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Interactive Effects of Straw Incorporation, Tillage Systems, and Wheat Growth Stages on Surface Energy Balance Dynamics in a Semi-Arid Agroecosystem

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Abstract

This study evaluated the individual and interactive effects of straw management, tillage systems, and wheat growth stages on surface energy balance (SEB) dynamics in a semi-arid wheat production system, with particular focus on net radiation (Rn), sensible heat flux (H), latent heat flux (LE), Bowen ratio (β), and energy partitioning (EP). A field experiment was conducted during the 2022–2023 growing season using a split–split plot design with two straw management treatments, four tillage systems, and three growth stages. Surface energy balance components were estimated through field-based micrometeorological measurements. Data were analysed using ANOVA, variance partitioning analysis, and Pearson correlation analysis. All experimental factors significantly affected SEB components, although growth stage represented the dominant source of variability, accounting for 42–58% of total variance. Flowering stage consistently promoted the highest LE values and the lowest β and EP values, indicating enhanced evaporative cooling during maximum crop development. Conservation-oriented tillage systems substantially modified thermal partitioning, with no-tillage (NT) significantly increasing LE and reducing H relative to conventional tillage (CT). The combination of straw incorporation and NT during flowering (IS + NT + S2) produced the highest LE value (129.15 W m^{-2}) and one of the lowest H values (18.35 W m^{-2}). Bowen ratio progressively decreased from CT (8.57) to NT (1.44), confirming a shift from sensible to latent heat exchange under conservation-oriented management. Crop phenology and conservation-oriented soil management jointly regulated thermal partitioning and evaporative cooling in semi-arid wheat systems. NT combined with straw incorporation substantially enhanced latent heat exchange while reducing sensible heating, particularly during flowering. This study provides novel field-based evidence regarding the combined influence of straw management, tillage systems, and wheat phenology on SEB dynamics under semi-arid conditions, contributing to improved understanding of land–atmosphere interactions and climate-adaptive agricultural management strategies.

Keywords: heat flux; net radiation; conservation agriculture; semi-arid wheat systems; land–atmosphere interactions; climate-adaptive management

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1. Introduction

Arid and semi-arid agroecosystems are increasingly exposed to rising air temperatures, declining water availability, and greater climatic variability, all of which threaten the sustainability of crop production systems [1,2]. In these environments, the surface energy

balance (SEB) plays a central role in regulating soil-atmosphere interactions, near-surface microclimate, evapotranspiration, and crop physiological performance [3–10]. Net radiation (Rn), the main energy source driving SEB processes, is partitioned primarily into sensible heat flux (H), latent heat flux (LE), and soil heat flux (G). The relative distribution of energy between H and LE strongly influences canopy temperature, soil moisture dynamics, and crop water use efficiency, particularly under water-limited conditions. Greater H generally increases soil and canopy temperature, intensifying heat stress and atmospheric evaporative demand [11,12]. Consequently, thermal partitioning metrics such as the Bowen ratio ($\beta = H/LE$) have become important indicators for evaluating surface energy dynamics in agricultural systems [11,13]. Soil management practices substantially modify SEB processes through their influence on soil physical properties and surface conditions. Conventional tillage commonly disrupts soil structure, reduces aggregate stability, increases crust formation, and decreases infiltration capacity, thereby increasing resistance to water vapour transfer and limiting soil moisture availability near the surface [14–18]. Under semi-arid conditions, these changes may favour greater sensible heating and suppress latent heat exchange, intensifying thermal stress and reducing water use efficiency (WUE) [9,19–21]. In contrast, conservation-oriented practices such as reduced tillage, no-tillage, and straw retention can improve soil moisture conservation, maintain surface protection, and enhance evaporative cooling through greater latent heat fluxes [18,22]. Crop residues may additionally alter surface radiative properties and reduce direct soil exposure, further influencing the partitioning of available energy between H and LE components [18,23,24].

Crop phenology also exerts strong control over surface energy dynamics. Variations in canopy cover, leaf area index, transpiration, stomatal conductance, and aerodynamic roughness throughout crop development directly affect radiation interception and energy exchange between the land surface and atmosphere [23,25–28]. During flowering stages, when canopy development and transpiration rates are typically maximal, LE may dominate the energy balance, whereas during early or senescent stages, a greater proportion of energy may be dissipated as H. Consequently, the effects of tillage and straw management on SEB components are likely to vary considerably across wheat growth stages.

Previous studies have examined the individual effects of tillage systems [19,20], straw management [18,23], and crop phenology [26,29] on SEB components in agricultural environments worldwide. However, these studies have typically addressed these factors in isolation or in pairwise combinations, with limited attention to their simultaneous and interactive effects. Furthermore, most existing SEB studies have been conducted in humid or temperate environments, with relatively few investigations in semi-arid agroecosystems where water limitation and heat stress are critical constraints.

Straw retention has been associated with changes in surface albedo, reductions in soil evaporation, and modifications in latent and sensible heat partitioning [18,23,24]. Similarly, tillage systems affect soil porosity, hydraulic conductivity, aggregation, and surface roughness, thereby altering soil water availability and thermal exchange processes [30,31]. However, despite these advances, the combined and interactive effects of straw management, tillage intensity, and growth stages on SEB components remain insufficiently understood, particularly under semi-arid field conditions. Limited information is available regarding their simultaneous influence on thermal partitioning indicators such as Bowen ratio (β) and energy partitioning ratio (EP), while relatively few studies have quantified higher-order interactions among these factors or evaluated their relative contribution to variability in energy balance components.

These limitations are especially relevant in semi-arid wheat production systems, where management-induced modifications of energy partitioning may substantially influence crop thermal stress and WUE. Although conservation agriculture practices are increasingly

promoted in Iraq, field-based evidence regarding their effects on surface energy dynamics remains scarce. Most existing SEB studies have been conducted in humid or temperate environments where climatic and soil conditions differ markedly from those of Iraqi agroecosystems. Consequently, there is still limited understanding of how conservation-oriented management practices interact with crop phenology to regulate thermal partitioning and evaporative cooling under Iraqi semi-arid wheat production conditions.

Unlike previous studies that examined these drivers individually or in pairwise combinations, the present study simultaneously evaluates straw management, tillage intensity, and wheat phenology within a single field experiment, while quantifying their relative contributions to surface energy balance variability through variance partitioning analysis.

This study evaluated the individual and interactive effects of straw management, tillage systems, and growth stages on Rn, H, LE, β, and EP in a semi-arid wheat production system in central-southern Iraq. Attention was given to the extent to which conservation-oriented practices modify thermal partitioning and enhance evaporative cooling under water-limited conditions. We hypothesised that straw incorporation and reduced soil disturbance, especially under no-tillage systems, would promote latent heat exchange and reduce sensible heating relative to conventional tillage practices, with the strongest effects occurring during the flowering stage when crop transpiration is maximal. We further hypothesised that growth stage would represent the dominant source of variability in SEB components, followed by tillage system and straw management. By integrating field-based energy balance measurements with variance partitioning analysis, this study aims to improve understanding of how management and crop phenology jointly regulate surface energy dynamics in semi-arid agroecosystems and to support the development of climate-adaptive wheat management strategies.

2. Materials and Methods

2.1. Study Area

The field experiment was conducted from October 2022 to May 2023 in Taj Al-Din Hand Village, near Al-Suwaira City, Kut province, central-southern Iraq (32°58′33.0″ N, 44°53′16.8″ E) (Figure 1). This region is characterised by an arid to semi-arid climate, with hot, dry summers and mild winters. Annual precipitation ranges between 120 and 150 mm, with most rainfall occurring from November to March. Mean annual temperature is 23 °C, while summer maximum temperatures frequently exceed 45 °C and winter minimum temperatures may fall to 5 °C.

