of key phenological stages [5,6].

Garlic yield formation follows a biphasic developmental framework [7,8]. During the initial vegetative phase, the crop develops a photosynthetically active canopy that serves as the primary assimilate source. This phase requires relatively cool temperatures and short-day conditions, which promote leaf emergence and canopy expansion [9]. Subsequently, the crop undergoes a photothermal transition to the bulbing phase, during which the developing bulb functions as the principal sink for assimilate accumulation [10]. Flowering and bulbing proceed as parallel yet competing developmental pathways regulated by defined thresholds of accumulated thermal time and photoperiod exposure [11,12]. Therefore, final yield depends largely on the synchronization between canopy establishment and bulb expansion [13,14], requiring sufficient vegetative biomass formation before environmental signals trigger assimilate allocation toward bulb development [15].

To improve crop performance under variable field conditions, farmers increasingly adopt microenvironmental management strategies. In this context, mulching regulates soil temperature, conserves soil moisture, and stabilizes root-zone conditions [16]. For instance, Bohara et al. [17] report that plastic and rice-straw mulches markedly enhance garlic morphological traits and bulb yield by maintaining favorable soil hydrothermal conditions. Similarly, spatial field configuration strongly influences canopy structure and resource use efficiency. Fakhar et al. [18] demonstrate that appropriate plant density and row spacing can minimize canopy competition and enhance photosynthetic efficiency. Furthermore, Barakat et al. [19] and Rattan and Spehia [20] show that integrating mulching with appropriate irrigation and fertigation promotes leaf expansion and dry matter accumulation in garlic.

Despite these well-documented benefits, the extent to which micro-scale management can compensate for macro-scale environmental constraints—particularly delayed sowing—remains unclear. In this regard, shifts in planting windows fundamentally modify the crop thermal and radiative environments, restrict effective vegetative growth periods, and influence developmental and quality parameters such as allicin content [21,22]. Supporting this, Jamil et al. [23] and El-Zohiri and Farag [24] report significant interactions between planting date and management practices, including mulching, where yield gains under optimal early sowing do not offset reductions under delayed planting. Additionally, a global meta-analysis by Dadrasi [25] shows that late sowing accelerates maturity, shortens developmental duration, and reduces biomass and yield. Collectively, these findings suggest that macro-environmental constraints associated with planting date impose physiological limitations that localized agronomic management cannot fully offset.

Despite extensive research on individual practices—including irrigation, spacing, and mulching—their relative importance and interactive effects on garlic yield remain unclear [26,27]. Moreover, agronomic surveys indicate that management practices often explain yield gaps more effectively than climatic factors alone [28]. However, studies integrating thermal-time constraints, structural trait dynamics, and multifactor management within a unified hierarchical analytical framework for garlic remain limited. Consequently, this gap limits the ability to quantify the buffering capacity of localized management against physiological constraints driven by shortened developmental periods and disrupted source–sink coordination.

Recent advances in machine learning (ML) offer new opportunities to address this challenge. Unlike traditional regression approaches, ensemble algorithms, including Random Forest (RF), effectively model nonlinear relationships and collinear predictors without distributional assumptions while providing interpretable variable-importance metrics that directly support agronomic decision-making [29,30]. When combined with multivariate techniques such as principal component analysis (PCA)—which reduces data dimensionality while preserving biological covariance structure—these approaches enable variable selection and structural pattern recognition within a unified analytical framework [31,32].

Collectively, RF and PCA function as statistical alternatives and complementary approaches for decomposing hierarchical mechanisms governing yield formation under heterogeneous field conditions [33].

To our knowledge, limited field-based studies have jointly examined thermal-time accumulation, plant structural development, and localized management practices in relation to garlic bulb yield formation. In particular, it remains unclear whether differences in sowing date and field management are reflected directly in final bulb weight or indirectly through stage-dependent changes in canopy structure and sink morphology. We hypothesized that delayed sowing would be associated with reduced cumulative thermal-time availability and lower final BW, and that localized management practices would influence BW primarily through stage-dependent canopy development and structural traits rather than as isolated independent effects. Therefore, this study aimed to evaluate garlic growth and bulb yield formation under contrasting field-management conditions using a thermal-time framework. Specifically, the objectives were to: (1) characterize canopy and bulb growth dynamics along cumulative GDD; (2) examine relationships between canopy traits, bulb morphology, and final BW using correlation analysis and PCA; and (3) explore the relative contribution of management and early structural traits to final BW variation using RF-based variable-importance analysis. The RF analysis was used as an exploratory ranking approach rather than as a causal or predictive yield-forecasting model.

2. Material and Methods

2.1. Experimental Site and Management Design

2.1.1. Experimental Site and Environmental Characteristics

Field experiments were conducted during the 2024–2025 growing season at a large-scale smart-farm research site in Bongyang-myeon, Uiseong-gun, Gyeongsangbuk-do, Republic of Korea (36.3222° N, 128.6523° E). The study area comprised five experimental zones (A–E) defined based on cadastral parcel boundaries (Figure 1): Buntori 320 (Zone A, 1912 m²), Buntori 318–319 (Zone B, 3921 m²), Buntori 316–317 (Zone C, 3140 m²), Buntori 273-1 (Zone D, 8438 m²), and Buntori 273-2 (Zone E, 8438 m²), covering approximately 22,869 m².

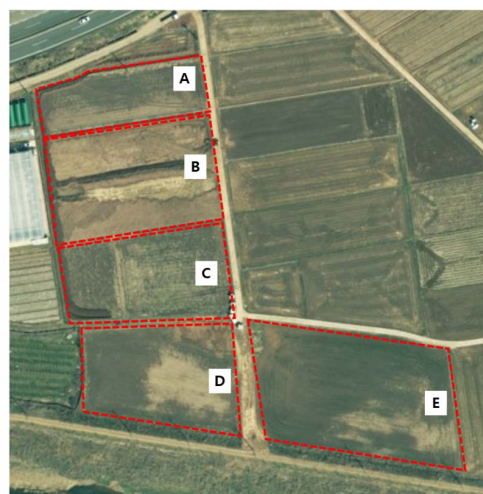


Figure 1. Aerial view of the experimental site showing classification of management zones (A–E).

All experimental zones were located within the same agro-climatic region, allowing comparative analysis of crop growth dynamics under heterogeneous management practices within a unified thermal-time framework.

2.1.2. Experimental Design and Planting Schedule

A total of 26 field plots were established to evaluate garlic growth and bulb yield formation under contrasting sowing dates and field-management configurations. The experimental layout reflected practical field-scale management conditions at the research site. The management factors included sowing date, row configuration, plant spacing, mulching type, and irrigation system (Table 1).

Table 1. Configuration of the 26 experimental treatment plots.

Plot No.	Zone	Ridge ID	Sowing Date	Row Configuration	Plant Spacing	Mulching Treatment	Irrigation System
1	A	A1	2024-12-05	8-row	10 cm	Vinyl	Subsurface drip
2	A	A2	2024-12-05	8-row	10 cm	Vinyl	Surface drip
3–5	B	B1–B3	2024-11-12	8-row	7 cm	Vinyl/liquid/none	Medium sprinkler
6–8	B	B4–B6	2024-11-12	8-row	10 cm	Vinyl/liquid/none	Medium sprinkler
9–11	C	C1–C3	2024-11-13	8-row	10 cm	Vinyl/liquid/none	Medium sprinkler
12–14	C	C4–C6	2024-11-13	10-row	10 cm	Vinyl/liquid/none	Medium sprinkler
15–17	D	D1–D3	2024-11-12	8-row	10 cm	Vinyl/liquid/none	Medium sprinkler
18–20	D	D4–D6	2024-11-12	8-row	7 cm	Vinyl/liquid/none	Medium sprinkler
21–23	E	E1–E3	2024-11-12	8-row	10 cm	Vinyl/liquid/none	Micro-sprinkler
24–26	E	E4–E6	2024-11-12	8-row	10 cm	Vinyl/liquid/none	Surface drip

Zones B, D, and E were sown on 12 November 2024, Zone C on 13 November 2024, and Zone A on 5 December 2024 as the late-sown treatment. Thus, the late-sown plots were located in Zone A, whereas the optimally sown plots were distributed across Zones B–E. Row configuration consisted of 8-row or 10-row ridges, plant spacing was 7 or 10 cm, and mulching treatments included plastic film, liquid sprayable mulch, and non-mulched conditions. Irrigation systems included subsurface drip, surface drip, medium-scale sprinkler, and micro-sprinkler irrigation.

The planting material used in this study was ‘Uiseong-jong’, a Hanji-type garlic (*Allium sativum* L.) commonly cultivated in the Uiseong region, Korea. The same planting material was used across all experimental plots to minimize genetic variation. Seed cloves were mechanically planted at an approximate depth of 5–7 cm according to the field operation protocol.

Fertilization, weed control, pest control, and disease control were applied uniformly across the experimental field as common background management and were not included as experimental treatment factors. Basal fertilization was conducted before sowing, and spring topdressing was generally completed during the vegetative growth period from mid-March to early April. Additional foliar nutrition and crop-protection operations were conducted according to field conditions and local management practice. Detailed management records, including materials, timing, and application rates, are provided in Supplementary Table S1.

Irrigation was managed based on soil moisture sensor readings, field assessment of soil dryness, rainfall occurrence, and crop growth stage. Field operation records indicated that irrigation was scheduled more frequently as crop water demand increased during spring growth, with approximate target intervals of 7 days in March, 5 days in April, and 4 days in May when irrigation was required. Detailed irrigation-management records and criteria are provided in Supplementary Table S2. Because irrigation volume was not

independently metered at the individual-plot level, irrigation was analyzed as an irrigation-system configuration rather than as a continuous quantitative water-input treatment.

Because several management factors were linked with zone-specific field configurations, individual treatment effects were interpreted within the present field context. In particular, sowing date was evaluated together with the associated zone-level irrigation and soil conditions, rather than as a completely isolated treatment factor.

2.1.3. Field Sampling and Growth Monitoring Protocol

A dual monitoring framework was implemented to systematically track the co-development of source (canopy) and sink (bulb) organs. In Zones A and B, three monitoring stations (#1–#3) were established at regular intervals along each selected ridge to provide internal replication and account for intra-plot variability (Figure 2). The same ridge-selection criteria and monitoring protocol were applied to Zones C–E; because their spatial configuration was identical, separate schematics were not required. For yield-related measurements, separated bulb weight was recorded as BW, whereas whole-plant fresh weight before organ separation was recorded as TPW. These two variables were treated as distinct traits throughout the analysis.

