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On-farm assessment of agronomic performance of rainfed wheat cultivars under different tillage systems

Reza Mohammadi *, Rahman Rajabi, Reza Haghparast

Dryland Agricultural Research Institute (DARI), AREEO, Sararood branch, Kermanshah, Iran

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A B S T R A C T

Evaluation of new cultivars for the agronomic performance under actual on-farm conditions is a highly recommended method for assessing the performance and stability of new cultivars in variable environments and under different management practices. The main purpose of this study was to evaluate the performance and agronomic characteristics of new wheat cultivars in on-farm conditions using different tillage systems to provide suggestions to help the improvement programs and increase the farmers' crop productivity from cropping systems and new cultivars. Seven wheat cultivars, including three bread wheat and four durum wheat cultivars, were evaluated under three tillage systems, including conventional tillage (CT), reduced tillage (RT), and no-tillage (NT) in farmers' fields conditions across two locations and three cropping seasons (2018–21). The results indicated that some of the traits were mainly explained by the genotype effect (thousand kernel weight, heading date and NDVI), while some others by the management practices (grain yield), some by the location (grain yield, spike density, heading date) and year (grain yield, TKW, NDVI, spike density, heading date) effects. Across years and locations, the highest productivity was recorded under CT (2603 kg/ha) followed by RT (2378 kg/ha) and NT (2295 kg/ha), indicating about 13% and 10% superiority production under CT compared with NT and RT, respectively. The wheat cultivars showed different responses to tillage systems, showing the performance of genotypes varied between tillage systems. The Shalan and Eminbey varieties did not interact with tillage systems, but other genotypes significantly differed in their adaptation to tillage systems. The highest mean yield was recorded for the Saji cultivar (durum wheat) under RT (2310 kg/ha), while the Shalan cultivar (bread wheat) performed well in NT (2058 kg/ha), and Saji, Imren, Zahab (durum wheat), and Rijaw and Paraw (bread wheat) had the highest yield under CT. According to GGE biplot analysis, the Shalan and Eminbey varieties had superior performance across on-farm trials, suggesting that they have a broad adaptation to diverse environments. The results identified genotypes with both specific and general adaptions to tillage systems in farmers' fields, that could be explored for increasing productivity and stability under rainfed conditions. Conservation agriculture principles must be incorporated into current wheat breeding program under CT system, to use wheat genetic diversity for conservation agriculture conditions to keep pace food insecurity.

1. Introduction

Wheat (*Triticum* sp. L.), as one of the most important staple crop, accounted for 219 million hectares of cultivation globally in 2020, equal to about one-third of the world's total area for cereal agriculture, with 760 million tons of production. It provides approximately 20% of the calories and 20% of the protein required for the human diet (FAO, 2022).

Developing a new wheat cultivar generally takes between 8 and 12 years (Fischer and Edmeades, 2010). Its performance is evaluated in on-station conditions that are usually under control (proper planting date, fertilization, crop management, etc.). Therefore, the results of management methods in station conditions differ from management methods in farmers' conditions, which may be much more different depending on the type of technologies and management applied (Mohammadi et al., 2016). On-farm trials can provide farmers with valuable information on more efficient crop management (Tanaka, 2021). Previous findings highlighted the high yield gap between on-station and on-farm trials, which should be considered when developing new varieties adapted to variable environments (Beres et al.,

* Corresponding author.
E-mail address: r.mohammadi@areeo.ac.ir (R. Mohammadi).

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2020; Clarke et al., 2010; Laidig et al., 2017; Mohammadi et al., 2016; Morris and Bellon, 2004). However, the successful development of new wheat varieties that meet the needs of farmers, industry, and consumers not only requires breeding programs that combine high yield, and high quality, but also requires evaluation and selection by farmers in different environments (Laidig et al., 2017).

Breeding programs are usually focused on conventional tillage (CT), and most released cultivars have been introduced for CT, so the agronomic performance of commercial cultivars in conservation agriculture (CA) systems, i.e. reduced (minimum) tillage (RT) and no-tillage (NT) are little known (Taner et al., 2015). The CA based on NT systems is gaining popularity in both rainfed and irrigated conditions, and farmers have no options to select and grow wheat cultivars under NT practices because limited research efforts have been made in this area (Herrera et al., 2013). Thus, it is unclear whether the wheat cultivars that were recently released under CT will perform to the same capacity under conservation systems, i.e. NT and RT.

Therefore, more research is needed to achieve science-based cultivar recommendations for different tillage systems and wheat production environments over the years. Such efforts will provide more information on agro-physiological traits related to grain yield and facilitate the genetic improvement of wheat genotypes adapted to conservation farming systems (Herrera et al., 2013). The genotypes selected on this basis, in addition to having more potential, have physiological characteristics that are determined for better stability, performance stability, and flexibility to reduce unpredictable weather conditions in rainfed conditions (Carranza-Gallego et al., 2018). Furthermore, CA is becoming more attractive to farmers, as it reduces production costs compared to CT (Cavalieri et al., 2009; Gathala et al., 2020, 2021; Herrera et al., 2013; Jat et al., 2020).

However, little is known about the interaction of wheat genotypes with different tillage systems, particularly in on-farm conditions. Thus this study was aimed to: (i) evaluate the agronomic performance of seven different durum and bread wheat cultivars under three tillage systems across two locations and three years in farmers' fields; (ii) identify the high-yielding stable and adapted genotypes to different tillage options across environments using GGE biplot analysis; (iii) study the relationship between grain yield and traits investigated in farmers' fields; and (iv) develop suggestions to aid farmers for more efficient and sustainable use of resources for the management practices and environments under analysis.

2. Materials and methods

Seven wheat genotypes, including three bread wheat and four durum wheat cultivars, were evaluated (Table S1) under three tillage systems: (i) conventional tillage (full tillage with residue removed), (ii) reduced tillage (chisel tillage with residue cover), and (iii) no-tillage (no-tillage with residue retained on the soil surface) under farmers' fields conditions across two locations of Sarabniloufar (34°24'17''N; 46°51'27''E; 1323 m a.s.l.) and Dalahoo (34°12'46''N; 46°16'48''E; 1458 m a.s.l.), Kermanshah province, Iran, for three cropping seasons (2018–19, 2019–20, and 2020–21). All experiments were sown followed the previous chickpea crop. The cultivars were assigned to each tillage system in large plots. The experiment in each environment was a split-plot design with large plots. The cultivars (subplot) were assigned to each tillage system (main plot) in large plots. Each plot included 13 rows with 35 m length and 17.5 cm inter-row spacing (plot size = 79.6 m^2). A zero-till drill Askeh-2002 was used for sowing in the three systems. More information on test environments is given in Table S2. The plant density was 400 grains per square meter for each cultivar and sowing date was based on the optimum sowing date of early October in the farmers' fields. Weeds were controlled and managed by herbicide and hand weeding as required. Fertilizers were used at rates of 100 kg ha^{-1} urea (46% N) and 100 kg ha^{-1} triple superphosphate (46% P_2O_5) at the time of planting.

Heading date was recorded when 50% of plants of a given genotype initiated heading. After the anthesis stage, normalized difference vegetation index (NDVI) using a Trimble GreenSeeker handheld crop sensor was recorded. The spike density was recorded based on three random samples per one-meter square for each genotype, and 1000-kernel weight (TKW) was recorded based on one sample of whole plot after harvest for each cultivar. The grain yield after physiological maturity was obtained by taking five random samples 1 × 2 m squares from each plot. Grain yield was measured as kg per plot, and then converted to yield per hectare (kg/ha).

The data collected first were subjected to normality and outliers prior to statistical analyses. Basic description, including average, minimum, maximum, and coefficient of variation (CV%), was applied to describe phenotypic variation for genotypes in each tillage system, location, and year. The distribution and variability of the phenotypic values of investigated traits were summarized using boxplots. The box plots showed the distribution of the data using the minimum, maximum, mean, and the first and third quartile values within the fifth and 95th percentiles after removal of outliers. Relationships between traits to study the trends over location and years were applied. The boxplots and relationships between traits were constructed by using Microsoft Excel. The performance and stability of genotypes across environments was assessed through the genotype main effect plus genotype × environment interaction biplot (GGE biplot; Yan and Tinker, 2006) following the genotype × environment interaction analysis with R package (GEA-R package; Pacheco et al., 2016).

3. Results

3.1. Climatic conditions

The three cropping seasons differed in amount and monthly rainfall distribution, which caused contrasting growing conditions and, therefore, a range in yield potential under rainfed conditions in each location (Fig. 1a). However, rainfall varied between cropping seasons, and the genotypes were exposed to drought stress. The driest year was 2020–21, with rainfall between 312.5 mm in Sarabnilofar and 328.1 mm in Dalahoo, and the highest amount of precipitation was in 2018–19, with 687.6 mm in Sarabnilofar and 909.4 mm in Dalahoo. In 2019–20 the amount of rainfall in Dalahoo was 454.4 mm and slightly less than long-term average annual rainfall (541 mm), and in Sarabnilofar (537 mm) was higher than long-term average annual rainfall (443 mm) and found to be normal due to higher rainfall than the long-term. However, in June which coincided with the grain-filling period, no rainfall received, so the crop suffered from water deficit right up to the harvest. However, in all three years, most the rainfalls received in winter coincided with no activity in plant growth. In contrast to rainfall, no marked variation in temperatures was observed across cropping seasons. However, flowering and grain filling stages followed by high daily mean temperatures, which coincided with high terminal drought stress (Fig. 1b).