The experimental site had previously been managed under a wheat-maize rotation system for several years prior to the study. According to the USDA textural classification, the soil was classified as silty clay loam, with 6% sand, 39% silt, and 45% clay. The soil presented an organic matter content of 4.6%, bulk density of 1.42 g cm^{-3}, pH of 7.1, and electrical conductivity of 1.81 dS m^{-1}, indicating non-saline conditions suitable for wheat cultivation.

2.2. Experimental Design and Crop Management

The experiment was arranged as a split-split plot design within a randomised complete block design (RCBD) with three replications. Straw management was assigned to the main plots (12 m × 8 m = 96 m^2 each), tillage system to subplots (6 m × 4 m = 24 m^2 each), and growth stage to sub-subplots.

The physical organisation of the experimental design in the field was as follows: Two straw management treatments were evaluated: without straw (WS) and straw incorporation (IS). In IS, residues from the previous maize crop were chopped into 5–10 cm fragments and incorporated into the upper 15 cm soil layer at a rate of 5 Mg ha^{-1} us-

ing a moldboard plough. Four tillage systems were assessed: conventional tillage (CT), reduced tillage (RT), strip tillage (ST), and no-tillage (NT). CT consisted of moldboard ploughing to 25 cm depth followed by two passes with a disc harrow. RT involved chisel ploughing to 15 cm depth followed by one disc harrow pass. ST was performed using a wheat seed-fertiliser drill machine equipped with 11 furrow openers and 11 press wheels, generating tilled strips of approximately 30 cm wide and 8 cm deep. NT involved direct seeding without mechanical soil disturbance. Measurements were conducted at three growth stages: S1 (early vegetative stage after tillage and crop establishment), S2 (flowering stage), and S3 (post-harvest stage). This hierarchical arrangement was selected because straw incorporation required larger management units, whereas tillage and stage-related measurements could be nested within these areas. Individual plots measured 6 × 4 m, with 1 m buffer strips between adjacent plots to minimise lateral interference among treatments. The total experimental area covered approximately 1200 m^2.

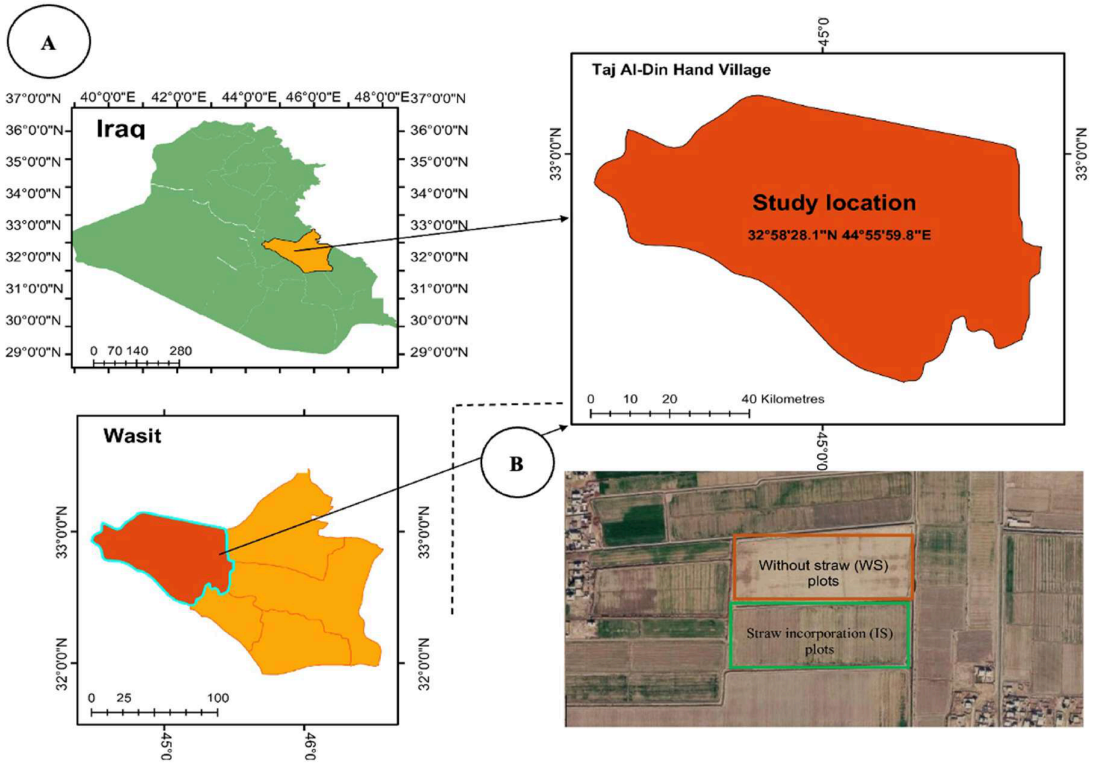


Figure 1. Location and experimental setting. (**A**) Location of Wasit Governorate and Taj Al-Din Hand Village in central-southern Iraq. (**B**) Satellite image showing the main experimental areas assigned to the without-straw (WS) and straw-incorporation (IS) treatments.

Wheat (*Triticum aestivum* L., cultivar Abu-Ghraib) was sown in mid-November at a seeding rate of 140 kg ha^{-1} with 20 cm row spacing and harvested in late May. Fertilisation and weed control were applied uniformly across all treatments following local agronomic recommendations, including 120 kg N ha^{-1} and 80 kg P_2O_5 ha^{-1}.

2.3. Soil Sampling and Analysis

Soil samples were collected from the upper 0–25 cm layer using a stainless-steel auger. Five subsamples were randomly collected within each replication and composited to obtain representative samples for laboratory analysis. Samples were air-dried, sieved through a 2 mm mesh, and stored under laboratory conditions prior to analysis.

Particle-size distribution was determined using the hydrometer method, while soil organic matter was measured using the Walkley-Black wet oxidation method. Soil pH and electrical conductivity were determined using standard electrode and conductivity

meter methods, respectively. Bulk density was measured using the core method with three replicates per plot.

During the growing season, gravimetric soil water content was determined at each growth stage using soil cores collected from three locations within each plot. Gravimetric values were converted to estimated volumetric soil water content using the measured bulk density. The resulting treatment-level values are presented in Supplementary Table S3.

2.4. Surface Energy Balance Measurements

2.4.1. Net Radiation

Net radiation (Rn) was monitored using an Arduino-based data acquisition system centred on an ATmega2560 microcontroller (Arduino Mega 2560, Monza, Italy). The system was installed at approximately 1.5 m above the soil surface at the centre of each subplot and operated continuously during measurement periods. The sensor assembly was maintained in a horizontal position using a bubble level and cleaned regularly to minimise dust interference. Net radiation measurements were used to characterise the available energy driving surface energy exchange processes. All sensors were sampled at 10 s intervals using the Arduino-based data-acquisition system, and the measurements were aggregated into 30 min means for subsequent Rn calculations. The sensors were cleaned daily to maintain optical clarity.

2.4.2. Sensible and Latent Heat Fluxes

Sensible heat flux (H) and latent heat flux (LE) were estimated using micrometeorological measurements combined with aerodynamic and thermodynamic relationships commonly applied in field-scale surface energy balance studies.

