

Article

Pre-Crop and Residue Management Effects on Photosynthesis Efficiency and Grain Yield of Dryland Wheat Genotypes

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Abstract: To evaluate dryland wheat genotypes' performance under different pre-crop and residue managements under dryland conditions, a split-split plot experiment based on the RCB design, with three replications, was conducted for two years (2017–2018 and 2018–2019). The site of the study has a long-term average precipitation, temperature, and relative humidity of 376 mm, 9 °C, and 50%, respectively. Wheat–wheat and vetch–wheat cropping systems were considered in the main plots, different wheat and vetch residue levels, including 0, 2, and 4 t ha^{−1}, were located in the subplots, and five dryland wheat genotypes, including Sadra, Hashtroud, Baran, Varan, and Ohadi, were allocated in the sub-sub plots. The results indicated that the leaf chlorophyll content index (CCI) and stomatal conductance (gs) were greater in the vetch–wheat cropping system compared to the wheat monoculture system for all genotypes. The normalized difference vegetation index (NDVI) of the genotypes improved by applying the crop residue. Over two years, the application of crop residues resulted in higher variable fluorescence at the J and I steps, as well as an increase in the photosynthesis performance index (PI). The Varan and Baran genotypes stood out as the superior genotype, exhibiting the highest values in physiological characteristics and grain yield under the application of 4 t ha^{−1} of vetch residue. The grain-filling rate (GFR) was reduced, while the grain-filling duration (GFD) was increased with increasing the crop residue levels. The enhanced grain yield of the wheat genotypes grown under vetch residue was attributed to factors such as improvement in leave pigments and photosynthetic efficiency, which facilitate longer grain filling duration, with high grain weight. As a result, it is advisable to adopt a vetch–wheat cropping system with a high proportion of crop residue in dryland regions to achieve increased and sustainable wheat production.



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1. Introduction

Increasing crop yields in recent decades have been strongly linked to the intensive use of chemical inputs, e.g., fertilizers and pesticides [1]. The adoption of intensive farming methods is a direct response to the increase in population size, which has subsequently led to heightened demands on agricultural areas and alterations in the nutritional composition of the soil [2] and soil and plant biodiversity [3]. In contrast to intensive agriculture, the set of management practices implemented in organic farming, e.g., returning crop residues to the soil, using organic and biological fertilizers, controlling weeds bio-mechanically, conservation tillage, applying different crop rotation systems, and intercropping [4], led to the improved recycling of soil nutrients, enhanced soil and crop biodiversity [5], and better yield quality [6].



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Crop residues represent a significant renewable resource, rich in essential nutrients. The integration of straw into agricultural practices plays a crucial role in sustainable farming [7]. It has been reported that recycling crop residues could maintain soil fertility [8] and support sustainable agriculture in cropping systems [9]. In addition, due to increasing awareness of sustainable agriculture, the area of straw incorporation is becoming larger and larger [10]. In the arid regions of Iran, the implementation of crop rotation under no-till conditions emerges as a practical approach to enhance soil organic matter and ensure the stability of crop production by preserving plant residues.

Improving crop yield can be achieved by utilizing mineral and organic fertilizers effectively, managing crop residue, choosing suitable crop varieties for specific environments, and implementing bio-mechanical pest control techniques as an alternative to pesticides [11]. However, it was reported that the use of organic matter (e.g., crop residues) in the soil may reduce grain yield due to the immobilization of nutrients, especially during the initial growth stage of plants [12]. This situation can be improved by the combined use of these organic resources with inorganic fertilizers, which can improve wheat grain yield by positively affecting the biological–chemical properties of the soil [13]. For instance, the utilization of both organic and inorganic nutrient resources in wheat led to an increase in nitrogen supply and a notable enhancement in wheat yield components such as 1000-grain weight, tillers, wheat yield, and nitrogen uptake by the grain when compared to wheat that was provided only with inorganic fertilizers [14]. In addition, the maintenance and build-up of soil C are essential in improving soil functions and offsetting atmospheric CO₂ concentrations [15], which is a key challenge for humankind [16]. Crop residue management affects CO₂ emissions, primarily via altering C and nitrogen (N) cycling [17]. However, multiple factors regulate CO₂ emissions from the soil [1]. Soil respiration is influenced by variations in the soil temperature and moisture levels, as well as the introduction of organic matter from decomposing residues, which in turn affect faunal and microbial activities [18,19].

The chlorophyll content, which reflects the health of crop leaves, plays a crucial role in the photosynthetic process and, therefore, dry matter production [20]. The slow but steady release of minerals from organic matter resources increases cereal grain yield by improving the photosynthetic capacity and chlorophyll content, especially during flowering and grain filling [1]. Iqbal et al., [20] noted that a combination of organic manure and chemical fertilizer application increases the levels of chlorophyll a and chlorophyll b and also increases the production of photoassimilates. Aside from photosynthesis, crop yields can also be improved by remobilizing the dry matter accumulated in vegetative parts before anthesis to the grains during grain filling [21]. However, the chlorophyll content and the translocation of photoassimilates within a plant can be affected by a variety of farming practices and climate conditions [22]. The remobilization of the assimilate is the main source of the dryland wheat yield production. Farming management and crop rotation affect crop productivity by influencing factors such as soil properties and plant characteristics, such as leaf chlorophyll content and its photosynthetic activity [1]. The production of dry matter through the photosynthetic activity of leaves is the most important source of grain filling in cereals. Hence, the primary aim of this research was to assess pre-crop and residue management using vetch and wheat on physiological and grain yield characteristics in various dryland wheat genotypes.

