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Impact of climate-resilient technologies on the physiological studies of soybean-wheat cropping systems

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Abstract
The adoption of climate-resilient technologies can significantly influence the growth and productivity of soybean-wheat cropping systems by enhancing their ability to withstand climate variability and stressors. A field experiment was conducted during the *kharif* as well as *rabi* seasons of 2020-21 and 2021-22 at CAAST-CSAWM Farm, Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri, Dist-Ahilyanagar (M.S.) The research experiments were aimed to study the effect of climate resilient technologies on growth attributes in soybean- wheat cropping system. The present research was conducted using a strip-split-plot design with three replications. Results from the two-year study revealed that conventional tillage (T_1) in the horizontal plot, combined with residue management (R_2) in the vertical plot, and the use of BBF for soybean and FIRB for wheat, significantly maximum chlorophyll content, photosynthetic rate, CO_2 concentration, transpiration rate, stomatal conductance and long with reduced leaf temperature and stomatal resistance in the soybean-wheat cropping system.

Keywords: Climate resilient technologies, soybean-wheat and cropping systems

Introduction
Climate-resilient technologies are innovative solutions that help sectors like agriculture, water management, energy, and infrastructure adapt to climate change by reducing vulnerabilities and maintaining productivity. Examples include drought- and flood-resistant crops, precision farming, climate-smart practices, efficient irrigation, adaptive livestock management, water harvesting, flood barriers, early warning systems, and renewable energy.

Tillage significantly impacts soil properties and crop yield, contributing up to 20% to crop production. Proper tillage improves soil constraints, while excessive or improper tillage can harm soil structure, increase erosion, deplete organic matter, and disrupt nutrient and water cycles, compromising sustainability (Khurshid *et al.*, 2006) [7]. Conventional tillage involves extensive soil preparation but raises concerns about compaction, erosion, and greenhouse gas emissions. Advances like GPS-guided systems improve efficiency, while alternatives such as no-till and minimum tillage focus on reducing soil disturbance, conserving water, enhancing soil health, and sequestering carbon. These sustainable practices, supported by policies and research, contribute to soil conservation, nutrient cycling, and environmental sustainability in modern agriculture. Burning crop residues in India harms the environment, releasing greenhouse gases and nutrient loss. However, crop residues offer benefits like improving soil health, conserving moisture, reducing erosion, and providing nutrients. Reduced tillage enhances soil organic carbon and promotes long-term sustainability in agriculture (Verhulst *et al.*, 2011 and Aulakh *et al.*, 2012) [1].

Land configuration influences crop management practices like nutrient application, irrigation, and weed control. Proper configurations, tailored to regional climates (e.g., heavy rainfall, drought, salinity), help conserve rainwater, reduce soil erosion, and manage water stress. Techniques like broad bed and furrow or ridges and furrows improve water infiltration, increasing crop yield and addressing water crises by ensuring efficient water use and proper drainage (Deshmukh *et al.*, 2016) [3].

The soybean-wheat cropping system enhances soil health, boosts productivity, and supports sustainability. Soybeans fix nitrogen, benefiting wheat, while crop rotation reduces pests and improves soil fertility. This system increases farm profitability, conserves resources, and enhances climate resilience, making it a sustainable and economically viable practice that contributes to food security (Behera *et al.*, 2010) [2].

Materials and Methods

The experiment was conducted at the Centre for Advanced Agricultural Science and Technology for Climate Smart Agriculture and Water Management (CAAST-CSAWM) Farm, Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri, District-Ahilyanagar (M.S.) during the two consecutive years of 2020- 21 and 2021-22. Geographically the research farm located between latitude 19322' 26" N and longitude 74655' 25" E, at an elevation of 602.6 + 11m above MSL in the scarcity zone of Western Maharashtra which comes under the Western Plateau and Hilly Region of India. The soil of the experimental field was medium black Vertic which comes under great group Haplustept (Inceptisol) and clay in texture. The bulk density of the soil was 1.31 mg m-3 and porosity (54.12%) the per cent moisture held at FC and PWP of the soil was 32.90 and 16.90 per cent, respectively. The soil was moderately alkaline in reaction with soil organic carbon content (0.54%) pH 8.26 and EC (0.23dSm-1). It was low in available N (181.30 kg ha-1), available P was medium (15.20 kg ha-1) and very high in available K (415.04 kg ha-1).