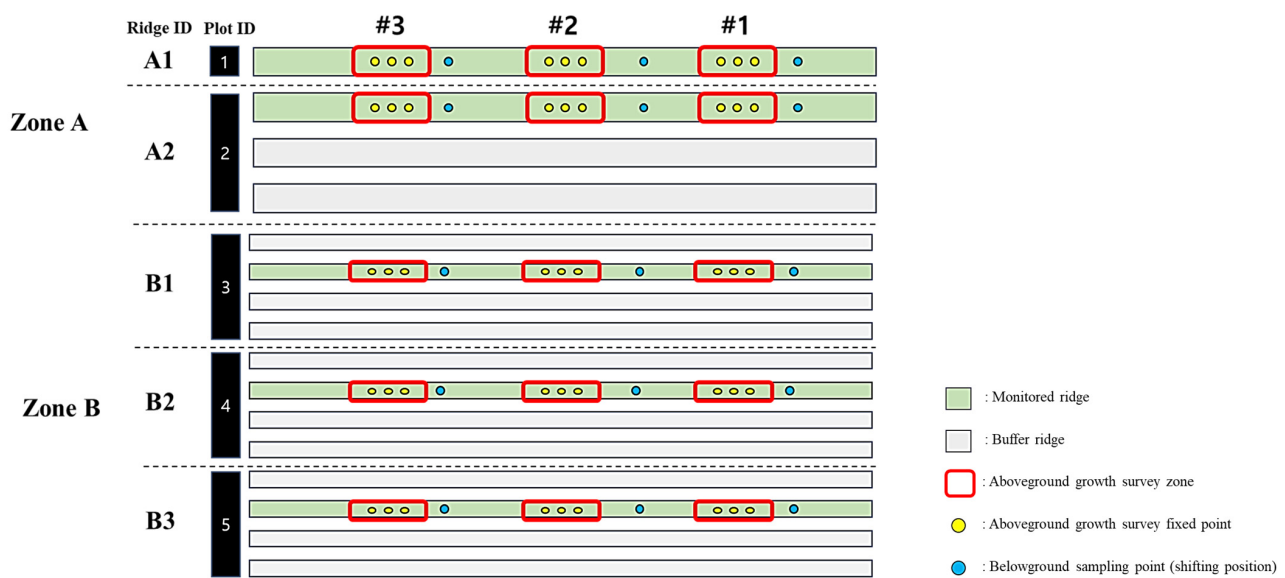


Figure 2. Schematic representation of the spatial sampling strategy and ridge configuration within treatment plots.

For aboveground monitoring, non-destructive measurements were collected repeatedly within a 1.0 m sampling window (± 50 cm from each observation point). Recorded canopy traits included plant height (PH), leaf number (LN), sheath length (SL), sheath diameter (SD), and leaf-tip senescence length (TLS). During the reproductive stage, scape length (SCL) was also measured. Vertical morphological traits—including PH, SL, TLS, and SCL—were measured using a 2 m folding wooden metric ruler (STABILA, Annweiler am Trifels, Germany; resolution: 1 mm). SD was measured using a digital Vernier caliper (EDC-200, EXPOWER, Cheonan, Republic of Korea; resolution: 0.01 mm). LN was determined by direct visual counting.

Belowground development was assessed using destructive sampling conducted adjacent to the canopy monitoring areas to avoid interference with repeated observations. During each sampling round, three representative plants per station were carefully excavated. Sink-related measurements included bulb diameter (BD), bulb height (BH), bulb weight (BW), total plant weight (TPW), and shoot biomass (SB). Morphological bulb di-

mensions were measured using a digital Vernier caliper. Biomass components (TPW, BW, and SB) were measured using a precision household electronic balance (resolution: 0.01 g). Morphological bulb dimensions (BD and BH) were measured using the same digital vernier caliper used for sheath diameter measurements.

In total, 3984 records were collected from November 2024 to June 2025. For this source-sink growth analysis, 13 key monitoring rounds conducted between 21 March and 17 June 2025 were used to characterize clove differentiation, bulb enlargement, late bulb expansion, and physiological maturity (Table 2).

Table 2. Summary of the growth monitoring schedule and measured variables.

Round	Date	Phenological Stage	Category	Measured Parameters
1–5	21 March 2025 to 25 April 2025	Clove differentiation	Canopy	PH, SL, LN, SD, TLS
6–9	30 April 2025 to 22 May 2025	Bulb enlargement/bolting	Canopy/bulb	PH, SL, LN, SD, TLS, SCL/TPW, BW, SB, BD, BH
10–12	29 May 2025 to 11 June 2025	Late bulb expansion	Canopy/bulb	PH, SL, LN, SD, TLS, SCL/TPW, BW, SB, BD, BH
13	17 June 2025	Physiological maturity	Canopy/bulb	PH, SL, LN, SD, TLS, SCL/TPW, BW, SB, BD, BH

PH, plant height; SL, sheath length; LN, leaf number; SD, sheath diameter; TLS, leaf-tip senescence length; SCL, scape length; TPW, total plant weight; BW, bulb weight; SB, shoot biomass; BD, bulb diameter; BH, bulb height.

2.1.4. Pre-Planting Soil Chemical Characteristics

Prior to crop establishment, the soil fertility status of each experimental zone was characterized through official pedological analysis conducted on 5 August 2024, by the Uiseong County Agricultural Technology Center (Gyeongsangbuk-do, Republic of Korea), under the Rural Development Administration (RDA) Soil Information System (soil.rda.go.kr). All analyses followed standard national protocols for upland soil diagnosis.

The physicochemical properties evaluated included soil pH (1:5 water suspension), organic matter (OM; g kg^{−1}), available phosphorus (P₂O₅; mg kg^{−1}), exchangeable cations (potassium, K, calcium, Ca, and magnesium, Mg; cmol⁺ kg^{−1}), and electrical conductivity (EC; dS m^{−1}).

Table 3 summarizes pre-planting soil conditions across the five experimental zones. Zones A, B, and C were classified as silty loam soils on alluvial terraces with moderately imperfect drainage, while Zones D and E were characterized as sandy loam soils on sloped uplands with well-drained drainage.

Table 3. Pre-planting soil physicochemical characteristics of the experimental zones.

Zone	pH (1:5)	OM (g kg ^{−1})	Available P ₂ O ₅ (mg kg ^{−1})	K (cmol ⁺ kg ^{−1})	Ca (cmol ⁺ kg ^{−1})	Mg (cmol ⁺ kg ^{−1})	EC (dS m ^{−1})
A	7.1	33	439	0.92	7.8	2.2	0.3
B	7.6	19	132	0.32	7.9	2.3	0.5
C	7.0	49	443	0.95	8.8	2.5	0.4
D	6.9	15	88	0.34	6.3	1.8	0.2
E	7.1	23	132	0.64	6.8	1.8	0.3

pH, soil reaction (acidity/alkalinity); OM, organic matter; P₂O₅, available phosphorus (as phosphorus pentoxide equivalent); EC, electrical conductivity.

OM content ranged from 15 g kg^{−1} (Zone D) to 49 g kg^{−1} (Zone C), while available P₂O₅ exhibited substantial spatial variability (88–443 mg kg^{−1}). Phosphorus levels in Zones A and C exceeded the recommended optimal range (300–400 mg kg^{−1}). Soil pH ranged from 6.9 to 7.6, with most zones slightly above the optimal range (6.5–7.0) for garlic cultivation. Electrical conductivity remained low across all zones (0.2–0.5 dS m^{−1}), indicating no salinity-related constraints.

2.2. Data Collection and Preprocessing

2.2.1. Meteorological Monitoring and Growing Degree Day Calculation

To characterize the thermal environment influencing garlic growth and phenology, official meteorological data were obtained from the National Institute of Agricultural Sciences, RDA, Republic of Korea. Environmental observations were sourced from the Bongyang-myeon automated weather station (station code: 769912A001; 36.32229° N, 128.64646° E) in Uiseong-gun, Gyeongsangbuk-do, located in close proximity to the experimental fields. The station has operated continuously since 2 September 2014, providing long-term, stable, and reliable datasets.

The meteorological dataset comprised air temperature and relative humidity recorded at 10 min intervals throughout the 2024–2025 growing season. These high-resolution data captured the field-scale thermal environment experienced by the crop.

Thermal time was expressed as GDD (°C·d) and used as the primary temporal variable representing the biological clock of garlic development. Daily GDD was calculated using the mean temperature method (Equation (1)):

$$GDD_d = \max(0, T_{avg,d} - T_{base}) \quad (1)$$

where $T_{avg,d}$ is the daily mean air temperature and T_{base} is the base temperature for biological growth. Following established physiological studies on garlic, T_{base} was set at 5 °C, with no upper temperature threshold applied [24].

Cumulative GDD was calculated by summing daily GDD values from each sowing date (Equation (2)):

$$GDD_{cum}(t) = \sum_{d=sowing}^t GDD_d \quad (2)$$

GDD accumulation began on 12–13 November 2024, for early-sowing zones (B–E) and 5 December 2024, for the late-sown zone (A). This plot-specific approach standardized developmental staging across staggered planting dates, thereby enabling direct comparison of growth trajectories under heterogeneous management conditions.

2.2.2. Thermal-Time Normalization

Since garlic development is primarily driven by thermal exposure rather than calendar time, direct comparisons among staggered sowing treatments based on chronological time may obscure physiological interpretation. To overcome this limitation, all growth observations were normalized to cumulative GDD as a common biological time scale.

This thermal-time framework enabled direct comparison of canopy growth, bulb development, and source–sink transition timing across all treatment plots, including the late-sown treatment. Accordingly, cumulative GDD served as the primary independent variable throughout the analytical workflow, including growth-curve modeling, transition analysis, multivariate analysis, and ML.

2.2.3. Data Preprocessing and Quality Control

All datasets underwent systematic quality control prior to statistical and model-based analyses. Outliers were identified using the Tukey interquartile range method ($k = 1.5$),

applied independently within each GDD $\times$ plot_id group. Observations outside the defined range were excluded only when attributable to measurement error or external disturbance, based on consistency checks across repeated measurements within the same group.