3.2. Traits performance of on-farm trials in tillage systems/locations/years

Descriptive statistics, including mean, minimum, maximum, and CV% under different tillage options, locations, and years for traits investigated, are presented in Table 1. In 2018–19 the highest coefficient variability (CV%) in both locations and three tillage options was observed for grain yield, spike density, and NDVI, and the lowest was observed for heading date, followed by 1000-kernel weight. The highest NDVI, spike density, TKW, and mean yield was expressed by genotypes under CT in the Sarabnilofar location. The highest mean yield and NDVI were observed under RT in the Dalahoo location. The highest TKW (34.2 g) was recorded under CT and NT, while under RT was 31.8 g. The highest spike density was recorded for genotypes under NT and CT. No difference in heading date was observed between tillage systems each

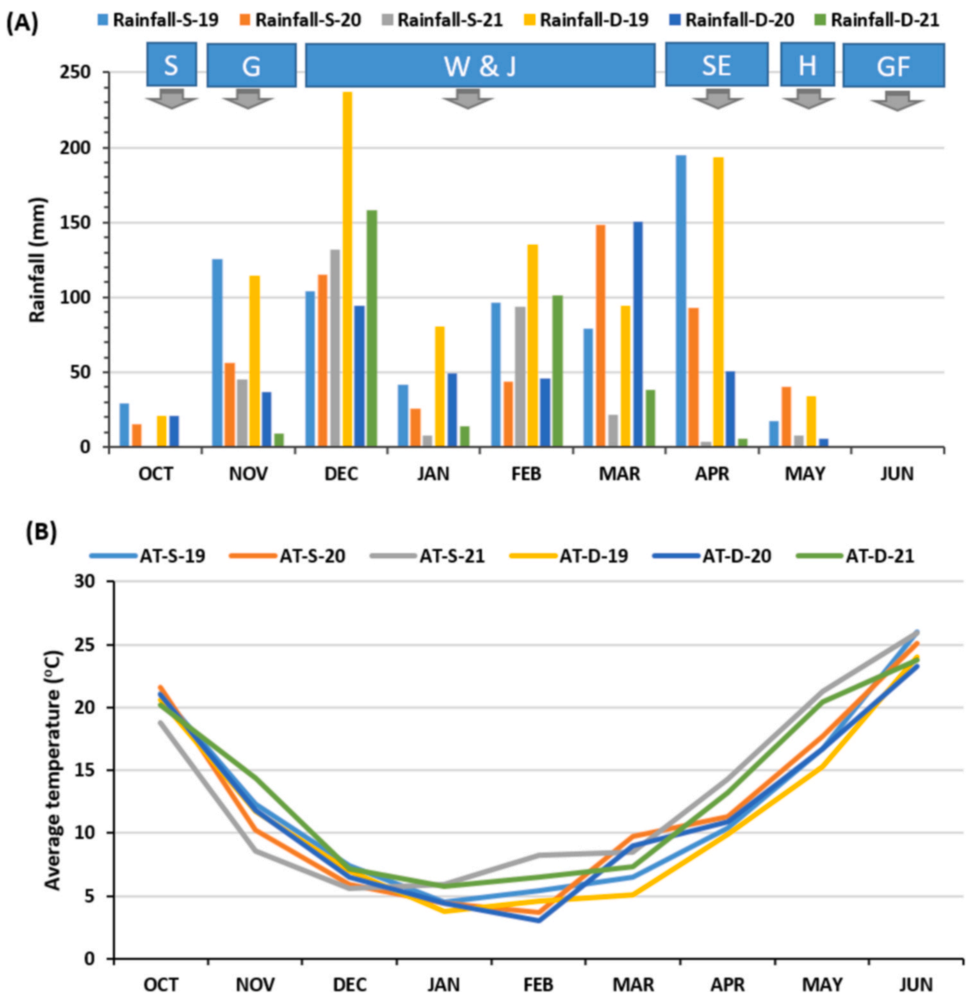

Fig. 1. Monthly rainfall distribution (A) and average temperature (B) across two locations and three cropping seasons (2018–19, 2019–20, and 2020–21). S: sowing; G: germination; W: wintering; J: jointing; SE: stem elongation; H: heading; GF: grain filling. Letters S and D stand for Sarabnilofar and Dalahoo locations, respectively; and numbers 19, 20 and 21 stand for 2018–19, 2019–20 and 2020–21 cropping seasons.

both locations, although genotypes expressed variations for heading date in each tillage system. For example, under CT, heading date varied between 124 and 136 day; under RT ranged from 128 to 136 day and under NT varied between 126 and 137 days in the Sarabnilofar location. Similar trends were also observed in the Dalahoo location.

In 2019–20 in the Sarabnilofar, the highest CV% was observed for grain yield in all tillage systems and varied between 22.8%–27.4%, while the lowest CV% was recorded for heading date in all tillage systems. Genotypes expressed the highest mean yield in RT (1505 kg/ha) followed by NT (1446 kg/ha), while genotypes under CT exhibited a mean yield of 1414 kg/ha. The high difference in heading date, NDVI, spike density, and TKW was also observed between genotypes in each tillage system.

In 2020–21, in the Sarabnilofar, the highest CV% was observed for spike density under CT and RT, while under NT the highest CV% was recorded for grain yield (17.7%), followed by spike density (17.4%). In the Dalahoo, the highest CV% were recorded for grain yield in CT and NT; and for spike density under RT. The lowest CV values were observed for heading date in all three tillage systems and locations.

3.3. Distribution of phenotypic values for studied traits

Fig. 2 shows differences among genotypes, tillage systems, locations, and years based on the traits investigated. The genotypes for grain yield showed the highest ranges, while for heading date exhibited a narrow range. Eminbey variety showed the highest mean yield, while Paraw, followed by Rijaw, showed the lowest mean yield across all treatments (Fig. 2a). The highest mean yield was observed under CT, followed by RT and NT, showing that genotypes were best expressed under CT condition. The genotypes had the highest mean yield in the Dalahoo location. In the case of year, the genotypes expressed the highest mean yield in the first cropping season, but in the two next cropping seasons, genotypes did not express a marked difference in mean performance.

In the case of TKW, a high significant difference between genotypes was observed (Fig. 2b). The highest mean TKW with a narrow range was recorded for the durum wheat Zahab cultivar. In contrast, the lowest TKW with a high range value was recorded for the Paraw bread wheat cultivar. Imren (durum wheat) and Shalan (bread wheat) also expressed high mean, but Shalan exhibited for highest range value and instability in grain weight. The TKW was highest under NT, followed by RT and CT. The range value of TKW under NT was narrow compared to other tillage systems. The highest mean TKW was obtained in the Dalahoo location, which remarkability being higher than in the Sarabnilofar location, showing that genotypes well best performed (Fig. 2a) with higher TKW in the Dalahoo location compared to the Sarabnilofar location (Fig. 2a, b). Genotypes expressed the highest TKW in the first cropping season, followed by the second and third cropping seasons.

High considerable variation in the heading date was observed between genotypes, among locations and between years (Fig. 2c). Genotypes Rijaw (bread wheat), followed by Zahab and Saji (durum wheat)

Table 1
Descriptive statistics for traits studied of genotypes under different tillage options, locations and years.