2. Materials and Methods

2.1. Experimental Site

The field experiment to investigate the photosynthesis activity and grain yield of dryland wheat genotypes was initiated in 2017–2019 at Dryland Agricultural Research Institute (latitude 37°12' N; longitude 46°20' E; 1730 m a.s.l.), 25 km east of Maragheh, East Azerbaijan Province, Iran. The region's climate is temperate continental with warm summers, according to the Koeppen's classification system. The long-term (1989–2016) average precipitation, temperature, and relative humidity of the station are 376 mm, 9 °C, and 50%, respectively. The annual precipitation and average temperature per month of the

experimental site are detailed in Table 1. The soil (Fine Mixed, Mesic, Vertic Calcixerepts, USDA system; Calcisols, FAO system, Rome, Italy) at the study site had a clay loam texture in the 0–15 cm surface layer and a clay texture at a depth of 15–80 cm. Before the beginning of the experiment, the physical and chemical properties of the soil were determined, and the values of some physical and chemical properties of the soil are given in Table 2.

Table 1. Monthly rainfall distribution and mean temperature all over the year during 2017–2019.

Month	2017–2018		2018–2019	
	Precipitation (mm)	Average Temperature (°C)	Precipitation (mm)	Average Temperature (°C)
January	29	1.4	41	−2.5
February	85	−0.9	86	−1.2
March	80	4.3	56	0.2
April	55	8.6	116	5.2
May	67	10.4	43	9.6
June	23	16.7	4.2	18.1
July	0	24.6	0	22.7
August	0	24.8	0.5	23.6
September	1.8	20.0	0	19.2
October	0.2	11.4	9.7	13.7
November	36	8.5	47	5.5
December	48	−0.8	91	2.3

Table 2. Physical and chemical properties of the soils (from the field of the experiment site).

Soil Depth (cm)	Soil Texture (%)			pH	K	P	T.N.	O.C.	CaCO ₃	S.P.
	Sand	Silt	Clay		mg kg ⁻¹			%		
0–30	39	42	19	7.6	453	7.33	0.13	0.66	7.1	51

K: potassium; P: phosphorus; TN: total nitrogen; OC: organic carbon; CaCO₃: calcium carbonate; SP: soil saturation percentage.

2.2. Experimental Design and Treatments

A split–split experiment based on RCBD, with three replications, was conducted. Wheat–wheat and vetch–wheat cropping systems were considered in main plots; three levels of wheat and vetch residues (0, 2, and 4 t ha^{−1}) were located in the sub-plots, and five dryland wheat genotypes (Sadra, Hashtroud, Baran, Varan and Ohadi) were allocated to the sub-sub-plots. The subplots of the experiment were 44 square meters (10 × 4.4 m).

An experiment was set up under a conservation agriculture system (no tillage) and the only soil disturbance occurred during the seeding operation. In October of both years before sowing the crops, the gathered residues of vetch and wheat were uniformly distributed across the field in accordance with the specified treatments, with 8.8 and 17.6 kg per plot used for the 2 and 4 t ha^{−1} treatments (44 square meters) of crop residue, respectively. On the other hand, all crop residues were removed from the field for the control plots. The residues were collected in various sizes from the thresher’s output. Wheat and vetch (*Vicia pannonica*), with the rate of 380 and 240 seeds per m², respectively, were sown by an Aske model 2200 seeder (13 planting rows with a 17.5 cm distance between rows) at a depth of 4–5 cm in the soil. Each plot for both wheat and vetch consisted of 26 rows, spaced 17.5 cm apart. Fertilizers, including 90 kg ha^{−1} of urea and 45 kg ha^{−1} of triple superphosphate, were used for wheat, while 45 kg ha^{−1} of urea and 30 kg ha^{−1} of triple superphosphate were used for vetch at sowing time. Weeds were controlled by applying Bromicide MA herbicide (1.5 L ha^{−1}) to the wheat site and Gallant™ Super herbicide (1 L ha^{−1}) to the vetch site.

2.3. Filed Detected Physiological Traits

Normalized difference vegetation index (NDVI) from each plot, stomatal conductance (gs), and chlorophyll content index (CCI) from three plants in each plot were recorded in both years at the anthesis stage (65 on the Zadoks scale) by a portable chlorophyll meter (SPAD 502 plus), GreenSiker (Trimber), and Porometer (AF4), respectively.

Photosynthesis activity and PSII performance were monitored with a Handy-PEA portable fluorimeter (Hansatech Instruments Ltd., Norfolk, UK) at the anthesis stage (65 on the Zadoks scale). Three plants from each plot were randomly selected, and the flag leaves of plants were dark-adapted for 30 min using a leaf clip provided by the producer of handy-PEA. Measurements were performed on the middle of plant flag leaves following the standard protocol, under illumination with continuous red light (peak at a 650 nm wavelength, with a spectral line half width of 22 nm), provided by an array of three light-emitting diodes. The light pulse intensity used was 3500 $\mu\text{mol (photon) m}^{-2} \text{ s}^{-1}$, and the duration of the light pulse was 1 s. The measured data were used to calculate the photosynthetic parameters using Biolyzer v. 3.06 HP software (the software was provided with the handy-PEA device). Some of the parameters we discussed in this article due to their significance are F_0 = minimum fluorescence, F_M = maximum fluorescence, F_V/F_M = the maximum quantum efficiency of PSII, V_J = the relative variable fluorescence in step J after 2 ms, V_I = the relative variable fluorescence in step I after 30 ms, and PIABS = performance index.