Employing a strip-split-plot design, the research experiment was organized into three replications. Here, the horizontal plots were allocated to the different tillage practices, and vertical plot allocated residues management while the subplots were dedicated to the distinct layouts. The horizontal plots included three tillage practices: T_1 - conventional tillage, T_2 - minimum tillage, and T_3 - zero tillage. The vertical plots comprised residue management treatments: R_1 - without residue and R_2 - with residue. Sub-plot treatments consisted of three layout designs: L_1 - flat bed, L_2 - broad bed furrow (BBF), and L_3 - furrow irrigated raised bed (FIRB). Thus, the entirety of the experiment encompassed a total of 54 distinct treatments. The seeds of soybean variety Phule Kalyani (DS-228) were sown using a seed drilling machine with a spacing of 30 x 15 cm, while the seeds of wheat variety Phule Samadhan were sown using a Happy Seeder machine with 22.5 cm line spacing.

(Note: The data from the Kharif soybean trial (2020-21) showed non-significant results due to the absence of crop residue addition during the experiment. However, after the soybean harvest, residues were incorporated during the Rabi season (2020-21), resulting in significant findings for the Rabi wheat crop).

Data on various growth parameters was recorded under field condition. The technique followed for recording each of the observations is outlined in table 1.

Table 1: The technique followed for recording each of the observations is outlined

Sr. No	Particulars	Procedure / formula	Period
1.	Photosynthetic rate (μ mol m^{-2} s^{-1})	Physiological parameters *viz.*, photosynthetic rate, stomatal conductance, CO_2 concentration, transpiration rate, leaf temperature and stomatal resistance were recorded by using Portable Photosynthesis System (IRGA) LI -COR make LI 6400XT periodically at an interval of 15 days starting from 30 DAS to 90 DAS in respect of both the crops (*kharif* soybean and *rabi* wheat). The observations were recorded between 11-13 hrs. at every time.	28, 56, 84, and at harvest
2.	CO_2 Concentration (μ mol Co_2 m^{-2} s^{-1})		28, 56, 84, and at harvest
3.	Transpiration rate (m mol H_2O m^{-2} s^{-1})		28, 56, 84, and at harvest
4.	Stomatal conductance (m mol m^{-2} s^{-1})	Principle:- Infrared Gas Analyzers (IRGA) are used for the measurement of a wide range of hetero atomic gas molecules including CO_2, H_2O, NH_3, CO, SO_2, N_2O, NO and gaseous hydrocarbons like CH_3. Heteroatomic molecules have characteristic of absorption spectrum in the infrared region. Therefore absorption of radiation by a specific hetero atomic molecule is directly proportional to its concentration in an air sample	28, 56, 84, and at harvest
5.	Leaf temperature (^{0}C)		28, 56, 84, and at harvest
6.	Stomatal resistance (μ mol m^{-2} s^{-1})		28, 56, 84, and at harvest
7.	Chlorophyll content (%)	Treatment wise SPAD reading was recorded from sample plants by Chlorophyll Meter (SPAD-502) and expressed in percentage	28, 56, 84, and at harvest

The data on various parameters was subjected to statistical analysis by employing standard statistical methods for Strip Split Plot Design as proposed by Panse and Sukhatme [10].

Results and Discussion

Soybean

Cholorophyll Content (%)

The data in Table 2 showed that maximum chlorophyll content was observed during both years of experimentation. At 56 DAS, the maximum chlorophyll content was observed under conventional tillage, with (54.56%) in 2020 and (55.90%) in 2021. Whereas the lowest chlorophyll content was recorded under zero tillage in both years. The higher chlorophyll content in conventional tillage is attributed to better soil conditions, such as improved aeration, nutrient availability, and moisture retention, which promote plant growth and chlorophyll production. These results are supporeted by Zhang *et al.* (2017) and Salar *et al.* (2021) in Soybean [11, 16].

The treatments with residue management of soybean recorded numerically maximum chlorophyll content at 56 DAS (52.46%) during 2020. However, in 2021 significantly higher chlorophyll content were observed (54.02%) as shown in Table 2. Conversely, the minimum chlorophyll content were observed under without residue in both years. Residue management increased chlorophyll content by improving soil moisture and nutrient retention, supporting plant nutrient uptake and metabolism, consistent with Xiao-li *et al.* (2015) [15].

The Broad Bed Furrow (BBF) system recorded the highest chlorophyll content in soybean at 56 DAS, with (53.59%) in 2020 and (54.97%) in 2021 (Table 2), while the flat bed system showed the lowest values in both years. The BBF system improved chlorophyll levels by enhancing soil drainage, aeration, and moisture retention, leading to better nutrient uptake and photosynthesis. Proper water management remains essential in low-rainfall areas. These findings are supported by Jat *et al.* (2019) [6].