Year	Location	Tillage	Genotype	DHE	NDVI	Spike density	TKW	Yield (kg/ha)	Yield: relative to CT (%)
2018–19	**Sarabnilofar**	**CT**	**Average**	**130.6**	**0.62**	**506.4**	**32.5**	**2975.0**	**100**
			Min	124	0.47	420	29.1	2550	
			Max	136	0.74	565	34.75	3475	
			CV (%)	3.3	15.7	11.8	7.7	12.9	
		RT	**Average**	**131.7**	**0.60**	**442.1**	**32.3**	**2721.4**	**91.5**
			Min	128	0.46	320	26.6	2300	
			Max	136	0.68	545	37.6	2900	
			CV (%)	1.8	13.2	16.5	12.4	7.8	
		NT	**Average**	**131.3**	**0.50**	**390.0**	**31.6**	**1850.0**	**62.2**
			Min	126	0.38	320	28.7	1350	
			Max	137	0.57	525	35.65	2500	
			CV (%)	3.3	14.9	18.5	8.0	19.8	
	Dalahoo	**CT**	**Average**	**137.6**	**0.50**	**329.7**	**34.2**	**3019.6**	**100**
			Min	135	0.39	256	30.55	2750	
			Max	140	0.57	492	40.7	3325	
			CV (%)	1.4	12.4	27.5	9.4	7.0	
		RT	**Average**	**137.1**	**0.56**	**310.3**	**31.8**	**3139.3**	**104**
			Min	130	0.44	252	29.2	2325	
			Max	140	0.63	468	35.4	3750	
			CV (%)	2.7	11.2	23.5	6.5	17.4	
		NT	**Average**	**137.9**	**0.50**	**330.9**	**34.2**	**2975.0**	**98.5**
			Min	136	0.37	256	31.25	2425	
			Max	141	0.68	416	40.05	3775	
			CV (%)	1.5	18.0	16.6	11.5	17.6	
2019–20	**Sarabnilofar**	**CT**	**Average**	**126.4**	**0.60**	**366.4**	**26.2**	**1413.6**	**100**
			Min	118	0.59	302	24.25	1025	
			Max	132	0.73	420	29.15	2025	
			CV (%)	4.3	6.8	11.4	6.6	24.4	
		RT	**Average**	**130.0**	**0.65**	**394.0**	**28.1**	**1505.7**	**106.5**
			Min	118	0.55	345	23	1000	
			Max	134	0.78	442	32.75	1990	
			CV (%)	4.6	10.3	9.1	11.4	27.4	
		NT	**Average**	**126.7**	**0.67**	**373.6**	**27.7**	**1446.1**	**102.3**
			Min	118	0.61	302	25.5	998	
			Max	132	0.77	500	30.75	2075	
			CV (%)	4.1	7.6	18.5	7.3	22.8	
2020–21	**Sarabnilofar**	**CT**	**Average**	**117.3**	**0.50**	**220.0**	**26.4**	**825.0**	**100**
			Min	115	0.36	135	22.25	700	
			Max	122	0.55	370	33	925	
			CV (%)	2.2	15.5	37.4	13.6	9.3	
		RT	**Average**	**117.6**	**0.45**	**212.1**	**27.5**	**992.9**	**120.4**
			Min	115	0.41	150	20.5	775	
			Max	124	0.48	330	33.4	1125	
			CV (%)	2.7	5.6	30.6	19.1	13.1	
		NT	**Average**	**117.6**	**0.45**	**232.1**	**27.6**	**937.9**	**113.7**
			Min	114	0.37	180	23.5	775	
			Max	124	0.56	300	31.75	1200	
			CV (%)	2.9	14.4	17.4	11.5	17.7	
	Dalahoo	**CT**	**Average**	**131.4**	**0.61**	**286.4**	**31.2**	**2185.7**	**100**
			Min	126	0.47	225	24	1250	
			Max	137	0.73	350	34.65	2600	
			CV (%)	2.9	16.9	14.6	11.7	21.8	
		RT	**Average**	**131.4**	**0.64**	**274.3**	**31.3**	**1617.1**	**74**
			Min	126	0.51	210	23	1250	
			Max	137	0.76	350	35.05	1900	
			CV (%)	2.9	15.4	18.4	12.9	14.9	
		NT	**Average**	**131.4**	**0.65**	**288.6**	**31.8**	**1614.3**	**73.8**
			Min	126	0.58	235	26	1250	
			Max	137	0.77	350	36.65	1950	
			CV (%)	2.9	12.6	14.7	10.5	16.1	

DHE: days to heading; NDVI: normalized difference vegetation index; TKW:1000-kernel weight; CT: conventional tillage; RT: reduced tillage; CA: no-tillage

were earlier in heading, while Paraw (bread wheat) followed by Eminbey, Imren (durum wheat), and Shalan (bread wheat) were late in heading date across locations and years. In the case of tillage systems, genotypes slightly expressed early heading in CT followed by NT and RT. Variability in heading date was lower in RT compared to CT and NT. Heading date was late in the Dalahoo compare to the Sarabnilofar, as Dalahoo location was slightly cooler than Sarabnilofar. High difference in heading date was observed between years. In 2020–21 heading date for genotypes due to drought started earlier, while in 2018–19 with maximum rainfall and optimal condition, heading date was longer.

A high variation in NDVI during post-flowering between genotypes was observed. Genotypes Rijaw, Saji, and Zahab, with earlier in the heading (except durum wheat Zahab cultivar) showed the lowest NDVI, while the highest NDVI was recorded for Eminbey (durum wheat with late in heading), followed by Zahab cultivar (early in heading), showing this genotype have green-stay character. Genotypes under RT slightly exhibited higher NDVI, followed by CT. In the Dalahoo genotypes expressed higher NDVI with narrow-range values compared to genotypes in the Sarabnilofar. The highest NDVI with narrow-range values for genotypes was observed in 2019–20, while in the two other cropping

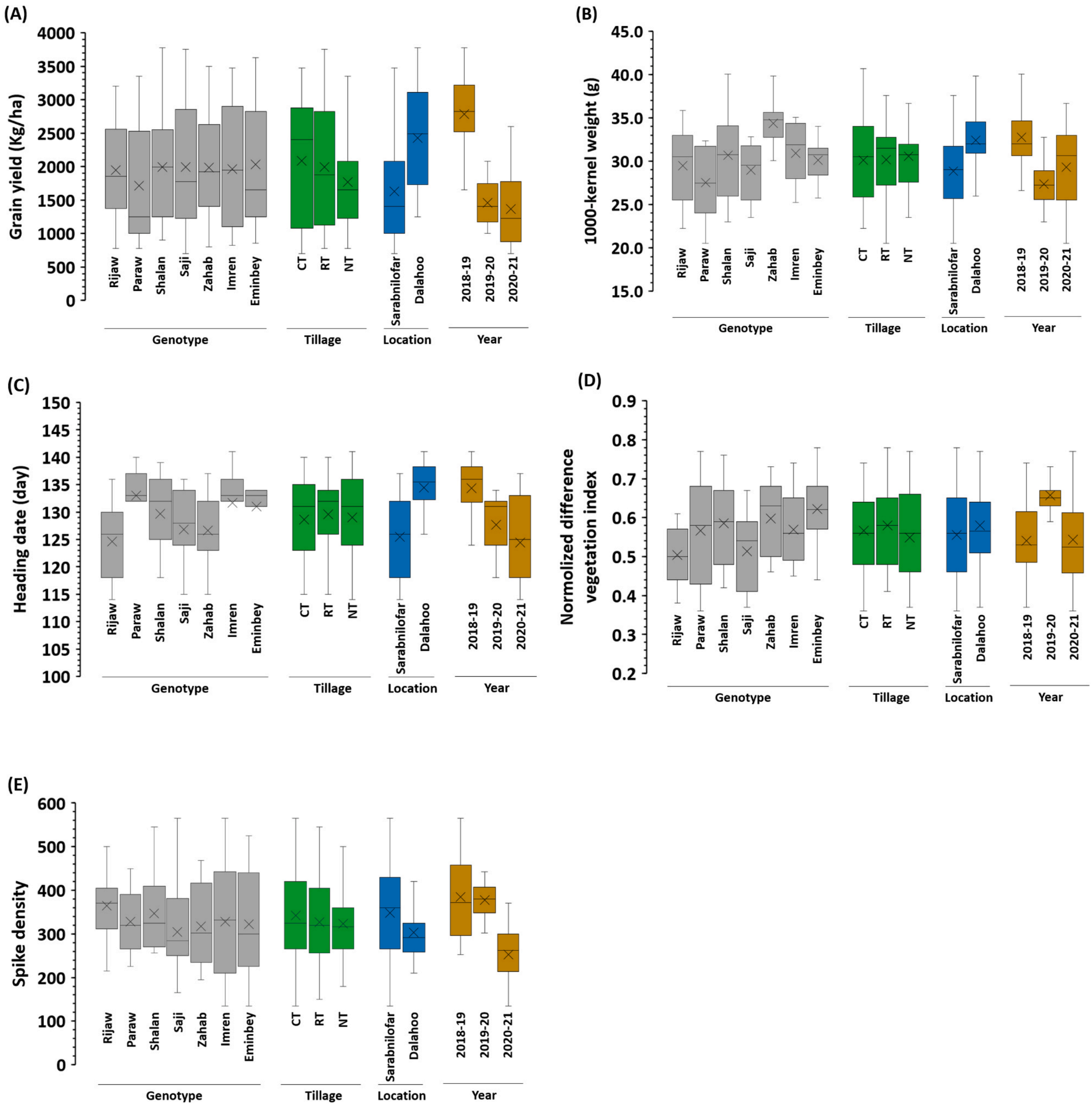

Fig. 2. Variations of the studied traits with genotype, tillage, location, and year. CT: conventional tillage; RT: reduced tillage; CA: no-tillage. A: grain yield; B: 1000-kernel weight; C: days to heading; D: normalized difference vegetation index; E: spike density.

seasons, similar results were observed.

High variation in spike density was observed among investigated genotypes. The Rijaw bread wheat cultivar expressed the highest spike density, followed by the Shalan bread wheat cultivar. The spike density was the lowest for the Saji durum wheat cultivar. In the case of tillage systems, genotypes under CT produced the highest spike density. Genotypes showed highest spike density in the Sarabnilofar with high variability in comparison with the Dalahoo location. Genotypes exhibited higher spike density in 2018–19 and 2019–20 with higher rainfall compared to 2020–21 with less rainfall than optimal condition.