The surface energy balance is expressed as follows (Equation (1)):

$$\boldsymbol{Rn = H + LE + G} \quad (1)$$

where Rn is net radiation, H is sensible heat flux, LE is latent heat flux, and G is soil heat flux.

In the present study, soil heat flux (G) was not measured directly because the objective was to compare the relative responses of surface energy partitioning among management treatments rather than to achieve complete energy balance closure. Consequently, the analysis focused on the relationships among net radiation, sensible heat flux, latent heat flux, Bowen ratio, and energy partitioning under comparable meteorological conditions. This limitation is further discussed in Section 4.5. LE was estimated from atmospheric humidity gradients and aerodynamic transport parameters following the aerodynamic approach described by [32]. Equations (2) and (3) are presented only to illustrate the theoretical formulation of turbulent latent and sensible heat fluxes. In the present study, these covariance terms were not measured directly because an eddy covariance system was not available. Instead, H and LE were estimated using an aerodynamic micrometeorological approach based on routine measurements of air temperature, relative humidity, and wind speed, following the methodology proposed by [32,33].

$$\boldsymbol{LE = \rho_a . L_v . \overleftarrow{\omega' q'}} \quad (2)$$

where ρ_a is air density (kg m^{-3}), L_v is the latent heat of vaporisation (approximately 2.45×10^6 J kg^{-1}), w is vertical wind speed (m s^{-1}), and q is specific humidity (kg kg^{-1}).

Air temperature and relative humidity were measured using a digital thermohygrometer, while wind speed was monitored at 1.5 m height using an airflow anemometer (GM8902). Measurements were recorded at 10 s and averaged over 30 min periods for flux

calculations. The aerodynamic calculations assumed horizontally homogeneous conditions and near-neutral atmospheric stability during the selected measurement periods.

H was estimated from air temperature gradients and turbulent transport relationships following Equation (3) [33].

$$H = \rho_{a.} C_{\rho} \overline{\omega' T'} \quad (3)$$

where C_p is the specific heat capacity of air at constant pressure (J kg^{-1} K^{-1}), w′ is the fluctuation in vertical wind speed from its mean (m s^{-1}), and T′ is the fluctuation in air temperature from its mean (K).

Accordingly, the covariance terms shown in Equations (2) and (3) were not directly measured but were represented through the aerodynamic formulation described in the cited studies. Consequently, the reported H and LE values should be interpreted as field-based aerodynamic estimates rather than direct eddy covariance measurements.

The Bowen ratio was calculated according to Equation (4):

$$\beta = H/LE \quad (4)$$

and the EP was calculated as indicated by Equation (5):

$$EP = H/R_n \quad (5)$$

Measurements were conducted between 10:00 and 14:00 local time, encompassing the period around solar noon, on clear and calm days. Measurements were restricted to clear-sky conditions, incoming solar radiation > 300 W m^{-2}, wind speed < 2 m s^{-1}, and no rainfall. The measurements were conducted on three consecutive days at each growth stage to capture day-to-day variability, with reported values representing the average across these repeated measurements. The measured schedule was S1 through 14–16 October 2022; S2 through 10–12 February 2023; and 14–16 October 2022 for S1, 10–12 February 2023 for S2, and 25–27 May 2023 for S3. A total of 72 observations were collected (8 soil treatment combinations × 3 growth stages × 3 replications), with each observation representing the average of 30 min flux density measurements conducted over the measurement period.

The objective of these measurements was to compare treatment-induced differences in surface energy partitioning under standardised atmospheric conditions rather than to quantify complete ecosystem energy balance closure. Because fluxes were estimated from micrometeorological observations using an aerodynamic approach rather than direct eddy covariance measurements, post-processing corrections specific to eddy covariance datasets (e.g., coordinate rotation or WPL corrections) were not applicable. Quality assurance was based on sensor maintenance, stable atmospheric conditions, and repeated measurements under standardised field conditions.

2.5. Statistical Analysis

Statistical analyses were performed using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). Analysis of variance (ANOVA) was conducted using the General Linear Model (GLM) procedure for a split-split plot arrangement within a randomised complete block design. PROC GLM was selected because the experimental design was balanced and orthogonal, allowing the specification of the appropriate error terms for the split-split plot ANOVA. Straw management (A), tillage system (B), growth stage (C), and their interactions (A × B, A × C, B × C, and A × B × C) were treated as fixed effects, whereas replication was considered a random effect. Normality of residuals was evaluated using the Shapiro–Wilk test, whereas homogeneity of variances was assessed through residual diagnostics prior to ANOVA.

The statistical model included straw management (A), tillage system (B), growth stage (C), and their interactions (A × B, A × C, B × C, and A × B × C) as fixed effects, whereas replication and the corresponding whole-plot and subplot error terms associated with the split-split plot design were treated according to the hierarchical experimental structure.

Treatment means were compared using Fisher's protected least significant difference (LSD) test at $p \leq 0.05$. Model performance was evaluated using the coefficient of determination (R^2) and coefficient of variation (CV). Variance components were estimated using restricted maximum-likelihood (REML). PROC VARCOMP in SAS was used to quantify the relative contribution of each experimental factor to the total variability in the energy-balance components.

Pearson correlation coefficients (r) were calculated to evaluate relationships among Rn, H, LE, β, EP, and experimental factors. Statistical significance was assessed at $p < 0.05$, $p < 0.01$, and $p < 0.001$.

3. Results

3.1. Effects of Straw Management, Tillage Systems, and Growth Stages on Surface Energy Balance Components

The pooled split-split plot ANOVA revealed significant effects of straw management, tillage system, growth stages, and several of their interactions on net radiation, sensible heat flux, and latent heat flux (Table 1). The statistical models showed high explanatory capacity for all variables, with R^2 values ranging from 0.948 to 0.954 and relatively low coefficients for Rn (4.2%) and H (6.5%), whereas LE exhibited greater variability (CV = 24.1%), reflecting the stronger temporal and environmental sensitivity of evaporative processes. All three main experimental factors significantly affected the SEB components. Straw management significantly influenced Rn ($F = 111.27$, $p < 0.001$), H ($F = 117.36$, $p < 0.001$), and LE ($F = 124.47$, $p < 0.001$). Tillage system also exerted significant effects on Rn ($F = 42.77$), H ($F = 44.86$), and LE ($F = 48.96$). However, growth stage represented the dominant source of variation, with F-values of 330.36 for Rn, 177.65 for H, and 245.23 for LE, all significant at $p < 0.001$ (Table 1). Significant straw management × tillage system interactions were detected for all three variables, whereas straw management × growth stage and tillage system × growth stage significantly affected Rn and LE but not H. The three-way interaction (straw management × tillage system × growth stages) was significant for Rn and LE, indicating that management effects varied across crop growth stages.

Straw incorporation significantly increased Rn and LE relative to the treatment without straw, whereas H did not differ significantly between straw management treatments (Table 2). Tillage intensity produced a clear and consistent shift in EP: Rn and LE increased progressively from CT to NT, while H declined, with NT showing the highest Rn and LE and the lowest H. Growth stage also strongly affected all SEB components. Flowering produced the highest Rn and LE, whereas the S3 showed the greatest H, confirming that maximum crop development favoured latent heat exchange and evaporative cooling, while canopy senescence promoted sensible heat dominance.

