Proceedings of the Indian National Science Academy (2026) 92:695–712
https://doi.org/10.1007/s43538-025-00451-w

REVIEW ARTICLE

# Understanding the interplay of genotypes, sowing time and rice residue management for optimizing wheat (*Triticum aestivum* L.) growth and yield: a comprehensive review

**Manbir Kaur Josan[1] · Jagroop Kaur[1] · Puja Srivastava[2] · S. S. Manhas[1]**

Received: 27 February 2024 / Accepted: 1 May 2025 / Published online: 8 May 2025
© Indian National Science Academy 2025

**Abstract**
Wheat (*Triticu*m *aestivum* L.) is one of the most important cereal crops in the world. In this paper, we focus on the various factors that affect wheat growth and development as well as yield parameters and go into precise detail about the dynamic relationship of genotypes and sowing timewith residue management in rice–wheat system. On-farm rice residue burning is one of the major threats to environment and sustainability of agricultural systems in Indo-Gangetic plains. Drilling of wheat in rice stubbles is such an excellent illustration of an innovative residue management strategy that holds promise for boosting soil health, wheat yield and environment. In terms of developing to resilient cultivars, genotype variability plays a key role in wheat performance in altered sowing condition, which needs to be acknowledged. The various ways that genotypes affect yield attributes highlight how extremely important it is to determine the suitable varieties for optimal yield. Proper timing of sowing is essential for healthy wheat growth under surface residue retention; postponing sowing can result in significant decreases in plant height and dry matter accumulation. Optimum sowing time enhances yield attributes and differences in sowing dates have a major effect on wheat maturity and productivity. An integrated approach of optimizing interaction of genotypes, sowing times and residue management is required for acquiring long-term sustainability of wheat production system. In order to boost wheat growth and yield under rice residue mulched environment, this comprehensive review emphasised the value of genotype selection, thoughtful sowing timing and innovative residue management. The key findings will help in giving easily achievable recommendations for agronomic practices and further study or research.

**Keywords** Genotypes · Happy Seeder sowing · Rice residue management · Sowing time · Wheat and yield

## Introduction

In Indian north-western plains, burning rice residue is a serious and pressing issue for the rice–wheat farming system. An enormous amount of crop residue roughly 87 million metric tonnes (mt) is burned in India every year (Datta et al. 2020), of which 60% (around 50 mt) contribution is of rice straw and nearly half (23 mt) of which is burned in northwestern states (Kaur et al. 2022). The burning of crop residues is primarily associated with rice–wheat systems, with significant contributions also coming from crops like maize, sugarcane, cotton and jute (Sahu et al. 2021; Jain et al. 2014). In 2020, Punjab was the leading state in burning activity, with approximately 27% (2 million hectares) of its total cultivated area subjected to burning. Surprisingly, during the same period Madhya Pradesh emerged as the second-largest contributor, representing 30% of the total burned area across India (Deshpande et al. 2023).

The recurrent burning of crop residues has caused substantial detrimental effects, depleting both overall nitrogen content and nitrogen available for potential mineralization while diminishing organic carbon of soil. This practice has also hampered the bio-activity of beneficial microorganisms crucial for nutrient cycling and other vital ecosystem functions, consequently impacting the chemical, biological and physical properties of the soil. These consequences have given rise to serious environmental concerns (Yadvinder-Singh et al. 2005; Dobermann and Fairhurst 2002; Chauhan

✉ Jagroop Kaur
jagroopsekhon@pau.edu

[1] Department of Agronomy, Punjab Agricultural University, Ludhiana 141004, Punjab, India

[2] Department of Plant Breeding & Genetics, Punjab Agricultural University, Ludhiana 141004, Punjab, India

et al. 2012; Bijay-Singh et al. 2008; Jain et al. 2014). The microbial population has notably suffered, including actinomycetes, fungi, bacteria, phosphate/potassium solubilizing microbes and cellulose degraders. Despite ceasing the burning, the recovery of microbial population and enzymatic activities crucial for biomass recycling has been slow, potentially impacting long-term productivity (Kumar et al. 2019). Crop residue burning (CRB) activities are indeed a significant source of various pollutants, including nitrogen oxides, sulphur dioxide, black carbon, carbon monoxide, particulate matter and volatile organic compounds during both pre-monsoon and post-monsoon harvest periods of crop (Grover and Chaudhry 2019; Zhang et al. 2019; Liu et al. 2022). The emissions resulting from these CRB activities heighten the vulnerability to acute respiratory infections and related diseases, ultimately impacting the well-being and quality of life in agrarian states and their neighbouring areas (Chakrabarti et al. 2019; Bikkina et al. 2019; Ravindra et al. 2019; Jethva et al. 2019). Recent research has also indicated that CRB exacerbates the adverse health effects linked to the COVID-19 pandemic (Chauhan et al. 2023). Certainly, CRB remains a popular and cost-effective method for farmers to manage pest and weed control, clear residues and nutrients recycle into the soil (Liu et al. 2020; Junpen et al. 2018; McCarty et al. 2009). However, balancing these benefits with the adverse environmental and health impacts remains critical for sustainable agricultural practices. Emissions have witnessed a substantial increase of approximately 75% for carbon monoxide (CO) and greenhouse gases–methane ($CH_4$), nitrous oxide ($N_2O$) and carbon dioxide ($CO_2$) during 2011–20. The total $CO_2$ equivalent emissions surged from around 19,340 gigagrams per year in 2011 to approximately 33,834 gigagrams per year in 2020. The majority of these emissions occurred at the end of the *kharif* season, followed by the *rabi* season, primarily due to the burning of rice and wheat residues (Deshpande et al. 2023).

In Punjab, where above 3.0 million hectares (mha) are dedicated to rice cultivation, a significant portion of this area is subsequently sown with wheat during the succeeding *rabi* season. Post-combine harvesting of rice, approximately 20.2 mt of rice straw remains in the fields, posing challenges during the sowing of the subsequent wheat crop and necessitating immediate disposal. The burning of rice straw on-farm is a common practice, primarily due to the lack of viable alternative economic uses. Furthermore, its high silica content renders it unsuitable for use as animal feed. Another contributing factor to the burning of rice residue is the narrow time window available between the rice harvest and the wheat sowing period for effective decomposition and land preparation, leading to delays in wheat sowing. The high costs associated with the incorporation of straw further exacerbate the prevalence of burning practices. Addressing these issues would require the implementation of innovative and sustainable solutions that promote the efficient management of crop residues, ensuring both environmental sustainability and economic viability within the agricultural landscape. To combat these challenges, inclusion of crop residue management component has been recognized as a potent strategy (Jat et al. 2016; Kumar et al. 2018), even the productivity of rice increased with the continuous addition of rice residue in rice–wheat system (Gupta et al. 2023). Worldwide, farmers are engaged in the adoption of conservation agriculture (CA) over an extensive land area of 157 mha as against 2.0 mha in India which is mostly clustered in the rice–wheat growing IGP region, particularly Punjab and Haryana (Gupta et al. 2021), effectively confronting issues associated with shifts in climate patterns, reduction of natural resources, the scarcity of both labour and essential agricultural inputs (FAO 2018). The on-site recycling of crop residues is identified as one of the ecologically and economically sound options to curtail the waste of natural resources and uphold the sustainability of the rice–wheat sequence in the Indo-Gangetic plains of north-western India (Begam et al. 2018; Thind et al. 2019),culminating in the innovation of the Turbo Happy Seeder (THS). In the context of northern India, the THS serves as a pivotal tool for no-till wheat sowing in rice residues (Sharma et al. 2008; Sidhu et al. 2007, 2008). Notably, variations in microclimate resulting from CA adoption impact the performance of wheat genotypes, underscoring the importance of tailored tillage and residue management strategies (Yang and Baker 1991; Tillman et al. 1991).

The integration of zero tillage (ZT) with the retention of crop residues as mulch (THS) has indeed shown promising results, enhancing the productivity of the rice–wheat system which was adopted on 4.98 lakh hectares in Punjab during 2019–20, though the area under othercrop residue management (CRM) practices is also increasing especially partial incorporation through superseeder (4.50 lakh ha) and incorporation using chopper, rotavator, mould board plough, harrow, etc. (2.85 lakh ha) as against mulching withTHS (2.54 lakh ha), smart seeder (0.14 lakh ha) and surface seeder (0.34 lakh ha) and residue removal with baler/manual (5.15 lakh ha) during 2022–23 (Buttar et al. 2023). This combined approach has led to a balanced nutrient composition and improved soil quality, reflected in reduced bulk density and soil pH, as well as heightened availability of $P_2O_5$by 5.8%, exchangeable $K_2O$ by 7.8%, and soil organic matter by 1.5% within intensive rice–wheat cropping systems (Sah et al. 2014). ZT effectively tackles issues like soil erosion, nutrient leaching and runoff, while fostering the heightened enzymatic activity of soil microbes. Furthermore, it aids in suppressing weed infestation by encouraging weed seed predation and reducing the seed bank, promoting enhanced germination from upper soil layers (Nichols et al. 2015). ZTalso results in reduced incidence of plant feeding nematodes, improved nutrient and water-use efficiencies by minimizing

nutrient losses and soil water evaporation, and allows for earlier sowing times (Zhong et al. 2017; Gupta et al. 2024, 2022a; Balwinder-Singh et al. 2011a, 2011b; Hobbs et al. 2008). Simultaneous wheat sowing with the happy seeder during rice harvest, facilitated by straw management system (SMS) equipped combines, can lead to a conservation of approximately 1.0 million litres of pre-sowing irrigation water per hectare (Jat et al. 2017). The application of straw mulching contributes to a decrease in weed proliferation, subsequently reducing the need for herbicides (Kaur et al. 2021; NAAS 2017). Additionally, the retention of residue on the soil surface modifies temperature dynamics, consequently influencing the crop's phenology (Balwinder-Singh et al. 2016; Singh et al. 2022a). Moreover, the benefits of residue retention as mulch cannot be harnessed with other CRM technologies involving incorporation of residue in soil.

The response of wheat varieties to various sowing dates and mulched or un-mulched conditions is intricately linked to their genetic composition. Varieties possessing heat-tolerant traits demonstrate better performance under delayed sowing conditions, while those without such capabilities fare well under early sowing conditions. Adjusting the sowing time to an optimal date serves as a strategy to mitigate the adverse effects of terminal heat stress, ensuring the attainment of high grain yields. Enhancing wheat grain yield is closely linked to the implementation of an optimal sowing time, recognized as a crucial management approach (Hossain and da Silva 2012). Stephens and Lyons (1998) suggested that sowing dates play a critical role in determining possible crop yields, particularly in the context of temperature fluctuations. The timing of sowing significantly influences the crop's resilience in various environmental conditions such as temperature, air and humidity. Determining the ideal sowing date for wheat involves considering factors like temperature, rainfall distribution and the specific maturity period of the chosen variety (Qasim et al. 2008). Early sowing of high yielding wheat genotypes under CST practice enhanced the productivity and profitability of wheat under rice–wheat cropping system along with lesser noxious impact on the environment (Chhokar et al. 2023). Postpone sowing beyond the optimal date (November 5) for long-season wheat genotypes results in considerable yield reduction, ranging from 1 to 1.5% day$^{-1}$ (Ortiz-Monasterio et al. 1994; Aslam et al. 1993). October sowing has been proven advantageous for mulched wheat due to the exposure to optimal temperatures during the early and grain-filling stages, given the observed delay in reproductive stages and possible shortening of grain filling period in long duration varieties under mulch as compared to no mulch as it is well established that mulch aids in moderating the temperatures (Balwinder-Singh et al. 2016; Chhokar et al. 2023) Consequently, to capitalize on residual moisture from rice fields and mitigate the adverse effects of altered temperature on crop yield under residue, advancing the wheat sowing time and evaluating genotypes suitable for early and medium sowing periods under rice residue becomes crucial for achieving maximum wheat productivity. The title "Understanding the Interplay of Genotypes, Sowing Time and Rice Residue Management for Optimizing Wheat Yield and Growth: A Comprehensive Review" was chosen to reflect the comprehensive exploration of the intricate relationships among wheat genotypes, sowing times and rice residue management practices, with a focus on optimizing wheat growth and yield within the context of the rice–wheat cropping system.The review delved into these specific areas thereby contributing to a more comprehensive understanding of their combined effects on wheat performance.

## Methodology

The present review research employs a methodical approach to thoroughly evaluate the effects of sowing time, wheat genotypes and tillage techniques on wheat yield. Analysing the interactions between these variables and how they affect production, quality standards and financial results in various agroclimatic zones and farming techniques is the goal of the research. Using databases like Google scholar, Researchgate and web of science, a thorough literature search was carried out using keywords including wheat, sowing time, genotypes, varieties, tillage methods, grain yield, rice residue management, crop residue, etc. Based on inclusion criteria that prioritised experimental designs, field trials and comparison of various sowing dates genotypes, tillage techniques, studies published between 1990 and 2024 were evaluated. Details on the study site; experimental design, sowing dates, tillage techniques genotypes of wheat, yield characterises, quality features and economics assessment were among the data taken from a few chosen studies. To find trends and patterns, the findings were compiled subjectively. When it was practical, quantification analyses were also carried out. The studies' methodological quality was evaluated and the results were organised into sections Introduction; Rice residue management, influencing crop outcomes; Wheat genotypes, navigating environmental challenges; Sowing time, strategic decision for optimal growth; Interaction effect, unveiling synergies in wheat production; and Conclusion, future perspectives. Throughout the assessment process, academic standards were upheld and transparency was guaranteed by adhering to ethical rules in the management and reporting of data.