3.4. Productivity of wheat cultivars in tillage systems

Fig. 3 compares productivity in tillage systems across different locations and years. The highest productivity was obtained in 2018–19 as it received a remarkable rainfall (Fig. 1). Under these conditions, a significant difference between tillage systems was observed in Sarabnilofar, where the genotypes produced the highest yields in CT (2975 kg/ha), followed by RT (2721 kg/ha) and NT (1850 kg/ha). No considerable difference was observed between the three tillage systems in Dalahoo, and genotypes slightly yielded better under RT (3139 kg/ha) than CT (3020 kg/ha) and NT (2975 kg/ha) conditions.

In 2019–20 in Sarabnilofar, the genotypic mean yields were 1506 kg/ha under RT and 1446 and 1414 kg/ha under NT and CT, respectively. In 2020–21 genotypic mean yield in Sarabnilofar was most affected by severe drought compared with Dalahoo location. The highest productivity was recorded under RT (993 kg/ha), followed by NT (938 kg/ha) and CT (825 kg/ha), and in the Dalahoo location, genotypes under CT expressed the highest productivity (2186 kg/ha), followed by RT (1617 kg/ha) and NT (1614 kg/ha). Across locations and

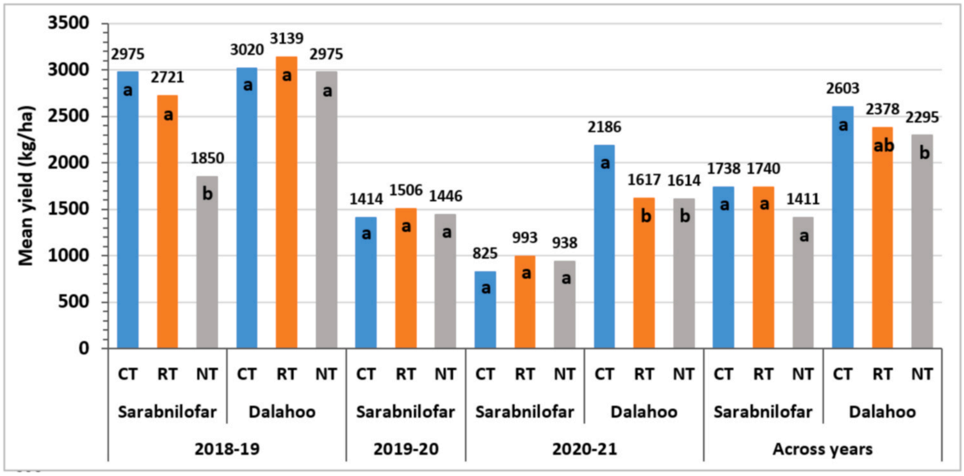

Fig. 3. Tillage × location × year interaction for grain yield of seven wheat cultivars. The bars with same letter at each location are not significant at 5% probability level. CT: conventional tillage; RT: reduced (minimum) tillage; NT: no-tillage.

years, the highest productivity was recorded under CT (2603 kg/ha), followed by RT (2378 kg/ha) and NT (2295 kg/ha) (Fig. 3), indicating about 10% and 13% superiority of production under CT compared with RT and NT, respectively.

3.5. *Cultivar × tillage interaction for grain yield*

The wheat cultivars showed different responses to tillage systems, showing the performance of genotypes varied between tillage systems (Fig. 4). The highest mean yield was recorded for the Saji durum wheat cultivar under RT (2310 kg/ha), and the lowest was obtained for the Paraw bread wheat cultivar under NT (1455 kg/ha). The Saji and Eminbey durum wheat cultivars performed well in RT, whereas the Shalan bread wheat cultivar yielded best in NT, and Imren, Zahab (durum wheat), Rijaw, and Paraw (bread wheat) had the highest yield under CT conditions. The Shalan and Eminbey did not considerably interact with tillage systems, but other genotypes significantly differed in their adaptation to tillage systems.

3.6. *Traits relations and performance traits of genotypes*

Fig. 5 presents the relationship between traits studied across three tillage options in two locations and three years. Grain yield showed a positive, and significant correlation ($P < 0.01$) with the TKW, heading date, and spike density, indicating that selection based on these traits may lead to increased grain yield under rainfed conditions. Heading date also showed positive and significant correlation ($P < 0.01$) with NDVI, spike density, and TKW. This may be due to high rainfall in first and second cropping seasons, which leads to more prolonged heading date resulting in better green-stay which resulted in higher grain weight and more productive tillers.

To better classification and separation of wheat cultivars based on studied traits, a PCA-based biplot analysis was constructed for each location (Fig. 6). The first two PCs explained 61.8% and 74.6% of the total variation in Sarabnilofar and Dalahoo locations, respectively. The biplot analysis distinctly separated high- and low-yielding cultivars, which indicated that high-yielding cultivars had their unique characteristics that led to the high yields. The cosine of the angle between the vectors of two traits approximates the Pearson's correlation between

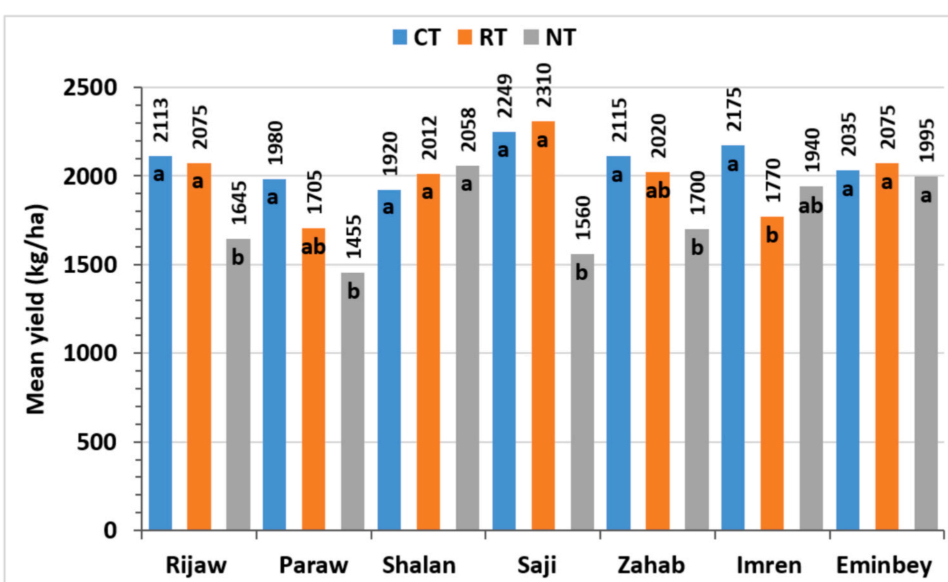

Fig. 4. Cultivar × tillage interaction for grain yield across locations and years. CT: conventional tillage; RT: reduced (minimum) tillage; NT: no-tillage. The bars with same letter at each cultivar are not significant at 5% probability level.