The interaction between straw management and tillage system significantly affected all SEB components (Table 3). The most favourable thermal partitioning occurred under straw incorporation combined with NT, whereas the treatment without straw under CT showed the greatest sensible heat dominance. Comparable stage-dependent patterns were observed for the straw management × growth stage and tillage system × growth stage interactions (Tables 4 and 5), with flowering consistently enhancing LE, particularly under NT. The three-way interaction confirmed that the combined effects of straw management and tillage depended strongly on crop phenology. The highest Rn and LE occurred under IS + NT + S2, whereas WS + CT + S1 produced the lowest LE and comparatively high H. Detailed treatment values are provided in Supplementary Table S1.

Table 1. Pooled split-split plot ANOVA for effects of straw management, tillage, and growth stage on Rn, H, and LE.

Source of Variation	DF	Rn (W m^{-2})			H (W m^{-2})			LE (W m^{-2})		
		Sum of Squares	Mean Square	F-Value	Sum of Squares	Mean Square	F-Value	Sum of Squares	Mean Square	F-Value
Replication	2	134.56	67.28	4.34 *	125.67	62.84	3.93 *	345.67	172.84	3.45 *
Straw Management (A)	1	1723.45	1723.45	111.27 ***	1875.45	1875.45	117.36 ***	6234.56	6234.56	124.47 ***
Error (a)	2	340.78	15.49		351.56	15.98		1101.98	50.09	
Tillage (B)	3	1987.67	662.56	42.77 ***	2150.67	716.89	44.86 ***	7356.78	2452.26	48.96 ***
A × B	3	276.33	99.11	5.95 **	299.55	99.85	6.25 **	976.55	325.52	6.50 **
Error (b)	12	743.52	15.49		767.04	15.98		2404.32	50.09	
Growth Stage (C)	2	10,234.56	5117.28	330.36 ***	5678.34	2839.17	177.65 ***	24,567.34	12,283.67	245.23 ***
A × C	2	567.89	283.95	18.33 ***	45.67	22.83	1.43 ns	1234.56	617.28	12.32 ***
B × C	6	789.45	131.58	8.49 ***	89.34	14.89	0.93 ns	1890.45	315.08	6.29 ***
A × B × C	6	345.67	57.61	3.72 **	78.4	13.08	0.82 ns	789.34	131.56	2.63 *
Error (c)	32	1487.04	15.49		1534.08	15.98		4808.64	50.09	
R-Square				0.948			0.952			0.954
CV (%)				4.2			6.5			24.1

Effects of straw management (A), tillage system (B), growth stage (C), and their interactions on net radiation (Rn), sensible heat flux (H), and latent heat flux (LE). Degrees of freedom (DF) and F-values are shown for each source of variation. Error terms correspond to the appropriate levels of the split-split plot experimental design. Model adequacy statistics include the coefficient of determination (R^2) and coefficient of variation (CV). Significance levels are indicated as *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, and ns = not significant.

Table 2. Main effects of straw management, tillage systems, and growth stages on Rn, H, and LE.

Effect	Level	Mean Rn (W m^{-2})	Mean H (W m^{-2})	Mean LE (W m^{-2})
A: Straw Management	Without Straw (WS)	103.22 b	66.42 a	37.09 b
	Straw incorporation (IS)	110.70 a	68.24 a	43.03 a
	$LSD_{0.05}$	0.95	0.96	1.73
B: Tillage System	CT	98.37 d	79.97 a	18.38 d
	RT	100.09 c	72.58 b	27.38 c
	ST	105.45 b	64.46 c	41.63 b
	NT	123.19 a	53.57 d	65.16 a
	$LSD_{0.05}$	1.35	1.35	2.44
C: Stage	Stage 1	87.62 c	62.40 b	26.45 c
	Stage 2	118.69 a	48.89 c	69.85 a
	Stage 3	114.58 b	90.69 a	23.88 b
	$LSD_{0.05}$	1.17	1.18	2.09

Means followed by different letters within each factor indicate significant differences according to Fisher's protected LSD test ($p \leq 0.05$). CT, conventional tillage; RT, reduced tillage; ST, strip tillage; NT, no-tillage; S1–S3, growth stages. LSD, least significant difference. Overall ANOVA results are presented in Table 1.

Table 3. Interaction effects of straw management and tillage system on Rn, H, and LE.

Straw Management	Tillage System	Mean Rn (W m^{-2})	Mean H (W m^{-2})	Mean LE (W m^{-2})
Without Straw	CT	98.10 d	82.04 a	16.07 f
	RT	99.59 d	74.60 b	24.98 e
	ST	103.60 c	67.25 c	36.35 d
	NT	118.37 b	56.52 d	61.98 b
Straw incorporation (IS)	CT	98.61 d	77.95 b	20.69 ef
	RT	101.26 cd	70.58 c	29.79 e
	ST	107.08 c	61.85 d	46.89 c
	NT	130.65 a	47.83 e	80.18 a
$LSD_{0.05}$		1.91	1.91	3.46

Means followed by different letters within each column indicate significant differences according to Fisher's protected LSD test ($p \leq 0.05$). LSD, least significant difference. Overall ANOVA results are presented in Table 1.

Table 4. Interaction effects of straw management and growth stage on Rn, H, and LE (W m^{-2}).

Straw Management	Growth Stage	Mean Rn (W m^{-2})	Mean H (W m^{-2})	Mean LE (W m^{-2})
Without Straw	Stage 1	85.76 e	66.23 c	19.82 d
	Stage 2	115.31 c	52.98 d	62.39 b
	Stage 3	113.43 c	91.09 a	22.33 d
Straw incorporation (IS)	Stage 1	89.47 d	58.57 d	33.09 c
	Stage 2	122.06 b	44.79 e	77.31 a
	Stage 3	115.72 c	90.30 a	25.43 d
$LSD_{0.05}$		1.65	1.66	2.99

Means followed by different letters within each column indicate significant differences according to Fisher's protected LSD test ($p \leq 0.05$). LSD, least significant difference. Overall ANOVA results are presented in Table 1.

Table 5. Interaction effects of tillage system and growth stage on Rn, H, and LE (W m^{-2}).

Tillage System	Growth Stage	Mean Rn (W m^{-2})	Mean H (W m^{-2})	Mean LE (W m^{-2})
CT	Stage 1	85.74 i	80.46 b	5.27 i
	Stage 2	103.15 g	67.48 d	35.71 g
	Stage 3	106.18 f	92.03 a	14.16 h
RT	Stage 1	80.03 j	69.06 cd	10.94 i
	Stage 2	110.47 e	56.65 e	53.82 f
	Stage 3	110.78 e	92.06 a	18.71 h
ST	Stage 1	79.78 j	56.35 e	23.46 h
	Stage 2	119.86 d	45.79 f	74.35 d
	Stage 3	116.40 d	91.32 a	25.07 gh
NT	Stage 1	106.32 f	43.54 fg	66.24 e
	Stage 2	141.26 b	25.62 h	115.52 b
	Stage 3	124.94 c	87.35 b	37.59 g
$LSD_{0.05}$		2.34	2.35	4.24

Means followed by different letters within each column indicate significant differences according to Fisher's protected LSD test ($p \leq 0.05$). LSD, least significant difference. Overall ANOVA results are presented in Table 1.

3.2. Bowen Ratio Responses to Straw Management, Tillage Systems, and Growth Stages

The Bowen ratio (β) was significantly affected by straw management, tillage system and growth stage (Figure 2). Straw incorporation reduced β from 5.88 under WS to 4.05 under IS, indicating a greater proportion of available energy dissipated through latent heat exchange under straw-retained conditions.