### Rice residue management: influencing crop outcomes

Crop residues represent the remnants of plants that remain in the fields following crop harvest and threshing. Residue

recycling contributes to the usefulness of transforming surplus agricultural trash into beneficial resources that fulfilled the nutrient urge of crops. Also, residue plays a vital role in sustaining the physical and chemical properties of the soil, contributing to an enhanced biological and ecological serenity within the crop production system.

### Impact of rice residue on growth and yield of wheat

This section looks at how rice residue affects wheat, with a great emphasis on effecton crop's development, growth, and yield. Meelu et al. (1994) demonstrated how several aspects of rice and wheat cultivation were positively influenced by the addition of residue. Furthermore, Vivek et al. (2005) observed that the application of residue in sowing slits and zero tillage techniques resulted in notable improvements in wheat yield attributes, including test weight, spike length, effective tillers per square meter and grains per spike. These improvements were attributed to better soil and water conservation as well as improved nutrient availability. Moreover, Verma et al. (1991) noted that no-tillage techniques efficiently exploited the residual moisture after rice harvest, leading to a 12.9% rise in wheat grain yield over traditional tillage techniques. Yadvinder-Singh et al. (2005) found that as compared to situations in which the straw was eliminated, the addition of rice straw improved the yield of wheat grains as well as straw. This beneficial effect was linked to the improvements noted in different yield components. Improved water availability over longer periods of time and less stress in between irrigations may be the cause of higher yields under ZT. Additionally, the plants in this environment may benefit from lower temperatures brought on by the residue cover (Honsdorf et al. 2018).

In-*situ* rice residue management technology particularly Happy Seeder, super seeder, strip seeder (PAU Smart seeder) and surface seedingis a beneficial option for farmers in rice-growing regions because it enables the timely sowing of the wheat crop in a single operation. Sowing wheat using the happy seeder is less susceptible to disruptions from rain and irrigation, ensuring maximum yield and leading to savings in terms of both fuel and energy. In a comprehensive evaluation conducted by Sidhu (2008) across fifteen different locations in Punjab, the performance of wheat sown with the happy seeder was found to either surpass or be on par with the traditional sowing method in terms of grain yield. Moreover, Singh et al. (2013) conducted an experiment in the Fatehgarh Sahib District of Punjab, India, involving the use of the happy seeder in farmer participatory research. Their findings indicated an average 8.8% increase in wheat yield in happy seeder plots, accompanied by a net savings of Rs 5135 per hectare in comparison to wheat sowing following the burning of rice residue. Over a two-year period, the average grain yield of wheat ranged from 3.18 to 5.08 t $ha^{-1}$ and 3.50 to 5.63 t $ha^{-1}$ for conventional seed drill and happy seeder plots, respectively.

Meena et al. (2018) observed a noteworthy difference in grain yield (5.73 t $ha^{-1}$) when retaining rice residue at a rate of 2.5 t $ha^{-1}$ as compared to rice residue retention at a rate of 5 $tha^{-1}$ (5.61 t $ha^{-1}$) and no rice residue retention (5.54 t $ha^{-1}$). This highlights the detrimental impact of increasing residue rates beyond the optimal level, leading to reduced crop stand and subsequently affecting wheat grain yield. Furthermore, the presence of mulch led to delays in phenological stages, particularly the grain-filling phase, by approximately 6–8 days. To mitigate the adverse effects of high temperatures during grain filling, early sowing was recommended, as suggested by Sial et al. (2005). The higher wheat yield achieved through zero tillage with residue is attributed to various factors, as indicated by Ram et al. (2010). These factors include increased dry matter production, the cumulative benefits of greater light interception, reduced soil canopy temperature, enhanced soil moisture retention, increased thousand grain weight, higher grain spike density and a greater number of tillers, in comparison to zero tillage without residue and conventional tillage methods for wheat. Additionally, Chakraborty et al. (2008, 2010) pointed out that rice straw mulch led to a significant 40% increase in root length density in the lower soil layers (beyond 0.15 m), resulting in improved wheat grain yield, increased water use efficiency by up to 25% and reduced crop water consumption by 3 to 11% due to enhanced moisture retention in deeper soil layers. Furthermore, weed growth was effectively suppressed by straw mulch through a combination of mechanisms, including its impact on soil temperature, reduced exposure to light, allelopathic effects and physical suppression, as discussed by Dhima et al. (2006). Wheat growth characteristics and yield features were not significantly impacted by the height of rice residue; however, wheat grain yield was noticeably greater (4.48 and 4.16 t $ha^{-1}$) when the residue was retained at 30 cm. Growth metrics, yield attributes and grain yield were all greatly impacted by nutrient management treatments; NE® guided management in conjunction with bio-fertilizer (N5) demonstrated the best results in terms of all parameters. This shows that the productivity of zero tillage wheat farming in this area can be improved by keeping residues at a height of 30 cm and applying NE® with bio-fertilizer (Reddy and Mitra 2024).

It was found that the impact on wheat yield became noticeable in the fourth year after the residue was added. Tillage operations affected the thermal conductivity and heat capacity of the soil as well as thermal diffusivity, which is the product of thermal conductivity and heat capacity (Gupta et al. 2007). The long-term crop residue retention following the conservation tillage resulted in enhanced wheat yield and yield attributes in the rice–wheat cropping system at Punjab Agricultural University, Punjab, India. The reduction

in wheat yields obtained with conventional sowing of wheat without straw/straw burning/removal cannot be compensated even with an additional 50 kg N $ha^{-1}$ to that obtained with straw retention or incorporation (Gupta et al. 2022a). Further the study reported that wheat sown under retention/incorporation of rice residue with application of half of the recommended dose of P-fertilizer (30 kg $P_2O_5$ $ha^{-1}$) produced similar grain yield as with the recommended dose of P-fertilizer (60 kg $P_2O_5$ $ha^{-1}$) with and without residue addition and continuous residue incorporation/retention of rice and wheat in rice–wheat system for 13 years required no P-fertilizer application (Gupta et al. 2024). Three wheat tillage and residue management techniques (subplots) and four rice tillage and crop establishment techniques (main plots) were assessed by Thind et al. (2023) throughout a four-year field research. The purpose of the study was to evaluate their effects on profitability, soil fertility and yield. The conventional till dry seeder rice (CTDSR) and conventional puddled transplanted rice (PTR) consistently produced greater yields (10–16% increase) in non-puddled soil than zero till dry seeded rice (ZTDSR) and zero till machine transplanted rice. Irrespective of the tillage and straw management techniques employed in preceding wheat crops, these production disparities were noted. After two years, wheat yields under zero till wheat (ZTW) with 100% surface retention of rice residue (+R) were considerably higher than those under conventional tillage without residue retention (ZTW − R). Compared to ZTW + R treatments, the wheat yield from ZTW − R treatments was 15% lower. The CTDSR-ZTW + R treatment produced the highest system yield, outperforming the traditional PTR-CTW − R technique by 5% and resulting in net returns of Rs 17,000 $ha^{-1}$. The amount of wheat grain produced during the course of the study varied greatly, with lower yields in 2010–11 and 2013–14 than in other years. Wheat grain output was highly impacted by the interplay between year and wheat establishment techniques, underscoring the significance of taking annual variations into account when evaluating system performance.

### Impact of rice residue on soil physical, chemical and biological properties

Considering the impact of rice residue on soil physical, chemical and biological properties, it is notable that these residues, as natural resources, contribute to the enhancement of soil's chemical, biological and physical characteristics. The management of residues significantly influences soil properties, thereby indirectly affecting overall soil quality and presenting either constraints or improvements for long-term agricultural sustainability and land productivity. The microbial population and enzyme activities were higher at zero tillage, as associated with traditional tillage, because of the accumulation of organic matter, which acts as food for microflora to thrive on (Gupta et al. 2022b).

The application of rice residue as mulch directly on the soil surface, without any tilling, was found to have a beneficial impact on soil hydro-physical properties, as highlighted in the study by Mondal et al. (2013). Similarly, Balwinder-Singh et al. (2011b) conducted research, indicating that plots where rice residue was utilized as mulch exhibited increased soil moisture levels, leading to a higher grain yield in the wheat crop. In a study conducted at PAU, Ludhiana, Punjab, Sidhu et al. (2007) obtained results that align with this pattern. They found that on sandy loam and loamy sand soils, mulching rice residue increased the gravimetric soil water content and increased wheat grain yield when compared to not mulching at all. This resulted in a longer initial drying phase, which was explained by the decrease in evaporation brought on by the accumulation of rice residue on the soil surface.

The application of rice residue had little effect on wheat yield over a three-year short-term period (Bijay-Singh et al. 2008; Yadvinder-Singh et al. 2005). Further, significant improvement in soil aggregation, bulk density, infiltration rate, soil organic carbon (SOC), available nutrient content (N, P, and K), microbial count, and enzyme activities was observed under conservation tillage and residue-treated plots compared to residue removal or residue burning after 13 years. The residue derived from both crops when was either retained/incorporated improved the soil organic carbon (0.80%) and resulted in a significant increase in SOC (73.9%) in the topsoil layer as compared to the conventional practice (Gupta et al. 2024). Shukla et al. (2003), Su et al. (2007) and Van Wei et al. (2013) found that these changes were related to changes in bulk density, moisture content, soil organic matter and inter-aggregate contact. The findings of Li et al. (2013) imply that a slower rate of soil temperature change was induced by crop residue on the soil surface in conservation tillage systems. The tendency of the surface residue to strengthen incident solar radiation reflection provided an explanation for this outcome. Likewise, Ram et al. (2012a) remarked that conservation tillage systems altered the thermal properties of the soil, which subsequently impacted the soil temperature.Over an 18-year period (1998–2016), a long-term conservation agriculture study investigated various combinations of tillage and residue management in a rice–wheat system by Dutta et al. (2022). Conducted in a split-plot design with three replications, the experiment compared zero tillage (ZT), conventional tillage (CT), and strip tillage (ST), alongside residue retention (R), residue burning (RB) and no residue (NR) options. Results indicated that ZT with residue retention significantly increased soil organic carbon (SOC) content by 20% in the top 0–5 cm layer compared to CT and residue removal. ZT with added residues also enhanced SOC stock by 25%,

promoted macro-aggregate formation, and increased labile and recalcitrant carbon fractions compared to CT practices. In order to better understand how tillage techniques and residue management affect the stabilization of Soil Organic Carbon (SOC) in soil aggregates and how they affect important yield-contributing traits in the rice–wheat cropping system, Choudhury et al. (2014) conducted a study. It has been investigated that using no-tillage technologies reduces soil evaporation, disturbance of the soil and crop residues, and erosion losses. Improved infiltration rates (7.80 mm $h^{-1}$) were the outcome of the ZT + R treatment, which showed the lowest bulk density (1.45 Mg $m^{-3}$) and surface soil penetration resistance (1306.02 kPa). When LT&RE was implemented instead of CT-R, soil organic carbon (SOC) stocks grew dramatically by 15.8–25.7% across all treatment combinations. Microbial activity was encouraged by elevated SOC levels and improved physical soil conditions. The ZT + R treatment demonstrated the most amounts of alkaline phosphatase activity (187.08 µmol p-nitrophenol $g^{-1}$ $h^{-1}$), dehydrogenase activity (122.00 µg TPF $g^{-1}$ 24 $h^{-1}$), and microbial biomass carbon (MBC) (271.63 mg $kg^{-1}$ soil) (Fagodiya et al. 2024). According to Lal et al. (2007), there were more stable aggregates in the top layer of no-till soils than in tilled soils, which increased the soil's overall porosity. The implementation of mulch was observed to reduce the soil's heat gain due to its thermo-insulating properties, resulting in lower soil temperatures by approximately 2–3 °C at a depth of 5 cmcompared to un-mulched soil, as demonstrated by Balwinder-Singh et al. (2011b). Furthermore, studies by Amani et al. (1996), Chakraborty et al. (2008) and Jat et al. (2009) found that the presence of mulch decreased post-anthesis canopy temperatures, which they attributed to increased transpiration. It was discovered that higher transpiration was directly correlated with biomass production (Tanner and Sinclair 1983; Passioura 1976). The results of Choudhary et al. (2018) showed that the soil in the zero tillage with residue retention treatment had higher levels of nitrogen, phosphorus and potassium than in the conventional tillage treatment. This phenomenon was attributed to the mobilization of nutrients from the soil by microorganisms and fauna, which facilitated the conversion of these nutrients into an available form. By adding rice residue to the soil, weed density is decreased and the physical, chemical, and biological qualities of the soil are enhanced. When rice residue is kept on the surface or used as mulch, it lowers the biomass of grass and broadleaf weeds in wheat fields more than when the residue is removed (Kaur et al. 2021).When applying techniques such as Happy Seeder, Super Straw Management System, reversible moldboard plow, paddy straw chopper/spreader, or no-till seeder for in-situ residue management, residues are either mulched or incorporated rather than burned. These methods are advantageous from an economic standpoint because they lower expenses, raise yields or accomplish both. Compared to residue removal, in-*situ* residue management enhances the physical, chemical and biological characteristics of the soil, improving its general health. By lowering pollutant emissions, ex-situ residue management—which includes using residues for biofuel, charcoal synthesis, energy generation and bale making—also helps the environment (Kaur et al. 2022).