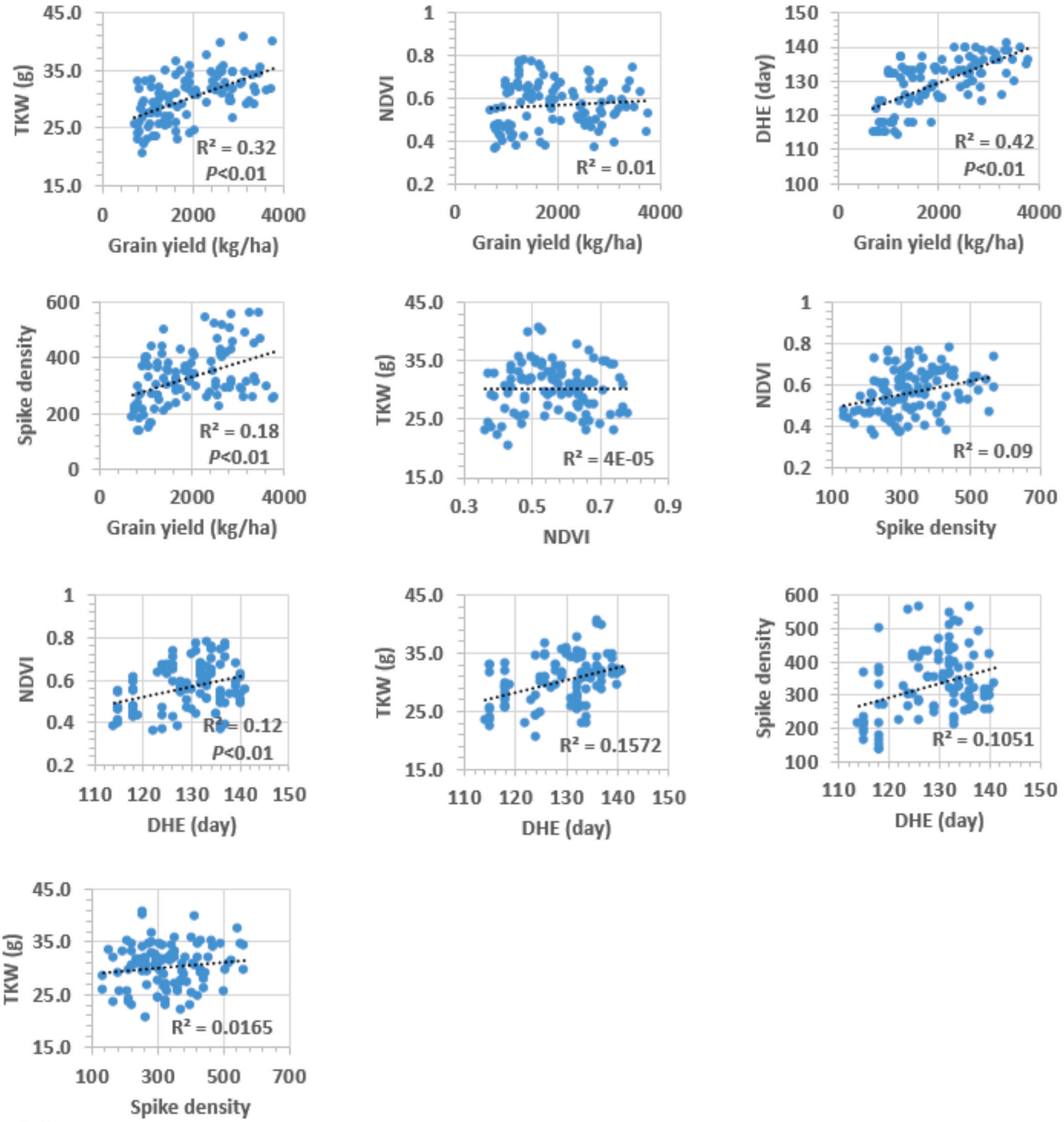

Fig. 5. Relationship among traits studied across three tillage options in two locations and three years. DHE: days to heading; NDVI: normalized difference vegetation index; TKW:1000-kernel weight.

them (Yan and Frégeau-Reid, 2018). Thus, acute angle (< 90°) indicates a positive correlation, while obtuse angle (> 90°) shows a negative correlation, and right angle (angle of 90°) indicates no correlation. The traits relations were slightly different from location to another. In Sarabnilofar, TKW closely correlated with mean yield (Fig. 6a), while in Dalahoo location TKW showed positive correlation with mean yield (Fig. 6b). In Sarabnilofar, NDVI positively associated with mean yield showing genotypes with higher value of NDVI slightly tend to higher mean yield under rainfed conditions. The heading date and spike density due to right angle between their vectors with mean yield were not correlated to grain yield. Based on the results, cultivars Shalan, Eminbey and Zahab positively interacted with grain yield and traits related to grain yield in Sarabnilofar.

In Dalahoo, TKW positively correlated with mean yield, while NDVI, DHE and spike density showed negative correlations with mean yield (Fig. 6b), suggesting genotypes with higher mean yield and TKW were earlier in heading with lower values of NDVI. These genotypes were Saji, Rijaw and Zahab, as they have already indicated as earlier cultivars in heading and maturity compared to other investigated cultivars.

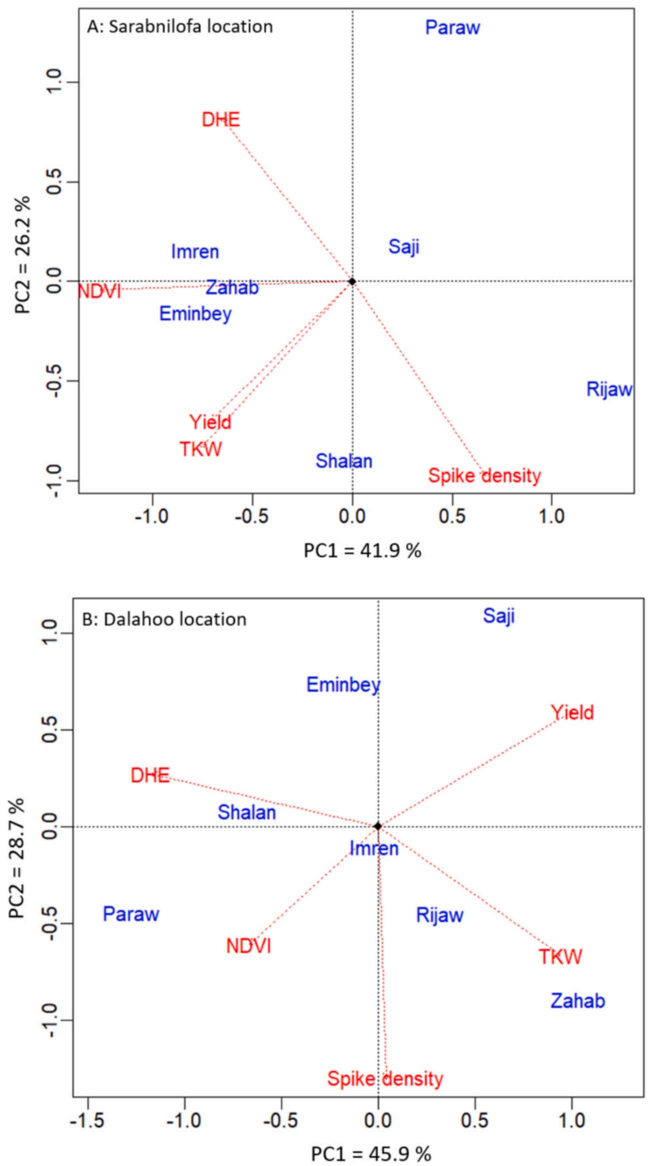

Fig. 6. Principal component (PC) analysis based on traits studied for seven wheat cultivars across three tillage systems and three cropping seasons in Sarabnilofar (A) and Dalahoo (B) locations. The arrows represent the traits, whereas a smaller acute angle between two arrows indicates a closer relationship between the two traits. A smaller distance between two cultivars indicates similar response of wheat cultivar to different conditions.

3.7. *Cultivar × environment (tillage-location-year combination) interaction for grain yield*

GGE biplot approaches were used to conduct a graphical analysis of genotype × environment (GE) interaction for grain yield and facilitate the identification of the best genotypes across the different tillage systems, locations, and years (Fig. 7). The GGE biplot, based on the first two principal components (PCs) was constructed and accounted for 60.63% of total variation (Fig. 7). The ''which-won-where'' pattern of the G×E interaction between cultivars and environments (combination of tillage systems, locations, and years), is presented in Fig. 7a. The Shalan, Eminbey, Imren, Paraw and Rijaw cultivars are located at the vertices of the polygon, which are the best or worst figures in one or more environments, as they are further in their direction from the origin of the biplot, and thus, are explicitly considered adapted cultivars. According to Fig. 7a, Shalan was the best performing genotype in the environments NTS20, CTS20, CTS21, RTS20, NTS21, RTD21, NTD19, and RTD19; Eminbey produced the highest yield in environments CTD19, NTS19, RTS21, and NTD19; and Paraw showed high yield in CTS19, CTD21, and RTS19, because these environments were placed in their correspondence sectors, respectively. Two cultivars of Rijaw, and Imren fall in sections without any environment, showing they are not best-performing in any environment; therefore, they were low-yielding genotypes in all or some of the environments.

The mean performance and stability of genotypes were graphically evaluated using the average environment coordinate (AEC) axis (Fig. 7b). The genotypes were divided into two groups. The first group, with above-grand mean were Shalan, Eminbey, Imran, and Zahab, respectively. The stability ranking of these genotypes from most to least was Zahab, Eminbey, Imren, and Shalan. The second group comprising of the rest genotypes (Saji, Rijaw, and Paraw) exhibited below-grand mean. A genotype with the highest mean yield and stability performance is regarded as an ideal genotype (Yan and Tinker, 2006). Therefore, considering both mean yield and stability performance, Zahab was most stable with average mean yield, while Eminbey and Shalan were relatively stable with higher mean yield (Fig. 7c). These genotypes should be considered as favorable across environments. Genotypes Paraw, Rijaw, and Saji were undesirable, as they were placed far away from the ideal genotype.

An ideal environment should have high differentiation power and at the same time, be able to represent other environments. These characteristics are essential for evaluating environments in terms of their ability to select superior genotypes effectively. Environments with more vector length have more discriminating power, and vice versa (Yan et al., 2007). The representativeness of an environment is measured according to the angle between its vector and the AEC axis. Environments with a slight angle with AEC are better representative of other environments. Environment NTS19, followed by CTD19, RTS21, NTD19, NTS20, RTS19, CTS20, and NTS21 exhibited the longest vector and thus were the most discriminating environments (Fig. 7D). Amongst NTD19 and NTS20 had small angles with the AEC, and were representative of the other environments and therefore, could be considered ideal. Therefore, such environments can be used to effectively select superior genotypes, which can consistently perform well across environments. RTD19 and NTD21 had small angles with the AEC axis, were the most representative environments but, due to short vector length, were relatively low discriminating ability. The other environments with the widest angle on the AEC axis were the least representative environments.