Groups with fewer than four valid observations were excluded from outlier detection to prevent unreliable quantile estimation. Missing observations arising from destructive sampling or data unavailability were handled using listwise deletion; no imputation or interpolation was applied. Zero values representing biologically valid measurements were retained unchanged.

Following quality control, all observations were reorganized along the cumulative GDD axis to generate comparable thermal-time trajectories across plots and treatment groups. This preprocessing ensured temporal consistency and provided a standardized framework for subsequent analyses of canopy development, bulb expansion, and source–sink transitions.

All preprocessing procedures were implemented using reproducible scripts to ensure transparency and analytical consistency across all analyses.

2.3. Trait Definitions and Dataset Structure

To enable the systematic analysis of garlic growth dynamics under heterogeneous field conditions, all measured variables were classified based on their functional roles within a source–sink framework and integrated into a unified longitudinal dataset. Canopy traits were defined as indicators of source capacity, whereas bulb and biomass traits represented sink development and assimilate allocation. All observations were indexed by plot ID, zone, treatment combination, observation round, and cumulative GDD, enabling direct comparison of developmental trajectories across staggered sowing dates and management conditions. Trait measurements were collected at approximately weekly intervals over 13 observation rounds from 21 March to 17 June 2025. Although sampling followed a fixed calendar schedule, all data were subsequently aligned along the cumulative GDD axis to ensure phenologically consistent comparisons across treatments. This normalization enabled the integration of temporally shifted growth patterns into a common developmental framework.

2.3.1. Canopy (Source) Traits

Vegetative traits representing source capacity were repeatedly measured using non-destructive sampling at fixed observation points. These variables were selected to characterize canopy expansion, structural vigor, and seasonal senescence.

The primary canopy traits included PH (mm), LN (count), SL (mm), and SD (mm). Among these traits, PH and SL represented vertical vegetative growth, LN reflected canopy establishment, and SD served as a structural proxy for assimilate transport and transient storage within the pseudostem. TLS (mm) was measured to quantify the onset and progression of canopy senescence during later growth stages. SCL was initially recorded during the bolting period but was excluded from all subsequent multivariate and ML analyses. In standard agronomic practice, developing scapes are manually removed (detopped) midway through the reproductive stage to redirect assimilates toward the bulb. Consequently, variance in harvest-stage SCL primarily reflects anthropogenic removal rather than natural physiological development, rendering it unsuitable as a structural predictor of yield.

2.3.2. Bulb (Sink) Traits and Biomass Components

Reproductive sink development was quantified through destructive sampling conducted adjacent to the canopy monitoring zones. Bulb-related traits were selected to describe final sink morphology and biomass accumulation. Bulb diameter (BD, mm) and bulb height (BH, mm) were measured using a digital Vernier caliper. Bulb weight (BW, g) was defined

as the fresh weight of the separated bulb after removal of aboveground plant parts and was used as the primary yield-related response variable.

Total plant weight (TPW, g) was defined as the whole-plant fresh weight before organ separation and was used to evaluate whole-plant biomass accumulation during the growing season. Shoot biomass (SB, g) was measured concurrently when applicable. Therefore, BW and TPW were treated as distinct variables: BW represented final bulb yield, whereas TPW represented whole-plant biomass status. All sink-related and biomass measurements were aligned with cumulative GDD at the time of sampling to ensure consistency within the thermal-time framework.

2.3.3. Dataset Organization and Analytical Units

All growth and environmental observations were integrated into a longitudinal dataset organized by plot ID, zone, treatment combination, observation round, and cumulative GDD. Each record was linked to the corresponding agronomic factors, including sowing date, irrigation system, mulching type, row configuration, and plant spacing.

Because the study involved repeated canopy measurements, destructive biomass sampling, and separated bulb measurements with different sampling intensities, analytical units were defined according to the objective of each analysis. For longitudinal growth analysis, all available observations were used to describe canopy development, bulb enlargement, and whole-plant biomass dynamics along cumulative GDD. For correlation analysis and PCA, plot-level means ($n = 26$) were used to preserve the plot as the primary experimental unit and to reduce pseudoreplication.

For RF-based variable-importance analysis, only harvest-stage observations with separated bulb weight (BW) records were used. The response variable was final BW per plant, not TPW. This resulted in 78 individual BW observations nested within 26 field plots. Because these observations were collected within plot-level field units, RF-derived importance values were interpreted as exploratory indicators of variables associated with BW variance partitioning rather than as causal or predictive evidence.

2.4. Statistical Analysis and Modeling Framework

2.4.1. Statistical Inference of Treatment Effects

Treatment comparisons for final BW and bulb morphology were conducted using harvest-stage data. Because individual plant observations were nested within field plots, the plot was regarded as the primary experimental unit for interpreting treatment effects. Individual BW observations were used to calculate plot-level means and within-treatment variability, whereas treatment-level inference was based on plot-level summaries to reduce the risk of pseudoreplication.

Data normality and homogeneity of variance were assessed using the Shapiro–Wilk and Levene’s tests, respectively. Because major yield and structural traits, including BW and BD, did not fully satisfy parametric assumptions, non-parametric Kruskal–Wallis tests were used for group comparisons. When overall significance was detected, Dunn’s post hoc test with Bonferroni adjustment was applied to control Type I error in multiple pairwise comparisons.

Because treatment comparisons were conducted under field-scale management configurations with zone-specific irrigation and soil conditions, statistical results were interpreted as treatment-associated differences within the present field context rather than as definitive independent effects of single management factors.

2.4.2. Multivariate and Correlation Analysis

Pearson correlation analysis was conducted on plot-level mean values to examine relationships between vegetative source and reproductive sink traits. Subsequently, PCA

was applied to reduce the morphological data dimensionality and visualize the structural relationships among the 26 experimental plots. The PCA biplot was used to assess source–sink coordination patterns and characterize the orthogonal separation between vegetative canopy expansion and actualized reproductive sink capacity.

2.4.3. RF-Based Variable-Importance Analysis

RF analysis was used as an exploratory variable-importance approach to identify management and early structural variables associated with final BW variation [34,35]. The analysis was not intended as a field-scale yield-forecasting model or as a causal inference method.

The RF dataset consisted only of harvest-stage observations for which separated bulb weight (BW) was available. The response variable was final BW per plant. TPW was not used as the RF response variable. Because BW observations were collected within field plots and the treatment configuration reflected practical field-scale management conditions, the effective level of independent field replication was lower than the number of individual BW observations. Therefore, RF-derived importance values were interpreted cautiously as within-dataset rankings of variables associated with BW variance partitioning.

Two RF model tiers were constructed. The first model, referred to as the management-only model, included static management variables: sowing date, irrigation system, mulching type, row configuration, and plant spacing. The second model, referred to as the combined model, included the same management variables together with early canopy and structural traits, including PH, LN, SL, and SD, measured before peak bulb enlargement. This two-tier structure was used to examine whether early plant structural status provided additional information associated with final BW variation beyond static management descriptors.

2.4.4. Model Interpretation and Computational Environment

For the RF models, feature importance was quantified using the MDI metric, reflecting the total reduction in node impurity contributed by each variable across all trees in the ensemble. Formally, for variable X_j , MDI is defined as (Equation (3)):

$$MDI(X_j) = \frac{1}{T} \sum_T \sum_{s \in S_t(j)} n_s \left[I(s) - \frac{n_L I(s_L)}{n_s} - \frac{n_R I(s_R)}{n_s} \right] \quad (3)$$

where T is the total number of trees, $S_t(j)$ is the set of internal nodes in tree t that split on variable X_j , n_s is the number of samples at node s , and $I(s)$ is node impurity (mean squared error for regression). The left and right child nodes are denoted s_L and s_R , with sample sizes n_L and n_R , respectively. MDI-based importance values were normalized to sum to 100% for interpretability. Because MDI-based feature importance can be biased toward continuous variables or predictors with greater variability or cardinality, permutation importance was additionally calculated as a sensitivity analysis. For each fitted RF model, each predictor was randomly permuted, and the resulting decrease in R^2 was recorded. This procedure was used to evaluate whether the MDI-derived importance ranking remained broadly consistent when predictor importance was estimated independently of impurity-based split selection. Permutation importance was interpreted as complementary evidence to MDI, rather than as an independent causal test.

All RF-derived importance values were interpreted as relative indicators of variables associated with BW variance partitioning within each model tier. They were not interpreted as absolute measures of predictive contribution or causal effects, because the purpose of the RF analysis was exploratory-variable ranking rather than field-scale yield prediction.

All statistical and ML analyses were conducted using Python (version 3.12). The pingouin library (v0.5.4) was used for non-parametric testing, including Kruskal–Wallis and Dunn’s post hoc tests. Pearson correlation analysis was conducted using scipy.stats,

and RF model construction, MDI feature importance, and permutation importance were implemented using scikit-learn (v1.4.1). To ensure reproducibility, a fixed random seed (random_state = 42) was applied to all RF model instantiations and permutation-importance procedures.

To avoid artificially inflating importance estimates through excessive hyperparameter tuning, the RF algorithm was implemented using standard scikit-learn settings: 100 decision trees (n_estimators = 100), unlimited tree depth (max_depth = None), a minimum of two samples required to split an internal node (min_samples_split = 2), and mean squared error as the node impurity criterion (criterion = squared_error), consistent with the variance-reduction basis of MDI in regression.

3. Results

3.1. Seasonal Environmental Conditions and Thermal-Time Progression

3.1.1. Weather Conditions During the 2024–2025 Growing Season

The meteorological conditions during the 2024–2025 growing season exhibited pronounced seasonal variability that strongly influenced garlic phenology (Figure 3). Total precipitation from sowing to harvest was 295.0 mm, including a major 81.5 mm rainfall event on 14 June, immediately before harvest.