TS exerted a particularly strong influence on β (Figure 2b). CT produced the highest Bowen ratio, whereas NT showed the lowest value, indicating a progressive shift from sensible to latent heat exchange as tillage intensity decreased. Significant differences were also observed among growth stages (Figure 2c). The highest β occurred during S1 (6.88), followed by S3 (4.48), whereas S2 showed the lowest value (1.99). These results indicate that evaporative cooling was greatest during the period of maximum canopy development and transpiration. Interaction effects further emphasised the combined influence of management and phenology on thermal partitioning. The TS × growth stages interaction showed that CT + S1 produced the highest β value (16.34), whereas NT + S2 generated the lowest (0.29) (Figure 2e). Similarly, the SM × growth stages interaction indicated that WS + S1 produced the highest β (8.54), while IS + S2 showed the lowest value (1.51) (Figure 2f). The SM × TS interaction revealed that WS + CT produced the highest overall β values, whereas NT treatments consistently maintained the lowest values regardless of straw management (Figure 2d). Although the three-way interaction was not statistically significant for β, substantial numerical contrasts were still observed among treatment combinations (Table S2). The highest value occurred under WS + CT + S1 (20.80), while the minimum value was recorded under IS + NT + S2 (0.26).

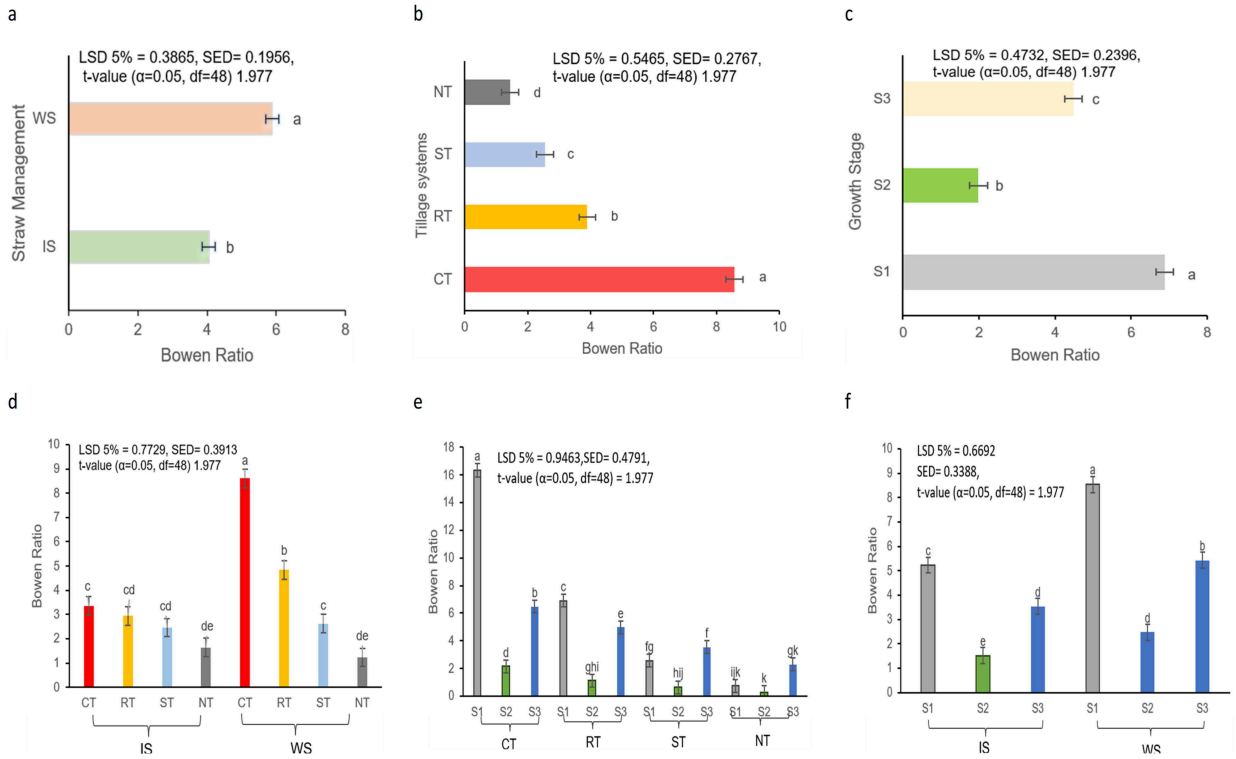


Figure 2. Effects of straw management, tillage system, and growth stage on the Bowen ratio (β). Main effects of straw management (**a**), tillage system (**b**), and growth stage (**c**), and two-way interactions between straw management and tillage system (**d**), tillage system and growth stage (**e**), and straw management and growth stage (**f**). Bars represent means ± SE. Different letters indicate significant differences according to Fisher's protected LSD test ($p \leq 0.05$). WS, without straw; IS, straw incorporation; CT, conventional tillage; RT, reduced tillage; ST, strip tillage; NT, no-tillage; S1–S3, growth stages. LSD, least significant difference; SED, standard error of the difference.

3.3. Energy Partitioning Responses

Energy partitioning (EP = H/Rn) was significantly influenced by straw management, tillage system, growth stage, and their interactions (Figure 3). Straw incorporation reduced EP from 0.644 under WS to 0.572 under IS, indicating lower relative sensible heat dissipation under straw-retained conditions.

A progressive reduction in EP was observed with decreasing tillage intensity (Figure 3b). Energy partitioning decreased progressively from CT to NT. These results are consistent with the observed reduction in H and increase in LE under conservation-oriented tillage systems.

Growth stage also significantly affected EP. The highest values occurred during the post-harvest stage (S3; 0.798), followed by S1 (0.726), where S2 produced the lowest value (0.428) (Figure 3c). This pattern indicates that the flowering stage promoted the most favourable energy partitioning conditions for evaporative cooling.

The interaction analyses showed that WS + CT generated the highest EP values, while NT treatments consistently exhibited the lowest values, particularly during S2 (Figure 3d–f). IS + NT + S2 produced the lowest EP, followed by WS + NT + S2, confirming that conservation-oriented management substantially reduced the proportion of energy dissipated as sensible heat during flowering. The three-way interaction was significant for EP ($F = 2.63$, $p < 0.05$) (Table S2), indicating that the combined influence of straw incorporation, tillage intensity, and crop growth stage played an important role in regulating surface energy partitioning.