4. Discussion

A remarkable difference in yield potential was observed between genotypes, tillage systems, locations, and years across different conditions, particularly between locations and years, showing the highest impact of environmental conditions on genotypic performance. The years and locations varied in total precipitation and their monthly distribution and average temperatures during growing seasons (Fig. 1), which provided different growing conditions, leading to terminal drought stress that coincided with terminal heat stress. The high genotype × tillage systems interaction also affected wheat genotypes performance, resulting in differences in cultivar adaptation to different tillage systems. In accordance to our results, many studies have reported significant genotype × tillage systems interaction in different crops i.e., wheat (Fischer et al., 2002; Herrera et al., 2013; Honsdorf et al., 2018); maize (Herrera et al., 2013), barley and chickpea (Piggin et al., 2015; Yau et al., 2010), safflower (Yau et al., 2010) and lentil (Piggin et al., 2015).

Across two locations and three years, wheat cultivars positively interacted with CT more than NT and RT. Accordingly, genotypes showed 13% and 10% of higher performance in CT compared with NT and RT, respectively. The reason for this better adaptation can be due to

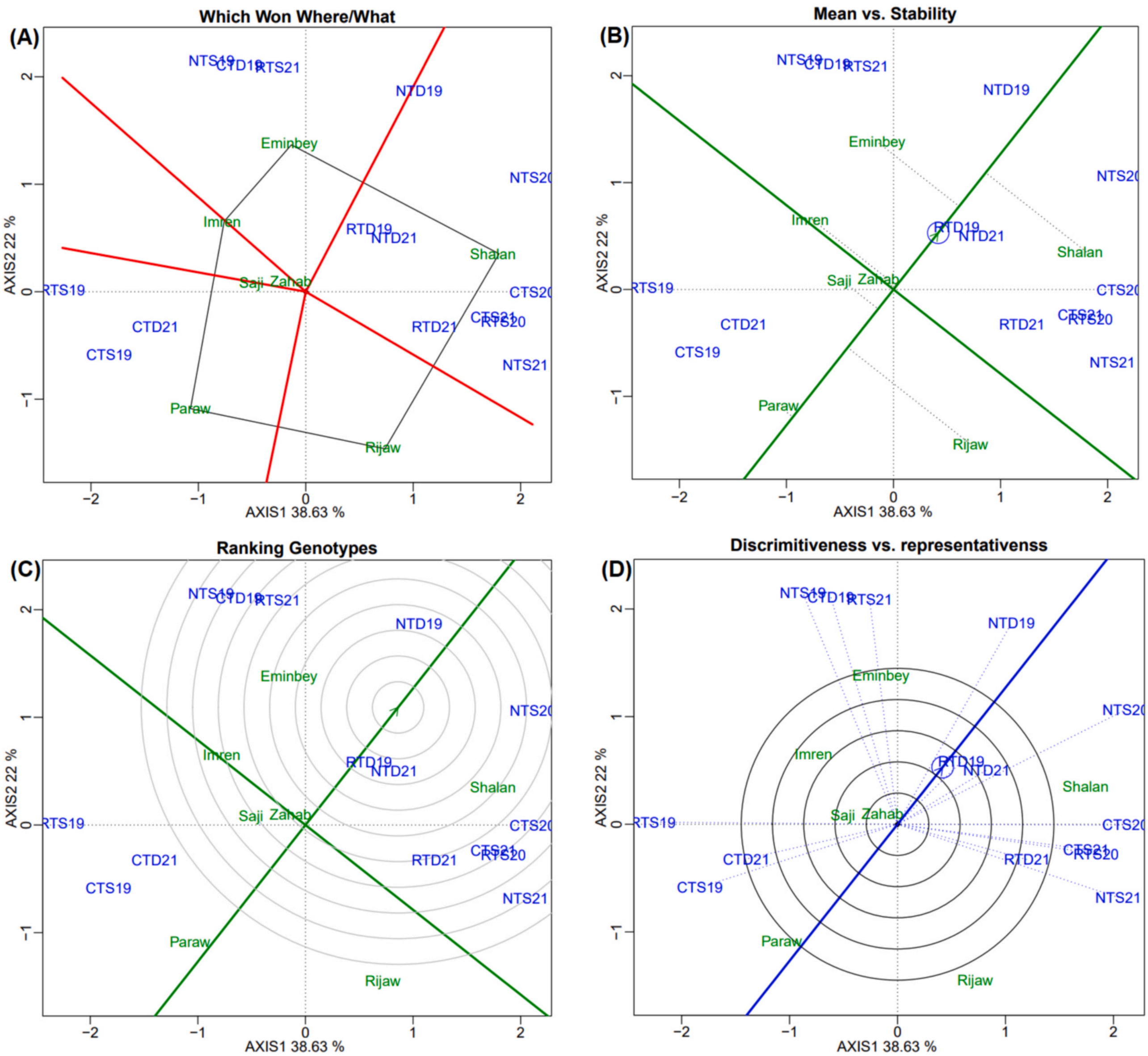

Fig. 7. GGE biplot analysis (A) showing which wheat cultivar performed better in which environment (combination of tillage-location-year) in term of grain yield; (B) showing ranking of wheat cultivars based on mean yield and stability performance; (C) comparison of wheat cultivars against the position of an "ideal" genotype for grain yield and stability performance across the test environments; and (D) showing discriminating ability and representativeness of test environments. In environment codes, the letters CT, RT, and NT, respectively, stand for conventional tillage, reduced (minimum) tillage and no-tillage; and S and D represent Sarabnilofar and Dalahoo locations, respectively; and numbers 19, 20 and 21 stand for 2018–19, 2019–20 and 2020–21, respectively. The arrows represent the environments, whereas a smaller acute angle between two arrows indicates a closer relationship between the two environments. A smaller distance between two cultivars indicates similar response of the two cultivars across environments. The concentric circles in the biplot shows the distance between each variety and the ideal genotype. The cultivars which are located close to the ideal genotype in the biplot, are desirable.

environmental conditions, i.e. CT systems, where these cultivars have already been tested, selected and released. This finding is following a global meta-analysis based on hundreds of studies consisting of 48 crops in 63 countries studied by Pittelkow et al. (2015), who reported a 5.1% decrease in yield under NT compared to CT. However, all genotypes tested in this study were developed under CT, and it is unclear whether crop performance under NT would be benefited more from the selection under NT conditions. To answer this question and conclude if specific adaptive traits become visible under NT selection, parallel selection in breeding programs can be performed in both conditions. While it is not yet clear whether selection for NT is beneficial, testing varietal performance under NT can be helpful (Herrera et al., 2013; Honsdorf et al., 2018). In 2018–2019, NT is adopted worldwide and covered 205 million hectares, about 14.7% of the total global arable land (Kassam et al., 2022). In our study, the selected fields for these experiments were just recently managed under NT. Therefore, their soil properties such as organic matter and beneficial microorganisms have not been modified yet. Moreover, subsoiling practice were not conducted before planting the experiments. Meanwhile some genotypes (i.e., Shalan cultivar) had better performance in NT in compared with CT. In Iran we are on the first steps of NT extension and it is not adopted by farmers and also many experts. But according to harsh conditions due to global warming and climate changes its extension and adoption is essential (Mohammadi et al., 2021b). Therefore, there are a big logic behind selection under NT in wheat breeding programs in Iran.

Ruisi et al. (2018) reported that the adoption of the NT technique by farmers must be accompanied by a reorganization of the components of crop management, such as crop rotation and the rate and timing of N fertilization. In a three-year study of wheat under rainfed condition by Mohammadi et al. (2021b), the wheat productivity under NT decreased by 4–35%, depending on crop rotation and cropping season, when compared to CT. In a four-year study of wheat and maize in the sub-humid tropical highlands conducted by Fischer et al. (2002), the productivity under NT at least equaled to other cultivation treatments, which was in agreement with many studies reported by Lal (1989) under temperate regions. They concluded that even equal yields is a significant result, economically in favor of NT, because residue would remain on filed until next sowing time for livestock feed. Additionally, further advantages of NT may be low production cost, improvement of physical, chemical, and biological properties of soil, and reduction of wind and water erosion (Mohammadi et al., 2021b). Kassam et al. (2022) concluded that the global burden of chronic crises includes food insecurity, climate change, loss of biodiversity, environmental degradation, could be addressed by adoption of conservation agriculture worldwide.

Martínez et al. (2008) studied the effects of CT and NT systems on soil physical properties and wheat root growth in the Mediterranean environment of Chile. They assessed soil water retention, bulk density, soil particle density, soil water infiltration, mean-weight diameter of soil aggregates, penetration resistance, grain yield, and root length density up to a depth of 15 cm. They concluded that the effect of NT on the soil properties was more evident near the soil surface. In contrast, fast drainage macrospores, soil particle density, and soil water infiltration rates were higher under CT than under NT. They also showed that the tillage treatments did not significantly affect soil particle density and yield. However, one of the main reasons for tillage practices is to increase root penetration ability in soil. Even in NT it is possible to enhance this root ability by subsoiling practices, once in every four years. Yang (et al. (2022) revealed that subsoiling can break the plow layer, enhance root penetration in soil, improve soil infiltration and moisture retention capacity, and increase water use efficiency (Zheng et al., 2011) and enhance productivity (Hu et al., 2013; Li et al., 2019). Studies have shown that subsoiling can maintain higher physiological activity in flag leaves, increase the accumulation of dry matter in the middle and later stages of wheat growth, and delay the senescence of wheat plants (Zhang et al., 2008; Chu et al., 2012). In addition, Piovanelli et al. (2006) and Kuzyakov and Xu (2013) found that subsoiling can improve crop root growth, which helps maintain optimal plant growth, increases the activity of urease and sucrose in the soil. It also increasing root stubble and root secretions, which in turn increase the growth and capacity of microorganisms in the soil, thereby activating soil nutrients and promoting nutrient absorption by crops (Sun et al., 2019). Thus, for the successful and effective expansion of NT cultivation in Iran, it is very essential to implement subsoiling before starting NT. In our investigation experiments, Shalan cultivar in NT performed well even without subsoiling.