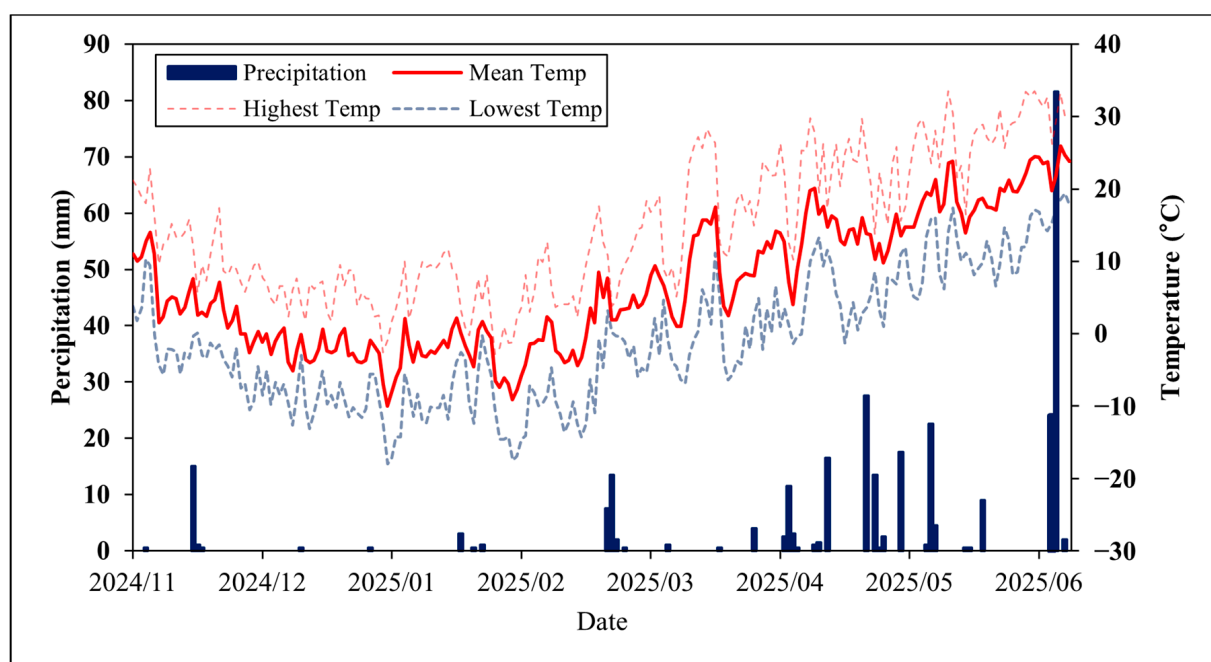


Figure 3. Seasonal meteorological conditions during the 2024–2025 garlic growing season.

Thermal conditions reflected a typical continental climate with marked extremes. During overwintering, the daily minimum temperature dropped to -18.0°C on January 10, indicating severe cold stress and prolonged dormancy. Conversely, spring warming was rapid, with daily maximum temperatures reaching 33.5°C by 20 May. This warming coincided with bulb enlargement, increasing evaporative demand during a critical phase of sink activation.

The diurnal temperature range (DTR) averaged 15.8°C throughout the growing season and peaked at 26.9°C during spring regrowth. Studies report that large DTR values can influence assimilate production and translocation, particularly during active canopy growth. Collectively, these conditions provide a wide thermal envelope, enabling clear differentiation of growth phases within a thermal-time framework.

3.1.2. Cumulative Growing Degree Day Patterns Under Different Sowing Dates

Cumulative GDD revealed a clear temporal offset among sowing dates (Figure 4). The optimal sowing group (Zones B–E; 12 November) accumulated 1011.0 °C·d at harvest, whereas the late-sown group (Zone A; 5 December) accumulated 966.0 °C·d. This ~45.0 °C·d difference closely reflects the thermal time lost during the 23-day sowing delay.

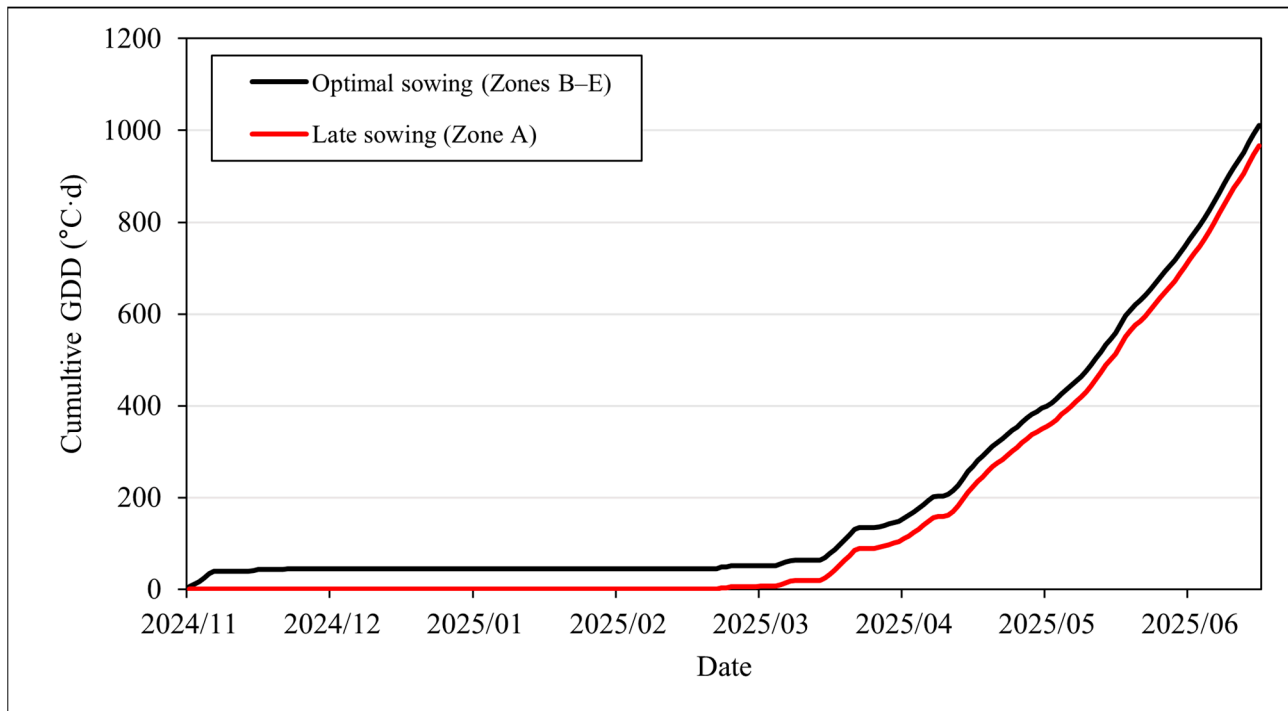


Figure 4. Cumulative GDD under different sowing dates.

Despite the initial lag, GDD accumulation slopes became nearly parallel after early December, indicating that once established, late-sown garlic followed the same thermal progression as optimally sown plots. This parallelism suggests that delayed sowing primarily shifts the thermal starting point rather than altering the intrinsic temperature response.

These findings highlight the limitations of calendar-based comparisons for evaluating physiological development across staggered sowing dates. Aligning growth observations based on calendar time artificially synchronizes plants at thermally distinct stages, while GDD-based normalization resolves these differences using a common biological time scale. Accordingly, the thermal-time framework used in this study provides a robust basis for analyzing canopy development, bulb expansion, and estimating the source–sink transition point, independent of sowing date-induced temporal distortion.

3.2. Thermal-Time-Aligned Canopy (Source) Growth Dynamics

3.2.1. Synchronization of Vegetative Traits Under Thermal Time

Vegetative growth trajectories, normalized through cumulative GDD, demonstrated a unified developmental pattern largely independent of sowing date (Figure 5). To isolate phenological responses to thermal time and mulching, data were pooled across irrigation treatments. While late-sown plots (plastic film mulching, late) began with a thermal lag relative to the optimally sown plots, their GDD-based elongation rates were closely synchronized.

PH increased rapidly and near-linearly during the early vegetative phase (approximately 200–500 °C·d). The canopy reached maximum height at 608.8 °C·d (22 May). At this stage, the non-mulched (Opt) treatment was the tallest (680.6 mm), followed by plastic film mulching (Opt) and liquid sprayable mulching (Opt), both at ~651.8 mm. The plastic film

mulching (late) treatment reached a comparable peak height (652.3 mm), indicating full catch-up in vertical growth from rapid thermal accumulation in late spring. After this peak, PH declined gradually across treatments as senescence and canopy bending progressed.

LN and SL saturated within a similar thermal window. LN stabilized at approximately 7.4–8.0 leaves across treatments, confirming that source establishment depends primarily on cumulative thermal exposure rather than calendar time. In contrast, SL continued to increase or remained near its maximum after PH and LN declined, indicating its structural role in supporting late-stage assimilate translocation.