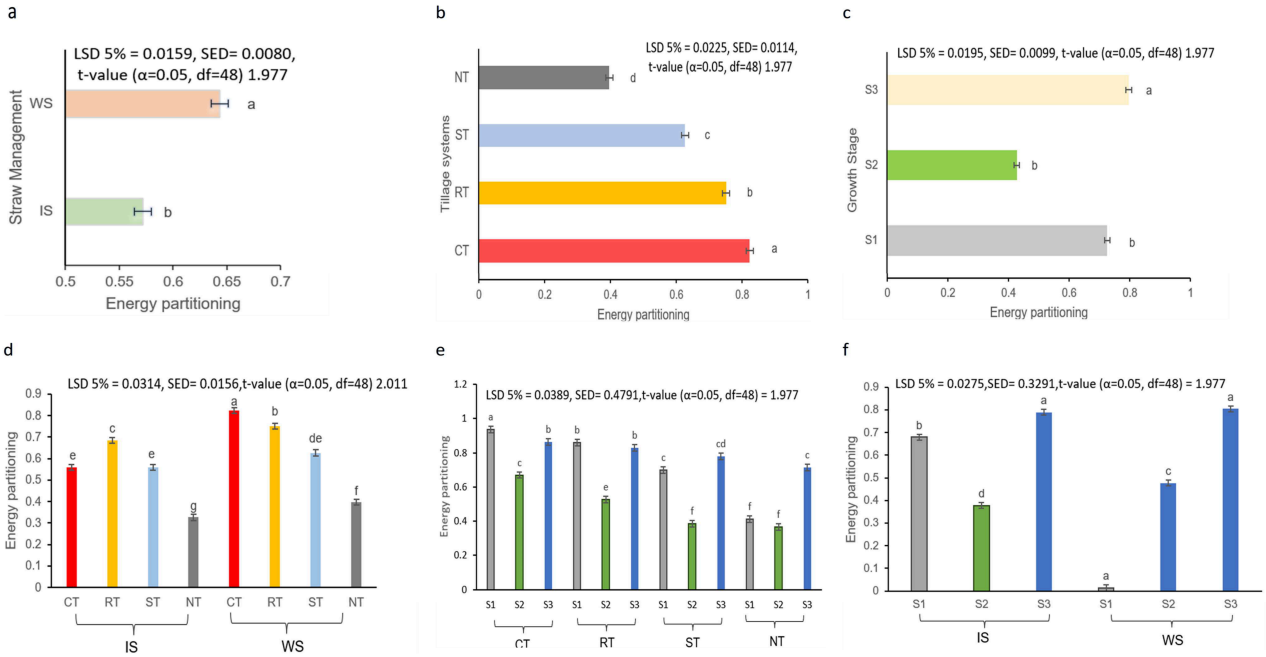


Figure 3. Effects of straw management, tillage system, and wheat growth stage on the energy partitioning ratio (EP). Mean effects (**a**–**c**) and two-way interactions (**d**–**f**). Letters above bars denote significant groupings at $p \leq 0.05$.

3.4. Relative Contribution of Experimental Factors to SEB Variability

To complement the ANOVA significance tests, variance partitioning analysis was performed to quantify the relative contribution (effect size) of each experimental factor to the variability of the analysed surface energy balance components (Figure 4). Growth stage accounted for 44.93% of the total variance in Rn, 51.98% in H, 48.68% in LE, 42.46% in EP, and 58.27% in Bowen ratio.

Tillage system represented the second most important source of variation, contributing between 23.34% and 34.78% depending on the variable analysed. Straw management explained a smaller but still substantial proportion of variance, ranging from 11.08% for Bowen ratio to 16.31% for LE.

Interaction terms generally contributed less than 4% of total variance, while residual variance remained minimal across all variables. These results indicate that crop phenology exerted the strongest control over surface energy dynamics, although management practices also played a major role in determining energy partitioning patterns.

3.5. Correlation Analysis Among SEB Variables and Experimental Factors

Pearson correlation analysis revealed strong relationships among energy balance components and management factors (Table 6). Net radiation showed a strong positive correlation with LE (r = 0.856, $p < 0.001$) and a weaker positive relationship with H (r = 0.312, $p < 0.01$). In contrast, Rn was negatively correlated with both the EP (r = −0.534, $p < 0.001$) and Bowen ratio (r = −0.678, $p < 0.001$). Complete treatment combinations for Bowen ratio and energy partitioning are presented in Supplementary Table S2.

Sensible heat flux exhibited strong positive correlations with EP (r = 0.867, $p < 0.001$) and Bowen ratio (r = 0.912, $p < 0.001$), whereas LE showed strong correlations with both variables (r = −0.789 and −0.845, respectively). As expected, EP and Bowen ratio were strongly positively correlated (r = 0.956, $p < 0.001$).

Regarding management factors, tillage system showed strong positive correlations with LE (r = 0.789, $p < 0.001$) and negative correlations with H, EP, and Bowen ratio. Straw management also correlated positively with LE and negatively with thermal partitioning in-

dicators. Growth stage exhibited significant relationships with all energy balance variables, particularly with Rn and LE.

Table 6. Pearson correlation coefficients (r) among Rn, H, and LE in (W m^{-2}) and experimental factors.

Variable	Rn	H	LE	H/Rn	Bowen	Straw	Tillage	Stage
Rn	1	0.312 **	0.856 ***	−0.534 ***	−0.678 ***	0.456 **	0.678 ***	0.567 ***
H	0.312 **	1	−0.234 *	0.867 ***	0.912 ***	−0.123 ns	−0.567 ***	−0.234 *
LE	0.856 ***	−0.234 *	1	−0.789 ***	−0.845 ***	0.567 ***	0.789 ***	0.456 ***
H/Rn	−0.534 ***	0.867 ***	−0.789 ***	1	0.956 ***	−0.456 **	−0.678 ***	−0.345 **
Bowen	−0.678 ***	0.912 ***	−0.845 ***	0.956 ***	1	−0.567 ***	−0.789 ***	−0.456 ***
Straw	0.456 **	−0.123 ns	0.567 ***	−0.456 **	−0.567 ***	1	0.000 ns	0.000 ns
Tillage	0.678 ***	−0.567 ***	0.789 ***	−0.678 ***	−0.789 ***	0.000 ns	1	0.000 ns
Stage	0.567 ***	−0.234 *	0.456 ***	−0.345 **	−0.456 ***	0.000 ns	0.000 ns	1

Significance levels are indicated as *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$, and ns: not significant.

No significant correlations were observed among the experimental factors themselves, confirming the independence and orthogonality of the experimental design.