We fitted linear models between grain yield and the studied traits and revealed that (Fig. 5) TKW, spike density and heading date had significant linear relationships with grain yield across environments. Although many traits are related to grain yield, their contribution to grain yield is different (Gutierrez et al., 2012; Li et al., 2018). Li et al. (2018) reported that spike density and grain number were most contributed to grain yield in wheat. Yang et al. (2018) reported that spike density, leaf area index, leaf chlorophyll, and leaf nitrate reductase were positively related to wheat yield. According to PC analysis, some traits positively correlated with grain yield (i.e., TKW), while some ones not correlated (i.e., spike density and NDVI) or negatively correlated (i.e., DHE) with mean yield on farmers' fields. One explanation is that there is trade-off among yield components, and thus declines in a yield component may not lead to decreases in grain yields (Quintero et al., 2018; Yang et al., 2018).

In this study, variation in grain yield, TKW, and spike density was most lower than in NT system compared to CT (Fig. 2), showing low variability for traits studied in NT which led wheat stability performance under variable rainfed conditions. In a study, Keil et al. (2020) concluded that NT provides stable yield in wheat and economic benefits under diverse growing season climates in the Eastern Indo-Gangetic Plains. They concluded the zero-tillage led to significant cost savings in all years of study, commensurate to a 5% increase in average total household incomes. Some patterns could be derived from the GGE biplot analysis combined with the agronomic performance of genotypes. Genotypes Eminbey and Shalan performed best for grain yield with good stability across tillage systems (Fig. 4); however, these genotypes had different performances for other studied traits: for NDVI, Eminbey had the highest value, while Shalan was second in TKW and spike density. Zahab, with the best in combining mean yield and stability performance (Fig. 6d), exhibited for highest TKW and most earliness. Rijaw and Paraw cultivars, were the furthest cultivars from the ideal genotype, showed the most unstable performances for grain yield, intermediate/low values for TKW, NDVI, and earliness (Rijaw) or the latest in maturity (Paraw), making they unsuitable genotypes and could be discarded from the breeding program.

The high G×E interaction across environments revealed different genotypic responses to different environments, and the necessity of phenotypic stability analysis in multi-environment trials. Similar studies are also reported in durum wheat (Mohammadi et al., 2021a) and bread wheat (Tabbita et al., 2023). According to the GGE biplot, an ideal variety should simultaneously have high mean yield, and stability performance across environments (Yan and Tinker, 2006). In this regard, Eminbey, Shalan, and Zahab were identified as the most desirable genotypes, as they were placed near the ideal genotype. Among these three varieties, Eminbey and Shalan, which had above-mean yield and were placed near the AEC, could be considered as stable with the highest a mean yield. Zahab variety had wide adaptation to different environments, as it had the least distance from the AEC with mean yield close to the grand mean. In contrast, the two high-yielding varieties of Eminbey and Shalan showed some specific adaptations to certain environments.

However, the mean performance of each variety varied with year, location, and tillage system. Variation pattern in grain yield among genotypes, was not in relation to their species and growth habit, as the durum and bread wheat genotypes were not separated into different groups, which is in accordance with other reports (Honsdorf et al., 2012; Mohammadi et al., 2021b). Under three tillage systems, the Saji cultivar (durum wheat) best yielded in RT and CT systems. A similar trend was observed for the Zahab cultivar (durum wheat) and the Rijaw (bread wheat) cultivars, whereas the Shalan (winter cultivar) exhibited the best performance in NT across locations and years. There is some evidence that grain size may influence adaptation to no-tillage as longer coleoptiles are associated with larger grains (Cornish and Hindmarsh, 1988; Botwright et al., 2001; Trethowana et al., 2012). In our study, the highest 1000-kernel weight was obtained for genotypes under NT. The Zahab cultivar, followed by Shalan, expressed the highest TKW. However, the Shalan cultivar showed the best adaptation to NT condition, while Zahab showed the highest stability across environments (combination of location-year-tillage systems).

In the case of tillage systems, Eminbey and Shalan cultivars were identified as the highest yielding cultivars with stability across tillage systems. Thus, these two cultivars could be considered for three tillage systems under rainfed conditions in the west of Iran. However, selection for high mean yield and stability performance in variable rainfed environments has become the most crucial goal in wheat breeding programs (Yan et al., 2007). For bread wheat, genotype-tillage interaction (G×T) was more frequent than for durum wheat; however, G×T was ignorable for some cultivars (Shalan and Eminbey). The results also indicate the need for separate breeding programs for each tillage system for some cultivars. However, the question of whether selection under conservation agriculture or zero tillage conditions could result in better progress under conservation agriculture, and possibly under conventional conditions, is yet to be answered (Honsdorf et al., 2018).

5. Conclusion

The results revealed that the genotype, tillage systems, location, year, and their interactions exerted different influences depending on the trait investigated. Based on the results, the highest mean performance for wheat varieties was recorded under CT, followed by RT and NT. Wheat cultivars showed different interactions with tillage systems, indicating that the performance of genotypes is different between tillage systems. Shalan and Eminbey varieties did not interact with tillage systems, but other genotypes differed significantly in their adaptation to tillage systems. According to GGE biplot analysis, Shalan and Eminbey cultivars outperformed other genotypes across the on-farm trials, indicating their wide adaptability to diverse environments. We concluded that the assessing new cultivars in on-farm trials is a valid and complementary strategy for on-station trials to improve the breeding process and resources applied by farmers, which could contribute for increasing productivity and stability in variable rainfed conditions. Moreover, in wheat breeding program genotype testing and selection from preliminary yield trials under NT must be considered.

Declaration of Competing Interest

There is no conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.still.2023.105902.

References

Beres, B.L., Rahmani, E., Clarke, J.M., Grassini, P., Pozniak, C.J., Geddes, C.M., et al., 2020. A systematic review of durum wheat: enhancing production systems by exploring genotype, environment, and management (G× E× M) synergies. Front. Plant Sci. 11, 568657.

Botwright, T., Rebestzke, G., Condon, T., Richards, R., 2001. The effect of rht genotype and temperature on coleoptile growth and dry matter portioning in young wheat seedlings. Aust. J. Plant Physiol. 28, 417–423.

Carranza-Gallego, G., Guzmán, G., Garcia-Ruiz, R., González de Molina, M., Aguilera, E., 2018. Contribution of traditional wheat varieties to climate change mitigation under contrasting managements and rainfed Mediterranean conditions. J. Cleaner Prod. 195, 111–121.

Cavalieri, K.M.V., Silva, A.P., Tormena, C.A., Leão, T.P., Dexter, A.R., Hakansson, I., 2009. Long-term effects of no-tillage on dynamic soil physical properties in a Rhodic Ferralsol in Paraná, Brazil. Soil Tillage Res 103, 158–164.

Chu, P.F., Yu, Z.W., Wang, D., Zhang, Y.L., Wang, Y., 2012. Effect of tillage mode on diurnal variations of water potential and chlorophyll fluorescence characteristics of flag leaf after anthesis and water use efficiency in wheat. Acta Agron. Sin. 38, 1051–1061.

Clarke, J.M., Clarke, F.R., Pozniak, C.J., 2010. Forty-six years of genetic improvement in Canadian durum wheat cultivars. Can. J. Plant Sci. 90, 791–801.

Cornish, P.S., Hindmarsh, S., 1988. Seed size influences the coleoptile length of wheat. Aust. J. Exp. Agric. 28, 521–523.

FAO, Food and Agriculture Organization, 2022. ⟨https://www.fao.org/faostat/en/#home⟩ (Accessed September 2022).

Fischer, R.A., Edmeades, G.O., 2010. Breeding and cereal yield progress. Crop Sci. 50, 85–98.

Fischer, R.A., Santiveri, F., Vidal, I.R., 2002. Crop rotation, tillage and crop residue management for wheat and maize in the sub-humid tropical highlands. I. Wheat and legume performance. Field Crops Res 79, 107–122.

Gathala, M.K., Laing, A.M., 2020. Lessons learnt from long-term experiments on no-till systems in semi-arid Regions. Y.P. Dang et al. (eds.), No-till Farming Systems for Sustainable Agriculture, Springer Nature Switzerland AG 2020. Chapter 24, 415–436.

Gathala, M.K., Laing, A.M., Tiwari, T.P., Timsina, J., Rola-Ruzben, F., Islam, S., Maharjan, S., Browm, P.R., Das, K.K., Pradhan, K., Chowdhury, A.K., Kumar, R., Datt, R., Anwar, M., Hossain, S., Kumar, U., Adhikari, S., Magar, D.B.T., Sapkota, B. K., Gerard, B., 2021. Improving smallholder farmers' gross margins and labor-use efficiency across a range of cropping systems in the Eastern Gangetic Plains. World Dev. 138, 105266.