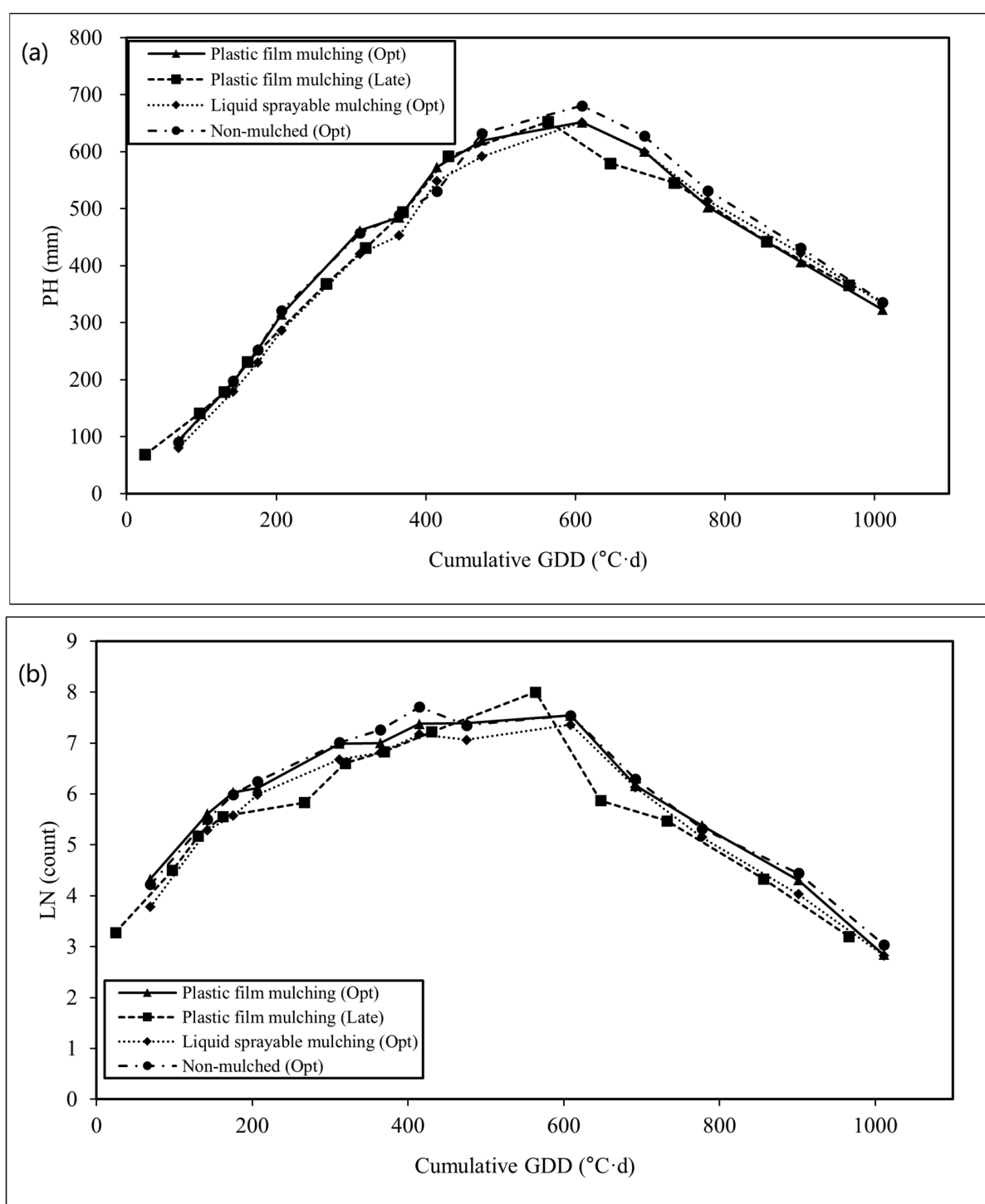


Figure 5. Cont.

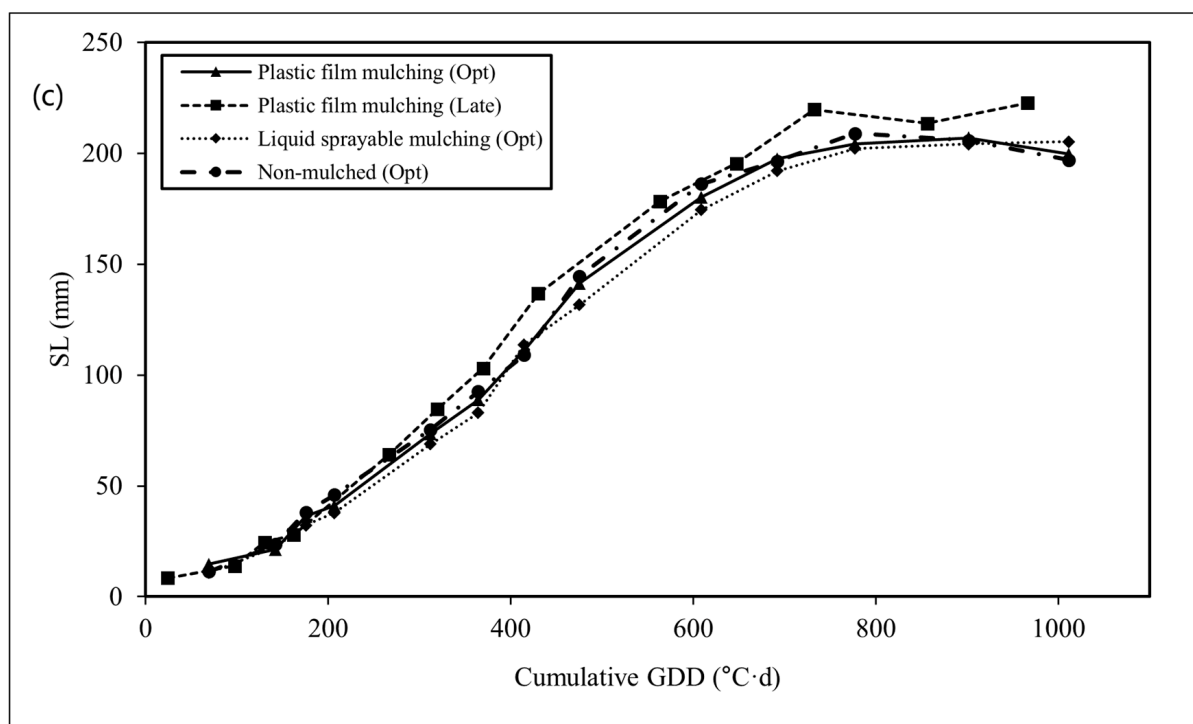


Figure 5. Thermal-time-dependent trajectories of vegetative canopy traits under different mulching and sowing conditions. Longitudinal changes in (a) PH, (b) LN, and (c) SL, each normalized through cumulative GDD.

3.2.2. Sheath Diameter as an Indicator of Vegetative Vigor

SD, representing assimilate storage and transport capacity of the pseudostem, showed a distinct temporal pattern compared to vertical canopy traits (Figure 6). While PH peaked at 608.8 °C·d, SD continued to increase until ~692.2 °C·d (29 May).

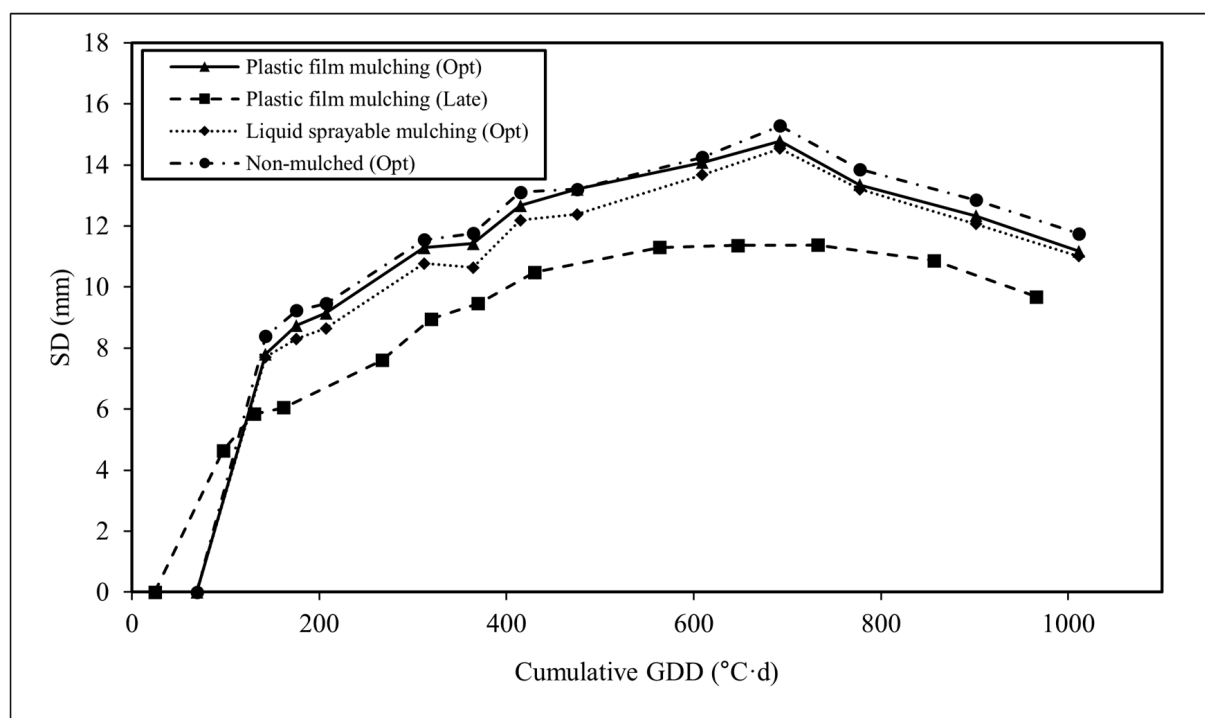


Figure 6. Dynamics of pseudostem radial expansion compared to thermal time.

This ~ 83.4 °C·d delay suggests a physiological strategy in which lateral thickening persists before intensive assimilate translocation to the bulb.

Among mulching treatments, liquid sprayable mulching (Opt) maintained a competitive SD (14.5 mm) comparable to plastic film mulching (Opt; 14.8 mm), while the non-mulched (Opt) treatment had the thickest pseudostem (15.3 mm). Conversely, plastic film mulching (late) reached a slightly lower maximum SD (14.1 mm), indicating that delayed sowing does not limit vertical growth recovery but partially limits radial pseudostem thickening owing to shortened vegetative duration.

3.2.3. Senescence Progression Inferred from Leaf-Tip Senescence

The transition from canopy establishment to reproductive sink dominance was evident in TLS progression (Figure 7). During the vegetative phase, TLS remained minimal (<35 mm) but increased sharply after ~ 608.8 °C·d, marking the onset of canopy functional decline.