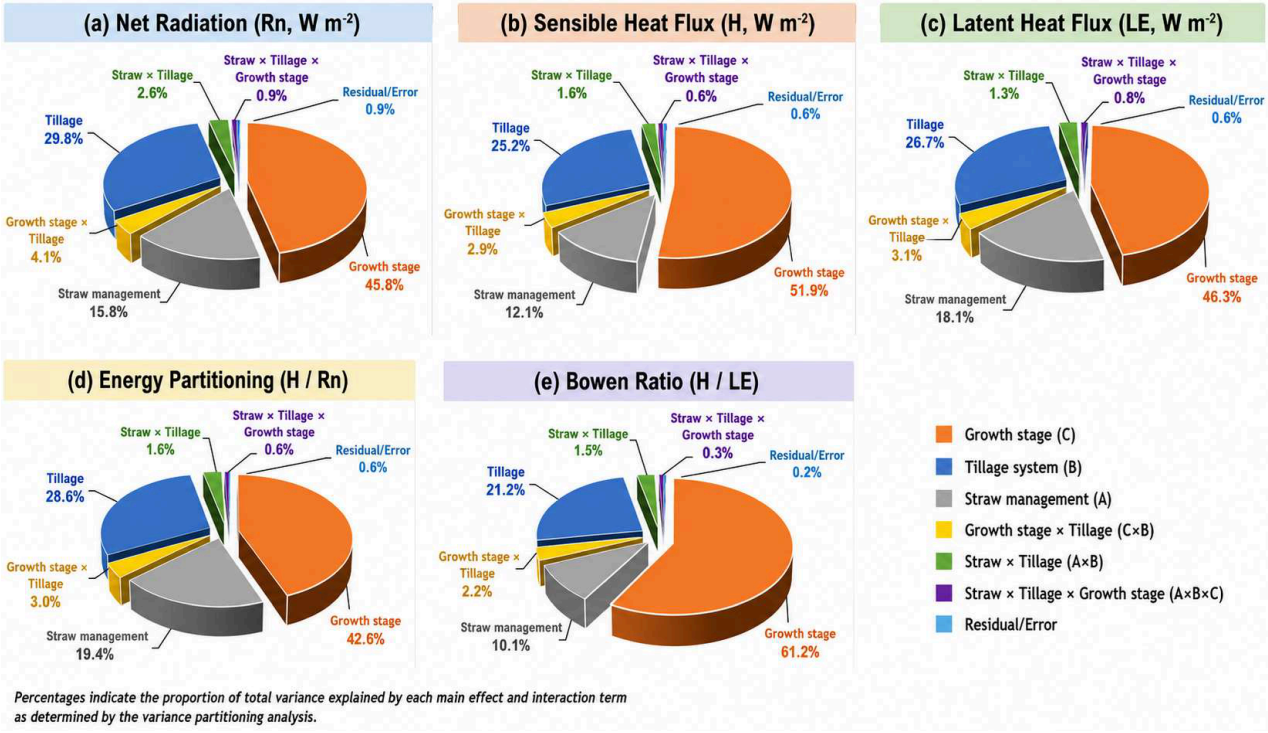


Figure 4. Relative contribution of straw management, tillage system, and growth stage to the variability of surface energy balance components. Percentage contribution of the main experimental factors, their interactions, replication, and residual variance to the total variability in net radiation (**a**), sensible heat flux (**b**), latent heat flux (**c**), energy partitioning (**d**), and Bowen ratio (**e**).

4. Discussion

4.1. Influence of Straw Management, Tillage Systems, and Crop Phenology on Surface Energy Balance Components

The results demonstrate that straw management, tillage systems, and growth stages significantly influenced surface energy balance dynamics under semi-arid conditions, confirming that both management practices and crop phenology play important roles in regulating thermal partitioning in wheat agroecosystems. Among the evaluated factors, growth stage consistently exerted the strongest influence on Rn, H, and LE, as indicated

by both ANOVA and variance partitioning analyses. This dominant phenological control reflects the major influence of canopy development, transpiration activity, and radiation interception on land–atmosphere energy exchange processes [26,28,29]. The marked increase in LE during S2 coincided with the period of maximum canopy development and transpiration activity. At this stage, enhanced canopy cover and stomatal conductance likely promoted stronger evaporative cooling and greater partitioning of available energy into latent heat flux. In contrast, S3 exhibited the highest H values, reflecting reduced transpiration capacity and greater direct heating of the soil and near-surface atmosphere following canopy senescence. Similar seasonal transitions from latent to sensible heat dominance have been reported in wheat and other annual cropping systems under water-limited conditions [12,20,34]. The tillage system also exerted a strong influence on SEB components. The progressive increase in LE and corresponding reduction in H from CT to NT indicate that conservation-oriented tillage systems substantially modified thermal partitioning. NT treatments consistently promoted greater latent heat exchange and lower sensible heating, which was accompanied by higher estimated soil moisture contents across all growth stages (Supplementary Table S3). These observations support the interpretation that conservation-oriented tillage enhanced soil moisture conservation and reduced resistance to water vapour transfer. These findings agree with previous studies showing that reduced soil disturbance improves aggregate stability, infiltration behaviour, surface roughness, and soil water retention, thereby favouring evaporative cooling processes [20,35,36]. The observed reduction in H under NT is particularly important in semi-arid systems, where excessive sensible heating may intensify canopy thermal stress and atmospheric evaporative demand [9].

Straw incorporation additionally enhanced LE and promoted more favourable thermal partitioning conditions. Residue retention likely reduced direct soil exposure, moderated soil temperature fluctuations, and contributed to higher soil moisture contents observed under straw incorporation treatments (Supplementary Table S3), thereby favouring latent heat exchange. Previous studies have similarly shown that crop residues can alter surface radiative properties, reduce evaporative resistance, and modify the partitioning of available energy between sensible and latent heat fluxes [18,37]. Although the influence of SM on H was less pronounced than that of TS or growth stages, its consistent effects on LE and thermal partitioning indicators suggest that residue management contributes meaningfully to SEB regulation under semi-arid conditions.

4.2. Interaction Effects and Thermal Partitioning Responses

The significant interaction effects observed among SM, TS, and growth stages indicate that SEB responses were strongly dependent on the combined influence of management and crop phenology. In particular, the combination of straw incorporation and no-tillage during flowering consistently produced the most favourable energy partitioning pattern, characterised by enhanced latent heat exchange and reduced sensible heating.

The strong contrast between the most conservation-oriented and the most intensive management combinations highlights the importance of integrated conservation practices in regulating thermal dynamics under semi-arid conditions. Under no-tillage during S2, latent heat exchange became the dominant pathway for energy dissipation, whereas CT during early growth promoted strong sensible heating and minimal evaporative cooling. These differences likely resulted from combined effects on soil moisture availability, canopy development, surface roughness, and resistance to vapour transfer. Similar interactions between conservation management and crop development have been described in previous studies examining land–atmosphere exchanges under dryland agricultural systems [18,34]. The progressive reduction in β from CT to NT further demonstrates the

capacity of conservation tillage systems to shift surface energy partitioning towards latent heat dominance. High β values observed under CT, particularly during S1, indicate that a large proportion of available energy was converted into sensible heat, potentially intensifying near-surface thermal stress. Conversely, the low β values recorded under NT during flowering suggest that most available energy was dissipated through evapotranspiration processes. Similar reductions in Bowen ratio under conservation agriculture systems have been associated with improved soil moisture conditions and greater canopy-mediated evaporative cooling [38,39].

The EP results showed patterns consistent with those observed for β. Lower EP values under NT and straw incorporation indicate reduced conversion of available energy into sensible heating relative to net radiation input. The S2 consistently produced the lowest EP values across management systems, confirming that this period represented the most favourable stage for latent heat dissipation. Together, the β and EP results demonstrate that conservation-oriented management practices substantially altered surface thermal dynamics, particularly during periods of maximum crop activity.

The interaction analyses also indicate that management effects were strongly stage-dependent. CT was particularly detrimental during early growth stages, when limited canopy cover exposed the soil surface directly to solar radiation and favoured sensible heat dominance. In contrast, conservation practices became especially effective during flowering, when higher canopy development and soil moisture availability enhanced latent heat exchange. These findings reinforce the importance of considering crop phenology when evaluating the effectiveness of conservation agriculture practices under semi-arid environments.

Together, these findings suggest that conservation-oriented management may modify surface energy partitioning through interconnected physical and physiological processes. Higher soil moisture availability may favour evapotranspirative fluxes, thereby shifting a greater proportion of the available energy towards latent rather than sensible heat exchange.

4.3. Relative Importance of Management and Phenological Controls

Variance partitioning analysis provided additional insight into the relative contribution of experimental factors to SEB variability. Growth stage explained between 42% and 58% of total variance across the analysed variables, confirming that crop phenology represented the dominant control on energy balance dynamics. These results are consistent with previous studies demonstrating that seasonal canopy development strongly regulates radiation interception, transpiration, and turbulent energy exchange in agricultural systems [26,29].

Although secondary to phenology, tillage system still explained a substantial proportion of variability, particularly for LE and thermal partitioning indicators. This finding highlights the important role of soil physical conditions in controlling energy exchange processes under semi-arid environments. Differences in soil disturbance likely altered porosity, aggregation, infiltration behaviour, surface roughness, and soil water storage, thereby influencing the balance between sensible and latent heat fluxes [31].

Straw management explained a smaller but still meaningful proportion of variance, especially for LE. Residue retention influences surface albedo, soil moisture conservation, and thermal buffering, thereby contributing to modifications in SEB dynamics [23]. Although interaction terms generally accounted for less than 4% of total variance, their statistical significance indicates that management responses cannot be interpreted independently of crop growth stage. The relatively low residual variance further suggests that the experimental design successfully captured the major sources of variation affecting energy partitioning during the study period.