Photosynthetic Rate (μ mol m-2 s-1)

The significantly higher photosynthetic rate (21.57) in 2020 and (22.51) in 2021 at 56 DAS respectively) were recorded in conventional tillage practice (Table 2). Similarly, the zero tillage practice registered significantly minimum photosynthetic rate during both the years. Improved soil physical conditions under conventional tillage promote better plant growth and increased absorption of photosynthetically active radiation (PAR), leading to enhanced photosynthetic rates. This trend is consistent with previous research, such as the findings of Tang *et al.* (2016) [13].

With residue management recorded numerically higher photosynthetic rate at 56 DAS (20.83) in 2020. In the year 2021, significantly higher photosynthetic rate was observed (22.04). Conversely, the minimum photosynthetic rate was observed under the without residue in both years. Crop residue management improves the photosynthetic rate in soybean by enhancing soil moisture retention, nutrient availability, and temperature regulation. It also reduces soil erosion, supports vigorous growth, and increases light interception, leading to higher photosynthesis. These results align with Zhang *et al.* (2017) [16].

The broad bed furrow system for soybean recorded significantly higher photosynthetic rate (21.77) in 2020 and (22.67) in 2021 respectively) (Table 2). In contrast, the lowest photosynthetic rate was observed under the flat bed system in both years. Broad bed furrow (BBF) systems enhance photosynthesis in soybean by improving soil drainage, aeration, and moisture conservation, which promote stronger root growth and greater nutrient uptake. These improvements lead to better vegetative development and larger canopy size, resulting in increased light interception and more efficient photosynthesis. Similar results were reported by Jat *et al.* (2019) [6].

CO2 Concentration (μ mol CO_2 m-2 s-1)

Significantly higher CO2 concentration was observed under conventional tillage practice, recording 384.44 in 2020 and 391.89 in 2021 at 56 DAS (Table 2). Conversely, zero tillage consistently resulted in the lowest CO2 Concentration across both years. Conventional tillage increased CO_2 concentration by improving soil aeration, microbial activity, and root respiration, leading to healthier crop growth, greater canopy development, and enhanced CO_2 uptake through higher evapotranspiration. Similar observations were made by Zhang *et al.* (2017) [16].

Treatments incorporating residue management recorded numerically higher CO2 concentration at 56 DAS in 2020 (380.41). In 2021, this treatment showed significantly greater CO2 concentration (388.56) In contrast, the absence of residue management consistently resulted in the lowest CO2 concentration across both years. Crop residues increase CO_2 concentration in soybean by improving soil moisture, nutrient availability, and root development and canopy growth, which enhanced crop uptake. This, in turn, increased leaf area and transpiration rate, leading to higher CO_2 intake. These findings are supported by Zhang *et al.* (2017) [16].

The broad bed furrow (BBF) system also demonstrated that significantly higher CO2 concentration, recording (382.33) in 2020 and 389.94 in 2021 (Table 2). Conversely, the flat bed system consistently recorded the minimum CO2 concentration during both years. The BBF system enhances CO_2 concentration in soybean crops by improving soil aeration, moisture retention, and nutrient availability, leading to better root and canopy growth, increased photosynthesis, and improved crop performance as supported by Jat *et al.* (2006) [5].

Transpiration rate (m mol H2O m-2 s-1)

Significantly higher transpiration rate was observed under conventional tillage, with values of (8.36) in 2020 and (8.69) in 2021 at 56 DAS (Table 2). However, in 2020, this rate was statistically comparable to that under minimum tillage. In contrast, zero tillage consistently recorded the lowest transpiration rate across both years. The higher transpiration rate observed under conventional tillage may be due to optimal moisture availability in the root zone, which enhances water uptake and promotes greater stomatal opening, thereby increasing evapotranspiration. These results are consistent with the findings of Morio *et al.* (2007) and Tang *et al.* (2016) [13].

Residue management treatments recorded numerically higher transpiration rate at 56 DAS in 2020 (7.71). In 2021, the residue management treatments significantly increased transpiration rate to (7.87). Conversely, the without residue consistently resulted in the lowest transpiration rate during both years. The application of crop residue significantly increased the transpiration rate by improving soil properties and microbial activity, which enhanced moisture and nutrient availability, leading to better canopy development and greater light interception. These findings align with Zhang *et al.* (2017) [16].