## Wheat genotypes: navigating environmental challenges

The role of genotype is crucial in influencing crop yield, as various genotypes exhibit differences in their input requirements, genetic traits, growth patterns, and adaptability to prevailing environmental conditions during the growing season.

### Impact of genotypes on growth of wheat

This section delves into the impact of genotypes on the growth of wheat. Nawaz et al. (2013) conducted an experiment examining the growth of ten wheat varieties, including Uqab 2000, Mairaj 2008, Dharabi 2011, C591, Sehr 2006, Lasani 2008, BARS 2009, Faisalabad 2008, Chakwal 50, and Shaqaf 2006. Their findings indicated that Mairaj 2008 demonstrated a prolonged green phase, necessitating more time for grain filling and increased costs in maintaining the number of grains per spike and grain weight under stress conditions. This variety exhibited high water use efficiency and grain yield. Conversely, varieties sensitive to heat stress, such as Shaqaf 2006 and BARS 2009, experienced a reduction in the rate of grain filling along with a significant decline in the duration of grain filling. Wahid et al. (2007) emphasized that photosynthesis, a fundamental physiological process, exhibits high sensitivity to increasing temperatures, resulting in a decline in photosynthesis that has direct repercussions on the growth and grain yield of wheat, as also noted by Ali et al. (2010). Gupta et al. (2015a) reported that RAJ 4083 effectively managed stomatal conductance and photosynthetic rates when compared to other genotypes, including PBW 590 (heat susceptible), PBW 373 and RAJ 4037 (heat tolerant). Notably, they identified a strong correlation between photosynthesis and yield in durum wheat under high-temperature conditions. Furthermore, they observed that the transpiration rate decreased in response to high temperatures and RAJ 4083 maintained the highest transpiration rate, which contributed to a cooling effect and consequently led to a higher photosynthetic rate. The transpiration rate was recognized as a vital parameter directly associated with temperature sensitivity.

In an experiment conducted by Gill et al. (2014), the phenological behaviour of wheat varieties, specifically PBW 621 and PBW 343, was studied under varying environmental

conditions in two distinct regions of Punjab, namely the South-western zone (Bathinda) and the Central plain zone (Ludhiana). Their findings revealed that PBW 621 exhibited a shorter duration for the initiation and completion of various phenological stages compared to PBW 343. Singh et al. (2012) evaluated the performance of the HI 1544 wheat variety and observed that critical stages such as booting, spike emergence, anthesis and physiological maturity were achieved at 66, 82, 92 and 132 days after sowing, respectively. Additionally, they noted that the maximum leaf area index was observed during the spike emergence stage. In a separate experiment, it was observed that PBW 550, HD 3086 and WH 1105 wheat varieties exhibited a shorter duration for maturity compared to other varieties, including PBW 677, PBW 621, HD 2967, PBW 725, PBW 59 and PBW 658. Notably, PBW 677 displayed the maximum plant height among all the varieties (Sandhu and Dhaliwal 2017). Chandrashekar et al. (2000) took observations on different wheat genotypes. They found that genotypes C 306, A 9–30-1 and HW 24 were capable of maintaining higher chlorophyll content under non-irrigated conditions when compared to the Hira genotype. In severe stress conditions, the most significant decline in chlorophyll content was noted in the PBW 343 genotype, with reductions of 41, 42, and 45% at tillering, anthesis and 15 days after anthesis, respectively. On the other hand, C 306 and AKAW 3717 showed smaller declines in chlorophyll index under severe and medium stress conditions than PBW 343 and HD 2687, which is a valuable trait contributing to drought tolerance as the preservation of chlorophyll is essential for photosynthesis under water stress conditions.

#### Impact of genotypes on yield attributes and yield of wheat

Varietal differences exerted the substantial impact on all yield and wheat crop characteristics. Notably, HD 3059 exhibited the maximum grains per spike (41.66), while WH 1021 demonstrated the minimum under late sowing conditions. The observed significant variation in the number of grains per spike was attributed to the genetic variability among the varieties (Kaur 2017). Furthermore, two key factors, namely the storage ability of carbohydrates in the stem and the remobilization of reserves for grain development, were identified as efficient contributors to grain yield (Ehdaie et al. 2006). The combined effects of heat and water stress on various wheat genotypes (C-306, HD-2967, KUNDAN, WH-1105, AKAW-3717, DHTW-60, HTW-11 and WH-730) were evaluated by Ram et al. (2018). According to the study, AKAW-3717 showed the lowest remobilization value, while HD-2967 and DHTW-60 showed faster remobilization. The phenomenon that was observed was explained by the combined influence of heat stress and water stress, which led to an accelerated remobilization of stem reserves in the peduncle and penultimate internodes. Moreover, under individual stress conditions, the peduncle displayed a faster and higher remobilization rate. Hakim et al. (2012) and Mohammadi (2012) documented a decline in both yield and associated attributes in wheat genotypes under high-temperature stress conditions. Notably, previous studies (Munjal and Dhanda 2004; Pradhan et al. 2012) highlighted the significance of grain weight as a pivotal yield component during heat stress. Additionally, the impact of high temperatures was observed through ultra-structural changes in the aleuronic layer and endosperm cells, leading to grain shrinkage (Dias et al. 2008). Abiotic (heat, drought) and biotic (rusts, fusarium) stressors, low technology adoption, high input prices, and poor infrastructure are among the problems. 88 wheat cultivars with an emphasis on productivity, drought tolerance, and disease resistance have been created since the 1960s by the Ethiopian Institute of Agricultural Research, CIMMYT and ICARDA. Increases in yield of 40 kg $ha^{-1}$ each year have been attained; in 2021, the 'Abay' variety have yielded 6.5 t $ha^{-1}$ (Tadesse et al. 2022). The unusually high temperatures caused serious problems for cattle, crops, and horticulture products in states like Punjab, Haryana, and Rajasthan. The heat wave occurred at crucial times in the wheat crop's development, causing the grains to shrink, become yellow and mature too soon, which led to a 15–25% reduction in output. Adoption of heat-tolerant wheat varieties like PBW 803, DBW 187 and DBW 222, which retain normal yields even under high-temperature conditions in comparison to the local variety HD-3086, is one of the possible strategies to offset these losses (Singh et al. 2023). In the highlands of southwest Ethiopia (Belete 2023), twelve bread wheat cultivars were evaluated throughout two cropping seasons (2021 and 2022) in three different settings. The purpose of the study was to determine yield stability and the impact of genotype by environment interaction (GEI) on grain production. With three replications and a randomized complete block design, the combined ANOVA revealed extremely significant differences ($P \leq 0.001$) between genotypes, environments and their interactions. In yield variability, the environment accounted for 77.6% of the variation, with genotype and GEI contributing 3.87% and 10.57%, respectively. Due to its higher yield and stability throughout test settings, Danda'a and ETBW9089 were recommended for wider cultivation in the southern Ethiopian highlands after a GGE biplot analysis classified the habitats into three mega-environments.At Ludhiana, Punjab, three wheat varieties (PBW 343, PBW 550 and DBW 17) were assessed and study revealed that PBW 550 exhibited a significantly higher grain yield per ear compared to the other varieties. Moreover, PBW 343 demonstrated the maximum ears per square metre (Ram et al. 2013). Similarly, in another evaluation BARI Ghom 28 outperformed Shatabadi and BARI Ghom 27 in terms of grain

yield, biomass yield, harvest index and other yield parameters (Hossain et al. 2017).In Uttar Pradesh, the performance of newly released wheat varieties, including DBW 39, CBW 38 and KRL 213, was assessed through frontline demonstrations on 25 hectares among 30 farmers, showcasing improved performance compared to the check varieties PBW 154, PBW 373 and HD 2285 (Gupta et al. 2015b). In a separate study, five wheat genotypes (SD-4085/3, SD-222, SD-502, NIA 8/7 and NIA-MB-II) were evaluated, with SD-4085/3 demonstrating superior performance in various growth and yield parameters, even under different potassium levels (Khaskheli et al. 2017). In an experiment assessing the performance of various wheat varieties (Saher 2006, S 24, AARI 10, and Lasani) under high-temperature conditions at different phenological stages, wheat variety AARI 10 demonstrated superior performance compared to the others (Javed et al. 2014). In a separate study, Hossain et al. (2012) observed significant yield reductions of 46, 43, 35, 32 and 27% in Sourav, Sufi, Prodip, Bijoy and Shatabdi, respectively, when sown late (December 27) over November 15 sowing. Shatabdi showed the best performance under high-temperature conditions in terms of growth, phenological attributes and yield, compared to Sourav, Bijoy, Sufi and Prodip, whereas Sufi and Sourav exhibited higher sensitivity to heat compared to Shatabdi, Prodip and Bijoy. Osmani et al. (2020) conducted field experiments for two consecutive spring seasons of 2017 and 2018 at experimental farm of Kabul University, to find out the adoptability of four local spring wheat varieties i.e., V1-Zardana Baghlan, V2-Sorkha-Andarab, V3-Safida-Kunduz and V4-Safida-Andarab varieties under Agro-climate conditions of Kabul. They observed that during both the seasons SafidaAndarab (V4) produced shorter plant height but significantly higher number of tillers, spikes, grains per spike, spike length, test weight and grain yield (4.17 and 4.43 t $ha^{-1}$) of wheat, which all these parameters were on par with variety of Safida-Kunduz during both the consecutive years. Using Synthetic Hexaploid Wheats (SHWs) from CIMMYT, Rosyara et al. (2019) investigated the genomic impact of chromosome D generated from Triticum tauschii. Their results showed a continuous increase in genetic diversity and an improved genetic gain for grain output (25.3%). In the years between 2000 and 2018, CIMMYT's efforts to increase genetic diversity have produced 1577 SHWs, or 21% of the germplasm. With 86 releases in 20 countries, these cultivars are widely in use. Adoption is highest in China (34%), next in India (7%) (Aberkane et al. 2020). In a study, Shaheen et al. (2019) focused on genotype-based differences in the number of spikelets per spike in wheat. Researchers found that the number of tillers on a plant affected the number of spikelets; plants with fewer tillers and spikelets per spike had higher seed weights because they were better at assimilating nutrients and filling grains (Xu et al. 2015; Bheemanahalli et al. 2019).Using late-sown wheat varieties, the research project examined the effects of tillage techniques on wheat variety growth and yield in the 2019–20 *rabi* season at the Research Farm of the College of Agriculture, Banda University of Agriculture and Technology, Banda using a split-plot design with three replications, five wheat varieties (HI1863, HI 1544, Raj 4120, K 1317, and Shriram bioseed 2001) as the subplots and two tillage methods (zero and conventional tillage) as the main plots. The findings showed that, in comparison to conventional tillage, zero tillage greatly increased the number of emergences, plant height, dry matter accumulation, tillers $m^{-2}$, root length, CGR and RGR. Comparing zero tillage to conventional methods, there was an 8.2% increase in straw yield and a 10.38% increase in grain output. K 1317 was the variety with the best growth characteristics, yield and benefit–cost ratio among the others (Yadav et al. 2024).

## Sowing time: strategic decisions for optimal growth

The time of sowing is a critical factor that significantly influences the phenological development of crops, total biomass production and the efficient conversion of biomass into a valuable yield. Identifying the optimal sowing date is of paramount importance, as it contributes to successful germination, robust crop growth and ultimately, a bountiful harvest. Climate change considerably affects wheat productivity. Handling the sowing period wisely is one of the most important measures for climate resilience in yield optimization. The best times to sow wheat have changed recently as a result of climate change. The suggested sowing dates are now October 22–28 for northeastern Punjab, October 24–30 for central Punjab, and October 21–27 for southwestern Punjab, based on meteorological data from 2006 to 2015. The production drops at different rates with each day that these optimal windows are delayed for sowing; northeastern Punjab has the slowest rate of decline (36.09 kg $ha^{-1}$ $day^{-1}$), while southern Punjab has the largest rate of decline (70.80 kg $ha^{-1}$ $day^{-1}$) (Sandhu et al. 2020).

### Impact of sowing time on growth of wheat

According to research conducted by Gupta et al. (2002) at the Indian Agriculture Research Institute in New Delhi, it was observed that regardless of the varieties used, the tallest plant height was recorded under normal sowing conditions compared to those under late sowing conditions. A delay in sowing by one month and two months from the regular sowing date (November 25) resulted in a reduction in plant height by 10 and 20%, respectively (Singh and Pal 2003). Over the course of two years, the analysis indicated a 4.8% reduction in the number of tillers per plant when wheat was sown on December 25 (3.9 tillers per plant)

compared to November 20 (4.1 tillers per plant) (Dhaka et al. 2006). Research by Ghosh et al. (2000) demonstrated that delayed sowing led to reduced dry matter accumulation during all stages of growth. Specifically, wheat sown on November 16 exhibited greater dry matter accumulation at all growth stages compared to the crops sown on November 26 and December 6. According to Shivani et al. (2003), delayed sowing from the timely date (November 21) to the very late date (January 7) on sandy loam soil in Jharkhand led to reduce dry matter accumulation. Additionally, Kamrozzaman et al. (2016) observed that wheat sown on November 25exhibited the highest plant height (97.9 cm) and dry matter yield compared to other sowing dates (November 5, November 15 and December 5), except for December 15 as maximum total dry matter (TDM) was achieved by the crop sown on November 25, which benefited from a longer growth time and favorable temperatures. This result is consistent with the observations made by Ahmad et al. (2005), who reported notable variations in dry matter output between different sowing dates. The ideal sowing circumstances are responsible for the highest TDM during the tillering to grain filling stages that were noted with the November 25 seeding. According to Qasim et al. (2008), plants planted on this date also grew higher, as a result of the prolonged vegetative growth period and advantageous environmental conditions like temperature and sun radiation.