2.4. Grain Filling Rate and Duration

Spikes of all genotypes were harvested after flowering, with a 7-day interval, in five stages. Then, grains were removed from the spike and, subsequently, dried, and the mean grain weight of each sample was determined. A two-piece regression model was applied to determine maximum grain and grain filling duration (GFD).

$$W = \begin{cases} a + bt & t < t_m \\ a + bt & t \geq t_m \end{cases}$$

where W is grain weight, a is the intercept, b is the slope, t represents the number of days after anthesis, and t_m is the end of the grain-filling period (time of mass maturity). Subsequently, GFR was calculated as follows:

$$\text{GFR} = \text{MGW} / \text{GFD}$$

where GFR is the grain-filling rate, MGW is the maximum grain weight, and GFD is the grain-filling duration [23].

2.5. Grain Yield and Weight

Five samples of 3 square meters (35% of the plot) were taken from each plot when the grain in the spike had around 14–15% moisture. After being harvested, each plot's worth of grain was packed and threshed. Then, grains of the whole plot were weighted, and the yield for 15 m^2 was determined. According to that, the grain yield (GY) was calculated in Kg per hectare. For measuring 1000 seed weight, an automatic seed counter was used, with eight repetitions.

2.6. Data Analysis

All the data were analyzed based on the experimental design, using SAS v. 9.1 software. The mean value of each trait was compared according to the Duncan multiple range test, at $p \leq 0.05$.

3. Results

3.1. Physiological Traits: CCI, Gs and NDVI

In both years of the experiment, the leaf chlorophyll content index (CCI) and stomatal conductance (gs) were found to be greater in the vetch–wheat cropping system compared to the wheat–wheat system for all genotypes. The highest and lowest values of the CCI and gs in both years of the experiment and the pre-crop treatments were recorded for the Varan and Baran genotypes, respectively. The CCI of the Hashtroud and Ohadi genotypes was statistically similar to the Varan genotype (Table 3).

Table 3. Leaf chlorophyll content index (CCI) and stomatal conductance (gs) of the wheat genotypes under two wheat and vetch pre-cropping systems during 2017–2019.

CCI	2017–2018		2018–2019	
<i>p</i> Value **	Wheat–Wheat	Vetch–Wheat	Wheat–Wheat	Vetch–Wheat
Sadra	31.67 EFG	32.74 DEF	31.24 FG	31.59 EFG
Hashtroud	33.83 CD	34.64 BC	30.74 GH	32.48 DEF
Baran	29.61 HI	32.38 DEF	29.26 I	30.27 GHI
Varan	37.16 A	35.99 AB	31.44 EFG	33.01 DE
Ohadi	34.99 BC	33.03 DE	31.16 FG	31.84 EFG
gs (mmol m^{−2} S^{−1})				
<i>p</i> value **				
Sadra	12.55 H	13.92 E	12.60 H	14.51 D
Hashtroud	13.34 FG	14.34 D	13.34 FG	14.61 D
Baran	13.77 E	15.44 AB	13.77 E	15.22 BC
Varan	13.72 EF	15.66 A	13.57 EFG	15.79 A
Ohadi	13.24 G	15.15 BC	13.84 E	15.00 C

Means followed by the same letter in each column are not significantly different at $p < 0.05$ according to the Duncan multiple range test. ** is significant at 1% probability levels.

The responses to crop residue levels among different genotypes did not exhibit any significant differences. The CCI of all genotypes increased with crop residue application. The enhancement in the CCI of the Sadra (16%) and Hashtroud (17%) was greater than that of other genotypes. The CCI in almost all genotypes under both 2 and 4 t ha^{−1} crop residue treatments was statistically similar. However, the CCI of the Varan genotype increased with increasing crop residue levels. The highest CCI was obtained from the Varan genotype under 4 t ha^{−1} crop residue (Figure 1).

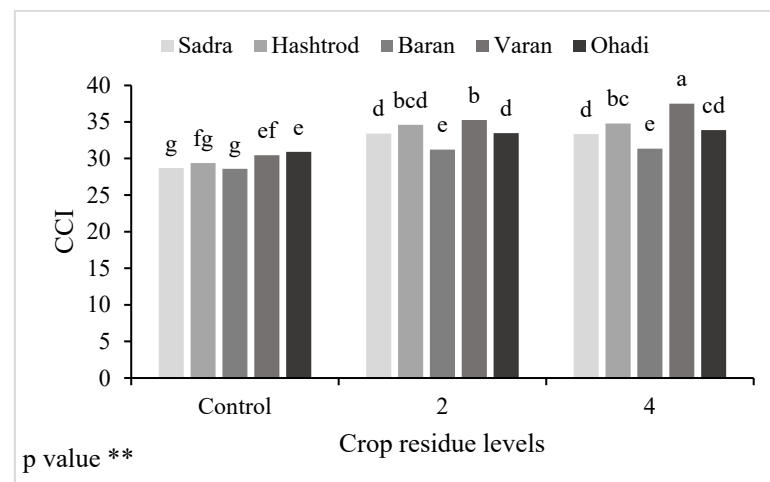


Figure 1. Changes in chlorophyll content index (CCI) of the wheat genotypes under different crop residue levels. Means followed by the same letter are not significantly different at $p < 0.05$ according to the Duncan multiple range test. ** is significant at 1% probability levels.

The normalized difference vegetation indices (NDVIs) of the wheat genotypes were improved in both rates of 2 and 4 t ha⁻¹ of wheat and vetch residues compared to the control condition. The NDVI of the genotypes significantly decreased at 4 t ha⁻¹ of wheat residue. However, NDVI of all genotypes at 4 t ha⁻¹ of the vetch residues increased. The highest NDVI was recorded for the Varan and Baran genotypes with vetch residue treatments. The Baran and Ohadi genotypes exhibited a greater degree of change in their NDVI values compared to other genotypes when subjected to both wheat and vetch pre-crop residue. In contrast, the Hashtroud genotype did not display a heightened sensitivity to crop residue (Table 4). The gs activity of the genotypes in the vetch pre-crop treatment generally exhibited higher levels compared to the wheat monoculture system. The gs of all genotypes increased by increasing the residue from both wheat and vetch crops. However, the gs of all genotypes were suspended/reduced at the 4 t ha⁻¹ of wheat residue. The highest gs were recorded for the Varan and Baran genotypes with 4 t ha⁻¹ of vetch pre-crop treatment (Table 4).