The Broad Bed Furrow (BBF) system recorded a significantly higher transpiration rate, with values of 8.16 in 2020 and 8.46 in 2021 (Table 2), while the Flat Bed system consistently showed the lowest transpiration rates in both years. The Broad Bed Furrow (BBF) system increases soybean transpiration by enhancing soil drainage, moisture retention, and root development, which support better water uptake and canopy growth. This leads to improved stomatal activity and higher transpiration, as noted by Jat *et al.* (2006) [5].

Stomatal conductance (m mol m-2 s-1)

Conventional tillage recorded significantly higher stomatal conductance at 56 DAS, with values of (0.314) in 2020 and (0.342) in 2021 (Table 3). In contrast, the lowest stomatal conductance was observed under zero tillage during both years. In conventional tillage, healthy and vigorous crop growth indicates optimal soil moisture, which increases turgor pressure in plant cells, ultimately opens the stomata resulted in increase the stomatal conductance. These findings are conformity with those reported by Tang *et al.* (2016) and Zhang *et al.* (2017) [13, 16].

The treatment with residue management also numerically maximum stomatal conductance, recording (0.273) in 2020 and, In 2021, the residue management treatments significantly increased stomatal conductance to (0.305), while treatments without residue showed the lowest values. Applying crop residue helps retain optimal soil moisture in the root zone throughout plant growth, which increases cell water potential and turgidity, leading to greater stomatal opening and higher stomatal conductance similar to findings by Zhang *et al.* (2017) [16].

Similarly, the broad bed furrow system achieved the maximum stomatal conductance (0.283 in 2020 and 0.307 in 2021), the broad bed furrow (BBF) system improves stomatal conductance in soybean by enhancing soil drainage, moisture retention, and root development, which support water uptake, maintain turgor pressure, and promote canopy growth aligning with findings by Jat *et al.* (2006) [5].

Leaf temperature (0C)

A significantly higher leaf temperature was observed under conventional tillage, with values of 26.57°C in 2020 and 27.91°C in 2021 at 56 DAS are presented in Table 2. In contrast, zero tillage recorded the minimum leaf temperature across both years. Conventional tillage causes greater evaporation and reduced soil moisture, limiting transpiration and raising leaf temperatures, whereas zero tillage conserves moisture in the root zone, meeting crop evaporative demand. These findings align with those reported by Zhang *et al.* (2017) [16].

Residue management treatments recorded numerically minimum leaf temperature at 56 DAS in 2020 (25.54°C), and significantly minimum leaf temperature in 2021 (26.03°C). Conversely, the without residue resulted in the maximum leaf temperature during both years. The application of crop residue significantly minimum leaf temperature might be due to addition of crop residue in the soil surface which reducing the evaporation losses and increasing water availability for the crop. Whereas the without crop residue caused more water evaporation, which reducing the transpiration rate and raised the leaf temperature.

The Broad Bed Furrow (BBF) system recorded significantly minimum leaf temperatures, with values of (24.85°C) in 2020 and (25.79°C) in 2021 (Table 2), compared to the flat bed system, which showed the maximum leaf temperatures in both years. Despite the higher leaf temperatures, the BBF system enhances soil moisture retention, drainage, and root development, leading to improved transpiration efficiency and supporting optimal plant growth. Consistent with the findings of Jat *et al.* (2006) [5].

Stomatal resistance (µ mol m-2 s-1)

Significantly minimum stomatal resistance values of 3.23 in 2020 and 3.02 in 2021 at 56 DAS were observed under conventional tillage (Table 2), whereas zero tillage consistently recorded the maximum stomatal resistance in both years This might be due to moisture stress occurs throughout the crop growth period, which reduces transpiration and restricts CO_2 entry, ultimately leading to higher stomatal resistance in zero tillage practice. These findings are similar with those reported by Zhengkai *et al.* (2019) [17].

Residue management recorded a numerically minimum stomatal resistance at 56 DAS in 2020 (3.76), while in 2021, a significantly minimum value of (3.44) was observed. In contrast, the maximum stomatal resistance was consistently recorded in the plots without residue during both years. Higher stomatal resistance in without residue management treatments throughout crop growth stages is likely due to low soil moisture, which reduces guard cell turgor, partially closing stomata. These findings align with Zhengkai *et al.* (2019) [17]. The Broad Bed Furrow (BBF) system for soybean recorded significantly minimum stomatal resistance, with values of (3.59) in 2020 and (3.33) in 2021 (Table 2). In contrast, the flat bed system exhibited the maximum stomatal resistance in both years. BBF systems improve soil moisture retention and aeration, reducing waterlogging and maintaining turgor pressure in guard cells, which lowers stomatal resistance and enhances gas exchange. These systems also stabilize microclimatic conditions, supporting consistent plant physiology, as reported by Zhengkai *et al.* (2019) [17].