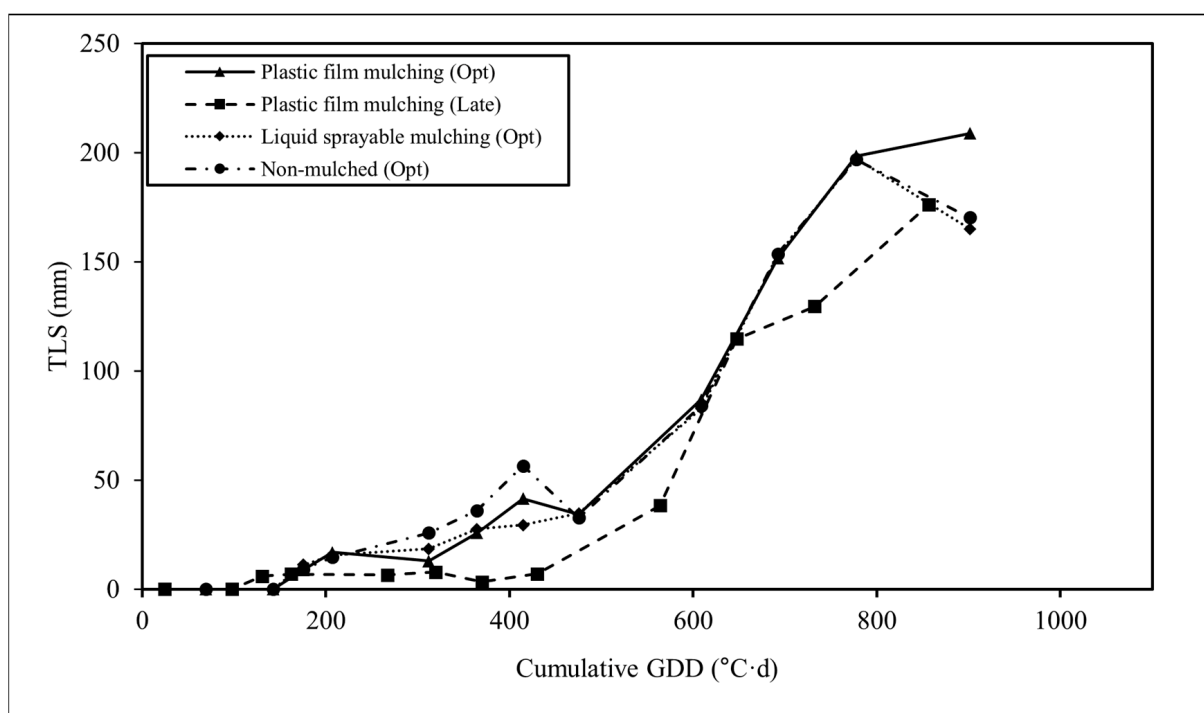


Figure 7. Progression of canopy senescence signaling the source-to-sink transition.

As cumulative GDD > 692.2 °C·d, TLS increased markedly across treatments. The non-mulched (Opt) plots exhibited the fastest senescence, with TLS reaching 153.6 mm by late May, indicating greater sensitivity to elevated temperatures. In contrast, plastic film mulching (late) showed delayed senescence (114.7 mm), suggesting that the younger physiological age of the late-sown canopy temporarily preserves green leaf area under high temperatures.

3.3. Thermal-Time-Aligned Bulb (Sink) Development

3.3.1. Initiation and Progression of Bulb Filling Under Thermal Time

When aligned with cumulative GDD, bulb development exhibited a consistent temporal pattern across mulching treatments, indicating that sink activation is primarily governed via thermal time rather than calendar date or management practice (Figure 8). Across all optimally sown treatments, BW began to increase noticeably from ~ 426.2 °C·d, marking the onset of bulb filling. Unlike total plant biomass, BW exhibited no mid-season peak but increased progressively toward harvest, reaching absolute maximum values at 1011.0 °C·d.

While the rate of mass accumulation varied slightly among treatments, the overall trajectory remained highly conserved. The non-mulched treatment demonstrated competitive bulb growth despite slower early canopy development, indicating robust compensatory allocation toward sink formation during later growth stages. These findings suggest that while sink initiation is strictly thermally regulated, actual bulb mass accumulation continues over an extended thermal window well beyond the peak of whole-plant biomass production.

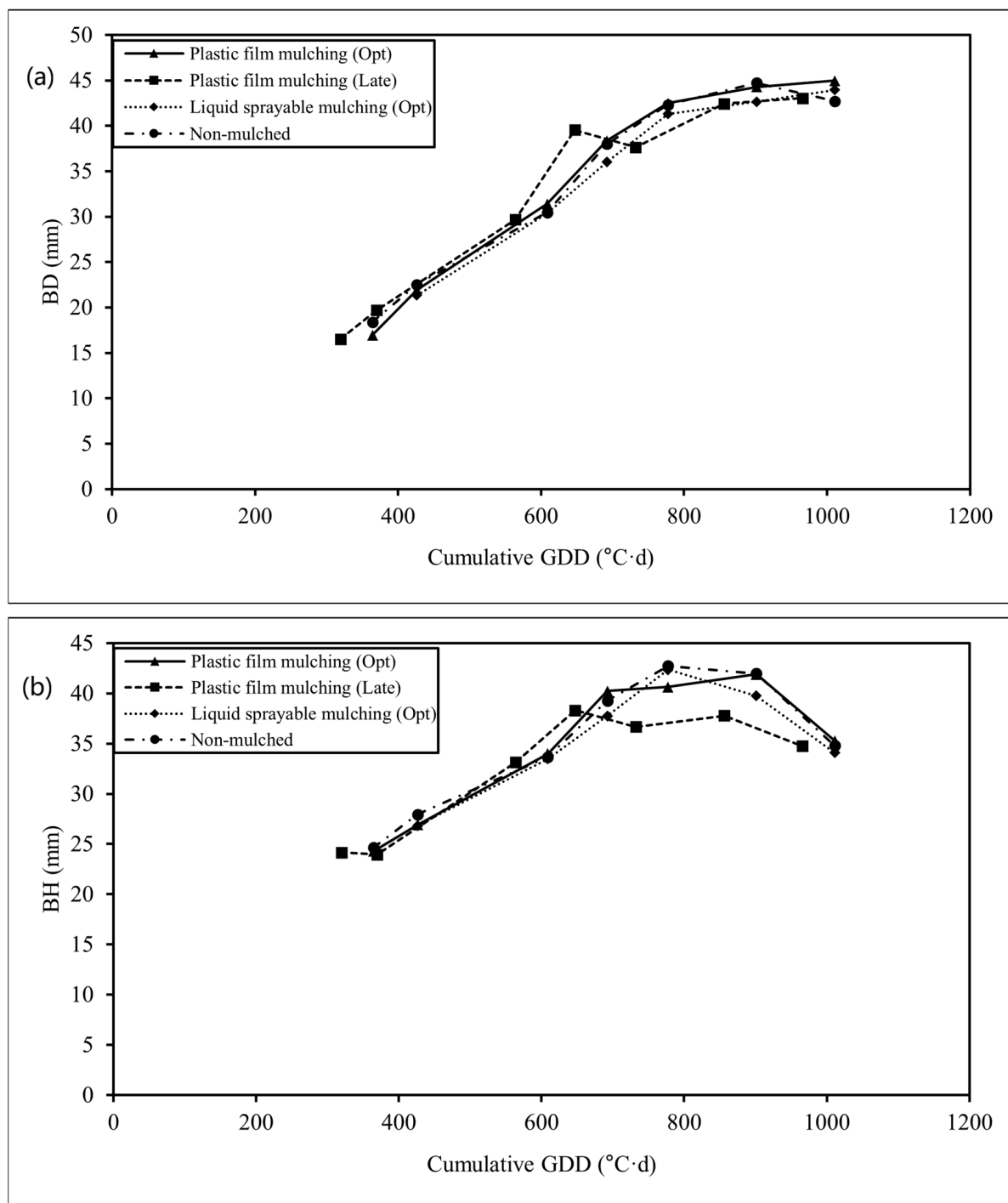


Figure 8. Cont.

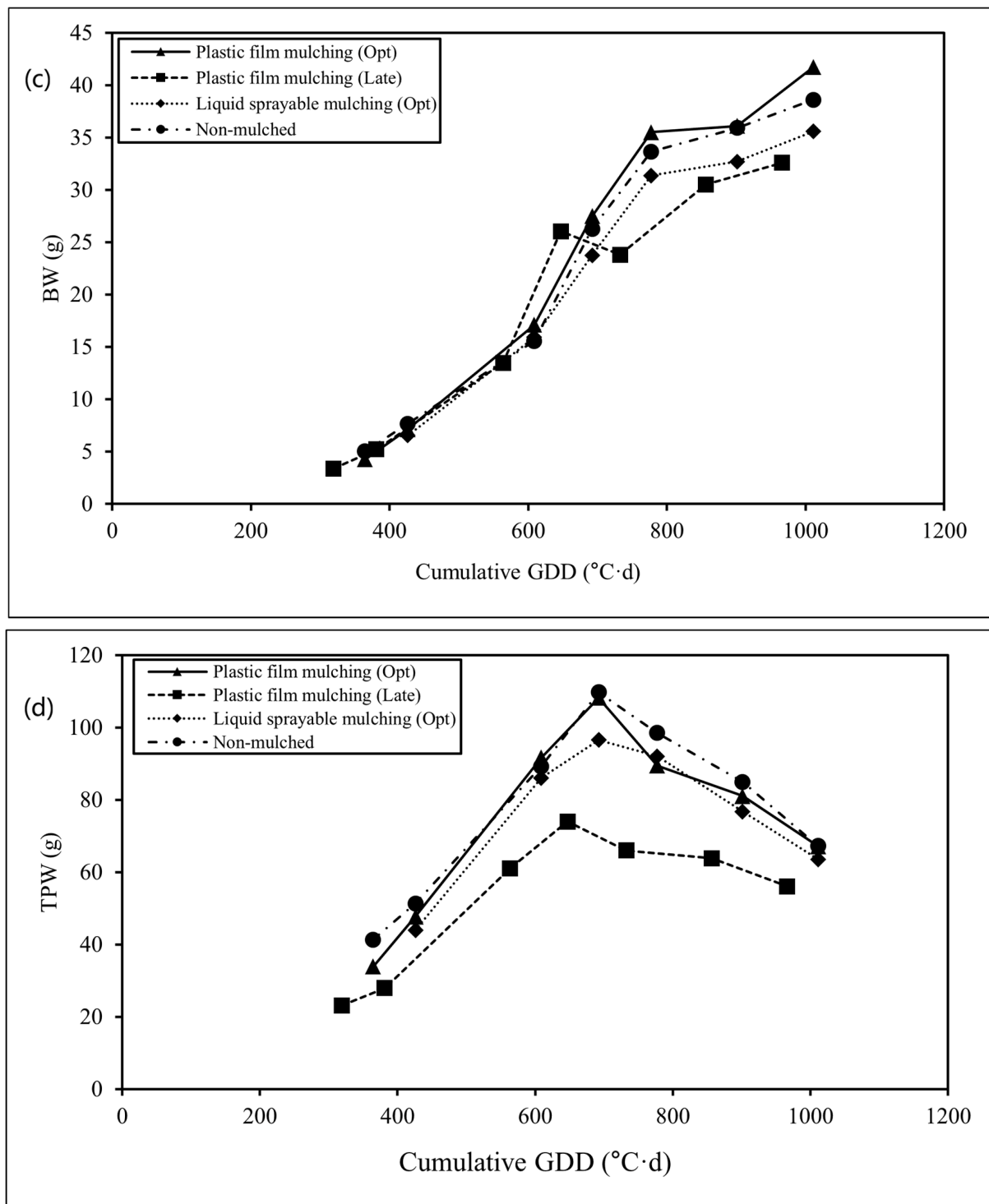


Figure 8. Thermal-time-dependent dynamics of bulb and whole-plant traits. Longitudinal changes in (a) bulb diameter, (b) bulb height, (c) bulb weight, (d) total plant weight.