In an investigation conducted in central Punjab, it was determined that the optimal sowing time for maximizing yield in sandy loam soil with a 50% soil water deficit irrigation schedule falls within late October to early November. In contrast, in clay loam soil, this optimal sowing window was observed to be approximately one week later (Balwinder-Singh et al. 2016). According to Singh (2016) research, sowing wheat on November 5 and November 20 significantly enhanced various growth parameters and economic returns compared to sowing on 5th December. Additionally, late-sown wheat experienced acceleration in flowering time by 10 to 24 days and earlier maturity by over 19 to 40 days compared to normally sown wheat, as observed by Singh and Ahmad (1997). As observed by Sattar et al. (2015), wheat sowing on November 10 resulted in the longest duration and highest accumulation of growing degree days for grain filling, anthesis and maturity, along with the highest heat use efficiency. In Jammu and Kashmir, wheat sown on October 15, October 30 and November 15 showed yield reductions of 10.6 from October 15-October 30, 7.6 from October 15- November 15 and 17.4% from October 15-November 15, respectively. The growth parameters, including dry matter accumulation, plant height, leaf area index and tillers per square meter, along with yield attributes such as grains per spike, effective tillers and test weight, were all highest in the case of October 15 sowing (Dar et al. 2018). In a similar vein,improved growth attributes such as fresh weight, plant height, dry weight, productive tillers per square meter and total number of tillers per square meter, except for plant populationwere observed in wheat sown on December 15 compared to other sowing dates (December 25 and January5). Under late sowing conditions, the wheat variety *Unnat* Halna exhibited superior growth and yield attributes (grain yield, straw yield and net return) in contrast to other varieties, namely Naina (K-9533), Halna (K-7903) and Mandakini (K-9533) (Pyare et al. 2015). Comparing early sowing (October 25) to normal (November 14) and late sowing (December 4), higher accumulated growing degree days (AGDD), heliothermal units (HTU), photothermal units (PTU) and heat use efficiencies (HUE) values, as well as higher grain and biological yields, were observed. Reduced accumulation of HUE and thermal indices resulted from delayed planting. Throughout both experimental years, the study demonstrated a highly substantial correlation between grain and biological yields with AGDD and HUE (Gupta et al. 2020).Wheat crop sown early (November 30) showed better growth metrics than those sown later (December 15 and December 30). The variety HD-2967, which was sown on November 30, had the highest growth metrics out of all the varieties (HD-2733, K-307 and K-9107), indicating that this sowing date is ideal for wheat production. In addition to exceeding the other cultivars examined in the study, HD-2967 had the greatest harvest index (39.34%) and grain production (42.30 q $ha^{-1}$). These results emphasize the significance of variety selection and timely sowing in optimizing wheat productivity in field settings (Singh et al. 2022b).

### Unveiling the impact of sowing time on yield attributes and yield of wheat

It is evident from the pooled results that early sowing of wheat i.e. on October 22 produced 16.0, 12.0 and 12.1% higher grain yield, biomass and thousand grains weight, respectively, over timely sowing around November 15 (Chhokar et al. 2023). In another study from China, Dong et al. (2022) found similar grain yield of wheat sown between 8 and 22 October but it decreased when sowing was delayed beyond 22 October. Sandhu et al. (1993) demonstrated that wheat sown on October 15 gave higher grain yield than sown on October 25, November 4 and November 14. This enhancement is attributed to the increased number of effective tillers and higher thousand grain weight associated with early sowing. Hobbs and Morris (1996) revealed that late sowing of wheat beyond November led to a gradual decline in wheat grain yield by 1.0 to 1.5% $ha^{-1}$ $day^{-1}$. Additionally, Tripathi et al. (2005) estimated a reduction in wheat yield of approximately 26.8 kg $ha^{-1}$ $day^{-1}$ for each day of delay in sowing beyond the optimum date (October 26 – November 4). Singh et al. (2011) further confirmed that wheat crops sown at the ideal time resulted in higher

grain yield compared to those sown late. Tiwari and Singh (1993) noted a consistent reduction in grain weight spike$^{-1}$ due to delayed wheat sowing. This reduction was attributed to the adverse impact of temperature on grain size and the grain growth period during the grain-filling stage. Spink et al. (2000) concurred, stating that late sowing of wheat shortened the duration of each development phase, resulting in a reduced grain-filling period and grain weight.

Likewise, Balwinder-Singh et al. (2016) demonstrated that late-sown wheat resulting in a shortened tillering period, terminal heat stress during the ripening stage, and the high temperature during the grain-filling stage led to premature maturity, ultimately reducing the grain yield. Kaur et al. (2010a) also confirmed a decrease in wheat yield with delayed sowing, as the delay in sowing accelerated crop phenology development. Wheat yield in the rice–wheat cropping system was negatively impacted by delayed sowing. The highest grain yield, reaching 4.56 t ha$^{-1}$ was achieved with end-October sowing. Late sowing of wheat resulted in grain yield reductions of 8.9, 17.3 and 30.1 kg ha$^{-1}$ during the first and second fortnight of November and in December, respectively, as observed in a four-year survey involving 1110 cultivars (Malik et al. 2007). In an experiment conducted by Jat et al. (2013) in Varanasi, it was noted that grains per ear, ear length, ear weight and test weight of wheat were significantly affected by sowing dates. Wheat sown on November 20 exhibited the highest values for grains per spike, test weight, spike length and spike weight, surpassing wheat sown on December 6 and December 23.

Progressive increments in the thousand grain weight, effective tillers, spike length, grains per spike, spikelets per spike, harvest index and grain yield were observed in the case of early and timely sown wheat. This trend may be attributed to the longer growing duration and more favourable environmental conditions and temperatures at reproductive stage, as compared to those observed in the case of late sowing (Singh 2016). Sardana et al. (2005) conducted a study in Gurdaspur, Punjab, and found that plant height and the number of kernels per ear head were slightly higher when wheat was sown later on November 19. However, the grain yield was significantly greater when sown earlier on November 4, primarily due to a notable increase in the number of ear heads per square metre compared to delay sowing. Similarly, Vijay et al. (2012) reported that the crop sown on November 15 yielded statistically higher grain and straw yield, which was on par with the wheat crop sown on November 1 but notably superior to those sown on December 1 and October 15.

### Impact of sowing time on quality of wheat

In a research study conducted in Hisar district of Haryana, the impact of three distinct sowing dates of wheat (specifically, November 15, December 5 and December 25) on wheat crop performance was examined. The results revealed that wheat sown on November 15, considered timely sowing, exhibited higher grain yield and a greater hectolitre weight. Conversely, late sowing of wheat was associated with higher protein content compared to timely sowing (Kaur et al. 2010b). Furthermore, the mid-sown crop demonstrated superior chapatti and bread quality, along with the highest protein content, when contrasted with the timely and early sown crops (Eslami et al. 2014).Similarly, a study in Egypt by El-Gizawy (2009) indicated that the wheat sown on November 15 demonstrated the highest grain protein content, along with increased uptake of grain phosphorus, potash and nitrogen.

## Interaction effect: unveiling synergies in wheat production

Over the course of three seasons in Mexico, a durum wheat breeding program was conducted to assess the impact of conventional and zero tillage on selected progenies. A total of 234 and 250 lines were chosen from 16 initial crosses under conditions of conventional tillage and zero tillage with full irrigation, as well as conventional tillage with reduced irrigation. The results indicated that in zero tillage, grain yield exhibited the highest values, with minimal differences of 0.11 t ha$^{-1}$ in 2013 and larger disparities of 0.65 t ha$^{-1}$ and 0.42 t ha$^{-1}$ in 2014 and 2015, respectively. Moreover, the discrepancies observed for yield were generally marginal and in most cases, not statistically significant (Honsdorf et al. 2020). In an evaluation of twenty-one wheat genotypes across three agro-ecological regions in India (Bihar, Madhya Pradesh and Punjab) HD-2967 and Munal were identified as the top-performing and highly stable varieties in zero tillage with residue and conventional tillage, respectively, across all three locations (Jat et al. 2017). Wheat production with mulching at optimal sowing time increased yield by an average of 0.5 t ha$^{-1}$ with 50% soil water deficit irrigation compared to no mulching. The application of mulch improved yield by 1.2–1.3 t ha$^{-1}$ with early sowing of wheat by October 15 (Balwinder-Singh et al. 2016). In order to determine how different tillage techniques and sowing dates affected wheat yield in the rice–wheat cropping system, Khan et al. (2015) conducted a study. It was discovered that early sowing (October 20) of wheat with zero tillage and straw retained and reduced tillage with straw incorporated produced higher grain yields, making it a sustainable method. Two-year results showed lower weeds population in CA- based wheat system when it was planted early (3rd week of October) with full rice residue retention (average 6–8 Mg ha$^{-1}$). Population of major weeds like *Phalaris minor, Rumex dentatus, Chenopodium album and Anagallis arvensis* were reduced by 61–64, 41–70, 14–32 and 43–68%,

respectively in zero-tillage (ZT) plots where 6–8 Mg ha$^{-1}$ and more rice crop residues were retained as compared to without residue (0.0 Mg ha$^{-1}$). The combination of early sowing and full rice residue retention (8–10 Mg ha$^{-1}$) reduced the *P. minor* population by 70–85% in wheat crop (Poonia et al. 2022).

Under conservation tillage, variety BISA 927 performed superior over other test entries with an average yield of 7.36 t ha$^{-1}$ under the early sowing condition. However, PBW 723 was the top performer (6.47 t ha$^{-1}$) with the shift in sowing time from early to timely condition (Chhokar et al. 2023). Similarly, Ortiz-Monasterio et al. (1994) conducted an experiment from 1985 to 1992, examining sixty-six spring wheat cultivars under ten different sowing dates. The study aimed to investigate the interactions among cultivars, sowing dates, and years and estimate losses associated with late sowing. The results revealed that for grain yield, the optimal sowing date was November 5 for long-duration varieties and November 15 for medium and short-duration varieties. Mahmud et al. (2022) included secondary plots with a variety of cultivars and main plots with different sowing dates. The highest grain yield was obtained from sowing on December 1 (5.9 t ha$^{-1}$), which was statistically comparable to sowing on December 15; the lowest yield was obtained from sowing on November 15 (5.3 t ha$^{-1}$). There were notable variations among the varieties. Baghdad1 had the largest grain output, measuring 6.3 t ha$^{-1}$ and weighing 48.8 g per 1000 grains. On the other hand, Al-Rashid had the lowest values for harvest index (31.5%), 1000-grain weight (43.7 g), grain filling duration (45 days), and grain yield (4.9 t ha$^{-1}$). The study revealed a noteworthy correlation between sowing dates and varieties. Specifically, varieties sown on different dates yielded less than 5.5 t ha$^{-1}$, but Abu Ghraib3, sown on December 1, yielded the maximum of 6.9 t ha$^{-1}$. According to Madhu et al. (2018), a study conducted at Bangladesh Agricultural University, Mymensingh, revealed that wheat sown on November 15 yielded better results and exhibited superior performance for varieties such as BARI Gom 25 and BARI Gom 26, compared to late-sown wheat (November 30, December 15 and December 30). Among the observed parameters, the highest plant height, plant population and grain yield were recorded in BARI Gom 25 sown on November 15, while the least performance was noted in Shatabdi when sown on December 30. Similarly, Jat et al. (2018) identified that genotypes CSW 18, DPW 621–50 and BAZ demonstrated the best performance during early, normal and late sowing dates, respectively. In a research effort at the Agronomy farm of the Institute of Agriculture and Animal Science (IAAS), Rampur, during the winter season, Marasini et al. (2016) investigated the performance of three distinct wheat varieties (Tillotama, Danfe and Vijay) sown on different dates (November14, November 29 and December 14). Their findings revealed that Tillotama and Danfe wheat varieties exhibited the highest yield when sown on November14, while Bijay variety excelled when sown on November29. Notably, the interaction between sowing date and variety was found to be significant for harvest index, plant height and grain yield. An investigation carried out in Ranchi involved the assessment of two distinct sowing dates (November 20 and December 20) in conjunction with five wheat varieties (K 0906, Raj 4229, K 0307, DBW 39 and HD 2733). The findings indicated that the wheat sown on November 20 exhibited superior characteristics such as increased leaf area index, plant height, dry matter, total tillers per square meter and a longer duration to maturity compared to the crop sown on December 20th, according to Alam et al. (2013). In a field experiment conducted in Ludhiana, Punjab, Ram et al. (2012b) evaluated six wheat varieties across seven sowing dates, ranging conversely, late sowing, particularly on December 25, led to a significant reduction in growth parameters and resulted in the lowest wheat yield. Furthermore, Malik et al. (2007) concluded that the implementation of zero tillage facilitated early and timely wheat sowing by minimizing the interval between rice harvesting and wheat planting. This approach resulted in a marked increase in grain yield.