Wheat

Chlorophyll content (%)

Conventional tillage recorded the highest chlorophyll content at 56 DAS, with values of (52.77%) in 2020 and (54.12%) in 2021 (Table 3). In contrast, zero tillage resulted in the lowest chlorophyll content in both years. Conventional tillage enhances chlorophyll content by improving soil aeration, nutrient availability, and moisture conservation, supporting vegetative growth and efficient light energy harvesting. These results are in conformity with those reported by Zhang *et al.* (2014) and Salar *et al.* (2021) [11, 16].

Residue management also significantly maximum chlorophyll content, recording at 56 DAS (52.23)% 2020 and (53.77)% in 202 (Table 3), while treatments without residue showed the lowest values. Residue management increased chlorophyll content by improving soil moisture and nutrient retention, enhancing nutrient uptake and plant metabolism. These findings are accordance with Xiao-li *et al.* (2015) [15].

Similarly, the furrow-irrigated raised bed system achieved the highest chlorophyll content, at 56 DAS (52.84%) in 2020 and (54.19%) in 2021 (Table 3), The FIRB system increases the content of chlorophyll in wheat through the enhancement of nutrient uptake, retention of soil moisture, and minimization of abiotic stress, thus sustaining root function and stimulating chlorophyll biosynthesis and plant growth (Gupta and Sayre (2007) and Sayre & Hobbs (2017) [4, 12].

Photosynthetic rate (µ mol m-2 s-1)

Data presented in Table 3 indicated that conventional tillage recorded a significantly higher photosynthesis rate (29.64) in 2020 and (30.84) in 2021 at 56 DAS, and was statistically comparable to minimum tillage in 2021 (Table 3). In contrast, zero tillage consistently resulted in the lowest photosynthesis rate. The increased photosynthetic rate in conventional tillage can be due to better physical conditions of the soil that improve plant growth and PAR absorption and thus enhance photosynthesis following the observations by Li *et al.* (2006) and Tang *et al.* (2016) [8, 13].

Residue management treatments showed numerically higher photosynthesis rate at 56 DAS (29.10) in 2020) and significantly higher values in 2021 (30.45), while treatments without residue recorded the lowest photosynthesis rate in both years. Residue management increases wheat's rate of photosynthesis by improving moisture, nutrient status, and temperature in the soil, while inhibiting erosion and stimulating canopy growth and light interception. The results agree with those of Zhang *et al.* (2017) [16].

FIRB system achieved significantly higher photosynthesis rate (29.45) in 2020 and (30.62) in 2021 compared to the flat bed system, which consistently recorded the lowest values (Table 3). The FIRB system enhances wheat photosynthesis by allowing improved soil aeration, water retention, and nutrient uptake, while avoiding waterlogging and compaction. Increased root growth and canopy architecture enhance CO_2 uptake and light interception, resulting in increased photosynthetic efficiency. These results concur with Gupta and Sayre (2007) and Sayre and Hobbs (2017) [4, 12].

CO_2 concentration (µ mol CO_2 m-2 s-1)

Conventional tillage recorded the highest CO_2 concentration at 56 DAS, with (331.96) in 2020 and (337.09) in 2021, while zero tillage showed the lowest values. (Table 3) Conventional tillage increased CO_2 concentration by improving soil aeration, microbial activity, and root respiration, supporting vigorous crop growth and larger canopy area, which maximized light capture and CO_2 absorption. These results align with Zhang *et al.* (2017) [16].

Similarly, residue management registered significantly highest CO_2 concentration, recording (329.84) in 2020 and (335.27) in 2021, compared to lower values in treatments without residues. Crop residues enhance CO_2 concentration in soybean through enhanced soil moisture, nutrient content, and development of root and canopy, thereby increasing CO_2 uptake via increased leaf area and transpiration. This is as affirmed by Zhang *et al.* (2017) [16].