3.3.2. Decoupling of Total Biomass and Bulb Accumulation

A clear divergence was observed between TPW and BW during the later growth stages. TPW peaked at approximately 692.2 °C·d across optimally sown treatments and then declined toward harvest. In contrast, BW continued to increase beyond this thermal point (Figure 8c). In the plastic film mulching (Opt) treatment, TPW peaked at 108.18 g at 692.2 °C·d and decreased to 67.19 g at harvest, whereas BW increased from 27.50 g to 41.73 g over the same period.

This divergence indicates a temporal separation between whole-plant biomass accumulation and bulb weight increase. Before approximately 692 °C·d, both whole-plant biomass and bulb traits increased. After this point, BW continued to increase while TPW declined, indicating that bulb filling progressed after the peak in whole-plant biomass.

3.3.3. Constraints on Sink Development Under Delayed Sowing

The late-sown treatment showed a shorter BW accumulation trajectory than the optimally sown treatments. BW increased after sink activation but showed limited additional increase after approximately 647.2 °C·d, whereas optimally sown treatments continued BW accumulation beyond 692.2 °C·d.

Final BW in the late-sown group reached 32.58 g at harvest, which was lower than the plastic film mulching (Opt) treatment (41.73 g). In contrast, BD continued to increase until harvest, indicating that bulb morphological expansion partly continued even when BW accumulation was limited. These results show that delayed sowing was associated with a shorter effective period of bulb weight accumulation under the present field conditions.

3.3.4. Total Plant Weight Dynamics

TPW exhibited a distinct temporal pattern compared with BW. Across optimally sown treatments, TPW increased during early vegetative stages and reached a maximum at approximately 692.2 °C·d. Peak TPW values were 109.71 g and 108.18 g in the non-mulched and plastic film mulching (Opt) groups, respectively.

After this peak, TPW declined toward harvest and converged at approximately 63–67 g. This decline occurred during the period when BW continued to increase, further supporting the observed temporal separation between whole-plant biomass accumulation and bulb filling. These results indicate that final BW should be interpreted together with both whole-plant biomass dynamics and the timing of bulb filling.

3.4. Multivariate Relationships Governing Source–Sink Coordination

3.4.1. Pearson Correlation at Physiological Maturity

Pearson correlation analysis was conducted using plot-level mean values ($n = 26$) at physiological maturity to examine relationships among canopy, bulb, and biomass traits (Table 4).

Table 4. Pearson correlation matrix of harvest traits based on 26 plot means.

Trait	PH	LN	SL	SD	BW	BD	BH
PH	-	0.42 *	0.51 **	0.10	−0.19	−0.22	0.00
LN	0.42 *	-	−0.10	−0.06	−0.55 **	−0.38	−0.03
SL	0.51 **	−0.10	-	0.06	0.27	0.20	0.51 **
SD	0.10	−0.06	0.06	-	0.15	0.42 *	0.31
BW	−0.19	−0.55 **	0.27	0.15	-	0.78 ***	0.38
BD	−0.22	−0.38	0.20	0.42 *	0.78 ***	-	0.47 *
BH	0.00	−0.03	0.51 **	0.31	0.38	0.47 *	-

Significance levels: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

BW exhibited the strongest positive correlation with BD ($r = 0.78$, $p < 0.001$), followed by BH ($r = 0.38$). This indicates that final BW was more closely associated with bulb morphological traits than with canopy traits at harvest.

Vertical canopy traits showed weak or negative relationships with BW. PH was not significantly associated with BW ($r = -0.19$), while LN showed a significant negative

correlation with BW ($r = -0.55$, $p < 0.01$). This negative relationship may reflect differences in developmental status at harvest, including senescence progression and maturity stage.

SD exhibited a weak, nonsignificant association with BW at harvest ($r = 0.15$), but it was significantly correlated with BD ($r = 0.42$, $p < 0.05$). This result indicates that SD was more closely related to bulb morphological development than to final BW itself at harvest.

3.4.2. Principal Component Analysis Biplot and Source–Sink Asynchrony

PCA of harvest-stage traits further clarified relationships among canopy and bulb variables (Figure 9).

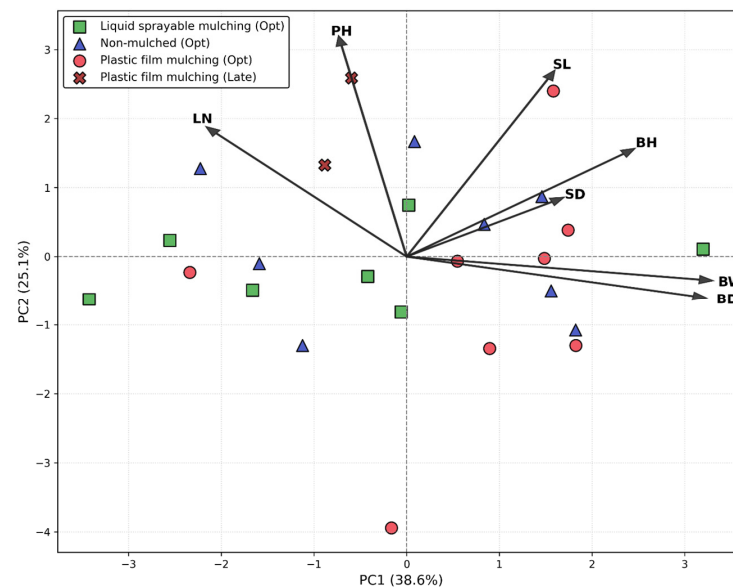


Figure 9. PCA biplot illustrating the structural relationships between vegetative canopy traits and reproductive sink traits across treatments.

The first principal component (PC1), explaining 38.6% of total variance, was strongly associated with bulb-related traits, including BW, BD, BH, and SD. Therefore, PC1 was interpreted as a sink size and structural development axis.

The second principal component (PC2), accounting for 25.1% of the variance, was primarily driven by PH and LN, representing a canopy size and vertical growth axis.

The biplot revealed substantial overlap among treatment groups, indicating considerable intra-treatment variability under field conditions. Despite this overlap, a clear structural separation was observed between canopy-related traits (PH and LN), aligned predominantly along PC2, and sink-related traits (BW, BD, and BH), oriented along PC1.

The near-orthogonal orientation between canopy and sink trait vectors suggests that variation in vegetative growth was not consistently aligned with that in final sink development. Specifically, several plots with relatively large canopy size (high PC2 scores) did not correspond to high sink values (PC1), indicating that canopy expansion alone is insufficient to ensure greater bulb development. Furthermore, the positioning of SD closer to the sink-related axis indicates that radial pseudostem development is more closely associated with sink morphology than with canopy expansion. This suggests that structural traits involved in assimilate transport and allocation mediate the relationship between vegetative growth and yield formation.

3.5. Exploratory RF-Based Variable Importance for Final BW

RF analysis was conducted to explore variables associated with final BW variation using the harvest-stage subset with separated BW records. The analysis was interpreted as

an exploratory variable-ranking approach rather than as a predictive or causal model. Because BW observations were collected within plot-level field units, the resulting importance values should be interpreted as within-dataset indicators of BW variance partitioning.

3.5.1. Management-Only Model

In the management-only model, MDI-based importance ranked mulching type as the highest contributor to BW variance partitioning (35.87%), followed by irrigation system (34.80%), plant spacing (12.64%), row configuration (9.78%), and sowing date (6.90%) (Table 5). Permutation importance showed a broadly similar pattern, with mulching type and irrigation system producing the largest decreases in model performance after permutation. Plant spacing, row configuration, and sowing date showed lower permutation importance.

Table 5. Exploratory RF-based variable importance for final BW: management-only model.

Rank	Feature	Category	MDI Importance (%)	Permutation Importance, Mean ΔR^2	Permutation Importance, SD
1	Mulching type	Management	35.87	0.3451	0.1173
2	Irrigation system	Management	34.80	0.2222	0.0683
3	Plant spacing	Management	12.64	0.0879	0.0345
4	Row configuration	Management	9.78	0.0300	0.0227
5	Sowing date	Management	6.90	0.0276	0.0206

Because the RF analysis was designed for exploratory variable ranking rather than field-scale yield prediction, the management-only model was interpreted only in terms of relative variable importance. These results indicate that localized management variables, particularly mulching type and irrigation configuration, were associated with BW variance partitioning within the present dataset.

3.5.2. Combined Model Including Early Canopy Traits

When early canopy and structural traits were included, RF importance shifted toward biological variables (Table 6). MDI-based importance identified LN as the highest-ranked variable (26.21%), followed by PH (24.51%), SL (19.87%), and SD (13.25%). Static management variables showed comparatively lower MDI values in the combined model, with irrigation system and mulching type accounting for 6.22% and 5.89%, respectively.

Table 6. Exploratory RF-based variable importance for final BW: combined management and early structural trait model.

Rank	Feature	Category	MDI Importance (%)	Permutation Importance, Mean ΔR^2	Permutation Importance, SD
1	LN	Biological	26.21	0.1673	0.0575
2	PH	Biological	24.51	0.0599	0.0321
3	SL	Biological	19.87	0.0619	0.0213
4	SD	Biological	13.25	0.0242	0.0153
5	Irrigation system	Management	6.22	0.0060	0.0082
6	Mulching type	Management	5.89	0.0140	0.0144
7	Row configuration	Management	2.21	0.0053	0.0047
8	Plant spacing	Management	1.63	0.0026	0.0029
9	Sowing date	Management	0.22	0.0001	0.0002

Permutation importance showed partial agreement with the MDI-based ranking. LN remained the highest-ranked variable based on permutation importance, while SL and PH also showed relatively high importance. SD showed moderate importance, whereas management variables had lower permutation importance values.

These results suggest that early canopy and structural traits were associated with final BW variation in the present dataset. However, RF-derived importance values do not indicate causal effects. Rather, they indicate that early plant developmental status may provide useful explanatory information for partitioning BW variation under heterogeneous field conditions.