In a study by Singh et al. (2010), an investigation to assess the influence of sowing time on wheat flour starch pasting and protein quality characteristics in two genotypes with varying water requirements was conducted under both irrigated and rainfed conditions for a duration of two years. The results indicated that elevated temperatures during the grain-filling phase due to delayed sowing led to a significant increase in total grain protein content. Moreover, in cases of early sowing, the prevalence of lower temperatures had a positive impact on the content of insoluble glutenin (IG) while decreasing the overall protein accumulation in both genotypes. Notably, the effect of higher temperatures under late sowing conditions appeared to be genotype-dependent, with a negative impact on the content of insoluble glutenin (IG) in C 306 but an increase in PBW 343. In a research investigation conducted by Silva et al. (2014) in Parana, Brazil, it was observed that initiating wheat sowing early contributed to the optimization of wheat productivity and baking quality among seven distinct wheat varieties tested across various sowing dates. PDW 315 and HP 4080 showed comparable yields, both significantly higher than that of Raj 4037, in a study evaluating the effects of different sowing dates on wheat genotypes. According to Vijay et al. (2012), there was a significant correlation between the genotype and sowing date in grain and straw yield. PDW 315 yielded the highest grains when sown on November 15, while HP 4080 yielded the highest straw under the same conditions. Dubey et al. (2019) at IARI, New Delhi reported that yield loss occurred by 70, 29 and 77 kg ha$^{-1}$ per day due to delay in sowing beyond second week of November in varieties, viz.

'HD 2932,' 'WR 544' and 'HD 2967,' respectively as the late-sown crop experienced higher temperature in its terminal growth stages.

Twelve treatment combinations were investigated in the study by Meena (2015), with an emphasis on varying sowing dates, tillage techniques and residue management strategies andfound that zero tillage with full residue and early planting on October 25 resulted in higher yields, improved weed control, and increased economic returns compared to other management practices. This approach also demonstrated superior growth parameters and better overall productivity for wheat. Chhokar et al. (2018) investigated the effectiveness of various wheat seeding techniques in Conservation Agriculture (CA) following the harvest of rice and sugarcane. According to their findings, the Rotary Disc Drill (RDD) is best suited for seeding under full trash in sugarcane ratoons, while the Turbo Happy Seeder (THS) is appropriate for wheat seeding under full residue retention following rice harvest. The study highlighted the comparable wheat grain yields between Conventional Tillage (CT) and CA. Specific cultivars, including HDCSW 18, HD 2967, MPO 1215, PBW 723, HI 8498, MACS 6222 and UAS 428 displayed superior yield performance. Additionally, using RDD in sugarcane ratoon could potentially lead to an extra wheat production of 3.2 mt annually across a 50% sugarcane area in India. The research emphasized the economic benefits of CA, with a potential additional profit of Rs 3125 $ha^{-1}$ due to reduced tillage costs. These results highlight how crucial it is to choose the right cultivar and seeding equipment in conservation agriculture based rice–wheat and sugarcane ratoon-wheat systems in order to increase wheat productivity, production and profitability. It is further studied that similar wheat yield can be obtained under conservation tillage as with CT but with higher profitability (saving of Rs 3035 $ha^{-1}$) and reduced CO2 release by 125 kg $ha^{-1}$ (Chhokar et al. 2023). The field experiment was carried out at Punjab Agricultural University in Ludhiana throughout the winter months of 2019–20 and 2020–21. With three replications in each of the two years, it was created in a split plot format. Two ways of managing rice residue were used in the main plot treatments: Happy Seeder sowing and traditional sowing. In the first year, twenty-four wheat genotypes were used in the sub-plots, comprising four standard check varieties and twenty advanced breeding lines. The primary plot treatments in the second year consisted of four planting dates (October15, October25, November 5 and November 15) and a combination of two rice residue management techniques. The three wheat genotypes that made up the sub-plots in the second year were BWL 7566, BWL 6986 and DBW 187. The results of the study showed that using the Happy Seeder approach increased soil quality and nutrient uptake in addition to enhanced growth and yield indices. In the study, certain genotypes of wheat—BWL 7566, DBW 187 and BWL 6986—performed better than others. Happy Seeder method of early October sowing produced more effective tillers and improved crop emergence. The study also demonstrated how important a sowing date is on the crop canopy and soil temperature at different phases of growth (Kaur 2022). A two-year field study conducted at two locations in 2019–2021 assessed how various cultivation techniques and types affected the rice–wheat cropping system's productivity and profitability by Saini et al. (2022). In terms of grain yield for both wheat and rice, conventional tillage consistently outperformed reduced tillage, zero tillage, and natural farming across all locations and years, according to the split-plot design with three replications. In particular, when compared to conventional tillage, natural farming dramatically decreased grain production by 34.0% for rice and 59.4% for wheat. Among the investigated varieties, Him Palam Lal Dhan 1 (HPR 2795) for rice and HPW 368 for wheat regularly produced greater grain yields and economic benefits, such as benefit–cost ratio, net return, and gross return, indicating their suitability for the conditions under study. The interaction between cultivation practices and varieties was determined to be non-significant for grain yield, straw yield, and biological yield. This finding implies that while cultivation practices and varieties individually affect yield, their combined effect did not show statistically significant differences in the outcomes measured.

It can be understood that a top performer wheat variety under early sowing may suffer yield lag under delayed sown condition as a result of reduced grain filling period. Therefore, sowing time is equally important like selection of suitable wheat variety for getting the higher productivity.

## Conclusion and future perspectives

### Towards sustainable wheat cultivation

To sum up, the altered environment of wheat under rice residue condition and changing climate necessitate the change in present set of genotypes and agronomic practices recommended for conventional sowing and sustainable practices need to be at the forefront. Adopting an integrated approach that considers genotypes, sowing times and residue management is essential for navigating the complexities of a changing agricultural landscape. The choice of wheat genotype significantly influences the crop's ability to withstand environmental stresses (Honsdorf et al. 2020). Optimal sowing times, as highlighted by Gupta et al. (2002), play a pivotal role in achieving successful germination, robust growth and bountiful harvests. Additionally, in-*situ*residue management techniques, exemplified by the direct seeding with Happy seeder (Kaur 2022) offer innovative solutions for enhancing crop productivity. This holistic strategy not only optimizes

yields but also contributes to the broader goals of food security and environmental sustainability.

### Key takeaways and recommendations

Key takeaways include sophisticated comprehension of the interactions among genotypes, sowing intervals and residue handling. Recommendations for future research involve further exploration of genotype-environment-management (GEM) interactions, extensive field experimentation to validate findings and the development of region-specific guidelines for wheat cultivation.

**Acknowledgements** We are very thankful to Department of Biotechnology, Ministry of Science and Technology, Government of India, New Delhi and Punjab Agricultural University, Ludhiana, India for providing necessary facilities during the research work.

**Funding** This work was supported by Department of Biotechnology, Ministry of Science and Technology, Government of India, New Delhi, Grant number: BT/PR31684/BIC/101/1205/2019.

**Data availability** Not Applicable.

## Declarations

**Competing interests** The authors declare that they have no known competing interests that could have appeared to influence the work reported in this paper.

## References

Aberkane, H., Payne, T., Kishi, M., Smale, M., Amri, A., Jamora, N.: Transferring diversity of goat grass to farmers' fields through the development of synthetic hexaploid wheat. Food Secur. **12**, 1017–1033 (2020). https://doi.org/10.1007/s12571-020-01051-w

Ahmad, N., Shaha, N.H., Habibullah, M., Khan, F.U.: Effects of different seed rates, sowing dates and weed control on grain yield of wheat. Pak. J. Weed Sci. Res. **11**(3/4), 109–113 (2005)

Alam, P., Kumar, S., Ali, N., Manjhi, R.P., Kumari, N., Lakra, R.K., Izhar, T.: Performance of wheat varieties under different sowing dates in Jharkhand. J. Wheat Res. **5**, 61–64 (2013)

Ali, M.A., Hussain, M., Khan, M.I., Ali, Z., Zulkiffal, M., Anwar, J., Zeeshan, M.: Source-sink relationship between photosynthetic organs and grain yield attributes during grain filling stage in spring wheat (*Triticum aestivum*). Int. J. Agric. Biol. **12**, 509–515 (2010)

Amani, I., Fischer, R.A., Reynolds, M.P.: Canopy temperature depression association with yield of irrigated spring wheat cultivars in a hot climate. J. Agron. Crop Sci. **176**, 119–129 (1996). https://doi.org/10.1111/j.1439-037X.1996.tb00454.x

Aslam, M., Majid, A., Hashmi, N.I., Hobbs, P.R.: Improving wheat yield in the rice-wheat cropping system of the Punjab [Pakistan] through zero tillage. Pak. J. Agric. Res. **14**, 8–11 (1993)

Balwinder-Singh, Humphreys, E., Eberbach, P.L., Katupitiya, A., Yadvinder-Singh, Kukal, S.S.: Growth, yield and water productivity of zero till wheat as affected by rice straw mulch and irrigation schedule. Field Crops Res. **121**, 209–225 (2011b). https://doi.org/10.1016/j.fcr.2010.12.005

Balwinder-Singh, Humphreys, E., Gaydon, D.S., Eberbach, P.L.: Evaluation of the effects of mulch on optimum sowing date and irrigation management of zero till wheat in central Punjab, India using APSIM. Field Crops Res. **197**, 83–96 (2016). https://doi.org/10.1016/j.fcr.2016.08.016

Balwinder-Singh, Eberbach, P.L., Humphreys, E., Kukal, S.S.: The effect of rice straw mulch on evapotranspiration, transpiration and soil evaporation of irrigated wheat in Punjab, India. Agric. Water Manag. **98**, 1847–1855 (2011a). https://doi.org/10.1016/j.agwat.2011.07.002

Begam, A., Roy, D.C., Ray, M., Biswas, S.: Conservation agriculture: a new paradigm in modern agriculture to increase resource use efficiency. Int. J. Agric. Sci. **10**, 7168–7171 (2018). https://doi.org/10.3390/s22239089

Belete, T.: Performance evaluation of bread wheat (*Triticum aestivum* L.) varieties in the highlands of Southwestern part of Ethopia. Intr. J. Adv. Res. Rev. **8**(12), 14–27 (2023)

Bheemanahalli, R., Sunoj, V.S.J., Saripalli, G., Prasad, P.V.V., Balyan, H.S., Gupta, P.K., Grant, N., Gill, K.S., Jagadish, S.V.K.: Quantifying the impact of heat stress on pollen germination, seed set, and grain filling in spring wheat. Crop. Sci. **59**, 684–696 (2019)

Bijay-Singh, Shan, Y.H., Johnson-Beebout, S.E., Yadvinder-Singh, Buresh, R.J.: Crop residue management for lowland rice-based cropping systems in Asia. Adv. Agron. **98**, 117–199 (2008). https://doi.org/10.1016/S0065-2113(08)00203-4

Bikkina, S., Andersson, A., Kirillova, E.N., Holmstrand, H., Tiwari, S., Srivastava, A.K., Bisht, D.S., Gustafsson, Ö.: Air quality in megacity Delhi affected by countryside biomass burning. Nat. Sustain. (2019). https://doi.org/10.1038/s41893-019-0219-0

Buttar, G.S., Sodhi, G.P.S., Manes, G.S., Sunidhi, K., Kaur, T., Brar, N.S., Kumar, A., Singh, R., Kaur, S.: Adoption pattern of farm-machinery based solutions for *in-situ* paddy strawmanagement in Punjab. Indian J. Ext. Edu. **59**(4), 103–108 (2023). https://doi.org/10.48165/IJEE.2023.59421

Chakrabarti, S., Khan, M.T., Kishore, A., Roy, D., Scott, S.P.: Risk of acute respiratory infection from crop burning in India: estimating disease burden and economic welfare from satellite and national health survey data for 250 000 persons. Int. J. Epidemiol. **48**, 1113–1124 (2019). https://doi.org/10.1093/ije/dyz022

Chakraborty, D., Nagarajan, S., Aggarwal, P., Gupta, V.K., Tomar, R.K., Garg, R.N., Kalra, N.: Effect of mulching on soil and plant water status, and the growth and yield of wheat (*Triticumaestivum* L.) in a semi-arid environment. Agric. Water Manag. **95**, 1323–1334 (2008). https://doi.org/10.1016/j.agwat.2008.06.001

Chakraborty, D., Garg, R.N., Tomar, R.K., Singh, R., Sharma, S.K., Singh, R.K., Trivedi, S.M., Mittal, R.B., Sharma, P.K., Kamble, K.H.: Synthetic and organic mulching and nitrogen effect on winter wheat (*Triticum aestivum* L.) in a semi-arid environment. Agric. Water Manag. **97**, 738–748 (2010). https://doi.org/10.1016/j.agwat.2010.01.006

Chandrashekar, V., Sairam, R.K., Srivastava, G.C.: Physiological and biochemical responses of hexaploid and tetraploid wheat to drought stress. J. Agron. Crop Sci. **185**, 219–227 (2000). https://doi.org/10.1046/j.1439-037x.2000.00430.x

Chauhan, B.S., Mahajan, G., Sardana, V., Timsina, J., Jat, M.L.: Productivity and sustainability of the rice-wheat cropping system in the indo-gangetic plains of the Indian subcontinent: problems, opportunities and strategies. Adv. Agron. **117**, 315–369 (2012). https://doi.org/10.1016/B978-0-12-394278-4.00006-4