Table 4. Normalized differences in vegetation index (NDVI) and stomatal conductance (gs) of the wheat genotypes under different levels of the wheat and vetch residue levels.

NDVI <i>p</i> Value *	Wheat–Wheat			Vetch–Wheat		
	Control	2 T ha ⁻¹	4 T ha ⁻¹	Control	2 T ha ⁻¹	4 T ha ⁻¹
Sadra	0.47 FG	0.51 BC	0.49 DE	0.45 HI	0.47 FG	0.49 DE
Hashtroud	0.45 HI	0.48 EF	0.45 HI	0.45 HI	0.48 EF	0.50 CD
Baran	0.46 GH	0.51 BC	0.48 EF	0.46 GH	0.52 AB	0.52 AB
Varan	0.48 EF	0.52 AB	0.48 EF	0.49 DE	0.53 A	0.53 A
Ohadi	0.43 J	0.48 EF	0.44 IJ	0.44 IJ	0.49 DE	0.51 BC
gs						
<i>p</i> value **						
Sadra	11.23 N	13.45 H-K	13.06 KL	12.16 M	14.97 E	15.53 D
Hashtroud	12.85 L	13.75 G-J	13.43 IJK	13.14 KL	14.27 F	16.03 C
Baran	13.21 KL	14.23 FG	13.87 F-I	13.33 JKL	15.41 DE	17.26 A
Varan	12.98 KL	14.02 FG	13.95 FGH	12.88 L	16.78 B	17.52 A
Ohadi	13.22 KL	13.95 FGH	13.45 H-K	13.37 I-L	15.12 DE	16.74 B

Means followed by the same letter in each column are not significantly different at $p < 0.05$ according to the Duncan multiple range test, and * and ** are significant at 5% and 1% probability levels, respectively.

3.2. Chlorophyll Fluorescence Parameters

In both years of the study, there was a significant decrease observed in the light absorption per active reaction center (ABS/RC) at 2 t ha⁻¹ of wheat residue and 2 and 4 t ha⁻¹ of vetch residue levels. In the initial year, the ABS/RC of the samples from both the control and the 4 t ha⁻¹ of the wheat residue exhibited no significant difference. However, in the subsequent year, the ABS/RC value surpassed that of the control treatment when 4 t ha⁻¹ of wheat residue was applied (Table 5). Over two years, the utilization of wheat and vetch residue resulted in higher variable fluorescence at the J and I steps, as well as an increase in the photosynthesis performance index (PI), in comparison to the control treatment. However, these increments were lower under 4 t ha⁻¹ of wheat residue compared to 2 t ha⁻¹. The greatest values for all chlorophyll fluorescence parameters were recorded with 4 t ha⁻¹ of vetch residue during the first year (Table 5).

The application of crop residue from wheat and vetch resulted in an increase in the chlorophyll fluorescence parameters across all genotypes. Nevertheless, when wheat residue was applied at a rate of 4 t ha⁻¹ it caused a reduction in the value of these parameters in all genotypes. Generally, the chlorophyll fluorescence parameters of the samples under vetch residue were higher than those of wheat residue, especially with 4 t ha⁻¹ of vetch residue. In terms of the chlorophyll fluorescence parameters, the Varan genotype stood out as the superior one, exhibiting the highest values for Fv/Fo, Fv/Fm, VJ, VI, and PI under the application of 4 t ha⁻¹ of vetch residue. However, there were no significant

differences between the Baran and Varan genotypes for the Fv/Fo and VJ parameters (Table 6).

Table 5. Dryland wheat chlorophyll fluorescence parameters' changes under different levels of wheat and vetch residues during 2017–2019.

Treatments			ABS/RC	VJ	VI	PI
<i>p</i> Value			**	**	**	**
2017–2018	wheat–wheat	control	2.206 GH	0.45 G	0.53 F	0.34 F
		2 T ha ^{−1}	3.314 B	0.66 D	0.77 B	0.61 B
		4 T ha ^{−1}	3.558 A	0.50 F	0.61 E	0.48 E
	vetch–wheat	control	2.250 FG	0.42 H	0.51 F	0.35 F
		2 T ha ^{−1}	2.924 D	0.73 C	0.74 BC	0.62 B
		4 T ha ^{−1}	2.236 G	0.82 A	0.92 A	0.67 A
2018–2019	wheat–wheat	control	2.1673 HI	0.42 H	0.46 G	0.32 F
		2 T ha ^{−1}	3.219 C	0.62 E	0.66 D	0.51 DE
		4 T ha ^{−1}	3.333 B	0.50 F	0.53 F	0.51 DE
	vetch–wheat	control	2.280 F	0.43 H	0.43 G	0.32 F
		2 T ha ^{−1}	2.7493 E	0.66 D	0.66 D	0.54 CD
		4 T ha ^{−1}	2.129 I	0.75 B	0.72 C	0.56 C

Means followed by the same letter in each column are not significantly different at $p < 0.05$ according to the Duncan multiple range test. ** is significant at 1% probability levels. ABS/RC, VJ, VI, and PI are the light absorption per active reaction center, relative variable fluorescence at the J step, relative variable fluorescence at the I step, and photosynthesis performance index, respectively.