3.6. Statistical Comparison of Final BW and Bulb Morphology

Statistical comparisons were conducted using plot-level harvest-stage means to preserve the plot as the primary experimental unit. Individual BW measurements were used to calculate plot means, but treatment-level inference was based on plot-level summaries. This approach was adopted to reduce the risk of pseudoreplication arising from individual plants nested within field plots.

3.6.1. Four-Group Comparisons at Harvest

Kruskal–Wallis analysis across the four treatment groups did not detect statistically significant differences in BW, BD, PH, or SD at the plot level (Table 7). Plastic film mulching under optimal sowing showed the highest mean BW (40.57 g), followed by non-mulched optimal sowing (39.77 g), liquid sprayable mulching under optimal sowing (35.59 g), and plastic film mulching under late sowing (32.58 g). Although this ranking was consistent with the observed lower BW under late sowing, the group differences were not statistically significant after using plot-level means.

Table 7. Plot-level comparison of harvest-stage bulb weight and morphological traits across treatment groups.

Treatment Group	BD (mm)	BW (g)	PH (cm)	SD (mm)
Non-mulched (Opt)	44.42	39.77	32.19	11.77
Plastic film mulching (Opt)	44.53	40.57	33.46	11.15
Liquid sprayable mulching (Opt)	42.65	35.59	33.32	11.01
Plastic film mulching (Late)	41.28	32.58	36.03	9.74
Kruskal–Wallis H	3.63	3.54	3.36	6.65
<i>p</i> -value	0.305	0.316	0.339	0.084

BD also tended to be lower in the late-sown treatment than in the optimally sown plastic film and non-mulched treatments. SD showed the lowest value in the late-sown treatment, with a marginal tendency among groups ($p = 0.084$), but this difference did not reach the 5% significance level. Therefore, these results were interpreted as descriptive treatment-associated trends rather than definitive independent treatment effects.

3.6.2. Individual Factor Effects Within the Optimally Sown Plots

Within the optimally sown subset, individual management-factor comparisons based on plot-level BW means showed no statistically significant effects of mulching type, irrigation system, row configuration, or plant spacing (Table 8). Among mulching treatments, plastic film mulching showed the highest mean BW (40.57 g), followed by non-mulched treatment (39.77 g) and liquid sprayable mulching (35.59 g), but the difference was not significant ($p = 0.289$).

Table 8. Plot-level comparison of individual management factors for final BW within optimally sown plots.

Factor	Treatment Levels	Mean BW (g)	Kruskal–Wallis H	<i>p</i> -Value	Significance
Mulching type	Plastic film	40.57	2.48	0.289	ns
	Non-mulched	39.77			
	Liquid sprayable	35.59			
Irrigation system	Med-sprinkler	38.16	0.06	0.972	ns
	Micro-sprinkler	41.60			
	Surface drip	38.56			
Row configuration	10 rows	41.07	0.55	0.458	ns
	8 rows	38.30			
Plant spacing	10 cm	39.97	2.56	0.110	ns
	7 cm	34.67			

ns, not significant.

For irrigation system, micro-sprinkler irrigation showed the highest mean BW (41.60 g), whereas medium sprinkler and surface drip irrigation showed similar values. However, the irrigation effect was not significant ($p = 0.972$). Row configuration also showed no significant effect ($p = 0.458$). Plant spacing showed a numerical trend in which 10 cm spacing produced higher mean BW (39.97 g) than 7 cm spacing (34.67 g), but this difference was not significant at the plot level ($p = 0.110$).

These results indicate that, after reducing pseudoreplication by using plot-level means, localized management factors showed descriptive trends but did not exhibit statistically significant independent effects within the optimally sown plots.

4. Discussion

This study evaluated garlic bulb yield formation under field-scale management conditions by integrating thermal-time analysis, source–sink trait relationships, PCA, and exploratory RF-based variable-importance analysis. Final bulb weight (BW) was associated with thermal-time availability, sink morphological development, early plant structural traits, and localized agronomic management. However, because the experiment reflected practical field configurations with zone-specific management and soil conditions, these relationships should be interpreted as a field-based explanatory framework for the present dataset rather than as evidence of independent treatment effects.

Delayed sowing reduced cumulative GDD by approximately 45 °C·d and was associated with lower final BW. After establishment, the late-sown treatment showed a GDD accumulation pattern broadly parallel to that of the optimally sown treatments, indicating that delayed sowing mainly shifted the biological starting point rather than altering subsequent thermal accumulation. This reduced the thermal budget available for canopy establishment and bulb filling, which is consistent with the temperature-dependent coupling of phenology, leaf development, and canopy growth described for garlic [7]. However, because the late-sown treatment was located in Zone A, where irrigation configuration and available soil P₂O₅ differed from some optimally sown zones, the observed BW reduction should be interpreted within the present field context rather than as the isolated effect of sowing date alone.

The thermal-time trajectories showed temporal separation between whole-plant biomass accumulation and bulb filling. TPW increased during vegetative and early bulb development, peaked around 692.2 °C·d, and then declined, whereas BW continued to

increase toward harvest. Because assimilate translocation was not directly measured, this pattern should be interpreted as indirect evidence of source–sink transition rather than direct proof of assimilate redistribution. Under delayed sowing, BW remained lower at harvest even though BD continued to expand, suggesting that reduced thermal-time availability may have limited the duration or effectiveness of bulb filling rather than completely preventing bulb enlargement. This interpretation is consistent with previous evidence that late sowing can reduce crop biomass and yield by limiting cumulative degree-day availability and shortening the effective growing period [25].

Correlation and PCA results indicated that final BW was more closely associated with sink morphology than with canopy size at harvest. BW showed the strongest relationship with BD, whereas canopy-related traits showed weaker or stage-dependent relationships with BW. The negative association between LN and BW may reflect delayed senescence or incomplete developmental transition rather than greater yield potential. SD was not strongly associated with BW at harvest, but its association with BD and its contribution in the RF analysis suggest that it may serve as an early structural indicator related to sink establishment. This interpretation is consistent with source–sink theory, in which yield depends not only on canopy size but also on the timing and efficiency of source-to-sink transfer [36]. The PCA biplot also showed partial separation between canopy- and sink-related traits, supporting the view that canopy expansion alone does not necessarily ensure high bulb yield when source–sink coordination is not maintained. Similar source–sink asynchrony under delayed or constrained development has been reported in other cropping systems [37].

The RF analysis provided complementary but exploratory evidence on variables associated with BW variation. In the management-only model, mulching type and irrigation system showed relatively high importance, suggesting that root-zone hydrothermal conditions were associated with BW variance partitioning. When early canopy and structural traits were included, biological variables such as LN, PH, SL, and SD showed higher relative importance than static management variables. However, RF-derived importance values should be interpreted only as exploratory associations, because variable-importance estimates do not demonstrate causal effects and may be influenced by sample size, predictor structure, and model instability. In addition, because MDI-based importance can favor continuous or high-variability predictors, permutation importance was used as a sensitivity analysis.

Agronomic management appeared to influence BW through indirect and interacting pathways. Although mulching and irrigation showed relatively high importance in the RF management-only model, plot-level statistical comparisons within the optimally sown subset did not detect significant independent effects of mulching type, irrigation system, row configuration, or plant spacing on BW. Therefore, these management variables should be regarded as possible modifiers of the developmental environment under the present field conditions. Mulching and irrigation may have contributed to stabilizing soil moisture and temperature, thereby supporting canopy development, structural growth, and bulb filling, as reported in previous agronomic studies [38]. This interpretation is consistent with the $G \times E \times M$ framework, in which yield outcomes arise from interactions among environmental constraints, management decisions, and plant responses rather than from any single factor [39].

Several limitations should be acknowledged. First, the experiment was conducted in a single growing season, at a single location, and using one regional garlic planting material, which limits broader generalization across years, environments, and genotypes. Second, the late-sown treatment was represented by only two plots and was linked with zone-specific irrigation and soil conditions. Third, although additional field-management records were

provided to improve reproducibility, irrigation volume was not independently metered at the individual-plot level; therefore, a complete plot-level water-balance analysis could not be performed. Most importantly, plot-level statistical comparisons did not detect significant differences in final BW, BD, PH, or SD among the main treatment groups, and the optimally sown subset also showed no significant independent effects of mulching type, irrigation system, row configuration, or plant spacing on BW. Accordingly, the observed differences among sowing-date and management categories should be interpreted as descriptive field-based trends rather than statistically confirmed treatment effects. The RF analysis was also limited by the relatively small harvest-stage BW dataset ($n = 78$) and should be regarded only as an exploratory variable ranking. Future studies should validate these patterns using multi-year and multi-location experiments with balanced plot-level replication, quantitative irrigation and fertilization records, and direct measurements of dry matter partitioning and photosynthetic activity.

5. Conclusions

This study examined garlic bulb yield formation under field-scale management conditions using thermal-time analysis, source–sink trait relationships, PCA, and exploratory RF-based variable importance. Delayed sowing was associated with reduced cumulative GDD and lower final BW, suggesting that shortened thermal-time availability may be related to limited bulb filling under the present field conditions. However, because the late-sown treatment was linked with zone-specific irrigation and soil conditions, this relationship should be interpreted cautiously rather than as an isolated sowing-date effect.

Final BW was most strongly associated with BD, indicating that bulb morphology was closely related to final yield expression. The contrasting trajectories of TPW and BW suggested temporal separation between whole-plant biomass accumulation and bulb filling, while RF analysis indicated that early canopy and structural traits were associated with BW variance partitioning. However, plot-level statistical comparisons did not detect significant treatment effects for final BW or major bulb morphology traits. Therefore, the observed differences among sowing-date and management categories should be interpreted as descriptive field-based trends rather than confirmed treatment effects.

Overall, garlic bulb yield formation under the present field conditions appeared to reflect interactions among thermal-time availability, source–sink coordination, sink morphological development, and localized management conditions. These findings provide a field-based framework for interpreting garlic growth and yield formation, but further multi-year and multi-location studies with balanced plot-level replication, quantitative irrigation and fertilization records, and direct measurements of dry matter partitioning are required to validate the observed patterns.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture16181942/s1>, Table S1, Summary of crop establishment, fertilization, weed control, and crop-protection management; Table S2, Summary of irrigation-management records and criteria.

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Conflicts of Interest: Authors Y.K., J.J., and S.J. were employed by the company VIVANS Corp. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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