Chauhan, A., Gupta, S.K., Liou, Y.A.: Rising surface ozone due to anthropogenic activities and its impact on COVID-19 related deaths in Delhi, India. Heliyon **9**, e14975 (2023). https://doi.org/10.1016/j.heliyon.2023.e14975

Chhokar, R.S., Sharma, R.K., Gill, S.C., Singh, R.K., Joon, V., Kajla, M., Chaudhary, A.: Suitable wheat cultivars and seeding

machines for conservations agriculture in rice-wheat and sugarcane-wheat cropping system. Wheat Barley Res. **10**, 78–88 (2018). https://doi.org/10.25174/2249-4065/2018/80127

Chhokar, R.S., Sharma, R.K., Kumar, N., Singh, R.K., Singh, G.P.: Advancing sowing time and conservation tillage - the climate-resilient approach to enhance the productivity and profitability of wheat. Int. J. Pl. Prod. **17**, 121–131 (2023). https://doi.org/10.1007/s42106-022-00216-1

Choudhary, M., Sharma, P.C., Jat, H.S., McDonald, A., Jat, M.L., Choudhary, S., Garg, N.: Soil biological properties and fungal diversity under conservation agriculture in Indo-Gangetic Plains of India. J. Soil Sci. Plant Nutr. **18**, 1142–1156 (2018). https://doi.org/10.4067/S0718-95162018005003201

Choudhury, S.G., Srivastava, S., Singh, R., Chaudhari, S.K., Sharma, D.K., Singh, S.K., Sarkar, D.: Tillage and residue management effects on soil aggregation, organic carbon dynamics and yield attribute in rice–wheat cropping system under reclaimed sodic soil. Soil Tillage Res. **136**, 76–83 (2014). https://doi.org/10.1016/j.still.2013.10.001

Dar, S.B., Kanth, R.H., Raja, W., Bangroo, S.A., Mir, S.A.: Performance of wheat in relation to sowing dates and nitrogen levels under rainfed conditions of Kashmir. Int. J. Currmicrobiol. App. Sci. **7**, 2600–2608 (2018). https://doi.org/10.20546/ijcmas.2018.704.296

Datta, A., Emmanuel, M.A., Ram, N.K., Dhingra, S.: Crop residue management: solution to achieve better air quality. The Energy Resour Inst, 15 (2020)

Deshpande, M.V., Kumar, N., Pillai, D., Krishna, V.V., Jain, M.: Greenhouse gas emissions from agricultural residue burning have increased by 75% since 2011 across India. Sci. Total. Environ. **904**, 166944 (2023). https://doi.org/10.1016/j.scitotenv.2023.166944

Dhaka, A.K., Bangarwa, A.S., Pannu, R.K., Malik, R.K., Garg, R.: Effect of sowing time and irrigation on growth and yield of different wheat genotypes. Agric. Sci. Digest **26**, 249–252 (2006)

Dhima, K.V., Vasilakoglou, I.B., Eleftherohorinos, I.G., Lithourgidis, A.S.: Allelopathic potential of winter cereals and their cover crop mulch effect on grass weed suppression and corn development. Crop. Sci. **46**, 345–352 (2006). https://doi.org/10.2135/cropsci2005-0186

Dias, A.S., Bagulho, A.S., Lidon, F.C.: Ultrastructure and biochemical traits of bread and durum wheat grains under heat stress. Braz. J. Plant. Physiol. **20**, 323–333 (2008). https://doi.org/10.1590/S1677-04202008000400008

Dobermann, A., Fairhurst, T.H.: Rice straw management. Better Crops Int. **16**, 7–11 (2002)

Dong, S., Zhang, X., Chu, J., Zheng, F., Fei, L., Dai, X., He, M.: Optimized seeding rate and nitrogen topdressing ratio for simultaneous improvement of grain yield and bread-making quality in bread wheat sown on different dates. J. Sci. Food Agric. **102**(1), 360–369 (2022). https://doi.org/10.1002/jsfa.11366

Dubey, R., Pathak, H., Singh, S., Chakravarti, B., Thakur, A.K., Fagodia, R.K.: Impact of sowing dates on terminal heat tolerance of different wheat (*Triticum aestivum* L.) cultivars. Natl. Acad. Sci. Lett. (2019). https://doi.org/10.1007/s40009-019-0786-7

Dutta, A., Bhattacharyya, R., Chaudhary, V.P., Sharma, C., Nath, C.P., Kumar, S.N., Parmar, B.: Impact of long-term residue burning versus retention on soil organic carbon sequestration under a rice-wheat cropping system. Soil till. Res. **221**, 105421 (2022). https://doi.org/10.1016/j.still.2022.105421

Ehdaie, B., Alloush, G.A., Madore, M.A., Waines, J.G.: Genotypic variation for stem reserves and mobilization in wheat: I. Post-anthesis changes in internode dry matter. Crop. Sci. **46**, 735–746 (2006). https://doi.org/10.2135/cropsci2005.04-0033

El-Gizawy, N.K.B.: Effect of planting date and fertilizer application on yield of wheat under no till system. World J. Agril. Sci. **5**, 777–783 (2009)

Eslami, H., Hadi, S.M.J.M., Arabi, M.K.: Effect of planting date on protein content of wheat varieties. Int. J. Farm. Alli. Sci. **3**, 362–364 (2014)

Fagodiya, R.K., Sharma, G., Verma, K., Rai, A.K., Prajapat, K., Singh, R., Biswas, A.K.: Computation of soil quality index after fifteen years of long-term tillage and residue management experiment (LT&RE) under rice wheat system. Agric. Sys. **219**, 104039 (2024). https://doi.org/10.1016/j.agsy.2024.104039

FAO: CA Adoption Worldwide, Food and Agriculture Organization of the United Nations,-CA website. http://www.fao.org/ag/ca/6c.html (2018)

Ghosh, D.C., Nandi, P., De, B.: Phenological development and productivity of wheat (*Triticumaestivum*) at different dates of sowing. Indian J. Agric. Sci. **70**, 393–395 (2000)

Gill, K.K., Babuta, R., Kaur, N., Sandhu, S.: Thermal requirement of wheat crop in different agroclimatic regions of Punjab under climate change scenarios. Mausam **65**, 417–424 (2014)

Grover, D., Chaudhry, S.: Ambient air quality changes after stubble burning in rice–wheat system in an agricultural state of India. Environ. Sci. Pollut. Res. **26**, 20550–20559 (2019). https://doi.org/10.1007/s11356-019-05395-5

Gupta, N., Pradhan, S., Jain, A., Patel, N.: Sustainable Agriculture in India 2021: What we know and how to scale up. New Delhi: Council on Energy, Environment and Water. https://www.ceew.in/publications/sustainable-agriculture-india-2021 (2021)

Gupta, N.K., Khan, A., Maheshwari, A., Narayan, S., Chhapola, O.P., Arora, A., Singh, G.: Effect of post anthesis high temperature stress on growth, physiology and antioxidative defence mechanisms in contrasting wheat genotypes. Indian J. Plant Physiol. **20**, 103–110 (2015a). https://doi.org/10.1007/s40502-015-0142-y

Gupta, N.K., Shukla, D.S., Pande, P.C.: Interaction of yield determining parameters in late sown wheat genotypes. Indian J. Plant Physiol. **7**, 264–269 (2002)

Gupta, R.K., Kaur, J., Kang, J.S., Singh, H., Kaur, S., Sayed, S., Gaber, A., Hossain, A.: Tillage in combination with rice straw retention in a rice–wheat system improves the productivity and quality of wheat grain through improving the soil physio-chemical properties. Land **11**, 1693 (2022a). https://doi.org/10.3390/land11101693

Gupta, R.K., Hans, H., Kalia, A., Kang, J.S., Kaur, J., Sraw, P.K., Singh, A., Alataway, A., Dewidar, A.Z., Mattar, M.A.: Long-term impact of different straw management practices on carbon fractions and biological properties under rice–wheat system. Agric. **12**, 1733 (2022b). https://doi.org/10.3390/agriculture12101733

Gupta, R.K., Sraw, P.K., Kang, J.S., Kaur, J., Sharma, V., Pathania, N., Kalia, A., Ansari, N.A., Alataway, A., Dewidar, A.Z., Mattar, M.A.: Interactive effects of long-term management of crop residue and phosphorus fertilization on wheat productivity and soil health in the rice–wheat. Sci. Rep. **14**, 1399 (2024). https://doi.org/10.1038/s41598-024-51399-8

Gupta, R.K., Sraw, P.K., Kang, J.S., Kaur, J., Kalia, A., Sharma, V., Manhas, S.S., Al-Ansari, N., Alataway, A., Dewidar, A.Z., Mattar, M.A.: Influence of 11 years of crop residue management on rice productivity under varied nitrogen levels in the rice-wheat cropping system. Pl. Soil Environ. **69**(7), 333–343 (2023). https://doi.org/10.17221/68/2023-PSE

Gupta, R.K., Yadvinder-Singh, Ladha, J.K., Bijay-Singh, Singh, J., Singh, G., Pathak, H.: Yield and phosphorus transformations in a rice-wheat system with crop residue and phosphorus management. Soil Sci. Soc. Am. J. **71**, 1500–1507 (2007). https://doi.org/10.2136/sssaj2006.0325

Gupta, S., Singh, S.P., Singh, C.K., Singh, V.K., Singh, V.: Performance of newly released wheat varieties at farmer's field. Ann. Plant Soil Res. **17**, 507–509 (2015b)

Gupta, V., Gupta, M., Bharat, R., Singh, M., Sharma, B.C.: Performance of wheat varieties under thermal regimes and N levels. Indian J. Agric. Sci. **90**(4), 775–779 (2020). https://doi.org/10.56093/ijas.v90i4.102222

Hakim, M.A., Hossain, A., da Silva, J.A.T., Zvolinsky, V.P., Khan, M.M.: Yield, protein and starch content of 20 wheat (*Triticum aestivum* L.) genotypes exposed to high temperature under late sowing conditions. J. Scientific Res. **4**, 477–489 (2012). https://doi.org/10.3329/jsr.v4i2.8679

Hobbs, P.R., Morris, M.L.: Meeting South Asia's future food requirements from rice-wheat cropping systems: Priority issues facing researchers in the post-green revolution era. NRG paper, CIMMYT, Mexico, DF, pp. 96–101 (1996)

Hobbs, P.R., Sayre, K., Gupta, R.: The role of conservation agriculture in sustainable agriculture. Philos. Trans. Royal Soc. B **363**, 543–555 (2008). https://doi.org/10.1098/rstb.2007.2169

Honsdorf, N., Mulvaney, M.J., Singh, R.P., Ammar, K., Burgueño, J., Govaerts, B., Verhulst, N.: Genotype by tillage interaction and performance progress for bread and durum wheat genotypes on irrigated raised beds. Field Crops Res. **216**, 42–52 (2018). https://doi.org/10.1016/j.fcr.2017.11.011

Honsdorf, N., Verhulst, N., Crossa, J., Vargas, M., Govaerts, B., Ammar, K.: Durum wheat selection under zero tillage increases early vigor and is neutral to yield. Field Crops Res. **248**, 107675 (2020). https://doi.org/10.1016/j.fcr.2019.107675

Hossain, A., da Silva, J.A.T.: Phenology, growth and yield of three wheat (*Triticumaestivum* L.) varieties as affected by high temperature stress. Not. Sci. Biol. **4**, 97–109 (2012). https://doi.org/10.15835/nsb437879

Hossain, A., Islam, M.R., Rahman, K.A.M.M., Rashid, M.H., Anwari, A.: Comparative performance of three wheat (*Triticum aestivum* L.) varieties under heat stress. Int. J. Nat. Soc. Sci. **4**, 26–42 (2017)

Hossain, A., da Silva, J.A.T., Lozovskaya, M.V., Zvolinsky, V.P.: The effect of high temperature stress on phenology, growth and yield of five wheat (*Triticum aestivum* L.) varieties. Asian Aus. J. Plant. Sci. Biotech. **6**, 14–23 (2012)

Jain, N., Bhatia, A., Pathak, H.: Emission of air pollutants from crop residue burning in India. Aerosol Air Qual. Res. (2014). https://doi.org/10.4209/aaqr.2013.01.0031

Jat, L.K., Singh, S.K., Latare, A.M., Singh, R.S., Patel, C.B.: Effect of dates of sowing and fertilizer on growth and yield of wheat (*Triticumaestivum* L.) in an Inceptisol of Varanasi. Indian J. Agron. **58**, 611–614 (2013)

Jat, M.L., Dagar, J.C., Sapkota, T.B., Yadvinder-Singh, Goaverts, B., Ridaura, S.L., Saharawat, Y.S., Sharma, R.K., Tetarwal, J.P., Jat, R.K., Hobbs, H., Stirling, C.: Climate change and agriculture: adaptation strategies and mitigation opportunities for food security in South Asia and Latin America. Adv. Agron. **137**, 127–135 (2016). https://doi.org/10.1016/bs.agron.2015.12.005

Jat, M.L., Gathala, M.K., Ladha, J.K., Saharawat, Y.S., Jat, A.S., Kumar, V., Sharma, S.K., Kumar, V., Gupta, R.: Evaluation of precision land levelling and double zero-till systems in the rice-wheat rotation: water use, productivity, profitability and soil physical properties. Soil Tillage Res. **105**, 112–121 (2009). https://doi.org/10.1016/j.still.2009.06.003