Gutierrez, M., Reynolds, M.P., Raun, W.R., Stone, M.L., Klatt, A.R., 2012. Indirect selection for grain yield in spring bread wheat in diverse nurseries worldwide using parameters locally determined in north-west Mexico. J. Agric. Sci. (Camb.) 150, 23–43.

Herrera, J., Verhulst, N., Trethowan, R., Stamp, P., Govaerts, B., 2013. Insights into genotype- tillage interaction effects on the grain yield of wheat and maize. Crop Sci. 53, 1845–1859.

Honsdorf, N., Mulvaney, M.J., Singh, R.P., Ammar, K., Burgueño, J., Govaerts, B., Verhulst, N., 2018. Genotype by tillage interaction and performance progress for bread and durum wheat genotypes on irrigated raised beds. Field Crops Res. 216, 42–52.

Hu, H.Y., Ning, T.Y., Li, Z.J., Han, H.F., Zhang, Z.Z., Qin, S.J., et al., 2013. Coupling effects of urea types and subsoiling on nitrogen-water use and yield of different varieties of maize in northern China. Field Crops Res. 142, 85–94.

Jat, M.L., Chakraborty, D., Ladha, J.K., et al., 2020. Conservation agriculture for sustainable intensification in South Asia. Nat. Sustain 3, 336–343.

Kassam, A., Friedrich, T., Derpsch, R., 2022. Successful experiences and lessons from conservation agriculture worldwide. Agronomy 12, 769.

Keil, A., Mitra, A., McDonald, A., Malik, R.K., 2020. Zero-tillage wheat provides stable yield and economic benefits under diverse growing season climates in the Eastern Indo-Gangetic Plains. Int. J. Agric. Sustain. 18, 567–593.

Kuzyakov, Y., Xu, X., 2013. Competition between roots and microorganisms for nitrogen: mechanisms and ecological relevance. N. Phytol. 198, 656–669.

Laidig, F., Piepho, H.P., Rentel, D., Drobek, T., Meyer, U., Huesken, A., 2017. Breeding progress, environmental variation and correlation of winter wheat yield and quality traits in German official variety trials and on-farm during 1983–2014. Theor. Appl. Genet. 130, 223–245.

Lal, R., 1989. Conservation tillage for sustainable agriculture: tropics versus temperate environments. Adv. Agron. 42, 85–197.

Li, C.X., Liu, Q., Shao, Y., Ma, S.C., Li, S.S., Li, X.B., et al., 2019. Effects of organic materials returning and nitrogen fertilizer reduction on nitrogen utilization and economic benefits of wheat. Agric. Res. Arid Areas 37, 214–220.

Li, N., Zhou, C., Sun, X., Jing, J., Tian, X., Wang, L., 2018. Effects of ridge tillage and mulching on water availability, grain yield, and water use efficiency in rain-fed winter wheat under different rainfall and nitrogen conditions. Soil . Res. 179, 86–95.

Martínez, E., Fuentes, J.P., Silva, P., Valle, S., Acevedo, E., 2008. Soil physical properties and wheat root growth as affected by no-tillage and conventional tillage systems in a Mediterranean environment of Chile. Soil Tillage Res. 99, 232–244.

Mohammadi, R., Abdolahi, A., Mohammadi, M., Elahi, K., Yari, S., 2016. Evaluation of Yield Gap of Durum Wheat Genotypes Under Research and Farmers' Fields Conditions. Res. Achiev. Field Hortic. Crops 5 (2), 133–141 (In Persian).

Mohammadi, R., Sadeghzadeh, B., Poursiahbidi, M.M., Ahmadi, M.M., 2021a. Integrating univariate and multivariate statistical models to investigate genotype × environment interaction in durum wheat. Ann. Appl. Biol. 178, 450–465.

Mohammadi, R., Jalal Kamali, M.R., Gathala, M.K., 2021b. Performance of rainfed bread and durum wheat cultivars under different tillage options in wheat-based dryland cropping systems. Int. J. Plant Prod. 15, 273–289.

Morris, M.L., Bellon, M.R., 2004. Participatory plant breeding research: opportunities and challenges for the international crop improvement system. Euphytica 136, 21–35.

Pacheco, A., Vargas, M., Alvarado, G., Rodríguez, F., Crossa, J., Burgueño, J., 2016. GEA-R (genotype x environment analysis with R for Windows). Version 2.0. CIMMYT. ⟨http://hdl.handle.net/11529/10203⟩ (accessed 20 June 2016).

Piggin, C., Haddad, A., Khalil, Y., Loss, S., Pala, M., 2015. Effects of tillage and time of sowing on bread wheat, chickpea, barley and lentil grown in rotation in rainfed systems in Syria. Field Crops Res 173, 57–67.

Piovanelli, C., Gamba, C., Brandi, G., Simoncini, S., Batistoni, E., 2006. Tillage choices affect biochemical properties in the soil profile. Soil . Res. 90, 84–92.

Pittelkow, C.M., Linquist, B.A., Lundy, M.E., Liang, X., van Groenigen, K.J., Lee, J., van Gestel, N., Six, J., Venterea, R.T., van Kessel, C., 2015. When does no-till yield more? A global meta-analysis. Field Crops Res 183, 156–16.

Quintero, A., Molero, G., Reynolds, M.P., Calderini, D.F., 2018. Trade-off between grain weight and grain number in wheat depends on GxE interaction: a case study of an elite CIMMYT panel (CIMCOG). Eur. J. Agron. 92, 17–29.

Ruisi, P., Saia, S., Badagliacca, G., Amato, G., Frenda, A.S., Giambalvo, D., Di Miceli, G., 2018. Long-term effects of no tillage treatment on soil N availability, N uptake, and 15N-fertilizer recovery of durum wheat differ in relation to crop sequence. Field Crops Res 189, 51–58.

Sun, K., Liu, Z., Hu, H.Y., Li, G., Liu, W.T., Yang, L., et al., 2019. Effect of organic fertilizer and rotational tillage practices on soil carbon and nitrogen and maize yield in wheat-maize cropping system. Acta Agron. Sin. 45, 401–410.

Tabbita, F., Ortiz-Monasterio, I., Piñera-Chavez, F.J., Ibba, M.I., Guzmán, C., 2023. Impact of different on-farm management practices on bread wheat quality: a case study in the Yaqui Valley. J. Sci. Food Agric. 103 (10), 4975–4982.

Tanaka, T.S.T., 2021. Assessment of design and analysis frameworks for on-farm experimentation through a simulation study of wheat yield in Japan. Precis. Agric. 22, 1601–1616.
Taner, A., Arisoy, R.Z., Kaya, Y., Gultekin, I., Partigoc, F., 2015. The efects of various tillage systems on grain yield, quality parameters and energy indices in winter wheat production under the rainfed conditions. Fresenius Environ. Bull. 24, 1463–1473.
Trethowana, R.M., Mahmood, T., Zulfiqar, A., Oldach, K., Gutierrez Garcia, A., 2012. Breeding wheat cultivars better adapted to conservation agriculture. Field Crops Res 132, 76–83.
Yan, W., Frégeau-Reid, J., 2018. Genotype by Yield*Trait (GYT) Biplot: a Novel Approach for Genotype Selection based on Multiple Traits. Sci. Rep. 8, 8242.
Yan, W., Tinker, N.A., 2006. Biplot analysis of multi-environment trial data: principles and applications. Can. J. Plant Sci. 86, 623–645.
Yan, W., Kang, M.S., Ma, B., Woods, S., Cornelius, P.L., 2007. GGE biplot vs. AMMI analysis of genotype-by-environment data. Crop Sci. 47, 643–653.
Yang, Y., Yu, L., Ni, X., Yang, Y., Liu, B., Wang, Q., Tao, L., Wu, Y., 2018. Reducing nitrogen loss and increasing wheat profits with low-cost, matrix-based, slow-release urea. Agron. J. 110, 380–388.
Yang, Y., Li, M., Wu, J., Pan, X., Gao, C., Tang, D.W.S., 2022. Impact of Combining Long-Term Subsoiling and Organic Fertilizer on Soil Microbial Biomass Carbon and Nitrogen, Soil Enzyme Activity, and Water Use of Winter Wheat. Front. Plant Sci. 12, 788651.
Yau, S.K., Sidahmed, M., Haidar, M., 2010. Conservation versus conventional tillage on performance of three different crops. Agron. J. 102, 269–276.
Zhang, J., Yao, Y.Q., Lu, J.J., Jin, K., Wang, Y.H., Wang, Y.H., et al., 2008. Soil carbon change and yield increase mechanism of conservation tillage on sloping drylands in semi-humid arid area. Chin. J. Eco Agric. 16, 297–301.
Zheng, C.Y., Cui, S.M., Wang, D., Yu, Z.W., Zhang, Y.L., Shi, Y., 2011. Effects of soil tillage practice on dry matter production and water use efficiency in wheat. Acta Agron. Sin. 37, 1432–1440.