The FIRB system also increased CO_2 concentration, recording (332.19) in 2020 and (337.39) in 2021, while the flat bed system consistently had the lowest values (Table 3). The FIRB system enhances CO_2 concentration in wheat through enhanced root zone activity and soil conditions, promoting photosynthesis and productivity. These results concur with Gupta & Sayre (2007) and Sayre & Hobbs (2017) [4, 12].

Transpiration rate (m mol H2O m-2 s-1)

Data presented in Table 3 indicated that the conventional tillage recorded a significantly higher transpiration rate (7.75) in 2020 and (7.88) in 2021 at 56 DAS, and was statistically comparable to minimum tillage in 2020 (Table 3), whereas the zero tillage resulted in the minimum transpiration rate. Conventional tillage showed a higher transpiration rate due to optimal root zone moisture, which promoted greater water uptake and stomatal opening. These results align with Tang *et al.* (2016) and Zhang *et al.* (2017) [13, 16].

Residue management treatments showed significantly higher transpiration rate at 56 DAS (7.71) in 2020 and (7.87) in 2021 (Table 3), while treatments without residue recorded the lowest transpiration rate in both years. Higher transpiration rates are due to added organic matter improving soil conditions, which boosts moisture, nutrients, and light interception. These findings are supported by Zhang *et al.* (2017) [16].

The FIRB system recorded a significantly higher transpiration rate, with values of (7.75) in 2020 and (7.88) in 2021(Table 3), while the flat bed system consistently showed the lowest rates. FIRB system enhances wheat transpiration by enhancing soil drainage, water retention, and root growth, resulting in improved water intake and stomatal functioning. These results align with Gupta and Sayre (2007) and Sayre and Hobbs (2017) [4, 12].

Stomatal conductance (m mol m-2 s-1)

The data in Table 3 indicated that conventional tillage recorded significantly higher stomatal conductance at 56 DAS, with values of (0.401) in 2020 and (0.429) in 2021. In contrast, zero tillage consistently showed the lowest stomatal conductance in both years. Conventional tillage enhances stomatal conductance by promoting healthy crop growth and optimal soil moisture, which increases cell turgor and stomatal opening. These findings align with Tang *et al.* (2016) and Zhang *et al.* (2017) [13, 16].

Residue management increased significantly maximum stomatal conductance, recording (0.337) in 2020 and (0.356) in 2021, compared to lower values in treatments without residues. This is due to maintaining optimal soil moisture, which enhanced plant cell turgor and promoted stomatal opening. These findings are consistent with Zhang *et al.* (2017) [16].

The FIRB system also significantly increased stomatal conductance, recording (0.366) in 2020 and (0.384) in 2021, while the flat bed system had the lowest values (Table 3). The FIRB system enhances stomatal conductance and transpiration by improving soil conditions, root growth, and canopy structure, supporting efficient water uptake and gas exchange.

Leaf temperature (0C)

Zero tillage recorded the lowest leaf temperature at 56 DAS, with values of (24.02°C) in 2020 and (25.13°C) in 2021 (Table 3), while conventional tillage showed the highest leaf temperatures in both years. Increased leaf temperature in conventional tillage is because of increased loss of water by evaporation, whereas zero tillage maintains soil moisture, favors transpiration, and maintains low leaf temperatures. These results corroborate Zhang *et al.* (2017) [16].

Residue management significantly reduced leaf temperature, recording (21.65°C) in 2020 and (22.25°C) in 2021, whereas treatments without residue recorded higher temperatures. Crop residue decreased leaf temperature by minimizing evaporation and enhancing water supply, and the lack of residue resulted in greater evaporation, decreased transpiration, and higher leaf temperature. These results corroborate Jat *et al.* (2019) [6].

Similarly, the furrow-irrigated raised bed (FIRB) system recorded the lowest leaf temperatures, with (21.29°C) in 2020 and (23.86°C) in 2021.In FIRB systems, reduced leaf temperatures in wheat are due to enhanced soil moisture retention, enhanced temperature control, and enhanced air circulation, which increase transpiration and minimize heat transfer. These results are consistent with Gupta and Sayre (2007) and Sayre and Hobbs (2017) [4, 12].

Stomatal resistance (µ mol m-2 s-1)

Conventional tillage recorded significantly minimum stomatal resistance (2.69) in 2020 and (2.50) in 2021 at 56 DAS, while zero tillage consistently resulted in higher stomatal resistance (Table 3). This might be due to moisture stress occurs throughout the crop growth period, which reduces transpiration and restricts CO_2 entry, ultimately leading to higher stomatal resistance in zero tillage practice. These findings are similar with by Zhengkai *et al.* (2019) [17].