In the second year of the study, the values of the Fv/Fo, Fv/Fm, and VI were significantly reduced (Figure 2A–C). Varan had the highest Fv/Fm value in both years. The differences among Sadra, Hashtroud, and Ohadi in the first year and between Sadra and Hashtroud in the second year in terms of Fv/Fm were not significant (Figure 2B). The wheat genotypes had more VI in the vetch pre-crop than the wheat monoculture treatment over the two years. The statistical similarity of the responses among almost all genotypes was observed in both years under the wheat pre-cropping system, as well as in the second year under the vetch pre-cropping system for VI. However, the highest VI value was obtained from Varan under the vetch pre-crop for wheat genotypes in the first year (Figure 2C).

Table 6. Chlorophyll fluorescence parameters' changes of dryland wheat genotypes under different pre-cropping systems of wheat and vetch and their residue levels.

Treatments		Fv/Fo	Fv/Fm	VJ	VI	PI	
<i>p</i> Value		**	**	**	**	**	
wheat–wheat	control	Sadra	1.38 IJ	0.59 KLM	0.42 IJ	0.49 KL	0.34 L
		Hashtrud	1.46 HI	0.60 JKL	0.44 HI	0.49 KL	0.34 L
		Baran	1.28 J-M	0.61 IJK	0.44 HI	0.50 K	0.33 L
		Varan	1.29 JKL	0.60 JKL	0.43 HIJ	0.5 K	0.33 L
		Ohadi	1.19 LM	0.58 LM	0.43 HIJ	0.48 KLM	0.33 L
	2 T ha ^{−1}	Sadra	1.67 FG	0.63 GHI	0.63 F	0.70 HI	0.56 EF
		Hashtrud	1.65 G	0.64 FGH	0.63 F	0.71 H	0.55 FG
		Baran	1.46 HI	0.65 EFG	0.65 E	0.72 GH	0.56 EF
		Varan	1.52 H	0.67 CDE	0.66 E	0.75 EF	0.60 BCD
		Ohadi	1.45 HI	0.64 FGH	0.63 F	0.70 HI	0.54 FG
	4 T ha ^{−1}	Sadra	1.18 M	0.63 GHI	0.51 G	0.56 J	0.53 GH
		Hashtrud	1.18 M	0.63 GHI	0.51 G	0.58 J	0.49 IJ
		Baran	1.22 LM	0.62 HIJ	0.50 G	0.57 J	0.48 JK
		Varan	1.20 LM	0.61 IJK	0.51 G	0.58 J	0.51 HI
		Ohadi	1.26 LKM	0.60 JKL	0.49 G	0.56 J	0.46 K

Table 6. Cont.

Treatments		Fv/Fo	Fv/Fm	VJ	VI	PI	
<i>p</i> Value		**	**	**	**	**	
vetch–wheat	control	Sadra	1.53 H	0.59 KLM	0.45 H	0.47 LM	0.34 L
		Hashtrod	1.51 H	0.58 LM	0.41 J	0.47 LM	0.34 L
		Baran	1.37 IJ	0.59 KLM	0.42 IJ	0.47 LM	0.34 L
		Varan	1.26 KLM	0.6 JKL	0.42 IJ	0.48 KLM	0.33 L
		Ohadi	1.33 JK	0.57 M	0.42 IJ	0.46 M	0.33 L
	2 T ha ^{−1}	Sadra	1.83 E	0.67 CDE	0.70 CD	0.68 I	0.59 CD
		Hashtrod	1.94 D	0.67 CDE	0.71 CD	0.70 HI	0.58 DE
		Baran	1.76 EF	0.68 BCD	0.69 D	0.71 H	0.58 DE
		Varan	1.97 D	0.70 AB	0.72 C	0.74 FG	0.59 CD
		Ohadi	1.66 G	0.66 DEF	0.66 E	0.68 I	0.58 DE
	4 T ha ^{−1}	Sadra	2.30 B	0.68 BCD	0.79 A	0.79 CD	0.61 BC
		Hashtrod	2.25 B	0.68 BCD	0.77 B	0.81 BC	0.61 BC
		Baran	2.33 AB	0.69 BC	0.80 A	0.77 DE	0.62 B
		Varan	2.40 A	0.72 A	0.81 A	0.89 A	0.66 A
		Ohadi	2.13 C	0.67 CDE	0.77 B	0.82 B	0.61 BC

Means followed by the same letter in each column are not significantly different at $p < 0.05$ according to the Duncan multiple range test. ** is significant at 1% probability levels. Fv/Fo, Fv/Fm, VJ, VI, and PI are water-splitting complexes in PSII, the maximum quantum efficiency of the PSII, relative variable fluorescence at the J step, relative variable fluorescence at the I step, and photosynthesis performance index, respectively.