Jat, M.L., Jat, R.K., Singh, P., Jat, S.L., Sidhu, H.S., Jat, H.S., Bijarniya, D., Parihar, C.M., Gupta, R.: Predicting yield and stability analysis of wheat under different crop management systems across agro-ecosystems in India. Am. J. Plant Sci. **8**, 1977–2012 (2017). https://doi.org/10.4236/ajps.2017.88133

Jat, R.K., Singh, P., Jat, M.L., Dia, M., Sidhu, H.S., Jat, S.L., Bijarniya, D., Jat, H.S., Parihar, A.M., Kumar, U., Ridaura, S.L.: Heat stress and yield stability of wheat genotypes under different sowing dates across agro-ecosystems in India. Field Crops Res. **218**, 33–50 (2018). https://doi.org/10.1016/j.fcr.2017.12.020

Javed, N., Ashraf, M., Fahad-Al-Qurainy, Akram, N.A.: Integration of physio-biochemical processes at different phenological stages of wheat (*Triticumaestivum* L.) plants in response to heat stress. Pak. J. Bot. **46**, 2143–2150 (2014)

Jethva, H., Torres, O., Field, R.D., Lyapustin, A., Gautam, R., Kayetha, V.: Connecting crop productivity, residue fires, and air quality over northern India. Sci. Rep. (2019). https://doi.org/10.1038/s41598-019-52799-x

Junpen, A., Pansuk, J., Kamnoet, O., Cheewaphongphan, P., Garivait, S.: Emission of air pollutants from rice residue open burning in Thailand. Atmos (Basel) (2018). https://doi.org/10.3390/atmos9110449

Kamrozzaman, M.M., Khan, M.A.H., Ahmed, S., Sultana, N.: Growth and yield of wheat at different dates of sowing under Charland ecosystem of Bangladesh. J. Bangladesh Agric. Univ. **14**, 147–154 (2016). https://doi.org/10.3329/jbau.v14i2.32688

Kaur, A., Pannu, R.K., Buttar, G.S.: Impact of nitrogen application on the performance of wheat (*Triticum aestivum*) and nitrogen use efficiency under different dates of sowing. Indian J. Agron. **5**, 40–45 (2010a)

Kaur, A., Pannu, R.K., Buttar, G.S.: Quality of wheat (*Triticum aestivum* L.) as influenced by sowing dates and nitrogen scheduling. Indian J. Agric. Sci. **80**, 781–785 (2010b)

Kaur, C.: Performance of wheat varieties under late and very late sowing conditions. Int. J. Curr. Microbiol. Appl. Sci. **6**, 3488–3492 (2017)

Kaur, M.: Performance of wheat (*Triticum aestivum* L.) genotypes under rice residue in relation to altered sowing time, M.Sc. Thesis Punjab agricultural University, Ludhiana, Punjab, India (2022)

Kaur, M., Malik, D.P., Malhi, G.S., Sardana, V., Bolan, N.S., Lal, R., Siddique, K.H.M.: Rice residue management in the Indo-Gangetic Plains for climateand food security. A review. Agron. Sustain. Dev. **42**, 92 (2022). https://doi.org/10.1007/s13593-022-00817-0

Kaur, R., Kaur, S., Deol, J.S., Sharma, R., Kaur, T., Brar, A.S., Choudhary, O.P.: Soil properties and weed dynamics in wheat as affected by rice residue management in the rice-wheat cropping system in South Asia: A review. Plants **10**, 953 (2021). https://doi.org/10.3390/plants10050953

Khan, M.A., Khan, E.A., Ullah, K.: Irrigated wheat response to different tillage systems, crop residue management practices and sowing dates in rice-wheat cropping system. Pak. J. Life Soc. Sci. **13**, 162–169 (2015)

Khaskheli, M.A., Ansari, M.A., Khan, M.A., Laghari, U.A., Shar, T., Bhutto, M.: Growth and yield performance of different wheat genotypes under various potassium levels. Int. J. Biosci. **10**, 106–115 (2017). https://doi.org/10.12692/ijb/10.5.106

Kumar, S., Sharma, D.K., Singh, D.R., Biswas, H., Praveen, K.V., Sharma, V.: Estimating loss of ecosystem services due to paddy straw burning in North-west India. Int. J. Agric. Sustain. **17**, 146–157 (2019). https://doi.org/10.1080/14735903.2019.1581474

Kumar, V., Jat, H.S., Sharma, P.C., Balwinder-Singh, Gathala, M.K., Malik, R.K., Kamboj, B.R., Yadav, A.K., Ladha, J.K., Raman, A., Sharma, D.K., McDonald, A.: Can productivity and profitability be enhanced in intensively managed cereal systems while reducing the environmental footprint of production? Assessing sustainable intensification options in the bread basket of India. Agric. Ecosyst. Environ. **252**, 132–147 (2018). https://doi.org/10.1016/j.agee.2017.10.006

Lal, R., Reicosky, D.C., Hanson, J.D.: Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil Tillage

Res. **93**, 1–12 (2007). https://doi.org/10.1016/j.still.2006.11.004

Li, R., Hou, X., Jia, Z., Han, Q., Ren, X., Yang, B.: Effect on soil temperature, moisture, and maize yield of cultivation with ridge and furrow mulching in the rainfed area of the Loess Plateau, China. Agric. Water Manag. **116**, 101–109 (2013). https://doi.org/10.1016/j.agwat.2012.10.001

Liu, T., Mickley, L.J., Patel, P.N., Gautam, R., Jain, M., Singh, S., De Fries, R.S., Marlier, M.E.: Cascading delays in the monsoon rice growing season and post-monsoon agricultural fires likely exacerbate air pollution in North India. J. Geophys. Res. Atmos. **127**, 1–16 (2022). https://doi.org/10.1029/2022JD036790

Liu, T., Mickley, L.J., Singh, S., Jain, M., DeFries, R.S., Marlier, M.E.: Crop residue burning practices across north India inferred from household survey data: bridging gaps in satellite observations. Atmos. Environ. X (2020). https://doi.org/10.1016/j.aeaoa.2020.100091

Madhu, U., Begum, M., Salam, A., Sarkar, S.K.: Influence of sowing date on the growth and yield performance of wheat (*Triticum aestivum* L.) varieties. Arch. Agric. Environ. Sci. **3**, 89–94 (2018). https://doi.org/10.26832/24566632.2018.0301014

Mahmud, R., Abdulhamed, Z.A., Alogaidi, M.A.: Effect of planting dates on growth characteristics and yield of six bread wheat cultivars. Iraqi J. Desert Stud. **12**(1), 69–78 (2022). https://doi.org/10.36531/ijds.2022.174582

Malik, R.K., Singh, S., Yadav, A.: Effect of sowing time on grain yield of wheat (*Triticum aestivum* L.) in rice-wheat cropping system. HAU J. Res. **37**, 103–105 (2007)

Marasini, D., Marahatta, S., Dhungana, S.M., Acharya, R.: Effect of date of sowing on yield and yield attributes of different wheat varieties under conventional tillage in sub-humid condition of Chitwan district of Nepal. Int. J. Appl. Sci. Biotech. **4**, 27–31 (2016)

McCarty, J.L., Korontzi, S., Justice, C.O., Loboda, T.: The spatial and temporal distribution of crop residue burning in the contiguous United States. Sci. Total. Environ. (2009). https://doi.org/10.1016/j.scitotenv.2009.07.009

Meelu, O.P., Singh, B., Singh, Y.: Effect of green manure and crop residue recycling on N economy, organic matter and physical properties of rice-wheat system in India, CCS HAU, Regional Res. Station, Karnal, pp. 61–76 (1994)

Meena, R.K.: Effect of residue and nitrogen management on productivity and soil health in aerobic Basmati rice (*Oryza sativa* L.)-wheat (*Triticum aestivum* L.) cropping system. Ph. D dissertation, ICAR-Indian Agricultural Research Institute, New Delhi, India (2015)

Meena, R.P., Tripathi, S.C., Sharma, R.K., Chhokar, R.S., Chander, S., Jha, A.: Role of precision irrigation scheduling and residue-retention practices on water-use efficiency and wheat (*Triticum aestivum*) yield in north-western plains of India. Indian J. Agron. **63**, 186–191 (2018)

Mohammadi, M.: Effects of kernel weight and source-limitation on wheat grain yield under heat stress. Afr. J. Biotechnol. **11**, 2931–2937 (2012). https://doi.org/10.5897/AJB11.2698

Mondal, S., Chakraborty, D., Tomar, R.K., Singh, R., Garg, R.N., Aggarwal, P., Sidhu, G.S., Behera, U.K.: Tillage and residue management effect on soil hydro-physical environment under pigeon pea (*Cajanus cajan*)-wheat (*Triticum aestivum*) rotation. Indian J. Agric. Sci. **83**, 502–507 (2013)

Munjal, R., Dhanda, S.S.: Associations for heat tolerance in bread wheat. Natl. J. Pl. Improv. **6**, 71–73 (2004)

NAAS Innovative viable solution to rice residue burning in rice-wheat croppingsystem through concurrent use of super straw management system-fitted combines and turbohappy seeder. Policy Brief No. 2, National Academy of Agricultural Sciences, New Delhi, p. 16 (2017)

Nawaz, A., Farooq, M., Cheema, S.A., Wahid, A.: Differential response of wheat varieties to terminal heat stress. Int. J. Agril. Biol. **15**, 1354–1358 (2013)

Nichols, V., Verhulst, N., Cox, R., Govaerts, B.: Weed dynamics and conservation agriculture principles: a review. Field Crops Res. **183**, 56–68 (2015). https://doi.org/10.1016/j.fcr.2015.07.012

Ortiz-Monasterio, J.I., Dhillon, S.S., Fischer, R.A.: Date of sowing effect on grain yield and yield components of irrigated spring wheat varieties and relationships with radiation and temperature in Ludhiana, India. Field Crops Res. **37**, 169–184 (1994). https://doi.org/10.1016/0378-4290(94)90096-5

Osmani, M.H., Fazily, T., Koshani, B., Mirzaee, M.: Comparison of adaptation assessment of four local spring varieties in Kabul climatic condition. EPRA Int. J. Res. Dev. **5**(1), 21–23 (2020)

Passioura, J.B.: Physiology of grain yield in wheat growing on stored water. Aust. J. Plant Physiol. **3**, 559–565 (1976). https://doi.org/10.1071/PP9760559

Poonia, T., Gora, M.K., Kakraliya, M., Kakraliya, S.K., Jat, H.S.: Rice residue load influences the wheat crop associated weed flora in rice-wheat system. J. Soil Salinity Water Qual. **14**(1), 131–137 (2022)

Pradhan, G.P., Prasad, P.V., Fritz, A.K., Kirkham, M.B., Gill, B.S.: Effects of drought and high temperature stress on synthetic hexaploid wheat. Funct. Plant Biol. **39**, 190–198 (2012). https://doi.org/10.1071/FP11245

Pyare, R., Singh, R.K., Dixit, K.K., Verma, V.K.: Comparative studies on wheat (*Triticum aestivum* L.) varieties and date of sowing under late sown conditions. Agriways **3**, 4–9 (2015)

Qasim, M., Qamer, M., Alam, M., Alam, M.: Sowing dates effect on yield and yield components of different wheat varieties. J. Agric. Res. **46**, 135–140 (2008)

Ram, A., Pannu, R.K., Prasad, D.: Effect of management practices on growth, yield and quality of late sown Wheat. Indian J. Agron. **57**, 92–95 (2012a)

Ram, H., Dadhwal, V., Vashist, K.K., Kaur, H.: Grain yield and water use efficiency of wheat (*Triticum aestivu*m L.) in relation to irrigation levels and rice straw mulching in northwest India. Agric. Water Manage. **128**, 92–101 (2013). https://doi.org/10.1016/j.agwat.2013.06.011

Ram, H., Kler, D.S., Singh, Y., Kumar, K.: Productivity of maize (*Zea mays*)-wheat (*Triticum aestivum*) system under different tillage and crop establishment practices. Indian J. Agron. **55**, 185–190 (2010)

Ram, H., Singh, G., Mavi, G.S., Sohu, V.S.: Accumulated heat unit requirement and yield of irrigated wheat (*Triticum aestivum* L.) varieties under different crop growing environment in central Punjab. J. Agromet. **14**, 147–153 (2012b). https://doi.org/10.54386/jam.v14i2.1414

Ram, K., Kumar, R., Sunita, M.R.: Stem reserve mobilization in relation to yield under different drought and high temperature stress conditions in wheat (*Triticum aestivum* L) genotypes. Int. J. Curr. Microbiol. Appl. Sci. **7**, 3695–3704 (2018). https://doi.org/10.20546/ijcmas.2018.704.415

Ravindra, K., Singh, T., Mor, S.: Emissions of air pollutants from primary crop residue burning in India and their mitigation strategies for cleaner emissions. J. Clean. Prod. **208**, 261–273 (2019). https://doi.org/10.1016/j.jclepro.2018.10.031

Reddy, M.S.L., Mitra, B.: Growth and yield performance of zero tillage wheat (*Triticum aestivum* L.) under varying rice residue load and nutrient management options. J. Cereal. Res. (2024). https://doi.org/10.25174/2582-2675/2024/140180