Residue management treatments recorded significantly minimum stomatal resistance, with values of (3.18) in 2020 and (3.0) in 2021, whereas treatments without residue showed the highest stomatal resistance in both years. This could be due to low soil moisture content throughout the crop growth period, which decreases the turgor pressure of guard cells, partially closing the stomata and ultimately increasing stomatal resistance. These findings are lines with by Zhengkai *et al.* (2019) [17].

The FIRB system recorded significantly minimum stomatal resistance, with values of (2.92) in 2020 and (2.80) in 2021, compared to the flat bed system, which consistently showed the highest values (Table 3). FIRB systems reduce stomatal resistance in wheat through enhanced soil aeration, moisture, and root function, which decrease water stress and enable greater transpiration. This is also supplemented by a conducive microclimate, as indicated by Gupta and Sayre (2007) and Sayre and Hobbs (2017) [4, 12].

Table 2. Periodical chlorophyll content, photosynthetic rate, co2 concentration, transpiration rate, stomatal conductance, leaf temperature

Treatment	Chlorophyll content (%)		Photosynthetic rate (μ mol m^{-2} s^{-1})		CO_2 Concentration (μ mol Co_2 m^{-2} s^{-1})		Transpiration rate (m mol H_2O m^{-2} s^{-1})		Stomatal conductance (m mol m^{-2} s^{-1})		Leaf temperature (^0C)		Stomatal resistance (μ mol m^{-2} s^{-1})	
	56 DAS		56 DAS		56 DAS		56 DAS		56 DAS		56 DAS		56 DAS	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
A. Horizontal plot: Tillage practices (T)														
T_1: Conventional tillage	54.56	55.90	21.57	22.51	384.44	391.89	8.36	8.69	0.314	0.342	26.57	27.91	3.23	3.02
T_2: Minimum tillage	52.56	53.72	20.78	21.61	380.39	387.94	7.93	8.20	0.258	0.270	25.74	26.77	3.88	3.71
T_3: Zero tillage	49.54	50.58	19.72	20.44	374.22	379.44	6.67	6.95	0.228	0.245	24.69	25.64	4.42	4.19
SE. m. (±)	0.62	0.41	0.25	0.25	0.81	1.15	0.13	0.20	0.006	0.009	0.14	0.22	0.06	0.10
C.D. at 5%	2.42	1.62	0.99	0.98	3.20	4.53	0.50	0.79	0.022	0.037	0.56	0.87	0.23	0.40
B. Vertical plot: Residue management (R)														
R_1: Without residue	51.98	52.78	20.55	21.01	378.96	384.30	7.50	7.63	0.261	0.266	25.80	27.52	3.92	3.85
R_2: With residue	52.46	54.02	20.83	22.04	380.41	388.56	7.81	8.26	0.273	0.305	25.54	26.03	3.76	3.44
SE. m. (±)	0.19	0.19	0.09	0.16	0.64	0.63	0.05	0.06	0.003	0.006	0.17	0.06	0.03	0.05
C.D. at 5%	NS	1.14	NS	0.95	NS	3.83	NS	0.36	NS	0.037	NS	0.37	NS	0.27
C. Sub plot: Layout (L)														
L_1: Flat bed	50.46	51.43	19.28	19.96	376.61	382.50	7.15	7.35	0.252	0.268	26.55	27.71	4.08	3.94
L_2: Broad bed furrow	53.59	54.97	21.77	22.67	382.33	389.94	8.16	8.46	0.283	0.307	24.85	25.79	3.59	3.33
L_3: Furrow irrigated raised bed	52.61	53.81	21.02	21.94	380.11	386.83	7.65	8.03	0.266	0.283	25.61	26.82	3.85	3.65
SE. m. (±)	0.36	0.33	0.26	0.29	0.70	1.16	0.10	0.17	0.004	0.008	0.16	0.16	0.05	0.08
C.D. at 5%	1.04	0.96	0.76	0.83	2.04	3.38	0.29	0.49	0.011	0.024	0.45	0.47	0.14	0.24
Interactions														
T x R	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
T X L	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
R X L	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
T x R x L	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
General mean	52.22	53.40	20.69	21.52	379.69	386.43	7.65	7.95	0.267	0.286	25.67	26.77	3.84	3.64

Table 3: Periodical chlorophyll content, photosynthetic rate, co2 concentration, transpiration rate, stomatal conductance, leaf temperature