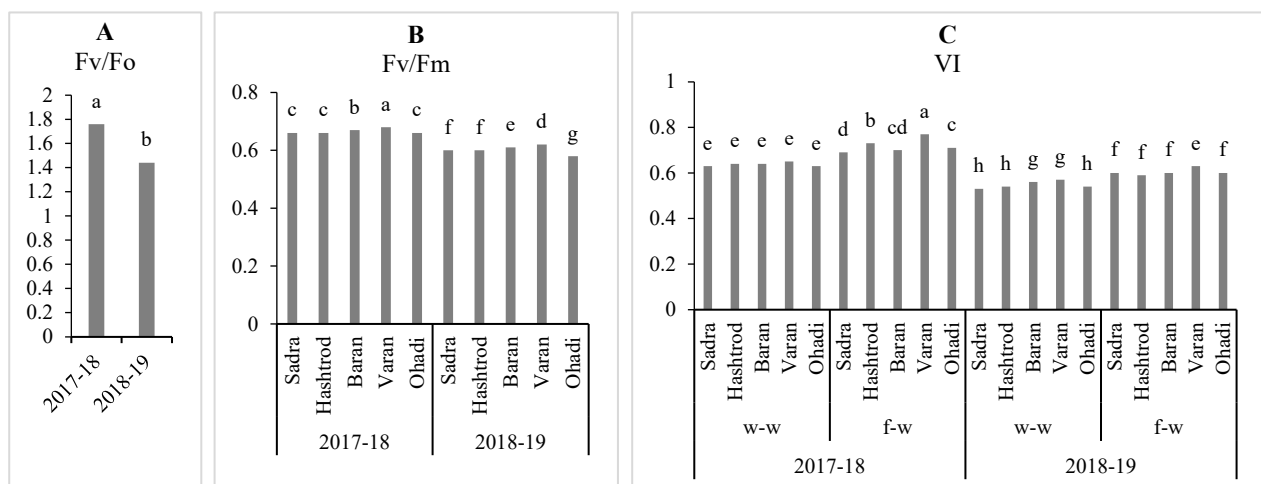


Figure 2. Changes in Fv/Fo (A), Fv/Fm (B), and VI (C) of wheat genotypes under wheat–wheat (w-w) and forage (vetch)–wheat (f-w) rotation during 2017–2018 and 2018–2019. Means followed by the same letter are not significantly different at $p < 0.05$ according to the Duncan multiple range test. Fv, Fo, Fv/Fm, and VI refer to the water-splitting complex in PSII, the maximum quantum efficiency of the PSII, and relative variable fluorescence at I step, respectively.

3.3. Grain Yield and Components

With the increases in crop residue levels, the 1000 grain weight (GW) of all genotypes increased. This increment for the vetch–wheat was more than the wheat–wheat cropping system. The highest grain weight was recorded for the Varan and Baran genotypes under 4 t ha^{−1} vetch residue. The grain-filling rate (GFR) of the genotypes was reduced with increasing the crop residue levels. This reduction in genotypes was different. The highest rate of grain filling was obtained from Varan and Baran under the vetch–wheat system when the crop residue was removed (control treatment). In contrast, the grain filling duration (GFD) of all genotypes increased with increasing vetch residue levels. The GRD of the genotypes under 4 t ha^{−1} of wheat residue decreased or remained unchanged in

comparison to the control. The duration of grain filling was the longest for the Ohadi, Varan, and Baran genotypes when subjected to a vetch residue of 4 t ha^{−1}. The genotypes exhibited higher grain yield as the wheat residue progressively increased up to 2 t ha^{−1}, while the vetch residue showed a similar trend up to 4 t ha^{−1}. The grain yield of wheat either decreased or remained unchanged, depending on different genotypes under 4 t ha^{−1} of wheat residue. Varan and Baran achieved the highest grain yields when subjected to 4 t ha^{−1} of vetch residue (Table 7).

Table 7. Changes in grain weight, filling rate, filling duration, and yield of wheat genotypes under different pre-cropping systems and residue levels.

Treatments		1000 GW (g)	GFR (mg grain ^{−1} day ^{−1})	GFD (day)	GY (t ha ^{−1})	
<i>p</i> Value		**	**	**	*	
wheat-wheat	control	Sadra	35.26 S	0.77 DE	37.52 FG	2.2941 K
		Hashtrod	35.78 R	0.77 DE	37.49 FG	2.5258 J
		Baran	36.86 NO	0.79 BC	37.28 FGH	2.5910 IJ
		Varan	37.07 L-N	0.80 B	37.27 FGH	2.7381 GH
		Ohadi	36.51 PQ	0.77 DE	37.58 F	1.8849 M
	2 t ha ^{−1}	Sadra	36.33 Q	0.70 HI	36.59 I	2.5832 IJ
		Hashtrod	36.43 Q	0.71 GH	36.92 F-I	2.6409 HIJ
		Baran	37.74 HI	0.77 DE	36.64 HI	2.9173 EF
		Varan	38.04 FG	0.78 CD	37.22 F-I	3.0400 DE
		Ohadi	36.97 MNO	0.75 F	38.15 E	2.1031 L
	4 t ha ^{−1}	Sadra	37.30 JKL	0.61 L	36.62 HI	2.5365 J
		Hashtrod	37.57 IJ	0.64 K	37.1 F-I	2.6107 HIJ
		Baran	38.62 CD	0.72 G	37.11 F-I	2.8448 FG
		Varan	38.86 C	0.71 GH	37.16 F-I	3.0761 CD
		Ohadi	37.26 KLM	0.71 GH	36.89 GHI	2.0758 L
vetch-wheat	control	Sadra	36.73 OP	0.75 F	37.22 F-I	2.6216 HIJ
		Hashtrod	37.247 LM	0.76 EF	37.21 F-I	2.6599 HIJ
		Baran	37.61 HIJ	0.82 A	35.63 J	2.7254 GHI
		Varan	37.95 GH	0.83 A	35.45 J	2.6518 HIJ
		Ohadi	37.75 HI	0.79 BC	36.7 HI	1.9110 M
	2 t ha ^{−1}	Sadra	37.73 HI	0.69 I	38.64 DE	3.0793 CD
		Hashtrod	37.66 HIJ	0.69 I	38.63 DE	3.1949 C
		Baran	38.81 GHI	0.75 F	39.11 CD	3.3286 B
		Varan	38.67 CD	0.76 EF	39.35 BC	3.4491 B
		Ohadi	37.507 IJK	0.72 G	39.83 AB	2.7091 G-I
	4 t ha ^{−1}	Sadra	38.243 EF	0.65 K	38.76 CD	3.3456 B
		Hashtrod	38.443 DE	0.67 J	38.89 CD	3.3667 B
		Baran	40.107 A	0.69 I	39.85 AB	3.7032 A
		Varan	40.387 A	0.71 GH	39.82 AB	3.8099 A
		Ohadi	39.353 B	0.69 I	40.09 A	2.8307 FG

Means in each column followed by the same letter are not significantly different at $p < 0.05$ according to the Duncan multiple range tests, and * and ** are significant at 5% and 1% probability levels, respectively; 1000 GW, GFR, GFD, and GY represent 1000 grain weight, grain filling rate, grain filling duration, and grain yield, respectively.