4.4. Relationships Among Energy Balance Components

The correlation analysis identified strong statistical associations among the measured SEB components. The positive association between Rn and LE indicates that periods or treatments with greater available energy also tended to exhibit greater latent heat exchange. Conversely, the negative associations of LE with EP and β indicate that greater latent heat flux coincided with a lower relative contribution of sensible heating. These relationships are consistent with the mathematical definitions of EP and β and should not be interpreted as evidence of independent causal effects.

The positive associations of H with EP and β were also expected because H is included directly in the calculation of both ratios. Consequently, these correlations primarily describe the internal structure of the energy-partitioning metrics rather than separate mechanistic relationships. Similar relationships between conservation agriculture practices and latent heat dominance have been reported in previous SEB studies under dryland agricultural conditions [9,40].

Associations between management treatments and energy-balance variables were consistent with the treatment contrasts identified by ANOVA. Nevertheless, the correlation analysis alone cannot establish that changes in soil moisture, hydraulic functioning, or canopy processes caused the observed flux responses. These mechanisms are proposed as plausible interpretations based on the experimental treatment effects, the supplementary soil-moisture information, and previous literature.

4.5. Implications for Semi-Arid Wheat Production and Study Limitations

The observed differences in thermal partitioning among management systems have important implications for wheat production under increasingly water-limited and high-temperature conditions. Conservation-oriented practices, particularly NT combined with straw incorporation, consistently promoted greater evaporative cooling and reduced sensible heating during critical growth stages. These effects may contribute to improved microclimatic conditions, reduced canopy thermal stress, and potentially greater water use efficiency (WUE) under semi-arid environments. This interpretation is consistent with the higher estimated soil moisture values observed under no-tillage and straw incorporation treatments (Supplementary Table S3).

The substantial increase in LE under conservation-oriented tillage indicates that a greater proportion of the available energy was dissipated through evapotranspirative processes rather than sensible heating. Although this pattern may favour canopy cooling, water-use efficiency was not measured directly and cannot be inferred from LE alone. Future studies should combine energy-flux measurements with evapotranspiration, biomass, and grain-yield data to determine whether the observed thermal responses translate into improved water-use efficiency.

The results showed a reduction in H under conservation tillage systems, suggesting lower canopy and near-surface thermal loading compared with CT. Although canopy temperature was not measured directly, the reduced sensible heat exchange indicates a greater potential for evaporative cooling under conservation-oriented management, particularly during the flowering stage. This cooling influence is especially valuable during flowering, the most sensitive period for yield formation, when heat stress can induce pollen sterility and substantial yield losses [19]. Indeed, the S2 emerged as the period most responsive to management-induced changes in EP, highlighting the importance of practices that maintain soil moisture and promote latent heat exchange during this critical developmental phase. Such practices may therefore contribute to mitigating crop heat stress under future climate scenarios. In contrast, the consistently high H values observed during S3 suggest that sensible heat dominance becomes increasingly difficult to mitigate

once canopy senescence has occurred. Under the environmental conditions of the present experiment, these findings highlight the potential contribution of conservation agriculture to climate-resilient wheat production under increasingly hot and water-limited conditions.

Several limitations should nevertheless be acknowledged. The study was conducted during a single growing season under site-specific environmental conditions, which may limit extrapolation to other climatic years or agroecological settings. In addition, soil heat flux was not directly quantified, and the study focused primarily on field-scale thermal partitioning dynamics rather than complete energy balance closure. Furthermore, the experiment was conducted under relatively homogeneous soil and climatic conditions, and therefore, broader spatial variability was not assessed. The experiment used three replications, which is standard practice in many agricultural field experiments; however, this may limit the statistical power to detect relatively small treatment effects and the robustness of treatment comparisons under field conditions. Although the high F-values and low coefficients of variation indicate that experimental error was well controlled, additional replications across sites and growing seasons would further strengthen the robustness and generalisability of the findings.

Future research should evaluate long-term responses across multiple seasons and environmental conditions while integrating continuous soil moisture monitoring, canopy temperature measurements, and broader micrometeorological observations. Greater integration between SEB measurements, crop physiological responses, and water use efficiency analyses would also improve understanding of how conservation agriculture practices regulate land–atmosphere interactions under semi-arid agricultural systems.

5. Conclusions

This study demonstrated that straw management, tillage systems, and growth stages significantly influenced surface energy balance dynamics in a semi-arid wheat production system during the 2022–2023 growing season. Among the evaluated factors, growth stage exerted the strongest control over net radiation, sensible heat flux, latent heat flux, Bowen ratio, and energy partitioning, confirming the dominant role of crop phenology in regulating land–atmosphere energy exchanges. The flowering stage consistently promoted the highest latent heat fluxes and the lowest Bowen ratio and energy partitioning values, indicating that this period represented the most favourable conditions for evaporative cooling and latent heat dissipation.

Tillage system represented the second most influential factor affecting thermal partitioning. Under the conditions evaluated in this study, conservation-oriented practices, particularly NT, increased latent heat exchange while reducing sensible heating relative to CT. Straw incorporation was also associated with more favourable energy-partitioning conditions and higher estimated soil moisture values. The combination of straw incorporation and NT during flowering consistently produced the highest latent heat fluxes and the lowest thermal partitioning indicators, demonstrating their potential to enhance evaporative cooling under the environmental conditions evaluated in this experiment.

The results further showed that management effects were highly dependent on crop phenology. CT promoted sensible heat dominance, especially during early growth stages characterised by limited canopy cover, whereas conservation-oriented systems became particularly effective during flowering, when greater transpiration activity enhanced latent heat exchange. Variance partitioning analysis additionally confirmed that, although management practices significantly affected SEB dynamics, crop growth stage remained the dominant source of variability across all analysed variables.

The strong relationships observed among latent heat flux, Bowen ratio, and energy partitioning indicate that conservation agriculture practices can substantially modify thermal

dynamics in semi-arid wheat systems. By promoting latent heat exchange and reducing sensible heating, these practices may contribute to improved microclimatic regulation under environmental conditions comparable to those evaluated in this experiment.

For farmers, the results suggest that combining no-tillage with straw incorporation may enhance evaporative cooling; however, its effects on water-use efficiency require direct evaluation. For land managers and policymakers, these findings support the promotion of conservation agriculture as a climate adaptation strategy in semi-arid environments, with particular emphasis on maintaining conservation practices throughout crop development to reduce thermal stress and improve system resilience.

Although the experiment was conducted during a single growing season and under site-specific conditions, the results provide important field-based evidence regarding the interaction between crop phenology and conservation-oriented soil management in regulating surface energy dynamics under semi-arid environments. Future research should expand these analyses across multiple seasons and environmental conditions while integrating continuous soil moisture, canopy temperature, and broader micrometeorological measurements to improve understanding of management-induced modifications in land–atmosphere interactions and their implications for climate-adaptive wheat production systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app16147173/s1, Table S1: Three-way interaction effects of straw management, tillage system, and wheat growth stage on Rn, H, and LE (W m^{-2}); Table S2: Complete treatment combinations for Bowen ratio (β) and energy partitioning (EP) under different straw management, tillage systems, and wheat growth stages; Table S3: Volumetric soil moisture content (cm^3 cm^{-3}) under the different straw management, tillage, and wheat growth stage combinations.

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