Rosyara, U., Kishii, M., Payne, T., Sansaloni, C.P., Singh, R.P., Braun, H.J., Dreisigacker, S.: Genetic contribution of synthetic hexaploid wheat to CIMMYT's spring bread wheat breeding

germplasm. Sci. Rep. **9**, 12355 (2019). https://doi.org/10.1038/s41598-019-47936-5

Sah, G., Shah, S.C., Sah, S.K., Thapa, R.B., McDonald, A., Sidhu, H.S., Gupta, R.K., Tripathi, B.P., Justice, S.E.: Effects of tillage and crop establishment methods, crop residues, and nitrogen levels on soil properties and crop yields under rice-wheat system in the terai region of Nepal. Glob. J. Biol. Agric. Health Sci. **3**, 139–147 (2014)

Sahu, S.K., Mangara, P., Beig, G., Samal, A., Pradhan, C., Dash, S., Tyagi, B.: Quantifying the high resolution seasonal emission of air pollutants from crop residue burning in India. Environ. Pollut. **286**, 117165 (2021). https://doi.org/10.1016/j.Envpol.2021.117165

Saini, A., Manuja, S., Kumar, S., Hafee, A., Ali, B., Poczai, P.: Impact of cultivation practices and varieties on productivity, profitability, and nutrient uptake of rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.) cropping system in India. Agriculture **12**(10), 1678 (2022). https://doi.org/10.3390/agriculture12101678

Sandhu, B.S., Dhaliwal, N.S.: Comparative performance of wheat cultivars in Muktsar district of Punjab. Adv. Res. J. Crop. Improv. **8**, 186–190 (2017). https://doi.org/10.15740/has/arjci/8.2/186-190

Sandhu, I.S., Hundal, S.S., Kumar, K.: Effect of sowing dates on performance of wheat varieties under rainfed conditions of *Kandi* region. J. Res. Punjab Agr. Univ. **30**, 135–141 (1993)

Sandhu, S.S., Kaur, P., Gill, K.K., Vashisth, B.B.: The effect of recent climate shifts on optimal sowing windows for wheat in Punjab, India. J. Water Clim. Change **11**(4), 1177–1190 (2020)

Sardana, V., Singh, R.P., Gupta, S.K., Chakraborty, D.: Influence of sowing time and nitrogen on productivity and quality of durum wheat (*Triticum durum* Desf). Ann. Agric. Res. **26**, 411–415 (2005)

Sattar, A., Iqbal, M.M., Areeb, A., Ahmed, Z., Irfan, M., Shabbir, R.N., Aishia, G., Hussain, S.: Genotypic variations in wheat for phenology and accumulative heat unit under different sowing times. J. Environ. Agric. Sci. **2**, 1–8 (2015)

Shaheen, N., Hussain, M., Abbas, A., Iqbal, M.A., Shahzad, K., Mushtaq, R., Ahmed, H., Mehboob-ur-Rahman: Characterization of bread wheat germplasm for yield traits. Int. J. Biosci. **15**, 249–260 (2019)

Sharma, R.K., Chhokar, R.S., Jat, M.L., Singh, S., Mishra, B., Gupta, R.K.: Direct drilling of wheat into rice residues: experiences in Haryana and Western Uttar Pradesh. In: Humphreys, E., Roth, C.H. (eds.) Permanent beds and rice-residue management for rice-wheat systems in the Indo-Gangetic Plain, Proceeding of a workshop held in Ludhiana, India, 7–9 Sept, 2006, ACIAR Proceedings No. 127, pp. 147–158 (2008)

Shivani, Verma, U.N., Kumar, S., Pal, S.K., Thakur, R.: Growth analysis of wheat (*Triticumaestivum* L.) cultivars under different seeding dates and irrigation levels in Jharkhand. Indian J. Agron. **48**, 282–286 (2003)

Shukla, M.K., Lal, R., Ebinger, M.: Tillage effects on physical and hydrological properties of a TypicAgriaquoll in central Ohio. Soil Sci. **168**, 802–811 (2003). https://doi.org/10.1097/01.ss.0000100470.96182.4a

Sial, M.A., Umar-Dahot, M., Arain, M.A., Mangrio, S.M., Naqvi, M.H., Nizamani, N.A.: Effect of time of planting and heat stresses on wheat advanced varieties. Pak. J. Biotechol. **2**, 13–23 (2005)

Sidhu, H.S.: Happy seeder-An effort for rice residue management. Indian J. Air Pollut. Control. **8**, 68–75 (2008)

Sidhu, H.S., Singh, M., Humphreys, E., Singh, Y., Singh, B., Dhillon, S.S., Blackwell, J., Bector, V., Singh, M., Singh, S.: The Happy Seeder enables direct drilling of wheat into rice stubble. Aust. J. Exp. Agric. **47**, 844–854 (2007). https://doi.org/10.1071/EA06225

Sidhu, H.S., Singh, M., Blackwell, J., Humphreys, E., Bector, V., Singh, Y., Singh, M., Singh, S.: Development of Happy Seeder for direct drilling into combine harvested rice. In: Humphreys, E., Roth, C.H. (eds.) Permanent beds and rice-residue management for rice-wheat systems in the Indo-Gangetic Plain, Proceeding of a workshop held in Ludhiana, India, 7–9 Sept, 2006, ACIAR Proceedings No. 127, pp. 159–170 (2008)

Silva, R.R., Benin, G., Almeida, J.L., Fonseca, I.C.B., Zucareli, C.: Grain yield and baking quality of wheat under different sowing dates. Acta Sci. Agron. **36**, 201–210 (2014). https://doi.org/10.4025/actasciagron.v36i2.16180

Singh, A., Singh, D., Kang, J.S., Aggarwal, N.: Management practices to mitigate the impact of high temperature on wheat: a review. IIOAB J. India **2**, 11–22 (2011)

Singh, B.: Response of wheat (*Triticum aestivum* L.) varieties to different sowing dates and growth regulator. M.Sc. Thesis, Punjab Agricultural University, Ludhiana, Punjab, India (2016)

Singh, G., Pandey, S.N., Prajapati, S.K., Yadav, S.: Effect of weather parameters, date of sowing on performance of wheat varieties (*Triticum aestivum* L.). Intr. J. Sci. Res. **11**(8), 1449–1451 (2022b). https://doi.org/10.21275/SR22822085307

Singh, R., Kaur, S., Murari, A.S., Brar, N.S., Brar, P.S., Kumar, A., Singh, A.K.: Heat wave in Northern India: farmer'sperspective. Division of Agricultural Extension, ICAR, New Delhi, India, p. 76 (2022a)

Singh, D., Shamim, M., Pandey, R., Kumar, V.: Growth and yield of wheat genotypes in relation to environmental constraints under timely sown irrigated conditions. Indian J. Plant Physiol. **17**, 113–120 (2012)

Singh, D., Yadav, A., Singh, S., Yadav, R.K., Sen, M., Yadav, A.K., Singh, A.K.: Heat waves and its impact on crop production and mitigation techniques: a review. Intr. J. Environ. Climate Change **13**(9), 377–382 (2023)

Singh, H., Raheja, A., Sharma, R., Kaur, T.: Happy seeder -A conservation agriculture technology for managing rice residue for central Punjab conditions. Int. J. Agric. Eng. **6**, 355–358 (2013)

Singh, N.B., Ahmad, Z.: Response of wheat varieties to different dates of sowing. Indian J. Agric. Sci. **67**, 208–211 (1997)

Singh, S., Pal, M.: Growth, yield and phenological response of wheat cultivars to delayed sowing. Indian J. Plant Physiol. **8**, 277–286 (2003)

Singh, S., Gupta, A.K., Gupta, S.K., Kaur, N.: Effect of sowing time on protein quality and starch pasting characteristics in wheat (*Triticum aestivum* L.) genotypes grown under irrigated and rain-fed conditions. Food Chem. **122**, 559–565 (2010). https://doi.org/10.1016/j.foodchem.2010.03.010

Spink, J.H., Kirby, E.J.M., Forest, R., Sylvester-Bradlely, R., Scott, R.K., Fouke's, M.J., Clare, R.W., Evans, E.J.: Agronomic implications of variation in wheat development due to variety, sowing, site and season. Plant Variety Seed **13**, 91–105 (2000)

Stephens, D.J., Lyons, T.J.: Variability and trends in sowing dates across the Australian wheat belt. Aust. J. Agr. Res. **49**, 1111–1118 (1998). https://doi.org/10.1071/A96173

Su, Z., Zhang, J., Wu, W., Cai, D., Lv, J.: Effects of conservation tillage practices on winter wheat water-use efficiency and crop yield on the Loess Plateau, China. Agric. Water Manag. **87**, 307–314 (2007). https://doi.org/10.1016/j.agwat.2006.08.005

Tadesse, W., Zegeye, H., Debele, T., Kassa, D., Shiferaw, W., Solomon, T., Assefa, S.: Wheat production and breeding in Ethiopia: retrospect and prospects. Crop Breed. Genet. Genom. (2022). https://doi.org/10.20900/cbgg20220003

Tanner, C.B., Sinclair, T.R.: Efficient water use in crop production: research or re-search? In: Taylor, H.M., Jordan, W.R., Sinclair, T.R. (eds.) Limitations to efficient water use in crop production.

ASA-CSSA-SSSA, Madison, pp. 1–27 (1983). https://doi.org/10.2134/1983.limitationstoefficientwateruse.c1

Thind, H.S., Sharma, S., Singh, Y., Sidhu, H.S.: Rice–wheat productivity and profitability with residue, tillage and green manure management. Nutr. Cycl. Agroecosyst. **113**, 113–125 (2019). https://doi.org/10.1007/s10705-018-09967-8

Thind, H.S., Sharma, S., Sidhu, H.S., Singh, V.: Tillage, crop establishment and residue retention methods for optimising productivity and profitability under rice–wheat system. Crop Pasture Sci. (2023). https://doi.org/10.1071/CP21595

Tillman, B.A., Pan, W.L., Ullrich, S.E.: Nitrogen use by northern-adapted barley genotypes under no-till. Agron. J. **83**, 194–201 (1991). https://doi.org/10.2134/agronj1991.00021962008300010046x

Tiwari, S.K., Singh, M.: Yielding ability of wheat at different dates on sowing a temperature dependent performance. Indian J. Agron. **38**, 204–209 (1993)

Tripathi, S.C., Mongia, A.D., Sharma, R.K., Kharub, A.S., Chhokar, R.S.: Wheat productivity at different sowing dates in various agroclimatic zones of India. SAARC J. Agric. **3**, 191–201 (2005)

Van Wie, J.B., Adam, J.C., Ullman, J.L.: Conservation tillage in dryland agriculture impacts watershed hydrology. J. Hydrol. **483**, 26–38 (2013). https://doi.org/10.1016/j.jhydrol.2012.12.030

Verma, U.N., Sinha, M.K., Srivastva, V.C.: Effect of tillage and N management in late sown wheat after transplanted rice. Indian J. Agric. Sci. **61**, 795–798 (1991)

Vijay, J., Madhavi, K., Rao, A.R., Sairam, A.: Evaluation of wheat (*Triticum aestivum* L.) genotypes for different sowing dates under irrigated conditions. J. Res. Angrau. **40**, 48–50 (2012)

Vivek, Tomer, S.S., Malik, R.K.: Effect of tillage practices and residue management on wheat in rice-wheat cropping system. In: Proceedings of the project workshop on accelerating the adoption of resources conservation technologies in Rice-Wheat Systems of the Indo-Gangetic plains. Directorate of Extension Education, CCS Haryana Agricultural University, Hisar-125004 (Haryana), India, pp. 279–281 (2005)

Wahid, A., Gelani, S., Ashraf, M., Foolad, M.R.: Heat tolerance in plants: an overview. Environ. Exp. Bot. **61**, 199–223 (2007). https://doi.org/10.1016/j.envexpbot.2007.05.011

Xu, H.C., Cai, T., Wang, Z.L., He, M.R.: Physiological basis for the differences of productive capacity among tillers in winter wheat. J. Integ. Agric. **14**, 1958–1970 (2015)

Yadav, R.K., Panwar, G.S., Maurya, S.K., Tiwari, A., Sah, D., Yadav, P., Gupta, D.: Performance of late sown wheat varieties to various tillage practices. Int. J. Environ. Clim. Change **14**(1), 522–528 (2024). https://doi.org/10.9734/ijecc/2024/v14i13865

Yadvinder-Singh, Bijay-Singh, Timsina, J.: Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping systems in the tropics. Adv. Agron. **85**, 269–407 (2005). https://doi.org/10.1016/S0065-2113(04)85006-5

Yang, R.C., Baker, R.J.: Genotype-environment interactions in two wheat crosses. Crop. Sci. **31**, 83–87 (1991). https://doi.org/10.2135/cropsci1991.0011183X003100010021x

Zhang, X., Lu, Y., Wang, Q., Qian, X.: A high-resolution inventory of air pollutant emissions from crop residue burning in China. Atmos. Environ. **213**, 207–214 (2019). https://doi.org/10.1016/j.atmosenv.2019.06.009

Zhong, S., Zeng, H.C., Jin, Z.Q.: Influences of different tillage and residue management systems on soil nematode community composition and diversity in the tropics. Soil Biol. Biochem. **107**, 234–243 (2017)

**Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.