4. Discussion

4.1. Physiological Parameters: CCI, NDVI, and Gs

The increase in the content of chlorophyll under the vetch–wheat system (Table 3) may be due to the release of nutrients such as nitrogen from the vetch (legume) residue. It was reported in a laboratory experiment that after 35 days, 51 and 36% of N in the incorporated and surface-placed vetch residue, respectively, were mineralized [24]. In addition, wheat straw has a C:N ratio of around 90:1 and will require N addition or C loss to decompose to the soil equilibrium value of 10:1 [25]; therefore, beyond the fact that wheat residues do not

contribute nitrogen to the soil, their decomposition process requires a significant amount of nitrogen, which can lead to nitrogen deficiency symptoms in plants, particularly when the wheat residue levels are elevated. The chlorophyll content is an index used to evaluate the health of leaves and the photosynthetic ability of crops, which is highly influenced by environmental conditions such as nutrition [26]. The conditions for the development of microorganisms are more favorable in the legume cropping system, which results in higher soil organic matter deposition and higher exudation of organic compounds by the roots [27]. These conditions provide N, resulting in increases in the chlorophyll content. Increasing the gs under the vetch–wheat system (Table 3) is related to the effects of the legume pre-crop on nutrient availability. Nitrogen availability can influence stomatal conductance in plants. Increased nitrogen availability can lead to higher stomatal conductance, as nitrogen is a crucial nutrient for plant growth and development [28].

The relationship between the crop residue quantity and the CCI is determined by how residue impacts soil water storage and nutrient availability for plant growth. The chlorophyll content in plants can vary depending on factors such as light intensity, temperature, and nutrient availability. The higher CCI under different levels of the crop residue (Figure 1) indicated that N in the root zone soil is often higher in cereal–legume cropping systems than in cereal monoculture [29]. Lotfi and Pessarakli [30] demonstrated that maintaining the residues, especially in the vetch–wheat cropping system, increasing the soil moisture storage, and also enhancing soil fertility through the rotation of legumes and cereals contributes to the improvement of plant growth by enhancing plant pigment production.

The NDVI is employed for assessing the health status of plants, and the elevated NDVI values observed in the wheat genotypes within the vetch–wheat cropping system (Table 4) signify the presence of favorable conditions conducive to plant growth. Lotfi and Pessarakli [30] found that plants from the vetch–wheat rotation had higher NDVI than the chickpea–wheat and safflower–wheat treatments. NDVI has previously been associated with plant water status, even though it is primarily affected by the relative water content and the cell wall elasticity of leaf tissues. Spectral vegetation indexes, such as NDVI, could successfully estimate the photosynthetic efficiency of the crop [30] and it is sensitive to the leaf area index and green biomass [31]. By estimating the mid-season N requirement, the NDVI sensor could act as a framework for rational N management in cereals [31]. A robust relationship between NDVI and grain yield showed higher NUEs than the conventional approach of N recommendation [32].

4.2. Chlorophyll Fluorescence Parameters

The impairment of PSII reaction centers during stressful conditions is impacted by electron transport and energy conversion. Certain OJIP-related parameters, such as ABS/RC, were computed to pinpoint the areas of damage on the acceptor side of PSII [33]. Reducing the ABS/RC at 2 t ha^{−1} of wheat residue and 2 and 4 t ha^{−1} of vetch residue levels (Table 5) showed that the plants had not been under stress conditions. Under stress conditions, ABS/RC dramatically increased, implying the dissipation of most of the absorbed energy by the PSII reaction center [34]. According to Strasser et al. [33], increasing ABS/RC under stress might indicate a change in the number of light-harvesting complexes (HLC) per PSII reaction center or inactivation of some reaction centers, i.e., a reduction in active QA-reducing reaction centers. Additional factors leading to the increase in ABS/RC levels include the deterioration of chlorophyll due to early leaf senescence caused by severe stress and the relocation of antennae from inactive PSII RCs to active ones [35]. In our research, the reduction in the ABS/RC was supported by the NDVI and CCI results (Figure 1, Table 4). Fv/Fo is the most sensitive component in the photosynthetic electron transport chain [32]. The increase in Fv/Fo (Table 5), as a consequence of crop residue application, results from photosynthetic electron transport construction. The maximal quantum efficiency of PSII (Fv/Fm) and the photosynthetic performance index (PI) are widely utilized metrics for evaluating the condition of PSII in response to abiotic stressors [36]. However, there is conclusive evidence that advises against reliance on Fv/Fm and PI as the most important

parameters [35]. The increasing F_v/F_m value under crop residue (Table 5) indicates high efficiency of the electron transport and quantum yield of the PSII, as Kalaji et al. [36] reported that the reduction in F_v/F_m under stress conditions could prevent the transfer of electrons from the PSII reaction center to electron transporters. Improving the F_v/F_m can be interpreted as a reversible effect of light inhibition, which has a protective and regulatory function for the photosynthetic system of leaves [35]. The reduction in F_v/F_m under high levels of wheat residue might indicate the fact that PSII RCs were impaired or not functioning effectively in photosynthesis.