Treatment	Chlorophyll content (%)		Photosynthetic rate (μ mol m^{-2} s^{-1})		CO_2 Concentration (μ mol Co_2 m^{-2} s^{-1})		Transpiration rate (m mol H_2O m^{-2} s^{-1})		Stomatal conductance (m mol m^{-2} s^{-1})		Leaf temperature (^0C)		Stomatal resistance (μ mol m^{-2} s^{-1})	
	56 DAS		56 DAS		56 DAS		56 DAS		56 DAS		56 DAS		56 DAS	
	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021	2020	2021
A. Horizontal plot: Tillage practices (T)														
T_1: Conventional tillage	52.77	54.12	29.64	30.83	331.96	337.09	7.75	7.88	0.401	0.429	24.02	25.13	2.69	2.50
T_2: Minimum tillage	51.44	52.60	28.83	29.96	327.61	332.11	7.58	7.69	0.291	0.307	22.85	23.93	3.55	3.36
T_3: Zero tillage	49.69	50.69	27.26	28.12	321.22	324.83	7.22	7.30	0.258	0.270	21.86	22.84	3.91	3.75
SE. m. (±)	0.35	0.44	0.24	0.25	0.95	1.30	0.05	0.04	0.005	0.008	0.21	0.15	0.07	0.08
C.D. at 5%	1.36	1.74	0.93	0.99	3.73	5.10	0.20	0.16	0.021	0.033	0.84	0.58	0.29	0.30
B. Vertical plot: Residue management (R)														
R_1: Without residue	50.37	51.17	28.06	11.96	324.02	327.42	7.32	7.38	0.297	0.315	24.16	25.68	3.59	3.38
R_2: With residue	52.23	53.77	29.10	13.11	329.84	335.27	7.71	7.87	0.337	0.356	21.65	22.25	3.18	3.03
SE. m. (±)	0.13	0.16	0.11	0.11	0.70	0.36	0.04	0.05	0.007	0.005	0.13	0.15	0.04	0.02
C.D. at 5%	0.80	0.99	0.65	0.69	4.28	2.19	0.26	0.32	0.033	0.030	0.79	0.89	0.26	0.15
C. Sub plot: Layout (L)														
L_1: Flat bed	49.70	50.66	27.47	28.35	321.13	324.13	7.29	7.36	0.266	0.283	24.76	26.00	3.93	3.69
L_2: Broad bed furrow	51.36	52.55	28.81	29.94	327.47	332.51	7.52	7.64	0.319	0.338	22.67	23.86	3.30	3.13
L_3: Furrow irrigated raised bed	52.84	54.19	29.45	30.62	332.19	337.39	7.75	7.88	0.366	0.384	21.29	22.05	2.92	2.80
SE. m. (±)	0.50	0.52	0.20	0.23	1.04	1.11	0.07	0.08	0.013	0.015	0.39	0.30	0.10	0.11

C.D. at 5%	1.45	1.52	0.60	0.67	3.03	3.23	0.22	0.22	0.037	0.044	1.14	0.88	0.30	0.33
Interactions														
T x R	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
T X L	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
R X L	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
T x R x L	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
General mean	51.30	52.47	28.58	29.64	326.93	331.34	7.52	7.63	0.317	0.335	22.91	23.97	3.38	3.20

Conclusion

The study demonstrates that conventional tillage consistently enhanced physiological parameters in both soybean and wheat across two consecutive years. It led to significantly higher chlorophyll content, photosynthetic rate, CO_2 concentration, transpiration rate, and stomatal conductance, indicating improved plant growth and gas exchange. Conventional tillage enhances crop physiological efficiency by improving soil aeration, moisture availability, and nutrient uptake, but it may increase leaf temperature and stomatal resistance due to moisture loss. Thus, while effective, it should be balanced with sustainable practices to protect long - term soil health. Similarly, Residue management improved the physiological performance of soybean and wheat by enhancing soil moisture retention, nutrient availability, and temperature regulation, leading to better plant growth. It is a sustainable and effective practice, particularly under moisture-limited or nutrient-deficient conditions. The BBF system in soybean and FIRB system in wheat improved key physiological traits by enhancing soil aeration, moisture retention, and drainage, which supported better root growth, nutrient uptake, and gas exchange. These systems offer a climate-resilient solution for efficient water and resource management in both crops.

This study underscores the importance of integrating optimal tillage, residue management, layouts and cropping systems for improving soil health and maximizing crop productivity, making them pivotal strategies for sustainable agriculture.

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