4.3. Grain Yield and Component

Environmental stresses during grain filling can lead to a reduction in mean grain weight [37]. Genetic factors can also contribute to grain weight, influencing the rate and duration of grain filling and their interaction [38]. Our results indicated that Baran and Varan had the highest grain filling duration and weight (Table 6). Environmental fluctuations such as temperature, water availability, light intensity, and nutrition caused by different crop rotations and residue levels have a significant impact on grain weight and yield. This is likely related to high environmental variations during the relatively long grain-filling period [39]. In some cases, the grain weight was more related to the grain-filling duration (GFD), while in others, it was more related to the maximum grain-filling rate [40]. Our results confirm that the crop residue levels had more significant effects on grain-filling duration compared to the grain-filling rate (Table 7). The GFD and GFR have major effects on final grain weight and can have significant effects on final yield [41]. Differential responses may easily emerge when the genotypes are exposed to a sufficiently wide range of growing conditions. In our study, we demonstrated that the determination of the grain weight and grain-filling parameters was influenced by both the genotypes and the environment. Crop residue, by affecting the soil properties such as moisture content and temperature, can affect plants' growing conditions. Lotfi and Pessarakli [30] reported that soil moisture storage is influenced by crop rotation and tillage methods in dryland conditions. In addition, several studies have demonstrated that genotype determines the grain-filling rate, whereas environmental factors, such as temperature, affect the duration of the grain-filling period [41]. The higher grain yield (Table 7) of the wheat genotypes under vetch crop residue is related to the improvement in the NDVI (Table 4), photosynthetic efficiency (Table 6), grain-filling duration, and grain weight (Table 7). Chlorophyll is a key component in the process of photosynthesis. The findings of our study indicate that reduced ABS/RC levels contribute to the maintenance of chlorophyll in leaves by delaying senescence. Additionally, increased values of F_v/F_o and F_v/F_m are associated with higher photosynthetic efficiency in plants. Therefore, higher values of CCI and/or NDVI, especially during grain filling, support the greater requirements of photosynthates during grain development [42]. A longer duration of grain filling facilitates more dry matter accumulation, which ultimately results in a high yield [43].

Possible factors for the higher crop performance under forage legumes are related to soil moisture availability and nutrient uptake. Soil texture and/or initial nutrient status or residue quality can affect plant responses to the different types of residue [8]. The literature on the effect of residue management on nitrogen (N) or phosphorus (P) uptake by plants is equally varied, with some studies reporting no effect (for N: [44]), positive effects (for N: [45]), or negative effects (for N: [46]). N is a key factor in the reaction of grains following legumes compared with grains following nonlegumes [47]. Geng et al. [48] conducted a global meta-analysis on the effects of legume–wheat rotation systems and indicated that legume–wheat rotations significantly increased wheat yields compared to gramineae–wheat rotations ($p < 0.05$). This is consistent with the results of Cernay et al. [49], whose meta-analysis found that previous legume crops significantly increased subsequent grain yields by 29% on average.

The potential decline or cessation in the growth and productivity of wheat genotypes when exposed to 4 t ha^{-1} of wheat residue (Table 7) could potentially be attributed to the

allelopathic impacts of the material. Allelopathy in wheat has been extensively studied and demonstrated by a consolidated scientific literature [50]. There are many allelochemicals involved in wheat allelopathy, belonging to three main chemical classes: phenolic acids (e.g., p-hydroxybenzoic, ferulic, syringic, vanillic, p-coumaric, etc.), benzoxazinoids (DIMBOA, MBOA, HMBOA, DIMBOA glycoside, BOA), and short-chain fatty acids (e.g., propionic, acetic, butyric, etc.) [47]. Scavo et al., [51] reported that ear extracts of durum wheat had the most active phytotoxicity, and they suggest that wheat residue could be left on the soil surface or soil incorporated after harvest for possible weed control. A reduction in the physiological properties such as the CCI (Figure 1) content and chlorophyll fluorescence values (Table 6) of the genotypes under 4 t ha⁻¹ wheat residue might be the allelochemical's adverse effect on the uptake of nutrients. For example, ferulic acid and cinnamic acid decrease the availability of Fe, P, and other nutrients [50]. This reduction is attributed to altered cell membrane permeability due to the presence of these allelochemicals [52]. Several physiological effects induced in response to allelochemicals include a reduction in overall plant growth [51]. Khaliq et al. [53] found that wheat straw-amended and infested rhizosphere soil had an allelopathic effect on *T. portulacastrum* and significantly reduced its germination, seedling growth, and biochemical attributes.

5. Conclusions

In both years of the experiment, the CCI and gs were greater in the vetch–wheat cropping system compared to the wheat–wheat system for all genotypes. The NDVI of wheat genotypes improved in both rates of 2 and 4 t ha⁻¹ of wheat and vetch residues compared to that of the control condition. The gs activity of the genotypes grown in vetch pre-crop generally exhibited higher levels compared to the wheat pre-crop. The gs activity of all phenotypes did not show an increase when the level of wheat residue reached 4 t ha⁻¹. Over two years, the utilization of wheat and vetch residue resulted in higher variable fluorescence at the J and I steps, as well as an increase in PI, but ABS/RC declined in comparison to the control treatment. The Varan genotype stood out as the superior one, exhibiting the highest values for Fv/Fo, Fv/Fm, VJ, VI, and PI under the application of 4 t ha⁻¹ of vetch residue. The highest GW grains were recorded for the Varan and Baran genotypes under 4 t ha⁻¹ of vetch residue. The GFR of the genotypes reduced with increasing crop residue levels. In contrast, the GFD of all genotypes increased with increasing vetch residue levels. The higher GY of the genotypes under vetch residue is related to improving the NDVI, photosynthetic efficiency, grain-filling duration, and grain weight. It can be concluded that a vetch–wheat cropping system with crop residue management in dryland areas is one of the key sustainable practices for wheat production, but this concept could be expanded by assessing the rotation of additional crops in conjunction with various tillage systems.

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